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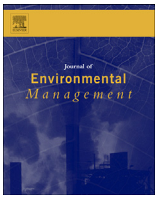

Optimality versus stability in water resource allocation

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ABSTRACT

Water allocation is a growing concern in a developing world where limited resources like fresh water are in greater demand by more parties. Negotiations over allocations often involve multiple groups with disparate social, economic, and political status and needs, who are seeking a management solution for a wide range of demands. Optimization techniques for identifying the Pareto-optimal (social planner solution) to multi-criteria multi-participant problems are commonly implemented, although often reaching agreement for this solution is difficult. In negotiations with multiple-decision makers, parties who base decisions on individual rationality may find the social planner solution to be unfair, thus creating a need to evaluate the willingness to cooperate and practicality of a cooperative allocation solution, i.e., the solution's stability. This paper suggests seeking solutions for multi-participant resource allocation problems through an economics-based power index allocation method. This method can inform on allocation schemes that quantify a party's willingness to participate in a negotiation rather than opt for no agreement. Through comparison of the suggested method with a range of distance-based multi-criteria decision making rules, namely, least squares, MAXIMIN, MINIMAX, and compromise programming, this paper shows that optimality and stability can produce different allocation solutions. The mismatch between the socially-optimal alternative and the most stable alternative can potentially result in parties leaving the negotiation as they may be too dissatisfied with their resource share. This finding has important policy implications as it justifies why stakeholders may not accept the socially optimal solution in practice, and underlies the necessity of considering stability where it may be more appropriate to give up an unstable Pareto-optimal solution for an inferior stable one. Authors suggest assessing the stability of an allocation solution as an additional component to an analysis that seeks to distribute water in a negotiated process.

1. Introduction

Water resource planning problems are multi-dimensional by nature, as they involve synthesizing hydrological, environmental, and socio-economic data for successful management of the system. Madani and Lund (2011) assert that water resource decision-making problems are multi-criteria (MC) and fall into two categories: single decision-maker (MC-SDM) and multiple decision-maker (MC-MDM), classified based on if a single entity acts as the decision maker or if decisions are to be made by multiple parties. Water resource management is increasingly grappling with adding stakeholders to its decision-making collective as supplies become more limited, demands increase, and water users rely more heavily on shared resources. Managers should be well informed on the complexity of water systems and the interests and needs of their stakeholders to be able to implement their plans. Multi-party negotiations over water resource allocation problems are complicated by inherent differences in political, social, and economic status among the parties involved in the negotiation.

Hajkowicz and Collins (2007) provide a review of the extensive applications of multi-criteria decision-making (MCDM) methods to water resource management problems. Conventional methods for assessing MCDM problems involve aggregating the multiple stakeholders into a single decision-maker, a process that lumps the parties' perspectives and behavior into a homogeneous entity and assumes unanimous agreement. In other words, these methods convert an MC-MDM problem to a MC-SDM problem in order to prescribe an optimal (efficient) solution to decision-making problems. This effectively omits the self-optimizing behavior that can be

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an important barrier to reaching an agreement over the system's optimal solution (Cardenas and Ostrom, 2004; Madani, 2010).

To improve upon convention, conflict resolution methods have been applied to facilitate water negotiations with increasing popularity in recent years (Madani, 2010; Bourget, 2011). These methods seek collaboration among parties to develop cooperative decision rules, sometimes using optimization methods from operations research (Lund and Palmer, 1997; Madani, 2010). In these works, finding the Pareto-optimal solution, or the one that provides the best solution for each user without compromising the benefits of another, is the primary objective. However, achieving Pareto-optimal (efficient) solutions in practice in a negotiation may not be feasible due to the complex external power dynamics that exist between decision makers (DMs) and the different reactions and strategies that DMs can adopt (Madani, 2013). In the water resources management context, factors such as lack of trust, information, and communication can result in tragedy of the commons (Hardin, 1968), as parties prefer to act based on individual-rationality as opposed to group-rationality (Madani and Dinar, 2012a). As long as parties have strong incentives for acting based on self-interest, even regulations and intervention by governments may be subject to failure (Madani and Dinar, 2013). On the other hand, "environmental policy and governance" researchers such as Ostrom (1998) and Lubell et al. (2002) have provided strong evidence for circumstances under which water resource stakeholders are more likely to develop cooperative institutions (Madani and Dinar, 2012b), rather than working individually to maximize their gains.

Lubell et al. (2002) identifies the presence of three factors – problem severity, institutional opportunities, and political incentives, in determining whether parties in negotiation are likely to form partnerships toward cooperative solutions or work for individual interests. Since behavioral and institutional factors can influence a negotiation and potentially destabilize otherwise ideal or optimal solutions, alternative solutions that address stability (feasibility) in addition to optimality in MC-MDM problems can provide additional insight. Fairness is another factor that contributes to the emergence of solutions which may differ from those identified by the Pareto-frontier. That is, sub-optimal (Pareto-inefficient) solutions exist that may be perceived as fair according to all parties, and will emerge as more stable. In these cases, parties will prefer a fairer allocation to an allocation which is not acceptable based on individual-rationality (Dinar and Howitt, 1997).

Game theory methods provide an appropriate framework for analyzing MC-MDM problems (Madani and Lund, 2011), as these methods can incorporate the individuality of players' strategies and behaviors in MC-MDM, provide valuable insights into real water resource conflicts (Rogers, 1969; Dinar and Alemu, 2000; Fisher and Huber-Lee, 2008; Wang et al., 2008; Teasley and McKinney, 2011; Madani and Lund, 2012) and offer different solutions from conventional systems methods in selecting the outcome. A classic example for highlighting the difference between Pareto-optimality (conventional solution) and stability (game theoretic solution) is the prisoner's dilemma, for which the outcome between the two players is not the one with the highest payoff for the system (Pareto-optimal), but is instead the one that emerges through simultaneous maximization of individuals' utilities. Thus, in the context of MC-MDMs, a stability analysis can form a different feasible solution set than an optimality analysis, since DMs are unlikely to reject a solution which they all find stable, i.e., an equilibrium (Madani and Hipel, 2011).

Systems engineering methods such as goal programming, least squares analysis, compromise programming, and Pareto-based optimality have been largely used to solve water resources allocation problems (Draper et al., 2003; Loucks & van Beek, 2005; Hollinshead and Lund, 2006; Zoltay et al., 2010). This discussion shows the breadth of optimization to solve water and resource problems, and also highlights a need to include stability analysis in MC-MDM issues. Optimality as a sole analysis is better suited for MC-SDM problems where an algorithm to optimize based on multiple criteria can be employed, and the relative dissatisfaction of parties is not preventive of implementing the optimal solution in practice (Madani and Lund, 2011). Conversely, MC-MDM problems can benefit from a mathematical formulation that includes stability as an evaluation metric, such as the power index method presented in this work. Stable solutions can provide important insight in practical MC-MDM cases where it is often difficult to reach consensus on the system's optimal solutions, since 'optimality' from a systems (social planner's) view does not consider stakeholders' perceptions of fairness and acceptability.

Generally defined, power may reflect decision makers' relative willingness to cooperate in the negotiation process. Rooted in economics literature (Shapley and Shubik, 1954; Gately, 1974; Loehman et al., 1979; Straffin and Heaney, 1981), power-based approaches rely on the premise that the most stable (feasible) solution is that which distributes powers equally. Mainly applied in the cooperative game theory literature, power index (Loehman et al., 1979) is considered to be an appropriate method for selecting the most stable or fair method to allocate the incremental benefits of cooperation (Dinar and Howitt, 1997; Teasley and McKinney, 2011; Madani and Dinar, 2012b). While this method has not been originally developed for applications in assessing the stability of water and resource allocation solutions, this paper adapts the power index method to develop discrete and continuous solutions for water resource allocation problems with multiple DMs. The main objectives of this work are: (1) to present a method for determining the relative stability (feasibility) of allocation solutions with multiple DMs, and provide a comparison to those calculated via socially optimal methods; (2) to characterize the relative satisfaction of DMs in a negotiation under socially optimal and stable methods in a continuous space; (3) to provide a case study for illustrating the practical significance of conducting a stability analysis through the power index method.

The paper is structured as follows. The next section presents the MC-MDM formulations of distance-based methods and compares them to applying a stability metric via the power index. Section three presents background on the Caspian Sea case study; and section four discusses the allocation results from using discrete predefined division rules to divide the Caspian Sea when all players have equal power in the negotiation. Section five presents a new allocation method based on the power index to calculate continuous solutions for MC-MDM problems, and presents results for the Caspian Sea case study. Section six discusses how external negotiator weights influence the allocation results for continuous and discrete formulations; the paper closes with a discussion of policy implications and concluding remarks.

2. Water allocation methods

In allocation problems, highly dissatisfied parties may find certain solutions unfair and resist implementing them (Dinar and Howitt, 1997; Madani and Dinar, 2012b). Therefore, several allocation methods in the literature focus on fair distribution of dissatisfaction among parties. Generally in the water resources literature these are distance-based allocation methods, which try to minimize the distance of the allocation solution from the ideal solutions of the stakeholders. To highlight the major differences between the operations research (OR) allocation methods and the economic method introduced in this study, i.e., power index, four commonly used distance-based methods are reviewed here.

2.1. Distance-based methods

Systems engineering literature on group decision-making utilizes distance to evaluate the performance of solutions. Distance from the ideal solution (request or claim) can be a reliable indicator of the dissatisfaction level of a given party. Goal programming (Charnes et al., 1955; Charnes and Cooper, 1961; Ijiri, 1965) and compromise programming (Zeleny, 1973; Duckstein and Opricovic, 1980) techniques are among the most common methods in the water resources literature (Tecle et al., 1987; Zekri and Romero, 1993; Chang et al., 1994; Ozelkan and Duckstein, 1996; Bella et al., 1996; Lee and Wen, 1997; Abrishamchi et al., 2005; Agha, 2006; Mohammadi et al., 2006; Hajkowicz and Higgins, 2008; Bravo and Gonzalez, 2009; Madani et al., in press).

2.1.1. Least squares solution

This goal programming method selects the most preferable allocation solution as the one with the minimum total squared distances from the parties' ideal solutions and the proposed resource shares as described by Equation (1):

$$Min\sum_{i=1}^{m}\left(w_i\left(f_i^*-f_{i,j}\right)\right)^2 \tag{1}$$

where $i=\{1,2,3,\ldots,m\}$ is the set of bargainers (negotiation parties), $j=\{1,2,3,\ldots,n\}$ is the set of possible allocation solutions, f_i^* is the ideal value (share) or claim of the bargainer i, $f_{i,j}$ is the share of bargainer i under allocation solution j, and w_i is the weight of bargainer i.

The least squares solution method is interested in minimizing the sum of dissatisfactions and does not differentiate between dissatisfaction of the negotiating parties. As a result, it may recommend a solution that favors parties with high claims, making this method inappropriate when parties' claims are heterogeneous. An improvement is to consider dissatisfaction as the percent deviation from the ideal solution as calculated by Equation (2):

$$\text{Min}\left[\sum_{i=1}^{m}\left(w_i\frac{f_i^*-f_{i,j}}{f_i^*}\right)^2\right],\quad \forall j \tag{2}$$

2.1.2. MINIMAX

This goal programming method selects a scheme that minimizes the overall maximum dissatisfaction of all parties. This approach is particularly applicable in situations where negotiation is likely to fail in practice if one of the players is extremely dissatisfied with the allocation solution. Thus, the MINIMAX solution tries to distribute dissatisfaction across all players homogeneously, which is expected to be more acceptable in practice than an imbalanced distribution of dissatisfaction. MINIMAX is formulated as Equation (3):

$$\text{Min}\quad \text{Max}\left\{w_i\left(f_i^*-f_{i,j}\right)\right\},\quad \forall i,\quad \forall j \tag{3}$$

Similar to the least square solution method, the term representing dissatisfaction in Equation (3) can be replaced with a relative dissatisfaction term to avoid favoring parties with high claims:

$$\text{Min}\quad \text{Max}\left\{w_i\frac{\left(f_i^*-f_{i,j}\right)}{f_i^*}\right\},\quad \forall i,\quad \forall j \tag{4}$$

2.1.3. MAXIMIN

Solutions from a MAXIMIN analysis maximize the minimum satisfaction level in order to raise the satisfaction level for the most marginalized parties. This approach adds robustness to the outcome by minimizing heterogeneity in dissatisfaction among the parties. It is dependent on the premise that highly dissatisfied parties are unlikely to agree if other parties receive disproportionally higher claims. MAXIMIN is formulated in Equation (5) as:

$$\text{Max}\quad \text{Min}\left\{\frac{f_{i,j}}{w_i f_i^*}\right\},\quad \forall i,\quad \forall j \tag{5}$$

2.1.4. Compromise programming

Compromise programming (CP) chooses the best solution as the one closest to the ideal point as defined by a series of distance measures that identify the feasible set (Yu, 1973; Lee, 2008). Compromise programming uses concepts of goal programming with normalized values of distance deviations to reduce the influences of large values and achieve a realistic comparison between dissatisfactions. CP calculates the best solution using Equation (6) (Zeleny, 1973):

$$\text{Min}\quad Lp=\left(\sum_{i=1}^{m}w_i\left|\frac{f_i^*-f_{i,j}}{f_i^*-f_i^-}\right|^p\right)^{1/p},\quad \forall i,\quad \forall j \tag{6}$$

where f_i^- is the anti-ideal value (could be revealed by bargainers), and p is a parameter with values in the range from $[1,\infty]$. Solving the equation for $p=1$ and $p=\infty$ ensures that the solution falls within the compromise set. As the value of p increases, the solution shifts from minimizing the sum of individual dissatisfactions to minimizing the individual's maximum dissatisfaction (Zarghami and Szidarovszky, 2010).

For example, inserting $p=1$ into Equation (6) yields:

$$\text{Min}\quad Lp=\left(\sum_{i=1}^{m}w_i\left|\frac{f_i^*-f_{i,j}}{f_i^*-f_i^-}\right|\right),\quad \forall i,\quad \forall j \tag{7}$$

For $p=\infty$, the best solution is one that seeks the lowest level of group regret by minimizing the maximum individual deviations. In other words, since the largest deviation has the greatest influence (Romero and Rehman, 2003), the CP problem is converted to a MINIMAX problem (if $f_i^-=0$) with the same allocation results.

2.2. Power index allocation method

The power index has been applied in economics literature to explain how the power structure among parties in a negotiation (game) can influence strategy and ultimately outcomes. This method is normally used for identifying stable solutions to cooperative problems in which the parties are negotiating agreement on the incremental benefits of cooperation (Dinar and Howitt, 1997; Teasley and McKinney, 2011; Madani and Dinar, 2012b). Normalized to compute relative power between parties, the power index formulation is presented in Equation (8) as (Loehman et al., 1979):

$$£_j=\frac{\Theta_j-v(\{j\})}{\sum_{j\in N}\left(\Theta_j-v(\{j\})\right)}\quad j\in N;\quad \sum_{j\in N}£_j=1 \tag{8}$$

where £ is the index value for each j player from the set of N players; Θ_j is the ideal benefit allocation to player j, and $v(\{j\})$ is actual benefit amount allocated to player j. The power index method can be rewritten in terms of allocation to measure stability in a negotiation problems as:

Fig. 1. An overview map of the Caspian Sea with surrounding countries.

$$\alpha_i = \frac{w_i\left(f_i^* - f_{i,j}\right)}{\sum_{i=0}^{m} w_i\left(f_i^* - f_{i,j}\right)}, \quad \forall i,\ \forall j \tag{9}$$

such that:

$$\sum_{i=0}^{m} \alpha_i = 1 \tag{10}$$

$$0 \le f_{i,j} \le f_i^* \tag{11}$$

where α_i is the power index of player i. The index compares the gains of a party to the total gains of the group with m players. The power index method suggests that the most stable and acceptable alternative is one that distributes power most equally between parties (Dinar and Howitt, 1997). Parties with greater index values signify that they are receiving a higher proportion of gains compared with the rest of the group. The authors propose to measure stability in MC-MDM water allocation problems as the coefficient of variation (CV), calculated across all players for a given alternative, and presented in Equation (12):

$$\mathrm{CV} = \frac{\sigma}{\overline{\alpha}} \tag{12}$$

where σ is the standard deviation of the set and represents the variability, and $\overline{\alpha}$ is the mean power index value calculated across m players. Lower values of CV represent solutions with greater stability (feasibility), that have a greater chance of reaching agreement based on the willingness for the negotiators to cooperate.

3. Caspian Sea case study

The Caspian Sea is an inland water body of about 370,000 km^2 nestled between five nations (Azerbaijan, Iran, Kazakhstan, Russia, and Turkmenistan) in Northwest Asia (Fig. 1). Governance over marine boundaries within the Caspian Sea have been a source of negotiation and conflict between the littoral states since the collapse of the Soviet Union in 1991 (Mehdiyoun, 2000; Nichol, 2011). Prior to 1991, governance of the Caspian Sea followed two bilateral treaties signed in 1921 and 1940 between Persia (Iran) and Russia, dividing the Sea into two sections and granting freedom of navigation and fishing rights to both countries (Ascher et al., 2000). After dissolution of the Soviet Union, the newly independent countries asserted claims on territorial oil, gas, and waters, challenging the legitimacy of the existing treaty agreements. As a result, conflicts between the nations arose and have remained unresolved despite continuous negotiations (Ivy, 2002).

Conflict over marine boundaries of the Caspian Sea carries considerable geo-political clout given the Sea's natural gas and crude oil resources available for production. As the surrounding countries continue to develop their nascent economies, accessing the Sea's natural resources is vital to regional growth. The five states each have different preferences to divide resources from a range of suggested methods for setting boundaries within the Caspian Sea (Sheikhmohammady and Madani, 2008a). As a result, negotiations have produced several bilateral and trilateral agreements, but fall short of the unanimous agreement needed to institute a binding legal status of the Sea (Pak and Farajzadeh, 2007).

One source of complexity in the Caspian Sea case arises from the number of parties both directly and indirectly involved in the negotiations. Conflict resolution and successful negotiations become increasingly difficult with five nations seeking solutions as compared to other few-party trans-boundary water resource cases. External parties also factor into the Caspian Sea agreement, as large international oil and gas companies have a substantial stake in the outcome, as do the United States, the European Union, and China (Effimoff, 2000; Przybylski, 2011). Another source of complexity is the unusual physical characteristics of the Caspian Sea, leading experts to debate its proper classification as either a sea or a lake (Ascher et al., 2000). This designation could dictate the set of potential legal structures for managing Caspian Sea-the world's largest inland water body. Confusion arises since the landlocked nature of the sea suggests that it does not qualify as a sea; however, the 1.2% salinity composition (about one-third the salinity of the ocean) supports adoption of the International Law of Seas (Barale, 2008). The on-going lack of consensus on a proper classification is a symptom of a larger disagreement on whether a body of law exists that is appropriate for the Caspian Sea – and thus whether the five states can build a customized legal structure for this unique water body (Ascher et al., 2000).

Several studies have focused on resolving the Caspian Sea conflict through systems engineering and economic methods in recent years. Sheikhmohammady et al. (2006) applied the Graph Model for Conflict Resolution (GMCR) to strategically analyze the Caspian Sea conflict using non-cooperative game theory solutions and predict how the Caspian Sea conflict may evolve over time. Sheikhmohammady and Madani (2008a) applied social choice rules to find the socially optimal method for dividing the Sea and fallback bargaining methods to predict the most likely outcome of the negotiation. In another study, used multi-criteria decision-making methods to find the optimal strategy for governing the Caspian Sea out of the division methods, which have been considered in the negotiations so far. Sheikhmohammady and Madani (2008b) developed a model to analyze the asymmetric multilateral negotiations in the conflict and predict the likely outcome of the game. They considered the powers (in terms of economic, political, and military) of the negotiators as determining factors in finding the final resolution of the conflict. Sheikhmohammady and Madani (2008c) used bankruptcy methods to suggest new division rules for sharing the Caspian Sea resources. Madani and Gholizadeh (2011) and Imen et al. (2012) used cooperative game theory methods to develop fair and efficient allocation schemes for sharing the Caspian Sea oil and gas resources. In another study, Madani et al. (2014) developed a negotiation support system, i.e., Caspian Sea NSS, which maps the location of the Caspian Sea gas and oil resources to suggest optimal nautical division boundaries under different sharing scenarios. Their results suggest a non-linear relationship between division of the sea surface and seabed and highlight the importance of considering the value of seabed resources in developing a fair legal method for sharing the Sea.

These studies provide valuable insights into the Caspian Sea negotiations; however, they do not consider the stability of the proposed allocation rules in practice. While some allocation solutions may seem fair or optimal from the third party's or social planner's point of view, these solutions may not necessarily be stable if the negotiators find them unfair.

Considering the stability of a solution to an allocation problem is essential to its success in practical application. This work intends to close the gap of previous Caspian Sea resource allocation studies by: (1) applying a range of OR/systems engineering and economics methods to evaluate the optimality and stability of previously-suggested division rules for the Caspian Sea (discrete solutions), and (2) suggesting a new method for finding a stable solution from a continuous space in allocation problems. This paper demonstrates how a stability analysis can lead to outcomes which differ from systems engineering optimality. Further, the paper discusses reasons why conventional systems engineering methods may not be suitable for stability evaluation in cases of multi-decision-maker problems.

Since 1993, the five littoral states have engaged in negotiations over the most appropriate legal structure for dividing the Caspian Sea's surface and seabed. The following list outlines five main options for division of the Sea, seriously considered by the negotiating parties to date (Kaliyeva, 2004):

1) Division based on the United Nations Convention on the Law of the Seas, or the median line principle (Dm);
2) Governance based on a Condominium regime (joint sharing) – applicable to both surface and seabed (C);
3) Division based on the old Soviet maps (Ds);
4) Equal division among all five states (i.e., each party receives 20 percent of the sea and seabed) (De); and
5) Division of the seabed based on Dm and division of the sea surface based on C (DC).

Table 1 shows the total resource share percentages for each nation according to the proposed division rules and each nation's corresponding ideal alternative.

As shown in Table 1, the five division rules allocate a different percentage of the oil and gas resources to each country, with the total exceeding the known estimated value by 32.6%, thus creating a conflict in need of a negotiated process. While it is then impossible to find a division rule that is considered optimal by all parties, it is feasible to identify rules that are achievable in practice and that share the total dissatisfaction ($X\%$) homogeneously in such a way that parties are willing to cooperate in the negotiation. For example, consider the alternatives described in Table 1, where C may appear to be best overall alternative given that the majority (three out of five) of negotiators rank C as highest. However, selecting the optimal solution based on this philosophy, i.e., social choice plurality rule, may not be stable in practice given the amount of dissatisfaction a party may develop if they are set to receive minority benefits. In this case, Kazakhstan finds C as the worst alternative for sharing resources, and therefore may show great resistance to adopting C in practice, leading to instability and a potential non-agreement. This suggests that qualitative decision-making methods which only consider ordinal information for ranking alternatives may produce unstable results for resource allocation problems involving multiple DMs. Analyzing the stability of the solution using cardinal information that quantifies the willingness to cooperate is an additional component that may be considered useful in finding feasible and fair solutions to allocation problems.

4. Discrete evaluation of proposed Caspian Sea division rules

In this section, all players are given equal weights in the negotiation (i.e., $w_i = 1$ for all parties). Table 2 shows percentages of negotiators' claims received (or met) under the five proposed division rules (left), and presents the ranking of suggested rules with respect to states' preferences (right). A ranking of "1" indicates that the party prefers this solution over the other four proposed because it yields the highest satisfaction rate (greatest resource benefits compared to their original claim).

Comparing the methods, rule C meets 100% of three out of five negotiators' claims (i.e., based on this rule, their achieved shares are equivalent to their claims). This division rule can fully satisfy Azerbaijan, Iran, and Russia, while Turkmenistan and Kazakhstan receive a relatively dissatisfying 70% and 45% of their claims, respectively. Rules Ds, Dm, and DC can completely fulfill Kazakhstan's claim and satisfy 91% of claims from both Azerbaijan and Turkmenistan; however, neither Dm nor DC are practical for Iran and Russia, whose claims are nearly three times their allotted shares under these solutions. Solution De fully satisfies Turkmenistan's claims and at least 70% of every other country except Russia, who receives a low 35%. Finally, rule Ds completely satisfies Kazakhstan and meets 95% of Azerbaijan and Turkmenistan's claims; however, high dissatisfactions for Iran (19% received) and Russia (29% received) are significant and likely prohibiting for reaching agreement.

In order to derive practical implications from these proposed rules and claims, there is a need to identify the ideal and anti-ideal shares for each party in the Caspian Sea conflict case. In this dispute, negotiators are enthusiastic to agree on alternatives that offer the greatest amount of resources (benefits). Therefore, based

Table 1
Share of oil and natural gas resources allocated by country according to the five proposed division rules (Madani et al., in press).

	Dm	C	Ds	De	DC	
Regional states	Resource share (%)	Resource share (%)	Resource share (%)	Resource share (%)	Resource share (%)	Ideal alternative
Azerbaijan	18.1	20.0	19.1	17.0	18.1	C
Iran	6.1	20.0	3.9	13.7	6.1	C
Kazakhstan	44.2	20.0	44.2	33.9	44.2	Ds, Dm, DC
Russia	5.8	20.0	5.8	6.9	5.8	C
Turkmenistan	25.8	20.0	27.0	28.4	25.8	De

Table 2
Preferences of states based on five proposed division rules.

Regional states	Percent of claim satisfied					Ranking of division rules				
	Dm	C	Ds	De	DC	Dm	C	Ds	De	DC
Azerbaijan	91	100	95	85	91	3	1	2	5	3
Iran	30	100	19	69	30	3	1	5	2	3
Kazakhstan	100	45	100	77	100	1	5	1	4	1
Russia	29	100	29	35	29	3	1	3	2	3
Turkmenistan	91	70	95	100	91	3	5	2	1	3

Table 3
Results of least squares solution method for the Caspian Sea case.

Regional states	Dm	C	Ds	De	DC
Azerbaijan	0.01	0.00	0.00	0.02	0.01
Iran	0.48	0.00	0.65	0.10	0.48
Kazakhstan	0.00	0.30	0.00	0.05	0.00
Russia	0.50	0.00	0.50	0.43	0.50
Turkmenistan	0.01	0.09	0.00	0.00	0.01
Total relative dissatisfaction	1.00	**0.39**	1.15	0.60	1.00

on Table 2, negotiators' ideal shares values are assigned as the maximum achievable share under all considered division methods, defined as the following:

$$f_i^* = \left(f_A^*, f_I^*, f_K^*, f_R^*, f_T^*\right) = (20\%,\ 20\%,\ 44.2\%,\ 20\%,\ 28.4\%)$$

where A = Azerbaijan; I = Iran; K = Kazakhstan; R = Russia; and T = Turkmenistan.

For this analysis, the anti-ideal share value (f_i^-) for each state is to receive no allocation of oil and natural gas resources, a situation that can occur in the absence of an agreement:

$$f_i^- = \left(f_A^-, f_I^-, f_K^-, f_R^-, f_T^-\right) = (0, 0, 0, 0, 0)$$

With these concepts in mind, the five division rules are evaluated using the distance-based and power index methods introduced in Section 2. Results presented in this section are derived from equations presented in Section 2, where the external negotiator weight, w_i, is equal (set to one) for all parties.

4.1. *Discrete distance-based allocation methods*

4.1.1. *Discrete least squares solution*

As previously described, the least squares method minimizes each party's dissatisfaction from ideal shares, using Equation (2) to calculate the total sum of deviations without discerning between the benefiting parties. This method uses the square of relative distance for comparison since non-linearity makes this method sensitive to large deviations. Thus, in comparing two solutions with an equal amount of total dissatisfaction, a solution characterized by several small dissatisfactions with a lower maximum dissatisfaction is preferred over one with a wide range mixed with large and small dissatisfactions. Table 3 shows the magnitude of the dissatisfaction from an ideal share for each state from the least squares solution. The solution method with the lowest value is nominated as the legal regime.

By the least squares method, solution C is the best candidate for enacting a legal regime in the Caspian Sea with a relative dissatisfaction value of 0.39. Alternative De is the second most favorable solution (0.60), and Ds is the worst division rule (1.15) by this method.

4.1.2. *Discrete MINIMAX solution*

The MINIMAX method enumerates the maximum deviation of each alternative without considering minor deviations and the distribution of deviations among beneficiaries. Table 4 shows the results of applying Equation (4) ($w_i = 1$), with solution C as the best choice as it yields the maximum minimal relative deviation of 0.55 with Azerbaijan, Iran, and Russia are completely satisfied; De is next with 0.65, and Ds is most unfavorable with a maximum relative deviation of 0.81.

4.1.3. *Discrete MAXIMIN solution*

The preferred solution for MAXIMIN is one that maximizes the minimum satisfaction to spread dissatisfaction more homogeneously among the parties. Table 5 shows results from applying Equation (5) ($w_i = 1$), indicating that solution C is the preferred rule with a maximum minimal relative satisfaction of 0.45; the implication of this value is that solution C provides the most dissatisfied party with more satisfaction than the most dissatisfied member under any other division rule. Ds is the least favorable option based on the MAXIMIN method.

4.1.4. *Discrete compromise programming solution*

When applying Equation (7) ($w_i = 1$) for CP with $p = 1$ and predefined anti-ideal shares (f_i^-) equal to zero, results identify division rule C as the most preferred solution and Ds as the worst solution (Table 6). Applying Equation (6) for CP with $p = \infty$ and $f_i^- = 0$ gives the same results as MINIMAX (Table 4). Consequently, rule C is most favorable compromise solution for the feasible set of CP solutions.

4.2. *Discrete power index allocation solution*

According to the power index method (Equations (9)–(12)), rule De is the most stable allocation rule for the Caspian Sea case as it has the lowest coefficient of variation (Table 7), indicating that power is more evenly distributed among the parties and there is a greater willingness to cooperate compared to other solutions. This suggests that under solution De parties are most likely to remain in the negotiation and seek agreement rather than leave prematurely. This suggests that De is more stable than a polarized solution where parties are either highly satisfied or dissatisfied, which is congruent with the stipulations of De, yielding an equal share to all parties. Alternatively, solution C has the highest CV

Table 4
Results of MINIMAX application for the Caspian Sea case.

Regional states	Dm	C	Ds	De	DC
Azerbaijan	0.09	0.00	0.05	0.15	0.09
Iran	0.70	0.00	0.81	0.31	0.70
Kazakhstan	0.00	0.55	0.00	0.23	0.00
Russia	0.71	0.00	0.71	0.65	0.71
Turkmenistan	0.09	0.30	0.05	0.00	0.09
Minimum relative dissatisfaction	0.71	**0.55**	0.81	0.65	0.71

Table 5
Results of application of MAXIMIN method on the Caspian Sea case.

Regional states	Dm	C	Ds	De	DC
Azerbaijan	0.91	1.00	0.95	0.85	0.91
Iran	0.30	1.00	0.19	0.69	0.30
Kazakhstan	1.00	0.45	1.00	0.77	1.00
Russia	0.29	1.00	0.29	0.35	0.29
Turkmenistan	0.91	0.70	0.95	1.00	0.91
Maximum relative satisfaction	0.29	**0.45**	0.19	0.35	0.29

value of 1.61, suggesting that it is the least stable allocation solution relative to the other choices because parties may be less willing to continue the negotiation.

Analysis of existing division rules under the first four distance-based methods (least squares, MINIMAX, MAXIMIN, and CP) leads to selection of rule C, whereas the power index allocation method selects rule De. Rule C can completely satisfy three (Azerbaijan, Iran, and Russia) of the five countries by providing total claims to each of these nations, making them enthusiastic to agree on this solution. Equal division of the Caspian Sea (rule De) is the second most favorable selection, followed by rule DC, which divides the seabed based on Dm and the surface based on C. Division based on the United Nations Convention on the Law of the Seas or the median line (Dm) and division based on the Soviet maps (Ds) are identified as most unfavorable among the five suggested division rules. The distance-based social planner methods described above do not consider the possibility of failure of negotiations when highly dissatisfied parties leave the negotiations. Instead, they focus on the system's optimal solution (social planner's view) rather than analyzing each negotiator's viewpoint. Moreover, such methods implicitly assume that all parties prefer benefits to the system/group rather than to the individual; however, especially in multinational negotiations, the social optimal solution is not necessarily the best choice in all parties' regards.

Table 6
Results of Compromise Programming method ($p = 1$) for the Caspian Sea case.

Regional states	Dm	C	Ds	De	DC
Azerbaijan	0.09	0.00	0.05	0.15	0.09
Iran	0.70	0.00	0.81	0.31	0.70
Kazakhstan	0.00	0.55	0.00	0.23	0.00
Russia	0.71	0.00	0.71	0.65	0.71
Turkmenistan	0.09	0.30	0.05	0.00	0.09
Total relative dissatisfaction	1.59	**0.84**	1.61	1.35	1.59

Table 7
Power index results for the Caspian Sea case.

Regional states	Dm	C	Ds	De	DC
Azerbaijan	0.06	0.00	0.03	0.09	0.06
Iran	0.43	0.00	0.49	0.19	0.43
Kazakhstan	0.00	0.74	0.00	0.31	0.00
Russia	0.43	0.00	0.43	0.40	0.43
Turkmenistan	0.08	0.26	0.04	0.00	0.08
Average	0.20	0.20	0.20	0.20	0.20
Standard deviation	0.21	0.32	0.24	0.16	0.21
Coefficient of variation	1.06	1.61	1.21	**0.81**	1.06

Power index analysis suggests that highly unsatisfied parties may change the outcome of the negotiation in ways that have not been previously studied. As suggested in this work, the power index is an approach that quantifies the likelihood of negotiators to engage in the cooperative process; and, consequently finds a solution that maximizes stability by equally distributing the willingness to cooperate, or power of the beneficiaries to affect (leave) the negotiation. According to the results of Section 4 for the Caspian Sea, the socially optimal solution is also the least stable solution.

5. Resource allocation in a continuous domain

So far this work has reviewed and applied four distance methods and the power index to select the best allocation solution among pre-defined discrete alternatives for dividing the Caspian Sea. While the methods introduced earlier are helpful in selecting the best solution when predefined alternative solutions exist, in many cases the alternative solutions are unknown and it is necessary for resource managers or stakeholders to identify the best solution out of undefined possible solutions in a continuous domain. This section focuses on reviewing and introducing methods for selecting an allocation solution from a continuous space. This perspective is most practical for water resource managers who must consider schemes for allocating benefits or resources to different stakeholders.

For the purposes of this study, all optimization models have a similar framework: a selected distance-based or power-based is method is formulated as the objective function and subject to two general constraints. The basic formulation of optimization models applied in this section is shown in Equation (13):

$$\text{Minimize } F(f_i) \tag{13}$$

Subject to:

$$0 \le f_i \le f_i^* \tag{14}$$

$$\sum_{i=0}^{m} f_i = E \tag{15}$$

where $F(f_i)$ is the objective function determined based on each allocation method introduced in this section, f_i is a decision variable representing the allocation of each negotiator, and E is the total resource value to share.

The first constraint (Eq. (14)) is the margin of each party's share, limited by its claim amount. This prevents solutions from impractically allocating shares that exceed claim amounts, as this would not be accepted by the group of negotiators. The second constraint (Eq. (15)) sets the total allocation less than or equal to the total resource value. This ensures a solution where the sum of the creditors' shares does not exceed the Caspian Sea resource reserve. These two constraints, along with non-negativity share values constraint, form a feasible set and are applied for each method. Results are presented as a summary in Table 8, comparing the relative satisfaction rates for each country based on each distance-based method.

5.1. Distance-based methods

5.1.1. Continuous least squares solution

According to this method, the objective function minimizes the total distance from ideal shares, or minimizes the sum of each negotiator's relative dissatisfaction. The objective function for this method is taken from Equation (2) by replacing $f_{i,j}$ with f_i.

Allocation and relative satisfaction results for the least squares optimization method report an integrated sum of squares deviation of 0.27. This value is an improvement over the result from Section 4.1.1, where the discrete least squares analysis yielded a minimum total dissatisfaction of 0.39 (Table 3). According to this allocation, Kazakhstan has the lowest satisfaction rate, receiving 64% of its claim, but also the highest overall resource share percentage. Azerbaijan, Iran, and Russia each receive equal shares since they start with equal claims. These countries receive 84% of their claims with a resource share of 16.7% of the total. Overall, the satisfaction levels are relatively high (>50%) and spread relatively evenly across all negotiators under this method.

5.1.2. Continuous MINIMAX solution

The objective function for the MINIMAX goal programming is taken from Equation (4) by replacing $f_{i,j}$ with f_i.

The MINIMAX method minimizes the maximum possible dissatisfaction by reducing the maximum dissatisfaction until values converge on a single dissatisfaction for all parties. This results in all negotiators receiving equal percentage satisfactions – in this case 75% satisfaction (or 25% dissatisfaction). This allocation scheme distributes the dissatisfaction equally among negotiators, a solution that may appeal to cases seeking homogenous deviations. This solution may serve as a starting point for discussion, as it assumes all parties have equal power in the negotiation and thus receive the same percentage of their claims.

5.1.3. Continuous MAXIMIN solution

Optimal allocation based on MAXIMIN follows the opposite logic from the MINIMAX method. In this case, the overall minimum satisfaction increases until a single value of satisfaction has converged for all parties. The objective function for the MAXIMIN method is taken from Equation (5) by replacing $f_{i,j}$ with f_i.

As with MINIMAX, all parties receive an equal percentage share of resources, in this case 75% satisfaction and 25% dissatisfaction, resulting in the same allocation scheme as MINIMAX shown in Table 8.

5.1.4. Continuous compromise programming solution

Section 2.1.4 discusses the rationale behind the CP method, where an allocation is selected based on finding an ideal point over a range of distances that comprise a feasible set (setting p). In this section, a continuous CP solution is solved for $p = 1$ as the lower bound of the compromise solution set by Equation (7) after replacing $f_{i,j}$ with f_i.

The CP ($p = 1$) results indicate that four of the five parties are 100% satisfied, but Kazakhstan is only 26% satisfied and left with the lowest relative resource share. While this scheme may be desirable for the majority of parties, it is unlikely that Kazakhstan will agree unless additional incentives are provided. Solving CP with $p = \infty$ as the upper bound to the compromise set yields the same allocation results as MINIMAX (where $f_i^- = 0$).

5.2. Continuous power index solution

Given the earlier discussion regarding the limitations of distance-based methods in addressing MC-MDM problems, an allocation method for continuous solutions based on the power index is developed. The power index allocation method is proposed as an additional metric that calculates how each division rule satisfies the individual compared to the group, since socially-optimal decisions do not account for the individualistic tendencies of players to maximize their own position and minimize losses. The proposed allocation optimization model minimizes the coefficient of variation (CV), thereby distributing the power to affect the negotiation, or willingness to cooperate, to all parties. Solutions from this method are expected to be more stable in practice because they strive to identify allocations that are acceptable enough for all parties to remain and cooperate in the negotiation. This application of the power index method for allocating benefits in MC-MDM problems has not been made so as the authors are aware, and the objective function formulation of the model based on the power index allocation method is given in Equation (16):

$$\text{Minimize} \quad CV \tag{16}$$

Subject to: Eq. 9 ($f_{i,j}$ must be replaced with f_i), Eq. 10, Eq. 12, Eqs. 14 and 15.

Table 8
Summary of optimal resource allocations of the Caspian Sea for distance-based methods.

Regional states	Least squares satisfaction (%)	MINIMAX satisfaction (%)	MAXIMIN satisfaction (%)	Compromise programming ($p = 1$) satisfaction (%)
Azerbaijan	84	75	75	100
Iran	84	75	75	100
Kazakhstan	64	75	75	26
Russia	84	75	75	100
Turkmenistan	77	75	75	100

Table 9
Optimal resource allocation of the Caspian Sea based on the power index.

Regional states	Relative satisfaction (%)	Resource share (%)
Azerbaijan	67	13.5
Iran	67	13.5
Kazakhstan	85	37.6
Russia	67	13.5
Turkmenistan	77	21.9

Table 9 shows the results for the power index allocation method in a continuous domain. In order to force the CV to a minimum (at zero), the resource distribution has a mean alpha (power index) value equal to 20%, indicating that each party receives an equal proportion of their resource claim compared with the group. Because the power index allocation method minimizes the variation of resource distribution across all parties, the results have a greater impact on states with lower claims such as Azerbaijan (loses about 32% of its claim), while less of an impact on states with greater claims like Kazakhstan (loses 15% of its claim).

In comparing the power index allocation method to results from the distance based methods, MINIMAX, MAXIMIN, and CP ($p = \infty$) offer an allocation scheme in which the deficit amounts are directly proportional to negotiators' claims. That is, parties with higher claims incurred a greater shortage (loss of benefits) than those with lower claims. This is the social planner's solution, where the results are meant to be fair but not necessarily practical given that parties with higher claims may hold more internal power in affecting an agreement. Results from the least squares analysis and CP ($p = 1$) yield allocation solutions with neither equal deficiency nor equal percentage of claims.

6. Negotiation power

In this section, the Caspian Sea dispute is analyzed using the same selected methodologies from Sections 2 and 5, but with the addition of external negotiation powers as a weighting factor in the formulations. Negotiator power is an external parameter calculated

Table 10
Criteria and indicators applied by Sheikhmohammady et al. (2010) to estimate countries' weights.

Criteria	Indicator
Economic independence and self sufficiency	GNI/capita
	Net trade/GDP
	GDP/Claimed Caspian
	Sea oil and natural gas
Military status	Yearly military expenditures
	Military expenditures/GDP
	Active troops/population
	Nuclear power status
US Support	US Financial support
	US Political support
Political influence and structure	Political influence
	Democracy level

Table 11
Weight values of negotiators (Sheikhmohammady et al., 2010).

Regional states	Normalized weights
Azerbaijan	0.181
Iran	0.167
Kazakhstan	0.165
Russia	0.367
Turkmenistan	0.120

for each party based on their political, economic, and social status. This power is different than the internal power referred to in the power index allocation method, as the latter is created based on the relative shares and claims within the group. Negotiator powers are important to include when available, as they help create a more realistic negotiation analysis, since parties likely have differing political, economic, and social positions that will influence their actions and decisions.

Sheikhmohammady et al. (2010) developed a model to quantify a country's power negotiator weight (or influence capacity) in the Caspian Sea negotiations. Table 10 describes the criteria used in the analysis, which evaluate a country's economic independence and self-sufficiency, military status, relationship with the U.S., and political influence and structure. Each criterion has indicators that help identify whether a country has the capacity to influence the negotiation. For example, the category of political influence and structure considers internal stability and the range of political influence of each country, indicated by the degree of influence and democracy level, which in the long term leads to stability for a country. Refer to Sheikhmohammady et al. (2010) for details on calculating the criteria, indicators, and weights for each country via the Data Envelopment Analysis method. This method identified Russia as the most powerful country due to its status as a military power and relatively strong economic influence over the region, while the newly formed and less developed countries like Turkmenistan and Azerbaijan have less power. Results from their weight analysis are normalized (Table 11) and used here to determine how the negotiating parties can influence the Caspian Sea resource allocation.

Table 12
Summary of discrete weighted allocations of Caspian Sea for distance-based methods.

Method	Dm	C	Ds	De	DC	Decision rule
Least Squares	0.52	0.25	0.54	0.43	0.52	C
MINIMAX	0.26	0.09	0.26	0.05	0.26	De
MAXIMIN	0.80	2.72	0.80	0.94	0.80	C
CP ($p = 1$)	0.40	0.13	0.41	0.36	0.40	C

6.1. Distance-based methods with negotiator weights

Table 12 summarizes the results of applying each distance-based analysis to the proposed division rules under the weighted case. Rule C is the best method according to a least squares analysis both with and without negotiator weights. This solution satisfies the three most powerful countries, Russia, Azerbaijan, and Iran, with 100% satisfaction. The differences in magnitude between solutions are primarily caused by the greater relative importance placed on countries with higher negotiator weights, i.e., Azerbaijan, Iran, and Russia. Because of this, Russia's dissatisfaction is the driver in the least squares analysis, leading to the selection of rule C as the only one that satisfies Russia within reason. According to the results of MINIMAX, solution De is identified as the best allocation scheme as it fully satisfies the three most powerful parties in the dispute; however, Russia is left with a disproportionately high dissatisfaction level, which may be unstable in resolving the negotiation. Rule C is the second best solution with Dm, Ds and DC as equally the most dissatisfying solutions. The MAXIMIN method selects solution C as the best division rule, again dominated by Russia's position as the most powerful country, and thus satisfying its claim to a higher degree. The CP ($p = 1$) analysis also yields decision rule C as it had without negotiator weights. In summary, results from least squares, MAXIMIN, and CP suggest that negotiator power does not change the allocation outcome under the proposed rules, while MINIMAX selects De, the rule preferred by Kazakhstan.

Table 13 summarizes the continuous allocation satisfactions for each country when negotiator weights are considered. The least squares analysis allocates a lower claim percentage of resources to those with higher claims (Kazakhstan) and to those with lower power (Turkmenistan). Meanwhile, Russia (the most powerful nation) receives 97% of its claim with the lowest dissatisfaction compared with others. According to MINIMAX, Russia's highest relative power earns it 89% of its claim, while Turkmenistan with the lowest relative power receives 66% of its claim. The MAXIMIN method fully satisfies Kazakhstan and Russia, the countries with the highest claim value, and the most powerful in negotiation, respectively. The remaining parties receive percentages of benefits in line with their relative power status. The CP ($p = 1$) solution has the same result as without consideration of negotiator weights and satisfies the claims of all countries except Kazakhstan, who is highly dissatisfied.

Negotiator powers did not change the final selection choice of any of methods except MINIMAX, but affected the order of secondary choices in MAXIMIN and CP ($p = \infty$) analyses. In the continuous cases, negotiator powers impacted the amounts of negotiators' shares. Minimum shares of Azerbaijan, Russia, and Kazakhstan increased as compared with cases where negotiator power values were not considered, especially for Russia whose shares increased by 3.4%. The minimum shares for Iran and Turkmenistan were reduced, most notably for Turkmenistan,

Table 13
Optimal weighted resource allocation of the Caspian Sea using distance based methods in a continuos domain.

Regional states	Least squares satisfaction (%)	MINIMAX satisfaction (%)	MAXIMIN satisfaction (%)	Compromise programming ($p = 1$) satisfaction (%)
Azerbaijan	87	77	87	100
Iran	85	75	46	100
Kazakhstan	66	75	100	26
Russia	97	89	100	100
Turkmenistan	59	66	33	100

whose share declined by over 50 percent as compared to analysis without negotiator power values. Thus, considering negotiator weight values in optimal allocation schemes is effective for expanding shares of more powerful members like Russia, while less powerful members like Turkmenistan experience a reduction in allocation. In comparing results across all methods, each country would likely favor a different distance-based method for dividing resources. This adds justification to using several distance methods for assessing the satisfaction and acceptability of the resource allocation, especially when negotiator weights are included.

6.2. Power index allocation method with negotiator weights

Results of the negotiator-weighted power index allocation method for discrete pre-defined rules are shown in Table 14. This method calculates the lowest CV for rule De and therefore selects it as the best solution, while solution C has the highest CV and is thus considered most unfavorable. As previously discussed, this allocation method seeks a solution which strives to distribute internal power equally among negotiators, quantified by the CV. Unlike other methods, results here leave Russia as the most dissatisfied member despite its power status. The power index names solution C as the most unfavorable rule regardless of whether negotiation power weights are included. From this, the power index allocation method is sensitive to external negotiator weights, since the resource allocation values change, but results show no change in the rule order indicating that no better solution exists.

Results from continuous optimal resource allocation based on the power index with negotiator weights are shown in Table 15. Optimality via the power index method allocates Russia 85% of its claim due to its high negotiator weight status, while Azerbaijan and Iran obtain 68% and 66% of their claims, respectively. Kazakhstan receives a higher share (84%) due to its larger claim despite its lower power status. These results suggest that the power index allocation method is sensitive to external negotiator weights and will divide resources differently considering the position of parties entering the negotiation.

7. Policy insights

This paper applied selected discrete and continuous methods to the Caspian Sea case to develop and identify proper resource allocation schemes. The discrete analysis evaluated pre-defined alternatives with selected methods, while the continuous analysis solved for optimal allocation schemes. Comparing the results of these two procedures indicates that the suggested discrete division rules (Table 1) offer a distinct set of solutions to direct the negotiation to a unanimous agreement; however, identifying solutions from the continuous domain helps to create additional allocation schemes to bring to the negotiation table. Distance-based methods selected rule C as the best solution regardless of considering negotiator powers, while the power index allocation method identified this as the least desirable solution. Rule De was selected by the power index method as most stable, and thus may be a reasonable starting point for negotiating a unanimous agreement. The findings of this study are consistent with those of Madani (2010), suggesting that Pareto-optimal solutions of MC-MDM water resource problems (games) are often different from the equilibria (stable solutions), implying that the social planner's solution does not offer a complete analysis of the complex negotiation dynamics. This paper provides support that optimality may not necessarily be the best single assessor when multiple decision-makers are present. In practice, bargainers are eager to agree on solutions that produce the greatest utilities, especially in multinational negotiations when the countries' economies may not directly impact one another. Allocation methods like goal programming and compromise programming may only offer one set of possible allocations in solving a dispute since they suggest solutions that may have highly unequal sharing of benefits and significant power disparities between parties. This disparity is unstable and may lead to a negotiation stalemate or inability to reach a unanimous agreement. Therefore, identifying a stable solution, or the one where parties are most willing to negotiate, is an additional assessor that puts priority on maximizing the benefits to the individual compared with the group. The power index allocation method is an alternative that selects a solution which represents the best opportunity for agreement, one with the highest willingness to cooperate among all parties, and thus can be considered applicable for MC-MDM problems as an additional analysis to optimality.

Table 14
Weighted power index of the proposed division rules.

Regional states	Dm	C	Ds	De	DC
Azerbaijan	0.04	0.00	0.02	0.07	0.04
Iran	0.28	0.00	0.33	0.13	0.28
Kazakhstan	0.00	0.80	0.00	0.21	0.00
Russia	0.63	0.00	0.63	0.59	0.63
Turkmenistan	0.04	0.20	0.02	0.00	0.04
Average power index value	0.20	0.20	0.20	0.20	0.20
Standard deviation	0.27	0.35	0.28	0.23	0.27
Coefficient of variation	1.34	1.73	1.39	**1.17**	1.34

Table 15
Optimal resource allocation in a continuos domain based on power index with negotiator weights.

Regional states	Relative satisfaction (%)	Resource share (%)
Azerbaijan	68	13.7
Iran	66	13.2
Kazakhstan	84	37.3
Russia	85	16.9
Turkmenistan	67	18.9

8. Conclusions

Systems optimality methods that select the Pareto-optimal decision as the solution may not result in the most stable decision because cooperation (group rationality) is not necessarily a stronger driving force than individual benefits (individual rationality). Stability analysis in water allocation negotiations leads to a different rule selection than optimization, and both are important for assessing possible allocation solutions. Borrowed from the economic literature, the power index allocation method provides a way to quantify the stability of solutions in MC-MDM and offers a unique allocation portfolio from optimality methods as illustrated through analysis in this paper. As discussed, solutions derived from the power index allocation can be more stable than distance-based solutions since the internal power of each negotiator, or their willingness to participate, is distributed across the group. This aids the negotiation process by encouraging agreement and discouraging pursuit of rules that are not acceptable to some parties. The optimal allocation by this method considers two factors: (1) the internal powers of the negotiators based on their claim values — which serve as a proxy for likelihood to leave the negotiation; and (2) their external powers in influencing the result – either in an individualistic or cooperative manner based on ability to support an agreement. In this way, the power index method tries to develop a stable solution to resolve a conflict instead of focusing on system's optimality as the main objective. Seeking the optimal allocation may be a method better suited for MC-SDM analysis, where MC-MDM negotiations may need to consider stability as well, as the influences of parties' inter-relations and power imbalances may significantly impact the allocation decision.

Again while system engineers seek the Pareto-optimal and efficient solutions, game theory suggests that such a solution may not be easily implemented as parties see things differently and are more likely to arrive at an equilibrium that satisfies all parties, even if it is not Pareto-optimal. Thus in cases with MC-MDM allocation problems such as the Caspian Sea, aiming for the inferior stable instead of the unstable socially optimal solution is encouraged to ensure participation and action in negotiations.

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