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Allocating Water in the Mekong River Basin during the Dry Season

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Abstract: With population numbers increasing and anthropogenic climate change, the amount of available fresh water is declining. This scenario can lead to an increase in the occurrence of water conflicts, especially in transboundary river basins. Prevention strategies to avert water conflicts by designing a fair, efficient, and sustainable water allocation framework are needed. Taking into account the socioeconomic and environmental differences among the riparian countries is one of the most important features an allocation scheme should have. In this article, bankruptcy and bargaining games were used to construct a new weighted water allocation model. The proposed method was applied to allocate the contested water capital of the Mekong River during the dry season. The Mekong River originates in China and flows through Myanmar, Laos, Thailand, Cambodia, and Vietnam. The results of the allocation showed that, except for China and Vietnam, all the other riparian countries get their full claim of the water demand from the river. The water allocation payoffs satisfy individual rationality, Pareto optimality, and maximization of the group utility. Therefore, the allocation outputs from the proposed scheme are self-enforceable and sustainable.

Keywords: water resources allocation; bargaining power; heterogeneous; transboundary river

1. Introduction

Water supports various social, economic, and environmental systems. This is main reason why most ancient and modern civilizations are on the banks of rivers. The Nile and Tigris-Euphrates river basins are typical examples. The major water demands are irrigation, domestic, and industrial water demands. Lack of water for these sectors negatively affects these systems, thereby endangering the socioeconomic security of a lot of people and environmental integrity. Therefore, preventing water scarcity is crucial for sustainable development.

With economic development, increasing population, and climate change, the competition for water is becoming more and more intense [1–4]. These contests are fiercer when water resources are internationally shared [5]. However, universally-accepted international agreements and mechanisms to allocate the water capital of these river basins are yet to exist [6]. There are around 286 internationally shared river basins in the world and approximately 42% of the world's population lives in these rivers basins [7], hence, implementation of fair, efficient, and sustainable water allocation schemes in these river basins is very important. Water allocation schemes based on optimization models have been suggested as good techniques to increase the efficiency and benefits of shared water resources [8]. Therefore, previous studies applied linear programming, mixed-integer linear programming, dynamic programming, evolutionary computation, and artificial neural networks to attain efficient allocation of disputed water capital [9–12]. These methods target maximizing the group utility based on the assumption of perfect cooperation, which is not always guaranteed in transboundary water sharing, where each riparian state's interest matters [13]. Therefore, even though water allocation outputs from multi-objective optimization models are efficient, they can be unrealistic, since these models do not take the strategic interactions among the sharing countries into consideration. These interactions within border-crossing river basins are very complex [14–16] and crucial for fair, efficient, and sustainable water sharing within the basins. As a result of this understanding, the strategic interaction among river sharing countries is one of the very important factors that needs to be considered in order to avoid water conflicts [17]. This understanding can be achieved through negotiations or discourses, thereby enabling the stakeholders to make decisions based on complete information.

Discourses on water scarcity are key to shape people's understanding of its causes, consequences, and interaction among stakeholders [4,15,16]. One element that is crucial to solving any water issue as a result of water-sharing problems under water scarcity is understanding how to maximize each stakeholder's benefits. Negotiation is one form of discourse that can help to come up with ways to achieve this aim [18]. During negotiations the stakeholders can learn information which might not be revealed by non-cooperative interaction, thereby avoiding the stakeholders' problem of making water use decisions under uncertainty. This prevents water conflicts and environmental degradation. These discourses or negotiations are based on the social, economic, and environmental differences among the stakeholders. Identifying the actors and their main bargaining elements of negotiations is key for successful concession [4]. In the process, each actor will analyze different courses actions based on the possible strategies of the other stakeholders involved in the water resources-sharing problem. These strategies take into account the historical, present, and future dynamics of social, economic, environmental, and political features of the participating water claimants [19–21]. It is very important that negotiations on water sharing within transboundary river basins are contextualized in the broader context, considering national security, regional geopolitics, intersectoral interests, and power asymmetries [22]. The dynamics of these elements over time need to be thoroughly investigated and the insights obtained can help to understand the interests of the different stakeholders [14]. A tool that can integrate all these aspects and identify the interests of each stakeholder is needed for this purpose. Game theory can serve as a tool to capture and integrate these factors that influence the negotiation strategies of the stakeholders in internationally-shared river basins [9].

Game theory is a mathematical method that can be used to capture the strategic interaction among stakeholders claiming a shared scarce resource. Hence, theoretical game models can serve as a tool to analyze cooperative and non-cooperative relationships among riparian countries of water-scarce transboundary river basins [23]. The method has been applied to allocate various scarce shared resources [24–31]. The water resources allocation based on game theory can make up for the shortcomings of multi-objective optimization models (Figure 1).

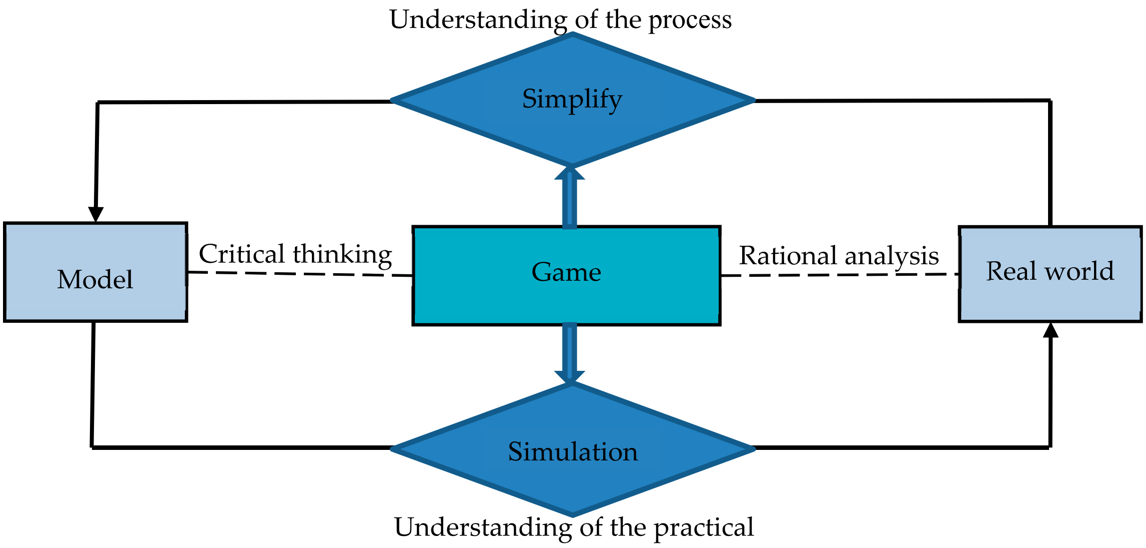


Figure 1. Conceptual map of water allocation using game theory.

A theoretical game approach will allow for negotiation and prevent hydro-hegemony [32]. A theoretical game method will take into account the interaction among the riparian countries, thereby enabling us to analyze conflict and cooperation [33]. This is important because it helps to internalize negotiation [34] and issue linkage [35] into an optimized water allocation framework.

In this article, an optimization method was combined with a theoretical game model to solve the water-sharing problem in transboundary river basins. Bankruptcy theory, which is one of the theoretical game approaches, was applied to frame the problem of water scarcity. This theory aimed to find a reasonable allocation pattern among water resource claimants using the available water capital and water claims as limits for efficiency and individual rationality, respectively. Therefore, based on bankruptcy theory, a novel weighted optimization allocation mechanism that satisfied most of the desired features was built. These desired properties were feasibility, efficiency, claim boundedness, equal treatment of equals, scale invariance, and exclusion. Then, the proposed allocation mechanism was demonstrated by using it to allocate the disputed water of the Mekong River basin.

2. Method

The bankruptcy theory describes a state where a limited resource, E, is not enough to fulfill the demands of all agents in the set N asserting their claims $c_i(c_i = c_1, c_2, c_3, \ldots, c_n)$ [36]. When the available water in the basin is not enough to satisfy the total water demand, the situation is called a water bankruptcy scenario. Therefore, designing a water allocation mechanism during water scarcity can be approached as a bankruptcy problem, since riparian countries' total water demand is greater than the water available for sharing [6].

$$0 \leq E \leq \sum_{i=1}^{n} c_i \tag{1}$$

Therefore, any mechanism that solves a resource sharing problem stated in Equation (1) by yielding allocation outputs $e_i(e_i = e_1, e_2, e_3, \ldots, e_n)$ should satisfy Equation (2).

$$\sum_{i=1}^{n} e_i = E \tag{2}$$

Cooperation in resolving water conflict within a transboundary river can result in greater economic, ecological, and political utility [37]. As a result, negotiation among sharing states is often accepted as the best way to solve the water-sharing problem [38,39]. A bargaining game is one of the non-transferable utility games that can be applied to resolve water-sharing problems through negotiation [40]. The Nash bargaining theory is one of the bargaining methods that yields water allocation payoffs that satisfies much-desired properties such as feasibility, invariance under changing utilities, Pareto optimality, and unanimity [41,42]. In this paper, the authors combine the bankruptcy theory with the Nash bargaining game model to capture a water sharing problem in a transboundary river as a non-transferable utility game [43].

The bargaining problem can be represented as $B : (S, D, u_1, u_2, \cdots, u_n)$, where S is the feasibility space $S : (e_1, e_2, e_3, \ldots, e_n)$, e_i represents the water resources allocated to each claimant, while the utility $\{u_i(S), i = 1, 2, \cdots, n\}$ of each riparian, i, in the feasibility space, S, is $u_i : S \to R$ [44]. It is difficult to accurately determine the utility function of water use because water is related to different social, economic, and environmental systems. Therefore, in this article the utility function is described as a linear interval function [45]:

$$u_i(e_i) = (e_i - d_i)/(c_i - d_i), \tag{3}$$

where $D = (d_1, d_2, \cdots, d_n)$ represents the disagreement points of each claimant involved in the allocation game. The disagreement point of each riparian country is defined based on the bankruptcy theory [46]:

$$d_i = (E - c(N/i)) = Max\{E - c(N/i), 0\}. \tag{4}$$

The disagreement utility point is $u_i(d_i) = 0$. Therefore, for any rational selection $s \in S$, the allocation solution should satisfy $u_i(d_i) \leq u_i(s)$.

The bargaining power of each riparian region, w_i, takes into account the asymmetry among riparian regions in terms of their social, economic, and environmental features [47].

$$\sum_{i=1}^{n} w_i = 1. \tag{5}$$

The solution set $S : (e_1, e_2, e_3, \ldots, e_n)$ that satisfies the following maximization function allocates the water in a fair and efficient manner.

$$\begin{gathered} u^N(s) = \{s \in S \big| \max[(u_1(s) - u_1(d_1))^{w_1}(u_2(s) - u_2(d_2))^{w_2} \cdots (u_i(s) - u_i(d_i))^{w_i}]\} \\ s.t. \begin{cases} 0 \leq e_i \\ d_i \leq e_i \leq c_i \\ \sum\limits_{i=1}^{n} e_i \leq E \\ \sum\limits_{i=1}^{n} w_i = 1 \end{cases} \end{gathered} \tag{6}$$

3. Computing Bargaining Power

The riparian countries are different in terms of their water demand, water contribution to river's main stem and vulnerability to water stress. Therefore, in order to build a holistic allocation mechanism, the social, economic, and environmental elements, as well as their variation through time and space, need to be taken into account. These factors can be incorporated into a water-sharing mechanism in the form of bargaining weight. Previous studies also provided water allocation mechanisms that considered these factors [48–51].

This section analyzes and develops the comprehensive and rigorous index system for determining bargaining weight of sharing countries in transboundary river basins during water bankruptcy. The indicators were chosen based on the widely known and used The Helsinki Rules on the Uses of the Waters of International Rivers [52] and Convention on the Law of Non-Navigational Uses of International Watercourses [53]. Although these international water laws are not binding and lack the much-needed enforcement mechanism, they promote equitable distribution of shared water capital without prejudice. Thus, these international rules can serve as guidelines for designing an allocation mechanism which is fair, efficient, and sustainable [54,55]. The following nine indicators (Table 1) were used to build the index for computing bargaining weight of riparian countries sharing a transboundary river [56–70].

Table 1. Factors used to build the framework for calculating the bargaining power.

Indicators	Indexes	Attribute
Geographical	Watershed area	Positive
Hydrological	Multi-year average flow	Positive
Climate	Average annual rainfall	Positive
Economic and social needs	Irrigated area	Positive
	Electricity demand	Positive
Population	Population density	Positive
Water quantity	Watershed contribution	Positive
Ecological needs	Forest cover rate	Positive
Cost of alternatives, availability, and increasing water use efficiency	Water productivity	Negative
	Internal renewable freshwater resources	Negative
May cause harm to other countries	Per capita gross domestic product	Negative

The bargaining power is a single exponential parameter in the bargaining game model (Equation (6)). Therefore, it is necessary to convert the calculation of bargaining power into a non-linear optimization problem. The two international water laws do not categorize and prioritize the influencing factors [52,53]. Hence, the authors used a projection pursuit model (PPM) to analyze the multiple variables and determine the bargaining weight. The process follows the following steps [71]:

(1) Standardization: Assume the value of each factor in the allocation framework $x*(i,j)$, in which $i = 1, 2, \ldots, n$ refers to the riparian countries and $j = 1, 2, \ldots, m$ refers to the value of the indexes defined in Table 1. The value of each individual index is normalized as follows:

For positive attribution indexes $x_p(i,j)$:

$$x_p(i,j) = \frac{x^*(i,j) - x_{\min}(j)}{x_{\max}(j) - x_{\min}(j)}. \tag{7}$$

For negative attribution indexes $x_n(i,j)$:

$$x_n(i,j) = \frac{x_{\max}(j) - x^*(i,j)}{x_{\max}(j) - x_{\min}(j)}. \tag{8}$$

(2) Construction of projection function: Projection provides the best way to understand the characteristics of the data. It transforms m-dimensional data $\{x(i,\ j)j = 1, 2, \ldots, m\}$ into one-dimensional data $Z(i)$:

$$Z(i) = \sum_{j=1}^{p} a(j) \cdot x(i,j), \tag{9}$$

where projection direction $a(j)$ is a unit length vector:

$$\sum_{j=1}^{p} a^2(j) = 1. \tag{10}$$

The projection function $Q(a)$ can be expressed as:

$$Q(a) = G_Z \cdot H_Z, \tag{11}$$

where H_Z is the standard deviation of $Z(i)$.

$$H_Z = \sqrt{\frac{\sum_{i=1}^{n} [Z(i) - E(Z)]^2}{n-1}} \quad (12)$$

G_Z is the local density for the projected value of $Z(i)$:

$$G_Z = \sum_{i=1}^{n} \sum_{j=1}^{p} (R - r(i,j)) \cdot u(R - r(i,j)), \quad (13)$$

where R is the radius of the local density. Assuming $R = 0.1H_Z$ [72], $r(i,j)$ is the distance between the regions, $r(i,\ j) = |Z(i) - Z(j)|$, $u(t)$ is unit step function:

$$u(t) = \begin{cases} 1, t > 0 \\ 0, t \leq 0 \end{cases}. \quad (14)$$

(3) Calculation: Different values of $a(j)$ correspond to different projection results. The optimal projection direction $a^*(j)$ satisfies Equation (15):

$$\text{Max}Q(a^*(j)) = G_Z \cdot H_Z. \quad (15)$$

In turn, $a^*(j)$ is used in Equation (9) to calculate the values of $Z^*(i)$. The bargaining weight (w_i) is determined by normalizing the set of values of $Z^*(i)$. The authors optimized the projection based on a real-coded genetic algorithm (RAGA), which helps to achieve global optimization by reducing the data dimension [72]. The structural framework of RAGA is shown in Figure 2.

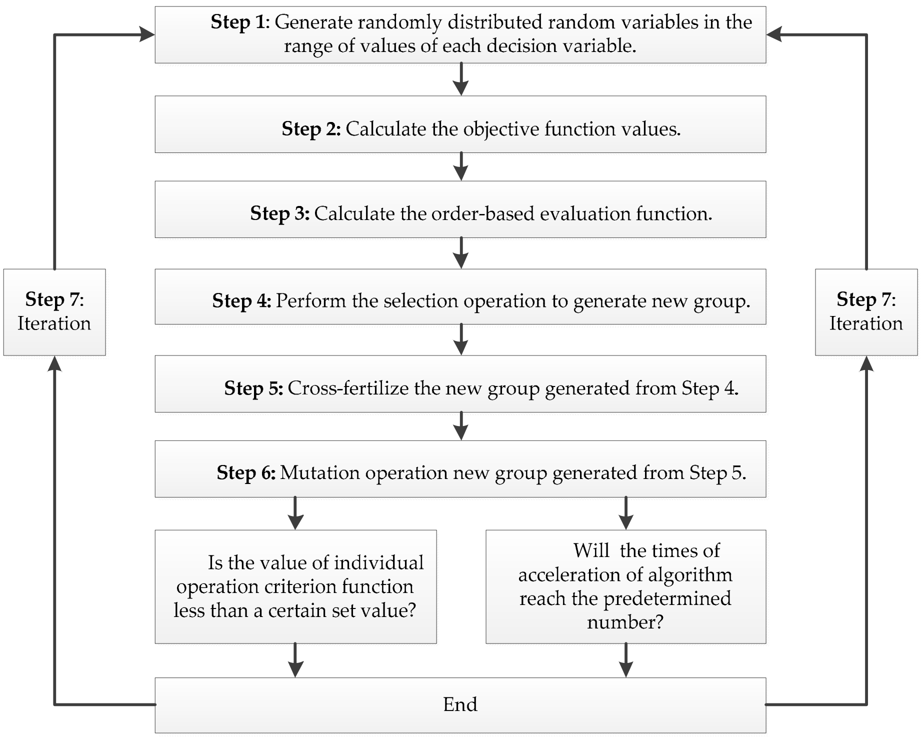


Figure 2. The structural framework of real-coded genetic algorithm (RAGA).

4. Case Study

Mekong River (Figure 3) is one of the most well-known transboundary river basins in the world. Its water capital is contested among its riparian countries mainly during the dry season. The river's estimated length is 4350 km and the basin drains have an area of 79.50×10^4 km^2 [73]. The river runs through China, Myanmar, Laos, Thailand, Cambodia, and Vietnam.

The Mekong River basin riparian countries began to negotiate and cooperate more than half a century ago. The Mekong Committee was established in 1957. The Interim Mekong Committee followed with four members (Cambodia, Laos, Thailand, and Vietnam) in 1978. After that, the Great Mekong Sub-Regional Cooperation (GMS) was formed in 1992 with all six riparian countries as members. Then, in 1995, the Mekong River Commission (MRC) was born with the signing of the cooperation agreement for the sustainable development of the river basin. However, despite the long history of negotiation among the sharing countries, clear agreements on how to share the river's water capital are yet to exist. Reaching a decision on how to allocate water resources is proving to be more difficult with the increasing population number, socioeconomic development, and the impact of climate change. However, the Mekong River basin's six riparian countries enjoy the deep political trust and healthy cooperation through comprehensive bilateral and multilateral strategic partnerships. The authors believe that the riparian countries are not willing to jeopardize these partnerships just because of the water sharing problem in the Mekong River basin [14,74], hence, it is reasonable to assume the riparian countries have the desire to work together on how to share the river basin's water capital.

Figure 3. Mekong River basin (Source: State of the Basin Report 2010, MRC).

4.1. Data and Modeling

The Mekong River discharges 475 km^3 of water annually. The main source of the water supply is precipitation, with nearly 80% of annual rainfall occurring during the wet season. The water availability per capita per year in the basin is about 8000 m^3, which is less than the global average [75]. From May to September, the degree of rainfall is high; as the result the water-sharing problem does not exist. However, from the middle of November to the end of April, the average precipitation is less than 300–600 mm, resulting in insufficient water availability [73]. During the dry season, the runoff of the Mekong River basin needs to increase by about 3000 m^3/s if it is to meet the water demand of all the riparian countries [76]. Consequently, the water deficit in the dry season is nearly 47.30 km^3.

The available water during the dry season is 82.26 km^3 [73,76]. The annual water withdrawal is used to calculate the water demand of each riparian country during the dry season (Table 2) [76,77].

Table 2. Water demand of riparian countries of the Mekong River basin during the dry season (2015).

Countries	China	Myanmar	Laos	Thailand	Cambodia	Vietnam
Water demand (km^3)	100.99	0.99	0.29	7.18	0.27	19.84

The data used to calculate the negotiation weight of each riparian country are obtained from the World Bank, AQUASTAT, and published papers [75,78] (Table 3).

Table 3. Social, economic, and environmental data of the Mekong River basin riparian countries (2015).

Indexes	Unit	China	Myanmar	Laos	Thailand	Cambodia	Vietnam
Area	10^4 km^2	16.50	2.40	20.20	18.40	15.50	6.50
Annual average precipitation	mm	645	2091	1834	1622	1904	1821
Average annual water quantity	m^3/s	2410	300	5270	2560	2860	1660
Forest cover rate	%	55.70	44.50	81.30	32.10	53.60	47.60
Internal renewable freshwater resources	km^3	112.72	1003	190.40	224.50	120.60	359.40
Watershed population density	people/km^2	46	24	33	147	107	366
Flow contribution	%	16	2	35	18	18	11
Electricity demand	10^3 MW	114.30	1.59	0.65	25.61	0.40	20.00
Irrigated area	10^4 hm^2	51.60	8.60	30.10	129	34.40	180.60
Water productivity	\$/m^3	14.90	2.30	2.80	6.70	6.80	1.80
Per capita gross domestic product	\$	4850	1152	1752	6100	1065	1963

The following projection values for the bargaining power of each country were used to solve the projection pursuit model based on RAGA by MATLAB software.

$$w_i = (17.34\%, 5.93\%, 26.48\%, 17.32\%, 17.35\%, 15.58\%),$$

where i = (*China, Myanmar, Laos, Thailand, Cambodia, Vietnam*).

As shown in Figure 4, the strongest bargaining power is that of Laos, while Myanmar has the weakest. Laos has the largest water contribution to the main stem of the river. The country includes the biggest portion of the basin area with a large river runoff and huge ecological water demand. On the other hand, the country's total freshwater capital, per capita GDP, and water productivity are relatively low compared with the other riparian countries. Myanmar has the lowest bargaining power. This is because the country's water contribution to the rivers main stem, basin area included with its borders, and irrigated area within the river's sub-basin are minimal. In addition, the country has a large, internal freshwater capital. The bargaining power difference among the riparian countries is insignificant, especially among China, Thailand, Cambodia, and Vietnam. This can help the riparian countries to adopt better negotiation and cooperative approaches for sharing the river's water capital.

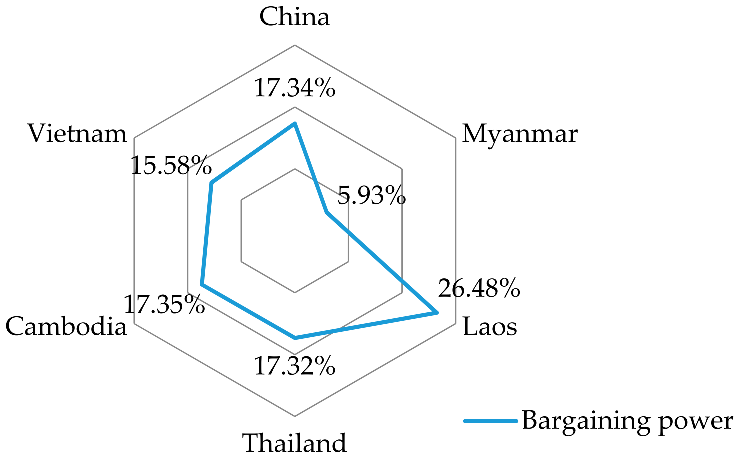


Figure 4. The bargaining powers of the Mekong River basin riparian countries.

For this case study, the water allocation optimization problem can be written as:

$$u^N(s) = \left\{ s \in S \left| \begin{array}{l} \max[(u_{CHN}(e_{CHN}) - u_{CHN}(d_{CHN}))^{w_{CHN}} \cdot (u_{MYA}(e_{MYA}) - u_{MYA}(d_{MYA}))^{w_{MYA}} \cdot \\ (u_{LAO}(e_{LAO}) - u_{LAO}(d_{LAO}))^{w_{LAO}} \cdot (u_{THA}(e_{THA}) - u_{THA}(d_{THA}))^{w_{THA}} \cdot \\ (u_{CAM}(e_{CAM}) - u_{CAM}(d_{CAM}))^{w_{CAM}} \cdot (u_{VIE}(e_{VIE}) - u_{VIE}(d_{VIE}))^{w_{VIE}}] \end{array} \right. \right\}$$

$$s.t. \begin{cases} 0 \le e_i \\ d_i \le e_i \le c_i \\ \sum_{i=1}^{6} e_i \le E \\ \sum_{i=1}^{6} w_i = 1 \end{cases} . \tag{16}$$

4.2. Results and Discussion

The optimum water allocation payoffs from the proposed allocation framework and MATLAB software for the dry season showed that, except for China and Vietnam, whose 63.48% and 47.47% of water demand is fulfilled, respectively, all the other riparian countries get their full claim (Table 4 and Figure 5).

Table 4. Water allocation payoffs from the proposed allocation scheme.

Countries	Water Demand (km^3)	Disagreement Point (km^3)	Bargaining Power	Water Allocation (km^3)
China	100.99	53.70	17.34%	64.43
Myanmar	0.99	0	5.93%	0.99
Laos	0.29	0	26.48%	0.29
Thailand	7.18	0	17.32%	7.18
Cambodia	0.27	0	17.35%	0.27
Vietnam	19.84	0	15.58%	9.10

The water allocated to Myanmar, Laos, Thailand, and Cambodia is significantly lower than that of China's and Vietnam's, however, their water demand is fully met. On the other hand, even though China and Vietnam are awarded most of the river's water, their water demand is not totally satisfied.

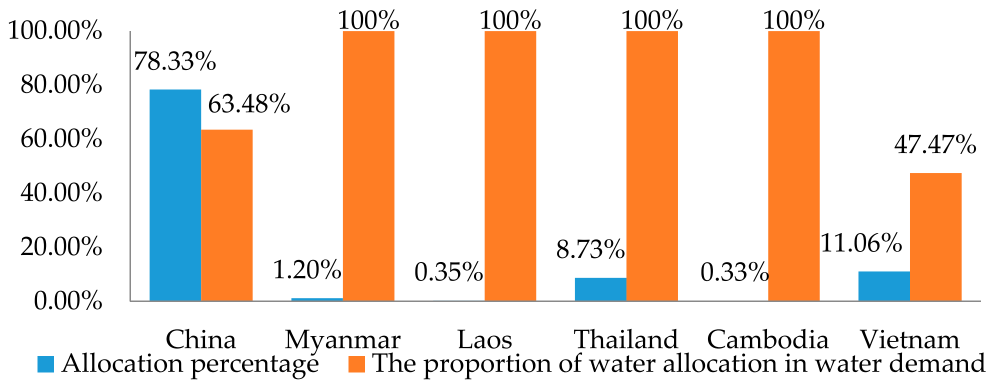


Figure 5. Water allocation payoffs from the proposed allocation scheme.

According to Equation (16), in order to achieve rational water allocation and maximum group utility, the following conditions must be met:

$$\begin{cases} d_i \leq e_i \leq c_i \\ \sum_{i=1}^{6} e_i \leq E \\ (e_i - d_i)/(e_j - d_j) = w_i/w_j \end{cases}. \tag{17}$$

The allocation of water is affected by water demand, bargaining power, and the disagreement point of each riparian country. Individual rationality and maximization of group utility depend on whether or not Equation (17) is satisfied.

As the water demand of riparian countries increases, their disagreement points also will increase. This decreases the possibility of finding an optimal solution for Equation (18). As the number of water-claiming riparian countries increases, the same problem arises. The bargaining powers of the riparian countries also influence the solution of Equation (18):

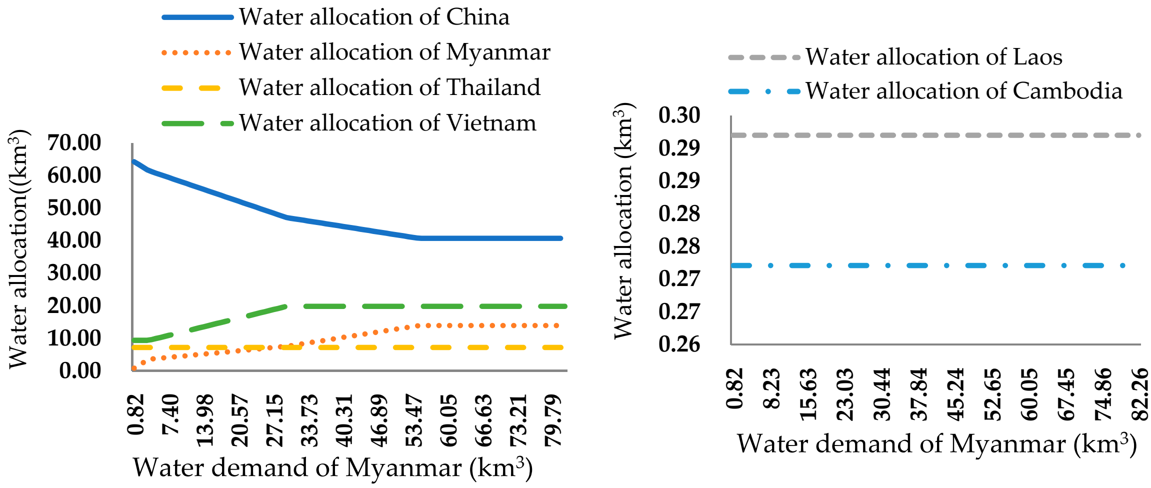
$$(e_i - d_i)/(e_j - d_j) = w_i/w_j. \tag{18}$$

If Equation (18) can't be met, due to $0 \leq u_i(e_i) = (e_i - d_i)/(c_i - d_i) \leq 1$, in order to maximize the group utility, the claim of the country, i_L, with the lowest water demand, $\min\{c_i\}$, will be satisfied first. Then, the water-sharing problem is rearranged with the rest of the riparian countries to find the optimal solution for Equation (19):

$$\begin{cases} e_{i_L} = c_{i_L} \\ d_{\{i/i_L\}} \leq e_{\{i/i_L\}} \leq c_{\{i/i_L\}} \\ \sum_{i=1}^{n-1} e_i \leq E - e_{i_L} \\ (e_{\{i/i_L\}} - d_{\{i/i_L\}})/(e_{\{j/i_L\}} - d_{\{j/i_L\}}) = w_{\{i/i_L\}}/w_{\{j/i_L\}} \end{cases}. \tag{19}$$

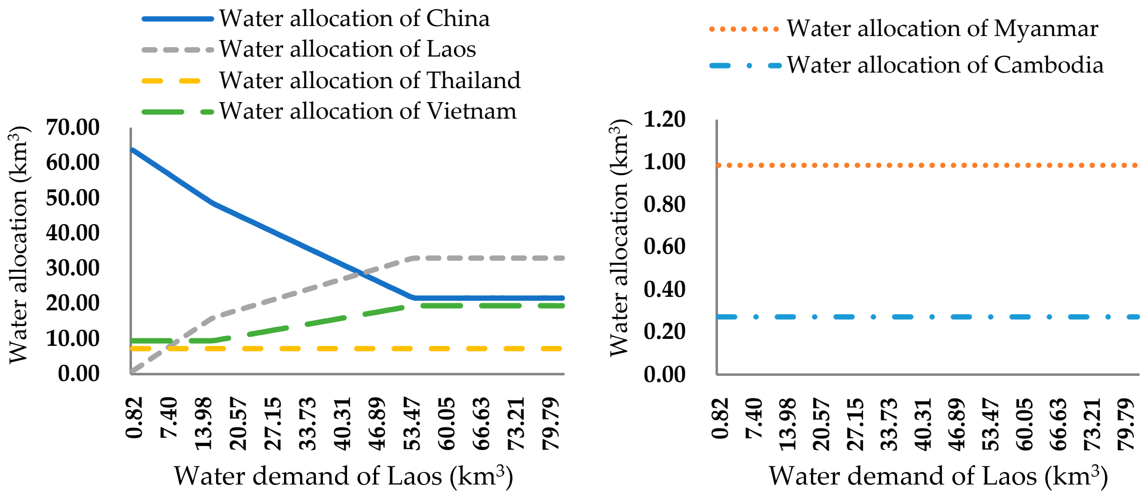
For riparian countries with minimal water demand such as Myanmar, Laos, Thailand, and Cambodia, the water allocated to them depends only on their water demand. On the other hand, the water allocated to China and Vietnam is influenced by the water demands and bargaining weights of all the riparian countries. This is because of the large water demands of these two riparian countries.

The authors also conducted sensitivity analysis for the bargaining power and water allocation outputs. This shows how the change in the water demand and bargaining power affect the water allocation payoffs of the riparian countries. The sensitivity analysis for the water demand showed that the allocation to each of the riparian countries is affected by the increase in water demand of the other river sharing countries. This is true only if a riparian country's water demand does not satisfy the exclusion property. The exclusion property states that if a water demand of the claimant is not larger than the water quantity it can secure through the average distribution of the available water capital, it will be awarded its full claim [38,79]. This is because if the water demand is very low the country should not be held responsible for the water bankruptcy in the river basin. Figures 6 and 7 shown below, as well as Figures S1–S4 in Supplementary Material, shows the sensitivity of the water allocation outputs to the water demands of the Mekong River basin riparian countries.



(**a**) (**b**)

Figure 6. The sensitivity of the water allocation outputs to the water demand of Myanmar: (**a**) The sensitivity of the water allocation outputs of China, Myanmar, Thailand and Vietnam to the water demand of Myanmar; (**b**) The sensitivity of the water allocation outputs of Laos and Cambodia to the water demand of Myanmar.



(**a**) (**b**)

Figure 7. The sensitivity of the water allocation outputs to the water demand of Laos: (**a**) The sensitivity of the water allocation outputs of China, Laos, Thailand and Vietnam to the water demand of Laos; (**b**) The sensitivity of the water allocation outputs of Myanmar and Cambodia to the water demand of Myanmar.

The sensitivity results for the bargaining power show that as the bargaining power of a country increases, the water allocated to it also increases, but only under the condition that the country's water demand does not fulfill the exclusion principle. If the water demand is below the water amount it can secure through average distribution, the riparian state will get 100% of its water claim, irrespective of the value of its bargaining power. On the other hand, when the water demand is above what the riparian country can obtain by average distribution, the allocation output and bargaining power have a positive relationship. Hence, an increase in the bargaining power of the riparian country is translated into an increase in the water allocation payoff. Therefore, a decrease in the other riparian countries water allocation payoffs will result. This is a result of the water demands of these riparian countries being greater than the ones they can be rewarded with under the average distribution rule. Figures 8 and 9 shown below, as well as Figures S5–S8 in Supplementary Material, depict the sensitivity of the water allocation outputs to the bargaining powers of the Mekong River basin riparian countries.

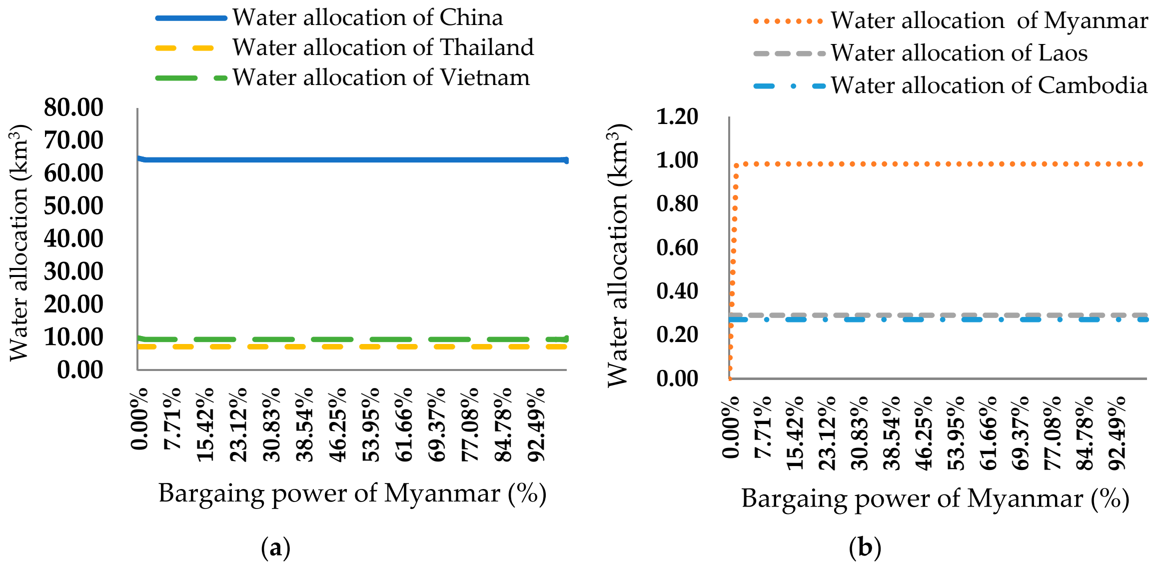


Figure 8. The sensitivity of the water allocation outputs to the bargaining power of Myanmar: (**a**) The sensitivity of the water allocation outputs of China, Thailand and Vietnam to the bargaining power of Myanmar; (**b**) The sensitivity of the water allocation outputs of Myanmar, Laos and Cambodia to bargaining power of Myanmar.

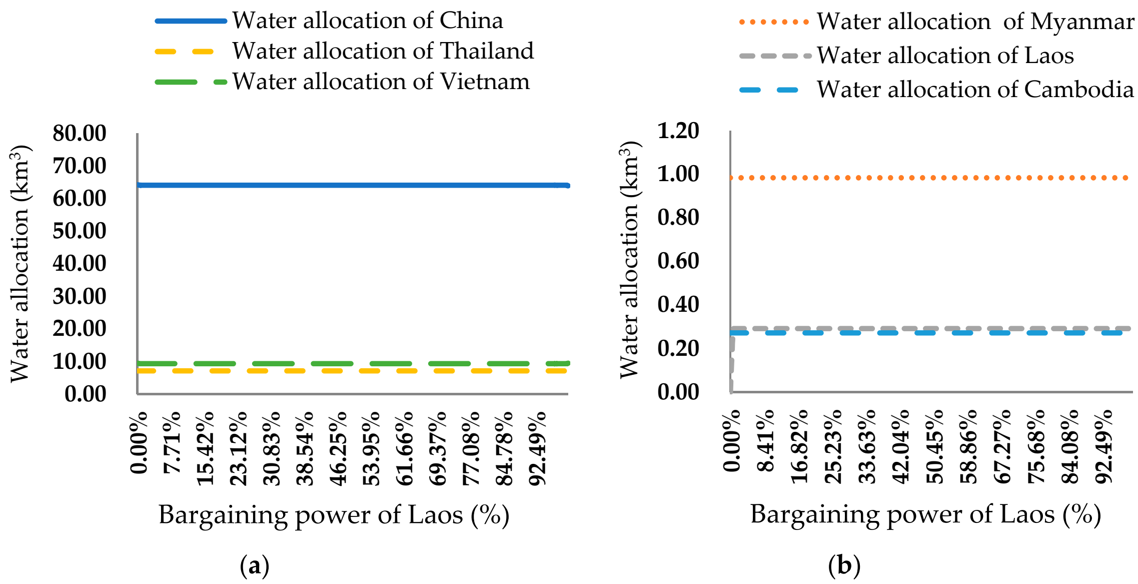


Figure 9. The sensitivity of the water allocation outputs to the bargaining power of Laos: (**a**) The sensitivity of the water allocation outputs of China, Thailand and Vietnam to the bargaining power of Laos; (**b**) The sensitivity of the water allocation outputs of Myanmar, Laos and Cambodia to bargaining power of Laos.

Generally, the results of this study show that the following desired properties are fulfilled by the allocation framework: (1) Feasibility; the allocation framework ensures that the total amount of water allocated to the riparian countries is less than or equal to the total available water. (2) Efficiency; the water assigned to be distributed to the sharing countries is completely allotted. (3) Claim boundedness; the maximum water allocated to the riparian countries by the proposed sharing mechanism is bounded by their claim, therefore, the Law of Diminishing Marginal Utility is respected. (4) Equal treatment of equals; the allocation rule treats the riparian countries with equal water demand, bargaining power, and disagreement point equally. (5) Scale in-variance; the allocation rule satisfies scale invariance in water demand and available water. (6) Exclusion; if the amount of water a riparian country can be rewarded with average distribution is greater than its water claim, the riparian will be rewarded its full claim.

This article proposed an allocation mechanism that can yield fair, efficient, and self-enforceable water allocation payoffs. But there is still room for improvement that needs to be addressed through further research. The following three are the main ones: (1) The issue of water quality should be taken into account through further research; (2) the environmental water need also needs to be considered; (3) the impact of anthropogenic climate change on the water allocation outputs should also be quantified; (4) the sensitivity of the allocation outputs to the different dynamic factors needs to be computed in detail through further studies. Addressing these issues through further research will make the proposed allocation framework more fair, efficient, and sustainable.

5. Conclusions

The allocation of scarce water resources within transboundary river basins has a complex and dynamic nature. In this paper, bankruptcy theory, bargaining games, and optimization algorithms were used to construct a new weighted theoretical game water allocation scheme. In addition, using well-known international rules, a novel water allocation framework that is capable of determining the bargaining powers of riparian countries in any international river basin was built.

The theory of bankruptcy was applied to establish a model that captures the water scarcity and strategic interaction among the riparian countries in a water-scarce river basin. The proposed scheme has the following novel characteristics: (1) The model takes into account the heterogeneous features of the riparian countries, which makes it more reasonable and realistic; (2) the allocation model satisfies the basic principles of individual rationality and group rationality; (3) it is a fair, reasonable, and self-adaptive water allocation framework that yields self-enforceable water allocation outputs. Furthermore, the proposed allocation model satisfies feasibility, efficiency, claim boundedness, equal treatment of equals, scale in-variance, and exclusion. The fact that the proposed allocation system fulfills these properties proves that it is consistent. Therefore, the allocation framework can be applied to allocate water in other transboundary river basins too.

The model was used to distribute the Mekong River basin's water among the riparian states during the dry season. The optimal solution obtained lies on the Pareto Frontier. In addition, the sensitivity of the water allocation outputs to the water demand and the bargaining power of the riparian countries were determined. Subsequently, how the water allocation outputs were influenced by water demand, the disagreement point, and the bargaining power of each riparian state were elaborated. The results depict that the water allocation outputs are barely sensitive to the water demands, disagreement points, and bargaining powers of most riparian countries because their water demands are very minimal. China and Vietnam are the two countries which have water demands, disagreement points, and bargaining powers that significantly affect the water allocation outputs.

In general, this paper establishes a water resource allocation model that takes into account the strategic interaction among transboundary river basins' riparian countries based on their socioeconomic and environmental status. Hence, the authors believe that this work is one step further in the efforts to find a water allocation method that is fair, efficient, and sustainable.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4441/11/2/400/s1: Figure S1: The sensitivity of the water allocation outputs to the water demand of China, Figure S2: The sensitivity of the water allocation outputs to the water demand of Thailand, Figure S3: The sensitivity of the water allocation outputs to the water demand of Cambodia, Figure S4: The sensitivity of the water allocation outputs to the water demand of Vietnam, Figure S5: The sensitivity of the water allocation outputs to the bargaining power of China, Figure S6: The sensitivity of the water allocation outputs to the bargaining power of Thailand, Figure S7: The sensitivity of the water allocation outputs to the bargaining power of Cambodia, Figure S8: The sensitivity of the water allocation outputs to the bargaining power of Vietnam.

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