

Water Allocation Management Under Scarcity: A Bankruptcy Approach

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Water Allocation Management under Scarcity: a Bankruptcy Approach

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Abstract

This study hopes to develop multi-criteria decision making (MCDM) method for equitable and efficient allocation water resource under scarcity. Based on the Bankruptcy problems, five classic plus one proposed allocation rules are introduced to generate water distribution alternatives. The “Core” solution of Cooperative Game Theory (CGT) and Security Restriction have been used to select the feasible alternatives. Additionally, five voting methods in Social Choice Theory (SCT) are launched to aggregate preferences and obtain “win” alternative. Apply this model on 2030 water allocation management project of Ezhou City, China, as a case study. Under the proposed rule, adjust minimal overlap rule (AMO), five regions, Urban Area, Gedian DZ and three counties, hold the water deficit rate of 5.9%, 15.8% and 4.7%.1%, respectively. By voting technique, AMO wins four fifths of aggregating processes and came in the second for the last, which provides some insights for allocating water in a fair and feasible way.

Keywords: Water allocation; Bankruptcy problem; Social choice theory; Multi-criteria decision making

1 Introduction

Water scarcity is becoming more prominent, as the intensification of global climate change and the acceleration of industrialization and urbanization (Salman, 2007). In the past decades, human activities have caused the global available water resources to decrease at a rate of about 100 billion $m^3/year$ (Mueller Schmied et al, 2014; Wang et al, 2018). At the same time, global water consumption has increased six times in the past 100 years and is still growing steadily at a rate of approximately 1% per year (WWAP, 2020). Uncontrolled water withdrawal and increased demand for fresh water are main causes of water shortages. Therefore, proposing effective methods to allocate water resources in an equitable, reasonable and sustainable manner is the effective way to solve the shortage of water resources.

Water resources management in a basin has changed from a single-goal problem into more complex multi-criteria decision making (MCDM) problems, which involving multiple feature, multiple aspects, and multiple stakeholders Huang et al (2011); Gebre et al (2021); Hipel (1992); Hajkowicz and Collins (2007). Water is a fundamental resource for economic development, social welfare, and environmental protection. The allocation of water resources is a complex process which needs to meet the basic needs of agriculture, industry, and domestic use, as well as to maintain the balance of the ecosystem. At the same time, different water users have different preferences and characteristics, coordinating the conflicts of interests and demands among watershed stakeholders is challenge for decision-makers.

Researchers try to solve the MCDM problems of water resources by using various methods, but defects accompanied. The classical tools transform the MCDM problem into a single objective function and solve it through optimization algorithms (Harou et al, 2009). Although those methods can obtain optimal results theoretically, they still face the low implementability problems in practice because of their complex algorithms and abundant assumptions. Therefore, Game Theory (GT) has been introduced to describe the relationship between the individual and/or group rationality and to analyze the global equilibrium (Kaveh, 2009; Thomson, 2003). Even GT can better reflect the reality and provide foreseeable consequences, reliable scenario requires accurate and large data as well as correct determine the utility functions, which is often difficult to quantify in reality (Kaveh, 2009; Yang et al, 2019; Li et al, 2019; Chih-Sheng, 2012; Zhao et al, 2013; Kaveh and Keith, 2011). Therefore, in order to maximize the comprehensive benefits of water resources allocation under MCDM, the following questions need to be answered: How to make reasonable and realistic alternatives and how to choice them fairly and effectively, when data is scarce or utility functions are difficult to obtain?

1.1 Reasonable allocation alternatives

The Bankruptcy problems, coming from enterprise bankruptcy scenario, mainly studies on how to distribute remaining the remaining assets E , which

less than the claims C , among shareholders and creditors (O'Neill, 1982). Distribution rules under Bankruptcy theory can offer equitable and reasonable solutions under limited resources, which has been widely used in many areas (Kim et al, 2010; van den Brink et al, 2013; Gimenez-Gomez and Penis, 2014; Dietzenbacher et al, 2021). In water resource management, when the available water cannot meet the demands from basin users, how to efficient and reasonable allocate water has similar scenario with bankruptcy problems.

Due to various interpretations of equity, several classic bankruptcy rules have been proposed, which includes: Proportional rule (PRO), Constrained equal awards (CEA), Constrained equal losses (CEL), Piniles rule (Pin), the Talmud rule (TAL), Constrained egalitarian (CE), Adjust Proportional (AP), Random arrival (RA) rule, and so on (Curiel et al, 1987; Mianabadi et al, 2014, 2015; Madani et al, 2014b; Thomson, 2003, 2015). In addition to classic rules, two branch of bankruptcy problems can be roughly extended: 1) weighted-based; 2) Sequential-based. Considering the contribution and corresponding claims, scholars re-determine the weight of each stakeholder by introducing coefficients or vectors from different standards, like marginal contribution to coalition (Degefu et al, 2016), willingness to pay criterion (Sechi and Zucca, 2015), multiple hydrological constraints (Yong et al, 2017), to adjust equitable consequences. Meanwhile, other scholars have considered spatial variability of river basins users, Ansink and Weikard (2012) transfer an basin-based bankruptcy problem to a linear order two-agent sharing problem, and Goetz et al (2008) define two different sequential allocation rules that respect asymmetry. Recent years, many studies integrate bankruptcy theory with other game-based theory to explore new allocation methods: Degefu et al (2016, 2017, 2018) systematically combine bankruptcy framework with the bargaining theory, Yuan et al (2017) construct a cooperation bankruptcy game model, and Yazdian et al (2021) develop a non-cooperative optimal management scenario under bankruptcy conditions.

Applying bankruptcy rules to water resources allocation has the following advantages: 1) Bankruptcy rules provide fair and reasonable allocations to the riparian stakeholders (Degefu and He, 2016). 2) They are game-theoretic based method, which can reflect the individual preference and group rationality of stakeholders. 3) They are well understood, easy implemented, which is more valuable for solving actual water conflict.

1.2 Equitably choice alternatives

Social Choice Theory (SCT) studies on the relationship between individual preferences and group choices, which can be considered as a voting technique that belongs to MCDM (Madani et al, 2014b). Due to few requirements and concise voting process, SCT has been widely accepted in the scenarios with incomplete information or with unknown utility functions (D'Angelo et al, 1998). By designing a voting process, individual stakeholders preferences are aggregated into collective decisions, and the "win" alternative is selected (Feldman and Serrano, 2006).

Water resources are managed by different stakeholders who have different characteristics and interests. Considering the heterogeneity of stakeholders, centralized optimization models cannot well reflect the individual preferences, and game-based models insufficiently consider of group decision-making process, which reducing the agent's motivation to participate and leading to deviations. SCT can rank and evaluate different water resources allocation alternatives based on the preferences of stakeholders. Although the result is not Pareto optimal, SCT can aggregate consensus among stakeholders and reach an acceptable solution, which is more stable and implementable (Read et al, 2014).

The advantages of SCT in water resources management can be summarized as follows: 1) Relatively simple and clear rules, which suitable for MCDM problems. 2) Concise voting process does not rely on detailed data and utility functions, which is particularly attractive when information is uncertain. 3) Better participation of stakeholders in preference aggregating provides better acceptability and stability, which is especially valuable for resolving conflicts under water scarcity.

1.3 Innovation and structure

In response to the questions raised previous, we use Bankruptcy rules to propose reasonable and realistic alternatives and SCT to solve decision-making problems fairly and effectively. This approach can provide MCDM solutions when data is scarce or utility functions are not available.

When processing this approach, we found that classic Bankruptcy problems mostly sets water allocation weights when facing with economic factors or contributions, while insufficiently consider the details and differences of participants that reflected by the factors. The influence of economic factors on water resource can be roughly summarized into two aspects: one is economic volume, which determines the total amount of water that claimed by participants; the other is economic structure, which reflects the demand for water security (tolerance of water deficit rate). The same amount of water shortage has less impact on larger water users (low deficit ratio), and different economic sectors (agriculture, industry, domestic, etc.) have different tolerance of deficit ratio. Failure to consider the characteristics and constraints of the sectors in each region may lead to a gap between theory and practice.

To solve this problem, we propose a novel distribution rule under Bankruptcy theory, which takes into account the impact of different claim amounts of different participants while ensuring fairness. Then, we propose a new restriction, the Security Restriction, which considers the influence of different economic factors to determine whether the alternatives are feasible.

In summary, this research aims to make water resource allocation decisions in an equitable, reasonable and sustainable manner, under the case of insufficient data or the utility function is unavailable. Based on the Bankruptcy problems, five classic plus one proposed distribution rules are introduced to generate water distribution alternatives. Through the double inspection, the

“Core” Solution in the Cooperative Game Theory (CGT) and Security Restrictions, acceptable alternatives are selected. Five voting methods in the SCT are launched to aggregate stakeholders preferences and to obtain a “win” alternative in different situation (Fig. 1). Apply this model on water resource planning problems of Ezhou City, Hubei Province, China as a case study. This study provides a concise and efficient decision-making solution for the multi-agent decentralized MCMD problem under the condition of insufficient information.

This paper organize in following structure: Section 2 mainly defines and describes the model, which consists three parts. The first part describes the basic rules of bankruptcy and proposes the new rules, the second part takes the economic factors as constraints to ensure the feasibility, the last part introduces the aggregating process under SCT. A case study application of the two parts is described in Section 3. The results and discussion of the model application will be presented in Section 4. The last Section 5 presents a summary of the study.

2 Methodology

The flowchart below illustrates the methodology of this research (see Fig. 1) and following sections discuss the methods involved in the model.

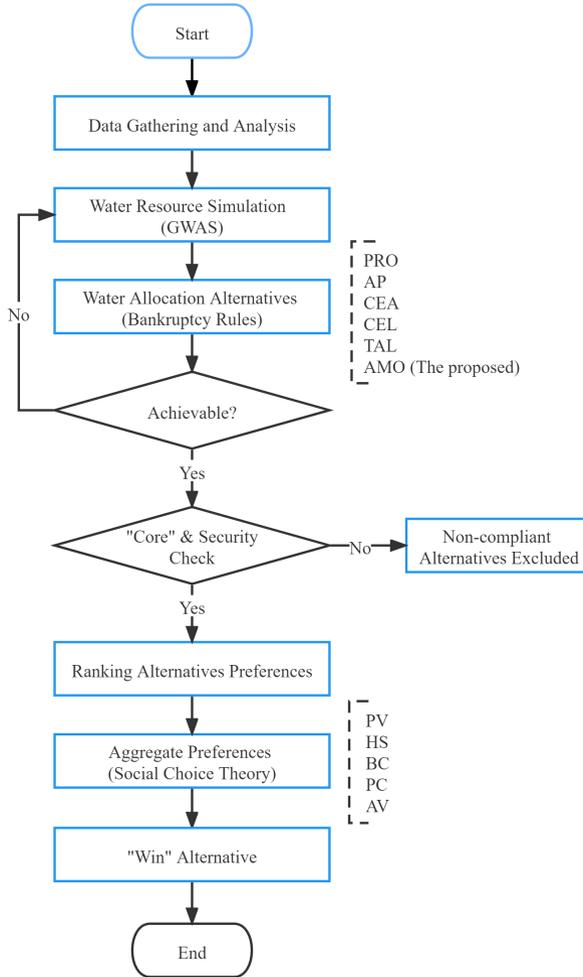


Fig. 1 Flowchart of Methodology

2.1 Bankruptcy Allocation Rules

This subsection generates alternatives through Bankruptcy rules. We use five widely accepted rules (PRO, CEA, CEL, PIN and TAL) and one proposed rule (adjusted minimal overlap rule, AMO) for water resource allocation.

2.1.1 Basic Scene

Consider a total amount E of water resource available for distribution among a set of agents $N = (1, 2, \dots, n)$ in the river basin. The claims of each agent are $c_i \geq 0$ for, and the sum for their claims C exceed E ($C \geq E$).

$$C = \sum_{i=1}^n c_i \quad (1)$$

$$E \leq C \quad (2)$$

The bankruptcy problem in basin system can be defined as $\Psi(N, E, c)$, and the objective is to determine the allocation amount of each agents, denoted by x_i , where $x = (x_1, x_2, \dots, x_n)$. There are three basic requirements for the bankruptcy problems:

Requirement(a), “efficiency”: the sum of all resources should not exceed the amount available and the entire amount available should be allocated (Thomson, 2003, 2015).

$$E = \sum_{i=1}^n x_i \quad (3)$$

Requirement(b), “non-negativity and feasibility”: each agent should receive a non-negative amount and should not larger than his claims (Mianabadi et al, 2014, 2015).

$$0 \leq x_i \leq c_i \quad (4)$$

Requirement(c), “equal treatment and monotonicity”: same claims receive the same treatment, and the amount of allocations should be positively correlated with the claims (Thomson, 2003, 2015).

For each $(N, E, c) \in \Psi$ and each $\{i, j\} \in N$:

$$\text{if } c_i = c_j, \quad \text{then } x_i = x_j \quad (5)$$

$$\text{if } c_i \leq c_j, \quad \text{then } x_i \leq x_j \quad (6)$$

2.1.2 Classic Rules

1. Proportional rule, PRO, is the most commonly used rule in practice, and its allocation principle is to allocate water resource according to a fixed proportion λ of claims in each agent:

$$PRO(x_i) = \lambda x_i \quad \text{where } \lambda = \frac{E}{C} \quad (7)$$

in which, $PRO(x_i)$ stands for the allocation x_i of each agent under the proportional rule, follows are same.

2. Adjusted proportional rule, AP, can be considered to ensure the minimal right of agents first, and then the PRO rule is launched on the remainder.

For $(N, E, c) \in \Psi$ and each $\{i, j\} \in N$, the minimal right of agents can be defined as:

$$m_i(E, c) = \max\{E - \sum_{j \in N \setminus \{i\}} c_j, 0\} \quad (8)$$

Then the AP rule:

$$AP(x_i) = m_i(E, c) + PRO(c_i - m_i(E, c)) \quad (9)$$

3. Constrained equal awards rule, CEA, takes “equal” as primary, assigns equal amounts to all agents, subjected to no one exceed his claims:

$$CEA(x_i) = \min\{c_i, \lambda\} \quad \text{where} \quad \sum \min\{c_i, \lambda\} = E \quad (10)$$

in which, λ represents an equal share of total amount E .

4. Constrained equal losses rule, CEL, also takes “equal” as primary but on another side, assigns equal loss to all agents, constrained to no claimant receiving a negative allocation:

$$CEL(x_i) = \max\{0, c_i - \lambda\} \quad \text{where} \quad \sum \max\{0, c_i - \lambda\} = E \quad (11)$$

in which, λ represents an equal loss of agents.

5. Talmud rule, TAL, generated by [Aumann and Maschler \(1985\)](#), draws on the half-sum idea. Determine whether the amount to divide (E) equals to the half of claims (C) firstly. If there is less, the CEA formula is applied; and if there is more, the CEL launched. In each case, the half-claims are used in the formula instead of the claims themselves ([Thomson, 2003](#)):

if $\sum(\frac{c_i}{2}) > E$, then:

$$TAL(x_i) = \min\{\frac{c_i}{2}, \lambda\} \quad \text{where} \quad \sum \min\{c_i/2, \lambda\} = E \quad (12)$$

if $\sum(\frac{c_i}{2}) \leq E$, then:

$$TAL(x_i) = c_i - \min\{\frac{c_i}{2}, \lambda\} \quad \text{where} \quad \sum [c_i - \min\{c_i/2, \lambda\}] = E \quad (13)$$

2.1.3 The Proposed rule

Adjust Minimal overlap rule, AMO, is inspired by the Minimal Overlap Rules (MO) mentioned by [O’Neill \(1982\)](#). The disadvantage of MO rule is that it can only be applied when the assets are no more than the maximum claim and no less than the minimum claim, which leading to insufficient applicability ([Thomson, 2003](#)). We put forward an improvement on MO, taking the total water deficits ($C - E$) as “assets” and applying MO rules to allocate them. The water allocation x_i of each agent equals to its claim c_i minus its share of the deficit, calculation steps are follows:

- a. Sort claims from small to large, and the new sequence marked as $k = 1, 2, \dots, N$.
- b. Divide the deficit ($C - E$) according to specific “units”, so that the number of units claimed by agent $k = N$ is maximized. Then, the size of each “unit” can be expressed as: $u = \frac{C-E}{c_n}$.

- c. Distribute claims over these units so as to minimal overlap claims of the “assets”. For each “unit”, equal division prevails among all agents claiming it. Denote the deficits shared by agent k as: $D_k(C)$, $k \in N$, then:

$$\begin{cases} D_1(c) = \frac{c_1}{n} \times u \\ D_2(c) = \left(\frac{c_2 - c_1}{n-1} + D_1(c)\right) \times u \\ \vdots \\ D_k(c) = \left(\frac{c_k - c_{k-1}}{n-k+1} + D_{k-1}(c)\right) \times u \\ \vdots \\ D_n(c) = \left(\frac{c_n - c_{n-1}}{1} + D_{n-1}(c)\right) \times u \end{cases} \quad (14)$$

- d. The amount of water allocation to each agent is its claims minus its share of deficit:

$$AMO(x_k) = c_k - D_k(c) \quad (15)$$

2.2 “Core” Solution and Security Restrictions

1) “Core” Solution

The Bankruptcy problems arise for total claims exceed the available resources, which can be considered as a branch of Cooperative Games Theory (CGT) that determine the fair allocation of assets among different agents (Aumann and Hart, 1992). CGT provides the necessary instruments to determine how benefits or assets can be fairly and efficiently distributed among agents, and where is the boundaries of grand coalitions or cooperation remain stable, called the “Core” solution.

To define a CGT, additional definitions are following:

- x_i represent the benefit when agent i cooperate with others;
- x_i^* represent the benefit when agent i act alone;
- $S \in N$ is a “coalition”, when $S=N$ is the “Grand Coalition”;
- $v(S)$ is the benefit linked to the coalition S ;
- $v(N)$ is the benefit linked to the Grand Coalition.

To obtain a “Core” solution, CGT exploits three fundamental principles:

The Efficiency, the benefits of the Coalition are all distributed among its participants.

$$\begin{cases} \sum_{i \in N} x_i = v(N) \\ \sum_{i \in S} x_i = v(S) \end{cases} \quad (16)$$

The Coalition Rationality, no agent or coalition gain benefit less than its standalone benefit:

$$\sum_{i \in S} x_i^* \leq v(S) \quad (17)$$

The Individual Rationality, for each agent, cooperative is no less than not

$$x_i \geq x_i^* \quad (18)$$

Sechi and Zucca (2015) establishes the connection between CGT and Bankruptcy problem in water resources allocation by treating the water allocation x_i as the benefits in CGT, so the we have: $v(N) = E$ for Eq.(16).

Here we refer Sechi and Zucca (2015) definition of the “core” solution characteristic function:

$$v(S) = \max\{(E - \sum_{i \in (N-S)} c_i), 0\}, \quad S \in N \quad (19)$$

Take the “Core” solution of CGT as one of the restriction conditions of the Bankruptcy alternatives.

2) Security Restriction

The “Core” solution ensures that participants can get more benefits in the Grand Coalition and maintain cooperation, but it does not mean that the alternatives will be accepted automatically. Different departments have different security requirements, and the economic structure of regions are different as well. In this research, we regard the maximum tolerance for water deficits as the bottom line, considering the actual economic structure of agriculture, industry, and domestic water use in different regions, and propose security restrictions as follows:

$$c_i - x_i = D_i(c) \leq d_i^{agr} + d_i^{ind} + d_i^{dom} \quad (20)$$

In which, $d_i^{agr}, d_i^{ind}, d_i^{dom}$ represents the maximum allowable deficit of agriculture, industry, and domestic water for region i , respectively.

2.3 Aggregate Preference under Social Choice Theory

SCT may be regarded as concise and efficient decision-making means that enhance the stability or acceptability of group endeavors (Srdjevic, 2007; Zolfagharipour and Ahmadi, 2016; D’Angelo et al, 1998; Madani et al, 2014a). The basic problems in water resource allocation area is: design a reasonable voting method on given water resource allocation alternatives. Voters (stakeholders) state their preferences for each alternative assuming that they have equal powers. Social choice rules are launched to aggregate voters’ preferences and produce the “win” alternative based on its specific notion of social optimality and fairness.

Here, five popular and practical voting process are introduced to the water allocation problem which include: Plurality voting (PV), Hare system (HS), Borda count (BC), Pairwise comparisons voting (PC), Approval voting (AV).

2.3.1 Basic Scene

A general mathematical formulation of social choice problems can be denoted as following way. Consider there are n stakeholders and m alternatives, stakeholders rank the alternatives based on their preferences (or utility functions). Therefore, a preference order matrix $R_{n \times m}$ can be constructed as below:

$$R_{n \times m} = \begin{pmatrix} r_{1,1} & \cdots & r_{1,m} \\ \vdots & r_{i,j} & \vdots \\ r_{n,1} & \cdots & r_{n,m} \end{pmatrix} \quad (21)$$

In which, $r_{i,j}$ represents the preference ranking value of stakeholder i for alternative j . If j is the best alternative for stakeholder i , then $i_{i,j} = 1$; If j is the second best alternative for stakeholder i , then $i_{i,j} = 2$, and so on; for the worst alternative, then $i_{i,j} = n$.

2.3.2 Voting Methods

1. Plurality voting, PV, is one of the oldest and perhaps the most commonly used method (Madani et al, 2014a). Based on the plurality rule, the “win” solution is the alternative with the largest number of first-place rankings:

Define:

$$p(r_{i,j}) = \begin{cases} 1 & \text{if } r_{i,j} = 1 \\ 0 & \text{otherwise} \end{cases} \quad (22)$$

For each alternative j , the sum:

$$P_j = \sum_{i=1}^N p(r_{ij}) \quad (23)$$

The number of p_j indicates how many times alternative j has been choice as the best, and the “win” alternative PV_j under Plurality voting rule is:

$$PV_j = \max P_j \quad (24)$$

2. The Hare system, HS, is based on the successive deletion of less desirable alternatives (D’Angelo et al, 1998). After each round of voting, the alternative with the least votes is eliminated and a new round of voting is done with the remaining alternatives, until there is an alternative that gets more than half of the votes or all remaining alternatives get equal votes.

For M alternatives election, the Hare system requires $M - 1$ rounds at a maximum.

At each step, the deleted alternative j^* is selected as:

$$P_{j^*} = \min P_j \quad (25)$$

Where P_j are defined in the Plurality rule (see Eq.23). After deleting the least desirable alternative, the preference order matrix changes to $R_{n \times (m-1)}$ and preference ranking value $r_{i,j}$ of stakeholder i modify as:

$$r_{i,j}^{new} = \begin{cases} r_{i,j} & \text{if } r_{i,j} \leq r_{i,j}^* \\ r_{i,j} - 1 & \text{otherwise} \end{cases} \quad (26)$$

The process terminates, and the “win” alternative HS_j under Hare system voting rule when:

$$HS_j = \begin{cases} P_j \geq \frac{M}{2} \\ P_j & \text{when } P_j \text{ equals to each other} \end{cases} \quad (27)$$

3. The Borda count, BC, follows the highest point to “win”. In this method, every alternative receives a point according to its rank for each stakeholder. When a lower rank means a better preference, the worst alternative gets 0 points, the second worst gets 1 point, and so on, the very best alternative gets points.

If $a_{i,j}$ is preference point, then:

$$a_{i,j} = m - r_{i,j} \quad (28)$$

Hence, the total point for each alternative j is:

$$P_j = \sum_{i=1}^n a_{i,j} = nm - \sum_{i=1}^n r_{i,j} \quad (29)$$

And the “win” alternative BC_j under Borda count rule is:

$$BC_j = \max P_j \quad (30)$$

4. Pairwise comparisons voting, PC, match alternatives with each other head-to-head (Srdjevic, 2007; Ghodsi et al, 2016). Each alternative gets 1 point for a one-on-one win and a half a point for a tie. The alternative with the most total points is the winner.

For each ordered pair j_1, j_2 of alternatives, let the number of stakeholders who prefer j_1 than j_2 denoted by $N(j_1, j_2)$. The overall j_1 is preferred to j_2 if:

$$N(j_1, j_2) \succ N(j_2, j_1) \quad (31)$$

And the compare point $b_{g,h}$ is:

$$b_{g,h} = \begin{cases} 1 & \text{if } N(j_g, j_h) \succ N(j_h, j_g) \\ 0.5 & \text{if } N(j_g, j_h) \equiv N(j_h, j_g) \\ 0 & \text{if } N(j_g, j_h) \prec N(j_h, j_g) \end{cases} \quad (32)$$

where: $g \neq h$ and $g, h \in \{1, 2, \dots, m\}$

Then, a preference matrix $P_{m \times m}$ can built by compare point $b_{g,h}$:

$$P_{m \times m} = \begin{pmatrix} - & b_{1,2} & \cdots & b_{1,m-1} & b_{1,m} \\ b_{2,1} & - & \cdots & b_{2,m-1} & b_{2,m} \\ \vdots & \vdots & - & \vdots & \vdots \\ b_{m-1,1} & b_{m-1,2} & \cdots & - & b_{m-1,m} \\ b_{m,1} & b_{m,2} & \cdots & b_{m,m-1} & - \end{pmatrix} \quad \text{where } b_{g,h} + b_{h,g} = 1 \quad (33)$$

For each alternative j , the sum of compare point is:

$$P_j = \sum_{g=1}^m b_{g,j} \quad (34)$$

The “win” alternative PC_j under Pairwise comparisons rule is:

$$PC = \max \{P_j\} \quad (35)$$

5. Approval voting, AV, is a method of voting in which stakeholders can vote for (approve for) as many alternatives as they wish (Brams and Fishburn, 1978). Similar to the plurality rule, ranking of options is not required, but the certain number l ($l < m$) of approved-group need to be determined. The alternative that has the largest number of approved votes will “win”.

Mathematically, this concept can be formulated as follows:

Define:

$$p(r_{i,j}) = \begin{cases} 1 & \text{if } r_{i,j} \leq \rho \\ 0 & \text{otherwise} \end{cases} \quad \text{where } 1 < \rho \leq l \quad (36)$$

For each alternative j the sum:

$$P_j = \sum_{i=1}^N p(r_{i,j}) \quad (37)$$

The number of P_j indicates how many times alternative j has been approved, and the “win” alternative AV_j under Approval voting rule is:

$$AV_j = \max \{P_j\} \quad (38)$$

3 Case Study

The aims of this section is to apply the proposed procedures in water resources allocation planning of Ezhou city (China) where the supply of water resources less than the claims of stakeholders. Initially, the General Water Allocation and Simulation Model (GWAS) is applied to simulate the natural-social water cycle process. Then, water allocation alternatives are proposed based on the bankruptcy theory and the feasibility is tested through the “Core” of cooperation game and practical Security constraints. Subsequently, the SCT is used to aggregate the preferences and select the “win” scheme. Finally, the stability of the results are tested

3.1 Study area

Ezhou city is located in the southeast of Hubei Province, China, with a total area of $1,594 \text{ km}^2$, including five regions: the Urban Area, Gedian Development Zone (Gedian DZ), and three counties (Echeng, Huarong and Liangzihu). The main water supply source of study area is provided Liangzi Lake basin, which covers 430 km^2 located in the southwest of Ezhou city (see Fig. 2). The five regional governments of Ezhou City will be regarded as stakeholders in the issue of water resource allocation.



Fig. 2 Location of the study area

3.2 Problem description

According to data from Ezhou Comprehensive planning of water resources, Ezhou City water resources bulletin, and Statistical Yearbook of Hubei Province, the estimation of total water demand in Ezhou will reach $1196.85 \text{ Mm}^3/\text{year}$ in 2030, including $304.75 \text{ Mm}^3/\text{year}$ for agriculture, $649.79 \text{ Mm}^3/\text{year}$ for industry and $242.32 \text{ Mm}^3/\text{year}$ for domestic use. However, by 2030, the planned water supply system can only offer $1,080.02 \text{ Mm}^3/\text{year}$, with deficit of $116.83 \text{ Mm}^3/\text{year}$. When the total water withdraw is determined, five stakeholders obtain quotas through negotiations, based on their

own development plans and economic predictions. As the total claims for water users exceeds the available supplies, the water resources planning can be characterized as a bankruptcy problem. At the same time, few measurable data available for the future scenarios, allocating water resource fairly and efficiently is a challenge for decision makers.

Water claims vary in the stakeholders, detailed illustration can be found in Table 1 and the structure of claims show in Fig. 3. From the perspective of water claim structure, the main residents of Ezhou City live in urban areas, causing domestic and light industrial water to become dominant. Heavy industry is mainly concentrated in Gedian DZ, where its industrial water use occupies 63.45% of total industrial water consumption in Ezhou City. The three counties, Echeng, Huarong and Liangzihu, are well-developed in irrigation, are the majority consumption of agricultural water.

Table 1 Water Claims in 2030*Mm*³/*Year*

Regions	Agriculture	Industry	Domestic	Claims
Urban Area	7.66	105.97	100.58	214.21
Gedian DZ	45.79	412.34	35.82	493.94
Huarong	55.06	52.47	18.61	126.14
Echeng	92.48	62.11	66.45	221.04
Liangzihu	103.75	16.90	20.87	141.52
Total Claims	304.74	649.79	242.32	1,196.85

**Fig. 3** The Structure of water claims

Each region wants to minimize the deficit of its own water claims, however, due to different economic structures, different regions have different maximum allowable deficit rate. Domestic water use, the basic social security resource, have the highest security requirements that guaranteed with the upper limit of 5% deficit rate; Industrial water use requires high level water supply stability, and the deficit rate needs to below 15%; Agricultural water is relatively flexible due to the precipitation, so this study control the deficit rate below 50%.

4 Results and Discussion

4.1 Water Allocation and Simulation

In this study, the General Water Allocation and Simulation model (GWAS) is used for water resources planning and management, which is further developed from the Water resources Allocation and Simulation model (WAS) (Sang et al, 2019, 2018). GWAS takes into account multi-objective problems such as regional water use and drain, reservoir operation, power generation, ecological flow, and characteristics of different economic sectors (Sang et al, 2010; Wang et al, 2014; Yan et al, 2020a,b, 2018; Zhai et al, 2017). With the help of two algorithms (the rule algorithm and NSGA-II algorithm) and multi-objective calculation scheme, this model can dynamically simulate the "natural-artificial" water cycle influenced by nature and human beings (see Figure 4. The model is applied to the water resources planning project in Ezhou City of China as a case study. We analyze the situation of regional water resources in the future scenario (on 2030), comprehensively consider the economic development and characteristics of each region, and make water resource allocation decisions.

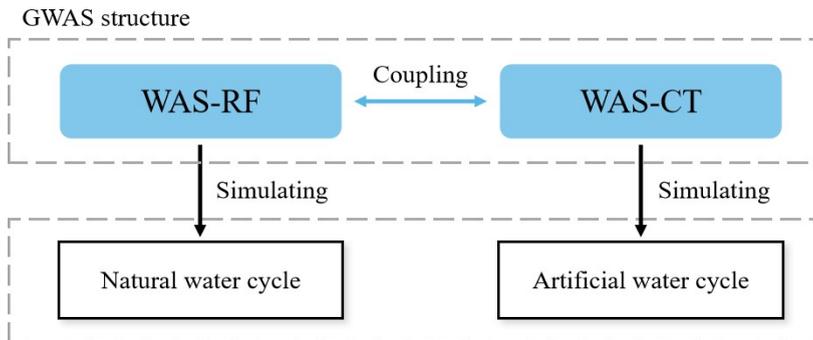


Fig. 4 The structure of GWAS model

4.2 Bankruptcy alternatives

Start with the previously definition, we applied PRO, AP, CEA, CEL, TAL and AMO (the proposed) allocation rules for water distribution, respectively, results are reported in Table 2.

In the water resource allocation alternatives, CEL and TAL achieved the same result without unsurprisingly, as the algorithm of TAL and CEL are the same when the water supply is greater than the half of the water claims. Gedian DZ suffered the least impact (deficit rate of 4.7%), which was due to its largest water claim; while the three counties had relatively serious water shortages (deficit rates of 18.5%, 10.6%, 16.5%, respectively), due to their low water demand. For the same reason, under the CEA rule, Gedian DZ will bear all losses (deficit rate 23.7%), while other regions in Ezhou City are fully satisfied. The AP rule is worth noting because we found that if the minimal rights of all stakeholder are not zero, then the allocation results of the AP will be consistent with CEL and TAL. The reason is that the non-zero minimal right guarantees a clear division of the distribution system into two parts, one is an undisputed part that only one participant claim on it, and the other is a disputed part that all participants claim against it. When PRO rule is applied on the disputed part, the value is equal to CEL.

The AMO rule makes the deficit “shared but differentiated” among all participating stakeholders. The greater water claim, the larger deficit. Since the water claims of Gedian DZ accounts for 41.3% of the total water claims, it bears the largest share of the deficit (66.7% of the total deficit); while Huarong and Liangzihu counties have the least, with 5.1% and 5.9% respectively. However, due to the share of other regions, the deficit rate of Gedian DZ is 15.8%, which is lower than CEA and higher than CEL.

4.3 Feasible test

Efficiency, Coalition and Individual rationality principles define the “Core” of solutions of the cooperative game (Sechi and Zucca, 2015), representing fairness and efficiency, and mean “feasible” by all stakeholders (Degefu and He, 2016; Degefu et al, 2018). Use the “Core” as one of the restriction conditions of the Bankruptcy alternatives, which refers that individuals cannot obtain more water resources through non-cooperation or partial coalition, Eqs.(16-19).

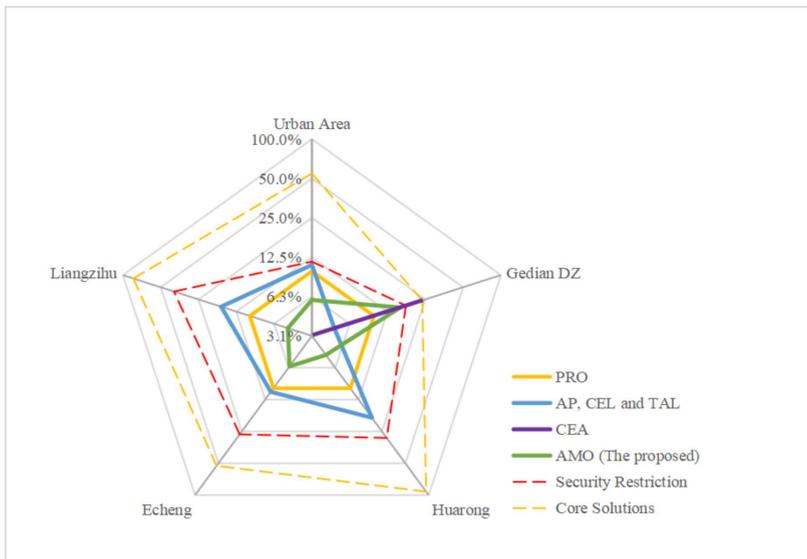
In Table 3, the “Core” solution and security restriction ranges are shown. A water allocation alternative within the upper and lower limits can be considered as feasible for all stakeholders. For this Bankruptcy problems with five stakeholders, two restrictions can be represented graphically by an equilateral pentagon with heights standing for the deficit rate of each participants, show in Fig.5.

*Mm³/Year***Table 2** Bankruptcy Allocation Rules and Deficits

Regions	PRO		AP		CEA		CEL		TAL		AMO (The proposed)	
	x_i	deficit	x_i	deficit								
Urban Area	193.30	9.8%	190.85	10.9%	214.21	0.0%	190.85	10.9%	190.85	10.9%	201.60	5.9%
Gedian DZ	445.73	9.8%	470.58	4.7%	377.12	23.7%	470.58	4.7%	470.58	4.7%	415.98	15.8%
Huarong	113.83	9.8%	102.77	18.5%	126.14	0.0%	102.77	18.5%	102.77	18.5%	120.17	4.7%
Echeng	199.46	9.8%	197.68	10.6%	221.04	0.0%	197.68	10.6%	197.68	10.6%	207.63	6.1%
Liangzihu	127.71	9.8%	118.15	16.5%	141.52	0.0%	118.15	16.5%	118.15	16.5%	134.64	4.9%

Table 3 Core Solutions and Security Restriction range*Mm³/Year*

Regions	Core Solutions		Security Restriction	
	Lower	Upper	Lower	Upper
Urban Area	97.39	214.21	189.46	214.21
Gedian DZ	377.12	493.94	407.41	493.94
Huarong	9.31	126.14	89.81	126.14
Echeng	104.21	221.04	162.16	221.04
Liangzihu	24.69	141.52	86.07	141.52

**Fig. 5** The Deficit Rate of Bankruptcy Rules with Core solution and Security Restriction

In this study, it is not difficult to find that the security restrictions are more stringent than “Core” solutions, and differences are vary from region to region. All alternatives meet the “Core” solutions, which means that participants cannot obtain greater benefits through non-cooperation or acting alone, but in the “Core” does not mean that the alternative will be automatically accepted. Regional decision-makers must also consider their own development needs and basic water security requirements when making decisions. Security requirement for domestic and industrial water is much higher than that for agriculture, resulting in a lower tolerance for water shortage in densely populated and industrially concentrated areas. This difference in economic structure has narrowed the scope of urban area and Gedian DZ in security restrictions. As a result, although the CEA rule complies with the “Core” solution, it would still be rejected by the Gedian DZ.

According to the two constraints, the final acceptable solutions are: PRO, AP, CEL, TAL and AMO(the proposed). These five alternatives are used as the preference aggregation process under the SCT to generate the final “win” alternative.

4.4 Social choice selection

As a concise and effective MCDM, SCT can properly design the voting process so that the opinions of all participants can be fully expressed. Although the result is not Pareto optimal, its result is more easily accepted by stakeholders (Read et al, 2014). Use five voting methods, PV, HS, BC, PC, and AV, to aggregate preferences on all the alternatives that meet the restrictions. Results can be found in Table 4.

Table 4 Social Choice voting methods for aggregating preferences

Voting methods	Preference order		
	1st	2nd	3rd
PV	AMO	AP, CEL and TAL	PRO
HS	AMO	AP, CEL and TAL	PRO
BC	AMO	PRO	AP, CEL and TAL
PC	AMO	PRO	AP, CEL and TAL
AV	PRO	AMO	AP, CEL and TAL

From the results of preference aggregation, AMO has achieved the 1st order (the most preferred) under PV, HS, BC, and PC voting process. For AV process, PRO rule acquires the “not bad” (the second preferred) choice from all participants, and gets points for any cases that choosing two or more out of five. So the result is that PRO defeated AMO by five to four. Although it is slightly worse than PRO in the AV process, the AMO solution still has a very stable and fair performance and can be consider as the most widely acceptable (maximum probability) by all stakeholders.

5 Conclusion

This study hopes to develop a water resource allocation management method, when data is lacking or utility functions cannot be obtained. Bankruptcy rules for water resource planning management are surveyed, and we propose a new allocation rule under water scarcity. The main feature of the proposed rule is that it favors the interests of disadvantaged groups while ensuring fairness and efficiency. In addition, we use the “core” solution from CGT and security restrictions to ensure the acceptability. Finally, different voting process under the SCT have been launched to aggregate the preferences of the alternatives to obtain the “win” proposal. We use the water resources allocation planning

of Ezhou City, Hubei Province, China, as a real case study. This study can provide a reference for decision makers to efficiently solve MCMD problems.

Five allocation rules, PRO, AP, CEA, CEL, TAL and AMO (the proposed), are applied as alternatives to Ezhou Water resources planning project. Although all the six alternatives are in line with “Core” solution, CEA has been excluded because of the security restriction of Gedian DZ. The proposed rule, AMO, holds the water deficit rate of Urban Area, Gedian DZ and three counties are 5.9%, 15.8% and 4.7% 6.1%, respectively, which considering both affordability and fairness. As a result, compared with five SCT voting processes, PV, HS, BC, PC, and AV, the AMO wins four fifth of them and comes in the second of the last, which proves that AMO has the maximum probability to obtain the feasible solution in terms of aggregating stakeholders’ preferences.

In short, the proposed water allocation mechanism may serve as a MCMD tool for resolving water resource planning problem under scarcity situations where data is lacking.

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