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Optimized allocation of water resources in the Jiulong River Watershed under cooperative game based on linear programming

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ABSTRACT

Optimized allocation of water resources in relatively water-scarce areas is the basis for rational development and utilization of regional water resources and the fundamental guarantee for sustainable utilization of water resources. In this paper, game theory and linear programming from the aspect of non-engineering measures are used to construct a cooperative game mode (maximizing economic benefits of urban agglomerations in the watershed) and a non-cooperative game mode (maximizing economic benefits of individual cities in the watershed), and it is concluded that the water consumption benefit of the cooperative game mode in the techno garden scenario (rationality of urban agglomerations in the Jiulong River Watershed) is 64.442 billion yuan higher than that of the non-cooperative game (rationality of each city). Moreover, under this scenario, water resource allocation is optimized and the water quality is also significantly improved. Therefore, the cooperative game is the optimum model for the development of urban agglomerations in the watershed, and more attention should be paid to the comprehensive management of water resources, ecological resources, and human activities from the aspect of the river catchment areas given the particularity of water resources.

Keywords: Optimized allocation of water resources; Cooperative game; Linear programming; Sustainable development

1. Introduction

Optimized allocation of water resources generally refers to changing the natural spatial-temporal distribution of water resources through engineering and non-engineering measures, which pay equal attention to increasing sources and decreasing costs, with both current and long-term interests taken into account. In optimized allocation, systematic and scientific methods, decision-making theories as well as advanced computer technology are used to realize the unified allocation of water resources, highlighting the maximization of the economic, ecological, and environmental benefits and improving the overall water-use efficiency of the region as much as possible, so as to promote the sustainable exploitation and utilization of water resources and the sustainable development of the region [1]. Water resource allocation by non-engineering measures is to reasonably allocate, plan and forecast regional water resources and economic development through models including computer simulation to achieve expected planning goals. To realize optimized allocation of water resources, two problems should be solved. One is to establish a mathematical model for the optimized allocation of water resources, and the other is to select an optimization method to solve this mathematical model. The former problem includes the determination of the objective function and the corresponding constraints.

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For the latter problem, available optimization methods mainly include linear programming, nonlinear programming, dynamic programming, fuzzy mathematics, neural network, genetic algorithm, etc. [2–7]. In this paper, linear programming is taken as an example and Jiulong River Watershed in Fujian Province is the research object. The cooperative game theory of economics is applied in the case study of the rational allocation of water resources.

2. Introduction to the research area and research methods

2.1. Introduction to the Jiulong River Watershed

Jiulong River is a major river in Fujian Province second to Minjiang River, whose name derives from its developed water system and dense branches. It has a total length of 1,923 km and a catchment area of about 14,741 km^2, accounting for about 12% of the land area of Fujian Province. The mainstream of Jiulong River is composed of the north, the west, and the south stream. The north stream originates from Meihua Mountain in Longyan City, and the west stream originates between Nanjing County and Pinghe County. The River runs from west to east and goes to the sea through the west sea area of Xiamen. Administrative districts in the Watershed include Xinluo District, Zhangping county-level City of Longyan, Zhangzhou District, Hua'an County, Changtai County, Pinghe County, Nanjing County, and Longhai County-level City of Zhangzhou, all of which are studied in this paper.

2.2. Game theory of water resource allocation

From the aspect of the watershed, in order to achieve sustainable development and water environmental protection, constraints on individual cities should be minimized and conflicts among urban agglomerations in the catchment areas should be coordinated. Therefore, the multi-objective decision-making method should be adopted in the rational allocation of water resources. First of all, the non-inferior solution should meet many goals, such as saving water resources, improving the water ecological environment and promoting urban development. If only one non-inferior solution exists, it can be set as the best solution. If multiple non-inferior solutions exist, there will be no best solution, and a "better solution" must be selected to meet the need. As a result, it is necessary to introduce the concept of cooperative coordination games. A cooperative game, also known as a positive-sum game, means that the benefits for both parties in the game increase, or at least the benefit for one party increases without prejudice to the other party, thus the benefits for the whole society increase. The concept of a cooperative game is applied to establish a coordination framework of urban agglomerations across borders under the constraints of water resources and the water environment. With this framework, the overall economic development and environmental protection of the urban agglomerations in the watershed reach an optimal state [8–10].

2.3. Solution to cooperative game mode-linear programming

Linear programming (LP), an important method in operational research, is relatively mature and has been widely used, which can realize scientific management in the environment to achieve the given goal. In 1939, Kahtopob and Hitchcock first adopted LP in production management and transportation planning [11]. In China, LP is rarely applied in the field of water resources and environmental management, and most studies on river water resources are based on administrative boundaries [12–15]. The basic structure of LP is the combination of the objective function and a series of constraints [16]. With the LP method, the coordination model of urban agglomerations in the watershed can be established with the whole watershed being the basic research unit to maximize the overall benefit and meet the constraints of water resources and water ecological environment, so that the goal of sustainable development of urban agglomerations in the watershed can be achieved.

2.4. Construction of cooperative game mode

Firstly, a non-cooperative game mode is established compared with cooperative game mode. A non-cooperative mode is the best development mode to study individual cities, while a cooperative mode promotes the coordinated development of cities in the watershed on the basis of each non-cooperative mode. Both non-cooperative and cooperative modes include water resource optimization, water quality improvement and coordination sub-models, and the coordination model further links water resources and water quality.

2.4.1. Non-cooperative game mode — the rationality of individual cities

2.4.1.1. Sub-model of water resources optimization

The objective function of LP is constructed based on the cost-effectiveness analysis of environmental economics, in which the net benefit coefficient is equivalent to the effective economic value brought by water use to each industry. The ecological water use benefit is omitted from the model due to its complexity and calculation difficulty. The objective function is expressed as follows:

$$\max Z_1 = B_1 \times Q_1 + B_2 \times Q_2 + B_3 \times Q_3 + B_4 \times Q_4 \tag{1}$$

where Z_1 = economic benefit of water use in the subsystem of water resources (yuan); B_1 = net benefit coefficient of domestic water (yuan/m^3); Q_1 = domestic water consumption (m^3); B_2 = net benefit coefficient of agricultural water (yuan/m^3); Q_2 = agricultural water consumption (m^3); B_3 = net benefit coefficient of industrial water (yuan/m^3); Q_3 = industrial water consumption (m^3); B_4 = net benefit coefficient of water consumption in tertiary industry (yuan/m^3); Q_4 = water consumption in tertiary industry (m^3).

Constraints on water resources are as follows:

$$Q_1 + Q_2 + Q_3 + Q_4 = D \times 40\% \tag{2}$$

where D = total amount of water resources (m^3). Water consumption in the watershed is limited to 40%.

Constraints on total water consumption are as follows:

$$Q_{\text{down}} \leq Q \leq Q_{\text{up}} \tag{3}$$

where Q = total water consumption (m^3); Q_{down} = total water resources in the downstream of the catchment area of the target city (m^3); Q_{up} = total water resources in the upstream of the catchment area of the target city (m^3).

2.4.1.2. Sub-model of water quality improvement

The objective function of the sub-model of water quality improvement is to minimize the economic losses caused by agricultural water, domestic water and industrial water. The objective function is expressed as follows:

$$\min Z_2 = C_1 \times M_1 + C_2 \times M_2 + C_3 \times M_3 + C_4 \times M_4 \tag{4}$$

where Z_2 = economic loss caused by water pollution in water quality sub-model (yuan); C_1 = personal economic loss caused by domestic water pollution (yuan); M_1 = population (person); C_2 = economic loss rate caused by agricultural water pollution (%); M_2 = agricultural output value (yuan); C_3 = economic loss rate caused by water pollution in secondary industry (%); M_3 = gross output value of secondary industry (yuan); C_4 = economic loss rate caused by water pollution in the tertiary industry (%); M_4 = gross output value of tertiary industry (yuan).

Water quality W can affect the loss C and constraints on ware set as follows:

$$W_{\text{down}} \leq W \leq W_{\text{up}} \tag{5}$$

where W_{down} = water quality in the downstream of the watershed of the target city; W_{up} = water quality in the upstream of the watershed of the target city.

Constraints on the three industries (primary industry, secondary industry and tertiary industry) are as follows:

$$1:5:4 \leq M_2 : M_3 : M_4 \leq 1:1:1 \tag{6}$$

2.4.1.3. Coordination model

In the final coordination model, the objective function is to maximize the net benefits of water resources utilization (Z), which equals the maximum economic benefit of the subsystem of water resources minus the minimum economic loss caused by water pollution of water quality subsystem:

$$\max Z = \max Z_1 - \min Z_2 \tag{7}$$

Whose constraints are expressed in Eqs. (2), (3), (5), and (6).

Multiple iterations are used in the coordination model to get close to the optimal coordination solution. The linear programming model (LP) is used to optimize water resources and water quality models. Economic benefits from water resource sub-models and pollution control costs from water quality sub-models change with the variation of water consumption. The best coordination solution is obtained at this point by changing the amount of water used until the economic benefit is greater than or equal to the cost of pollution control.

2.4.2. Cooperative mode — rationality of urban agglomerations

The optimization model of urban agglomerations is designed to maximize the net benefits of the entire region without prejudice to any city:

$$E = \max \sum_{i=1}^{n} \left(Z_{1i} - Z_{2i} \right) \tag{8}$$

where E = maximized net benefits (yuan); N = the number of cities; Z_{1i} = economic benefit of water use in the water resource sub-model of city i; Z_{2i} = economic loss caused by water pollution in the water quality sub-model of city i.

Firstly, constraints in the cooperative game mode are the sum of the constraints in each of the non-cooperative modes. Secondly, the minimum requirement for water quality in the cooperative mode must meet the quality objectives of the watershed planning, while the requirement for water quality in the non-cooperative mode mainly meets the needs of individual cities. In the cooperative and non-cooperative modes, population and industrial settings are both related to water amount and quality. Therefore, different scenarios are preset and systematic dynamics is adopted to analyze and predict the impact of population change and three industrial structures on water resources and water quality.

2.5. Scenario setting and analysis

The United Nations Millennium Ecosystem Assessment Panel (MA) proposes that in the first half of the 21st century, countries and regions face two different paths of world development, one being increasingly globalized, the other being increasingly regionalized. Meanwhile, they also face two different ecosystem management approaches, one being active, the other being passive [17,18]. Therefore, MA has constructed four scenarios: global orchestration, order from strength, adapting mosaic, and techno garden, among which techno garden is the best scenario for sustainable development, while order from strength is the worst scenario for unsustainable development.

With the combination of cooperative and non-cooperative game modes, four scenarios are set in this paper: a non-cooperative and order from strength scenario, unsustainable development (rationality of each city); a cooperative and order from strength scenario, unsustainable development (rationality of urban agglomerations in the watershed); a non-cooperative and techno garden scenario, in which the harmonious development of population and water environment is achieved (rationality of each city); a cooperative and techno garden scenario, in which the harmonious development of population and water environment is achieved (rationality of urban agglomerations in the watershed). The base year of the scenario analysis is 2010, and the forecast year is 2030. By the system dynamics analysis method [19], the population, GDP and water use benefit coefficient in 2030 are predicted.

2.6. Value of benefit coefficient of cooperative model

Benefit coefficient of domestic water: the benefit of domestic water should come from the total benefits from the treatment cost reduction of drinking water, human health benefit and the treatment cost reduction of bottled water, which is attributed to the improvement of water quality. The benefit coefficient of domestic water is equal to the benefit of domestic water divided by the total population, and the formula is:

Benefit coefficient of domestic water (yuan/person) = domestic water benefit (yuan)/total population (person)

Formulas of other benefits of water consumption are:

Benefit coefficient of agricultural water (yuan/m^3) = output value of primary industry (yuan)/agricultural water consumption (m^3).

Benefit coefficient of industrial water (yuan/m^3) = industrial output value (yuan)/industrial water consumption (m^3).

Benefit coefficient of tertiary industry water (yuan/m^3) = output value of tertiary industry (yuan)/water consumption in tertiary industry (m^3).

2.7. Value of pollution loss rate coefficient in cooperative mode

The loss rate caused by water pollution to industries can be expressed by the following formula [20]:

$$\gamma_i = K_i \left[\frac{e^{0.54(Q-4)} - 1}{e^{0.54(Q-4)} + 1} + 0.5 \right] \tag{9}$$

γ_i is the economic loss rate of water pollution; Q is the water quality; K_i is the maximum economic loss rate of water pollution on each calculation item.

In the formula, the pollution loss rate is linked with water quality, where K_i reflects the maximum economic loss rate that may be caused to each calculation item of social economy when water pollution reaches the highest degree. Different calculation items have different maximum loss rates due to their different requirements and closeness to water quality in production and life. At the same time, due to different living standards in different regions, different social strata have differences in the defensive consumer spending on water pollution. Therefore, under the existing conditions, the maximum loss rate of each calculation item of water pollution should be determined based on detailed investigation and calculation of economic loss of water pollution in typical regions of the watershed. It can be used to establish the water quality-economic loss impact function of the subitems of the watershed and to calculate the water pollution loss [21].

By referring to the Report on Comprehensive Treatment of Water Pollution and Ecological Damage in the Jiulong River Watershed, the calculation result of the economic loss caused by water pollution in the Jiulong River Watershed in 2003 is discounted to 2030 at an average annual interest rate of 3%, and the corresponding comprehensive evaluation result of the water quality is substituted into the

Table 1
Maximum economic loss rate of water pollution (K_i) on each calculation item of the Jiulong River Watershed in 2030

Different industries	K_i	Meaning of unit economic loss
Domestic water	529.5	Health loss expense (yuan)/person
Agricultural water	0.45	Economic loss (yuan)/agricultural added value (yuan)
Industrial water	0.04	Added value of production cost (yuan)/total production cost (yuan)
Tertiary industry water	0.106	Economic loss (yuan)/tertiary industry added value (yuan)

Table 2
Net benefits of economic output from water consumption under four different scenarios of Jiulong River Watershed in 2030 (100 million yuan)

Counties	Order from strength			Techno garden		
	S1 (rationality of each city)	S2 (rationality of urban agglomerations)	Value difference	S3 (rationality of each city)	S4 (rationality of urban agglomerations)	Value difference
Zhangping	163.07	105.55	–57.52	211.99	137.22	–74.77
Xinluo	561.69	493.07	–68.62	730.20	580.99	–149.21
Hua'an	163.60	205.02	41.42	182.68	266.53	83.85
Changtai	116.29	252.33	136.04	151.18	298.03	146.85
Zhangzhou District	230.99	499.61	268.62	300.29	649.50	349.21
Nanjing	143.68	124.94	–18.74	186.79	162.42	–24.37
Pinghe	148.29	120.33	–27.96	192.78	156.43	–36.35
Longhai	230.82	499.44	268.62	300.06	649.27	349.21
Jiulong River Watershed	1,758.43	2,300.29	541.86	2,255.97	2,900.39	644.42

economic impact function of water quality [Eq. (9)] to obtain the maximum economic loss rate K_i of the subitems of the Jiulong River Watershed in 2030 (Table 1).

3. Results and analysis

3.1. Net benefits of water consumption under four different scenarios of Jiulong River Watershed in 2030

Due to the emphasis on environmental technology innovation and environmental protection in the techno garden scenario, water pollution is improved, and the net economic benefits are greater than that in the order from strength scenario. In the non-cooperative game mode, only the economic development of individual cities is emphasized, so the overall economic benefits are not high from the aspect of the watershed (scenarios 1 and 3). However, in the cooperative game mode, due to the importance attached to the economic development of the urban agglomerations in the watershed which are taken as a whole, the economic benefits of the catchment areas are relatively high. In scenario 2 and 4, the economic benefits are 54.186 billion yuan and 64.442 billion yuan higher than that in scenarios 1 and 3 respectively (Table 2). It is worth being pointed out that the upstream cities highlight the overall development of the watershed, thus these cities have a higher input cost in water quality control and water environment protection. As a result, their own economic benefits are affected. As shown in Table 2, Zhangping and Xinluo areas in the upper reaches of the North stream of Jiulong River, Nanjing and Pinghe areas in the upper reaches of the South stream of the River have a negative net economic benefit. Therefore, the downstream cities should make corresponding compensation for the upstream cities, that is, ecological compensation for related catchment areas. Reasonable ecological compensation is key to the urbanization and sustainable development of the catchment areas.

3.2. Optimization of water resources allocation

Among these four scenarios, scenario 4 (cooperative mode of techno garden scenario) is the most suitable for the development of Jiulong River Watershed, with total predicted water consumption in 2030 being 4.967 billion m^3, including 488 million m^3 domestic water, 2.425 billion m^3 agricultural water, 1.767 billion m^3 industrial water, and 287 million m^3 water in tertiary industry. GDP of the whole watershed in 2030 is 2718 billion yuan, with the output value of the primary industry being 729 billion yuan, that of the secondary industry being 884 billion yuan, and that of the tertiary industry being 1105 billion yuan. Table 3 shows the water consumption and development of the three industries in counties and cities of the watershed. Water quality of the Jiulong River Watershed in 2030 is also significantly improved compared with that in 2010 (Table 4), especially in Zhangping, Xinluo, Changtai and Nanjing, whose water quality is upgraded from Class 4 or 5 to Class 2 or 3 respectively.

4. Discussions

There is a profound theoretical foundation to incorporate game theory into the research system of water

Table 3
Water consumption and output of the three industries under scenario 4 (cooperative mode of techno garden) in counties and cities of Jiulong River Watershed in 2030

Counties and cities	Domestic water (100 million m^3)	Agricultural water (100 million m^3)	Industrial water (100 million m^3)	Tertiary industry water (100 million m^3)	Total water use (100 million m^3)	Primary industry (bln yuan)	Secondary industry (bln yuan)	Tertiary industry (bln yuan)	GDP (bln yuan)
Zhangping	0.43	3.12	3.21	0.23	6.99	46	56	70	172
Xinluo	0.44	3.20	3.30	0.24	7.18	198	240	300	738
Hua'an	0.72	3.22	2.01	0.43	6.38	20	24	30	74
Changtai	0.54	2.42	1.51	0.32	4.79	36	44	55	135
Zhangzhou District	0.23	1.01	0.63	0.13	1.99	165	200	250	615
Nanjing	0.90	4.03	2.51	0.54	7.98	50	60	75	185
Pinghe	1.17	5.24	3.26	0.70	10.37	40	48	60	148
Longhai	0.45	2.01	1.25	0.27	3.99	175	212	265	652
Jiulong River Watershed	4.88	24.25	17.67	2.87	49.67	729	884	1,105	2,718

Table 4
Water quality improvement of Jiulong River Watershed

Counties and districts	Water quality class in 2010	Water quality class in 2030	Corresponding water quality section
Zhangping	4	2	North 5 Jitai
Xinluo	6	4	North 2 Dongxing
Hua'an	2	2	North 8 Guangzao
Changtai	5	2	North 10 Wuan
Zhangzhou District	4	3	West 5 Zhongshan Bridge
Nanjing	5	3	West 3 Shipyard
Pinghe	3	3	West 1 Brook
Longhai	5	4	West Shima

resource allocation. Game theory takes different modes as the main analysis variables and the satisfaction of Pareto optimality as the research result. In the process of water resource allocation, all water users make their own action choices that benefit themselves according to different institutional constraints, and only the system that meets the endogenous rules of the game can become an effective system. This research idea provides a theoretical basis for water resource allocation to shift from conflicts to cooperation. When game theory and LP are used to link the variables of economic, population and water resources with water environmental pollution, the contradiction between water ecological environmental protection and urban development can be solved.

To build the model, firstly, the water system in the watershed is divided into a subsystem of water resources and a subsystem of water quality; secondly, the scenario analysis is adopted to predict the supply and demand of water resources as well as the water pollution situation, and the damage cost caused by pollution of the water quality and various economic benefits from water consumption are estimated respectively in terms of domestic water, industrial water, tertiary industry water and agricultural water; thirdly, the sub-model of water resource optimization is established on the basis of economic, social and environmental factors, and the sub-model of water quality optimization is established under the constraints of water pollution, water environmental capacity and water quality indicators; fourthly, the coordination model of the two sub-models and the iterative computation of the coordination scheme are established after the comparison between the benefits obtained in the subsystem of the water resources and the pollution damage costs of the subsystem of the water quality; and finally, the solution to reasonable allocation of water resources in the urban agglomerations is determined based on the coordination results obtained from different situations. Conclusions drawn from this case demonstrate that water resources should be managed from the aspect of watershed given the particularity of water resource formation and movement.

The integrated management of water resources and other natural resources (such as land, vegetation, etc.) closely related to water of the watershed being the unit conforms to the natural migration law and economic and social characteristics of water resources, which can give full play to the overall functions of the watershed. In recent years, integrated management of watershed is not only a research hotspot in academia, but also an effective means for the government to promote regional resources and management.

5. Conclusions

In this paper, the cooperative and non-cooperative game modes of the urban agglomerations in the watershed are constructed by the game method and linear programming (LP). The cooperative game mode highlights the maximization of economic benefits of the urban agglomerations in the watershed, while the non-cooperative game mode stresses the maximization of economic benefits of individual cities in the watershed. In addition, a sub-model of water quantity optimization, a sub-model of water quality optimization and a coordination model incorporating water quantity and water quality are constructed respectively, and thus a coordination model based on the urban agglomerations in the watershed (cooperative game mode) is deduced. The forecast data of the model shows that the cooperative game mode sees the watershed from a holistic view and highlights the economic development of the urban agglomerations in the watershed, thus the economic benefits of the watershed are relatively highly with 54.186 billion yuan and 64.442 billion yuan higher in scenarios 2 and 4 than those in scenarios 1 and 3 respectively. Therefore, from the perspective of sustainable development, scenario 4 (techno garden scenario under the cooperative mode) is more in line with the economic development and rational allocation of water resources of the cities in the watershed. Hence, the cooperative game (rationality of urban agglomerations) mode of techno garden in the urban agglomerations of Jiulong River Watershed will have a total water consumption of 4.967 billion m^3 in 2030, including 488 million m^3 domestic water, 2.425 billion m^3 agricultural water, 1.767 billion m^3 industrial water, and 287 million m^3 water in the tertiary industry, with a benefit of 290.039 billion yuan from water consumption and a total GDP of 2718 billion yuan. Water quality of the catchment areas in 2030 will also be significantly improved compared with that in 2010, especially in Zhangping, Xinluo, Changtai and Nanjing.

To sum up, cooperative game is the optimum mode for the development of urban agglomerations in the watershed. In view of the particularity of water resources, more attention should be paid to the comprehensive management of water resources, ecological resources, and human activities from the aspect of the watershed, and the promotion of ecological compensation is the best ecological-environmental-economic management mode for urban agglomerations in the watershed.

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