Simulating water conflicts using game theoretical models for water resources management

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Abstract

Water quality degradation and water scarcity are two serious problems in developing countries. Water management related to these problems usually involves multi-stakeholders with contradictory interests. In the absence of market and exclusive property rights, conflicts among those multi-stakeholders are unavoidable. Game theory can be an appropriate approach to simulate and resolve such conflicts. In this paper, the conflicts of multiple water stakeholders involved in water management of the Hanjiang River Basin in China are modelled as non-cooperative and cooperative games. Statistical and econometric regression models are used to formulate the payoff functions of different players. Cost-benefit analysis (CBA) and the demand-supply principle (DSP) are applied to compare the game outcomes. The results of the game simulations show that cooperation can make all the players better off, although some players may be worse off before the benefit is shared among the players by side payment. The results are not only a comparison of the different water stakeholders, but also benefit water administration for decision support.
Keywords: water management, game theory, Hanjiang River, modelling and simulation, cost-benefit analysis.

1 Introduction

Water is essential for the existence of human and other species. However, water quality degradation and water scarcity are two serious problems in developing countries. It is estimated that in 2025, 5 billion out of the world’s 7.9 billion people will be living in areas where it will be difficult or even impossible to meet

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basic water demand for drinking, cooking and sanitation [1]. Degradation of water quality and water scarcity usually result in conflicts of multi-stakeholders competing for scarce water resources [2], such as the disputes between the Arabs and Israelis, Indians and Bangladeshes, Americans and Mexicans, and among all the 10 Nile basin co-riparian's [3]. The multi-stakeholders usually have contradictory or conflicting interests [4, 5], goals and strategies [2]. Wei and Gnauck [2] stated that the existing economic and regulation instruments do not work so well in solving these conflicts. The concept of considering the interests and benefits of the stakeholders are widely accepted in the world. Game theoretic analysis approach is an efficient technique to solve such conflicts since it studies the interests and benefits of the stakeholders.

As for the water management, game theory was originally applied into the cost distribution in joint water resource projects i.e. waste water treatment, disposal facilities [6, 7] and water supply projects [8, 9]. Thus, the methods of equally cost allocation have been developed such as Minimum Core, Shapley value, Nash Bargaining Solution, etc. [10]. Later on many studies have focused on the application of game theory in solving water conflicts, such as pollution of transboundary rivers [5] and water allocation problems [5, 11, 12].

In this paper, the conflicts of multiple water stakeholders resulted from water quality and water scarcity are modelled using non-cooperative and cooperative games. The example is taken from Hanjiang River Basin in China.

2 Methodology and data collection

2.1 Methodology

A water conflict or problem is modelled as a game or a set of games so that the problem can be analyzed and solved in the framework of game theory. The game modelling process consists of defining the conflicts, formulating these conflicts as a game, solving the game and interpreting the results. In this paper, non-cooperative and cooperative game methods are used separately to model and simulate the water conflict (real or potential). In order to formulate the payoff functions of the players, statistical and econometric regression methods are used. In detail, regression models (linear regression, semilog regression, double-log regression, polynomial regression) are used to establish models of added values, water demands and waste water discharge of industries. Cost-benefit analysis (CBA) and demand-supply principle (DSP) are applied to compare the outcomes and results of the game modelling.

2.2 Data collection

All the data is collected from monitoring stations, official reports, planning and Chinese yearly books. The main types of data include socio-economic data (population, industrial added value), water quantity data (water supply and water consumption of industry), hydrological data (inflow, outflow of Hanjiang River) as well as water quality data on Danjiangkou Reservoir in Hanjiang River Basin.

3 Theory of game

3.1 Game and game theory

A game is a metaphor of the rational behaviours of multi-actors in an interacting or interdependent situation, such as cooperating or coalition, conflicting, competing, coexisting, etc. [2]. An actor can be a country, a region, a group, an individual, organism, abiotic and biotic constituents and even nature proper. A game can be defined as $G = \{N, A, P, I, O, E\}$, i.e. N - Players, A - Action (Moves or Strategies), P - Payoff (or Utility), I - Information, Outcome and Equilibrium (NAPI-OE). *NAPI* are collectively known as the rules of a game. *OE* are the game results.

Game theory is an approach to model and simulate interacting situations by cooperative and non-cooperative games. It studies the strategies and equilibrium or equilibria of the actors, and analyzes how they can do things better. The main task of constructing game models is to define the game rules and get the solution from game results.

3.2 Process of establishing a game model

The process of setting up a game model can be summed up into the following questions:

- Who is involved in the conflict?
- What are their actions (strategies)?
- What is the payoff function of each player?
- Does every player know the payoff function of the others?
- Is the game a one-time game, continuous game, finite game or an infinite one?
- What is the equilibrium of the game if it is a non-cooperative game?
- Is the result better if all the players cooperate with each other?
- How to distribute the net benefit derived from cooperative games among the players?

4 Game theoretical models of water conflicts

Freshwater, especially transboundary freshwater has strong characteristics of public goods although it is not a real public good in economic sense. As for water use, there is a free riding problem. Every water user wants to use more water but pay less or nothing to treat water pollution. In game theory term, each player is rational and his aim is to maximize his payoff. At the end, water will be severely polluted if there is no cooperation between them. Such a kind of game is called the *prisoners' dilemma*. The method to solve the game of the *prisoners' dilemma* is to change the game rule and make players cooperate with each other. Cooperation may be self-organised through negotiations or it may be formed due to the forces of politics.

4.1 A non-cooperative game model

$$\underset{p,d,t}{Max}\, V_i = \int_t^n [B_i(d) - C_i(p)]\, e^{-\delta t} dt \tag{1}$$

where V_i is the payoff of every player i, d is water demand, p is water pollution (or waste water discharge), $e^{-\delta t}$ is discount factor, $B_i(d)$ is the benefit function of water use of every player i, $C_i(p)$ is the cost to abate pollution (or waste water discharge) of every player i.

In the model of non-cooperative game, each rational player tries to maximize his welfares by maximizing the benefit and minimizing the cost.

4.2 A cooperative game model

$$\underset{p,d,t}{Max}\, U = \int_t^n [B(d) - C(p)]\, e^{-\delta t} dt \tag{2}$$

$$Max U_i = V_i + \max \prod_i^n [(U_B / \Psi)_i] \tag{3}$$

where U is the total benefit obtained from cooperative game; $B(d)$ is the benefit function of water use in cooperative game; $C(d)$ is the cost to abate waste water discharge (or pollution); U_i is the payoff of each player i; U_B is the total net benefit obtained from cooperative game; Ψ is distribution factor of cooperative benefit.

In the case of a cooperative game, all the players maximize their overall welfare by maximizing the collective benefit and minimizing the collective cost. At end of game, each player usually will be better off if a side payment is made between the players.

5 A case study of conflicts involved in Hanjiang River Basin

5.1 Hanjiang River Basin

Hanjiang River Basin lies in 30°08′ - 40°11′N latitude, 106°12′ - 114°14′E longitude. The river originates in the southern part of Shaanxi Province, northwest China, flows through Shaanxi and Hubei provinces and joins the Yangtze River at Wuhan, capital city of Hubei, fig. 1. It is about 1,577 km long, being the longest tributary of Yangtze River. The basin covers an area of 159,000 km^2, the second largest river basin in Yangtze River catchment. On the upper reaches of the river, the U-shaped Danjiangkou Reservoir covers an area of 1050 km^2.

Hanjiang River Basin belongs to the sub-tropical monsoon area. The climate is temperate and moist, with an annual precipitation of about 873 mm. The average annual runoff of the watershed is 51.3 billion m^3. The river itself serves as water resource for drinking, industry as well as agriculture. According to the water quality monitoring data from 1989 to 2002, water quality in the Hanjiang River conforms to water class I ~ II of Chinese Environmental Quality Standards for Surface Water (GB 3838—2002). However, water quality of the middle and lower reaches of Hanjiang River has deteriorated in recent years and is mainly reflected by the increase of concentration of nutrients like nitrogen and phosphorus. The result has been four big algal blooms in low reach of Hanjiang River since 1992. The concentration of total phosphorus and total nitrogen reached 0.17 mg/L and 2.30 mg/L respectively in Hankou Monitoring Station during the algal bloom of February 2003.

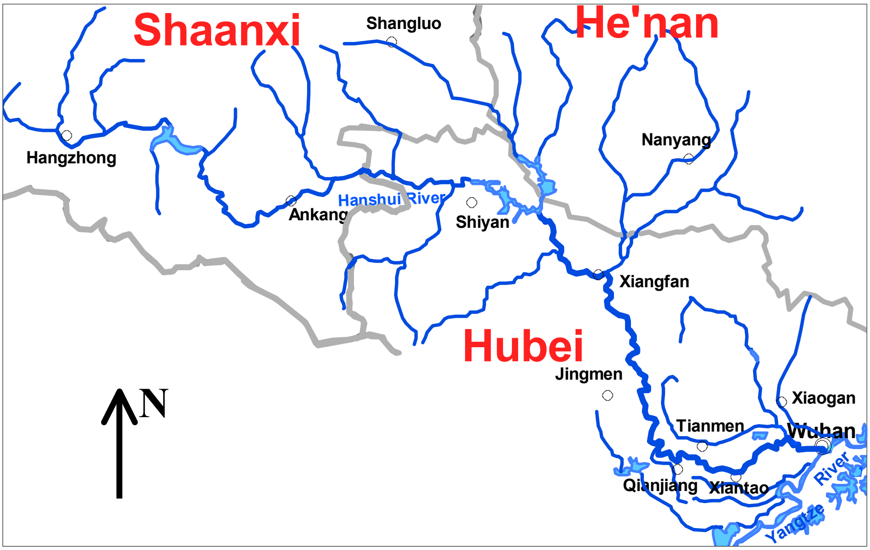

Figure 1: Sketch of Hangjiang River Basin.

5.2 Water conflicts Involved in Hanjiang River Basin

The Danjiangkou Reservoir is the water source of the Middle Route of South to North Water Transfer (MRSNWT) Project. The MRSNWT project aims at transferring water from Danjiangkou Reservoir for 20 big cities and 100 counties in Beijing, Tianjing Municipalities, and Hebei, Henan, Hubei Provinces in order to solve the sever water scarcity there. In the case of Hanjiang River, the conflicts mainly result from this water transfer project. Firstly, water transfer sets a higher standard on water quality in Danjiangkou Reservoir, which will raise cost to reduce pollutants discharged from the cities on the upper rivers and around the reservoir. Secondly, a substantial amount of water diverted will cause a reduction of runoff and water level, and thus it will change the ecological condition in the downstream of the river. Furthermore, the reductions of runoff and water level will in turn break the balance of water demand and supply of the main river, which will aggravate the conflicts of water demand and supply, and exacerbate the existing pollution (eutrophication) problem. The conflicts involved in Hanjiang River can be illustrated by fig. 2. However, this paper studies only the conflicts between industries. Industry here does not refer to a certain industry, but it is a general term for all industries.

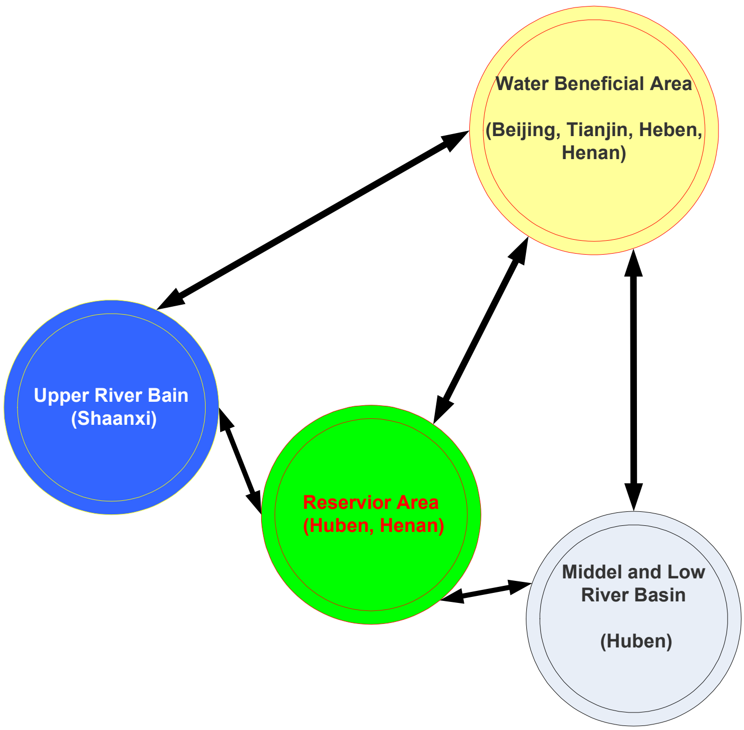

Figure 2: Water conflicts involved in Hanjiang River Basin.

5.3 Game theoretic modelling approach

5.3.1 The case

The industry in the City of Beijing (P_1) will transfer water from Danjiangkou Reservoir (R) in Hanjiang River. Water transfer will raise the cost to reduce pollutants produced by the cities on the upper river and around the reservoir, and it will also reduce the river flow and break the interests of the industry downstream of reservoir, fig. 3. Therefore, the conflict in this study area is unavoidable.

5.3.2 Assumptions

- The game is finite, dynamic and with complete information;
- All the players are rational, and their aim is to maximize their welfare;
- There is no intervention of administration during game processing, but the game processing is influenced by the current policies;
- The industries in the same administrative regions should cooperate with each other, say C_1, C_2, C_3, C_4, C_6, and C_7 cooperation with each other to form one player, it is the same for C_8, C_9, C_{10}, C_{11}, C_{12} and C_{13}, fig. 3;
- The water deficit of player 2 is zero due to his rich water resource or because he can solve the deficit by himself when there is a deficit in the non-cooperative game;

- 12.63% of the losses of player 2 and 3 is caused by player 1 he shares only 12.63% of the total transferable water;
- Player 1 can make up his water deficit if he transfers water from the Hanjiang River, i.e. cooperates with player 2 and 3;
- All data are authentic.

5.3.3 Defining the game

The players. The player set is expressed by N = {1,2,3}. Players 1, 2 and 3 refer to the industries in the City of Beijing and the provinces of Shaanxi, Hubei and He'nan in the upper river basin, as well as the Hubei part in the middle-low river, fig. 3.

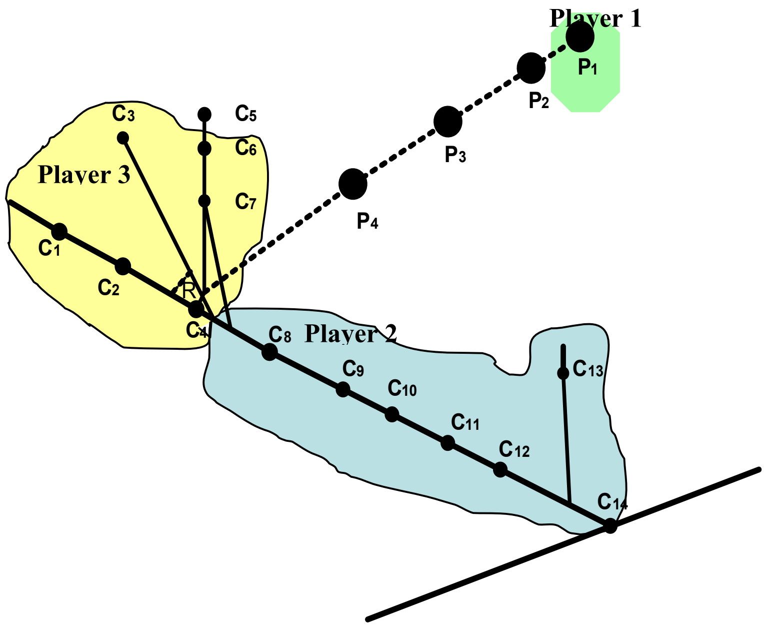

Figure 3: Sketch of the players, C_i refer to cities and P_i provinces or municipalities.

The strategies. Generally speaking, every player has two strategies: cooperation and non-cooperation. They can be expressed as follows:

$$S_i = \begin{cases} S_{i1} = C \\ S_{i2} = N_C \end{cases} \tag{4}$$

In the cooperative situation, player 1 will transfer water from Danjiangkou Reservoir and he would like to compensate other players' losses resulting from the water transfer. Player 2 agrees with the water transfer of player 1 and player 3 is willing to reduce waste water discharge. In the non-cooperative situation, players have their different strategies. For players 1 and 2, their strategies are the measures or plans to obtain sufficient water for their development in different periods of time t (year), and they are expressed by:

$$s_i = W_i^t \in S_i = [0, \infty), \quad i = 1, 2 \tag{5}$$

For player 3, his strategies are to reduce the waste water discharge, and they are expressed by:

$$s_i = P_i^t \in S_i = [0, \infty), \; i = 3 \tag{6}$$

The payoff functions. In this non-cooperative game model, the payoff functions of player 1 and 2 are formulated by water demand models since their strategies are to obtain sufficient water for development. For player 3, his payoff function is formulated by the model of waste water discharge. Equation (7) expresses the payoff function of the players.

$$V_i = \begin{cases} f(W_i^t), \; i = 1 \\ g(-W_i^t), \; i = 2 \\ h(-P_i^t), \; i = 3 \end{cases} \tag{7}$$

where W_i^t: the loss of water; P_i^t: reduction of pollutant source, i.e. waste water discharged from industry.

Table 1: Water demands and water deficits (10^8 m^3) in non-cooperative game.

Year	Water Demand of Player 1	Water Deficit of Player1	Water Demand of player 2	Water Deficit of Player 2
2010	5.39	0.26	46.15	0.00
2011	5.10	0.24	46.02	0.00
2012	4.83	0.24	45.77	0.00
2013	4.58	0.25	45.40	0.00
Total	19.90	0.99	183.34	0.00

Table 2: Water demands and water deficits (10^8 m^3) in cooperative game.

Year	Water Demand of Player 1	Water Deficit of Player1	Water Demand of player 2	Water Deficit of Player 2
2010	5.39	0.00	46.15	3.05
2011	5.10	0.00	46.02	3.14
2012	4.83	0.00	45.77	3.23
2013	4.58	0.00	45.40	2.87
Total	19.90	0.00	183.34	12.29

6 Results

Tables 1 and 2 show the water demands and water deficits of player 1 and 2 in non-cooperative and cooperative games respectively from 2010 to 2013. In the non-cooperative game, player has a total water deficit of 183.24 million m^3, but player 2 has no water deficit due to his rich water resource. In the cooperative game, player 1 gets the amount of water necessary to cover his deficit, i.e. zero water deficit, but player 2 will face a total water shortage of 1.229 billion m^3 due to the water transfer of player 1, table. 2. Besides, player 3 has to reduce 395 million tons waste water discharge in order to increase water quality for player 1 from 2005 to 2008 in cooperative game, table 3.

The game results of payoffs are presented in the table 4. In the table, the first number refers to different years, the second, third and fourth numbers are the payoffs of player 1, 2 and 3 respectively. The first column refers to the payoffs resulting from the non-cooperative game, and the second column is the payoffs resulting from the cooperative game. These results show that the non-cooperative game will cost player 1 a total loss of 73.85 billion RMB from year 2010 to 2013, but it yields player 2 and 3 a benefit of 61.83 billion RMB. However, comparing the overall costs and benefits, there is an overall loss of 12.02 billion RMB when each player does not cooperate with the others. The cooperative game result shows that there is an overall benefit of 12.02 billion RMB, though player 2 and 3 lose 61.83 billion RMB. Therefore, all the players will be better off if a side payment is made between them at the end of the cooperative game. These results prove that the players should cooperate with each other so as to maximize the overall benefits.

Table 3: Waste water discharge (10^8 tons) of player 3 in non-cooperative and cooperative game.

Year	Non-cooperation	Cooperation	Reducing Amount
2005	5.05	4.41	0.64
2006	5.37	4.59	0.79
2007	5.63	4.56	1.07
2008	6.01	4.56	1.45
Total	22.06	18.02	3.95

Table 4: Payoff matrix of non-cooperative and cooperative game.

$$\begin{bmatrix} (2005,-000.00,000.00,0.86) & (2005,000.00,-000.00,-0.86) \\ (2006,-000.00,000.00,1.06) & (2006,000.00,-000.00,-1.06) \\ (2007,-000.00,000.00,1.44) & (2007,000.00,-000.00,-1.44) \\ (2008,-000.00,000.00,1.95) & (2008,000.00,-000.00,-1.95) \\ (2010,-146.29,140.36,0.00) & (2010,146.29,-140.36,-0.00) \\ (2011,-163.56,152.54,0.00) & (2011,163.56,-152.54,-0.00) \\ (2012,-191.88,165.33,0.00) & (2012,191.88,-165.33,-0.00) \\ (2013,-236.79,154.78,0.00) & (2013,236.79,-154.78,-0.00) \end{bmatrix}$$

7 Conclusions

Water resource management is vital and complex because it usually involves water conflicts of multi-stakeholders with contradictory interests, goals and strategies. Game theory is a modelling approach which can be efficiently used to solve these challenges. The conflicts in the Hanjiang River Basin are caused by the Middle Road of South to North Water Transfer (MRSNWT) Project. The results of the game simulations show that a non-cooperative game will cause a collective loss of 12.02 billion RMB, while the cooperative game will yield a collective benefit of 12.02 billion RMB, though player 2 and 3 lose 61.83 billion RMB. Therefore, each player will be better off if a side payment is made among the players at the end of the cooperative game. In conclusion, this game theoretical simulating approach not only facilitates a clear comparison of the different water users, but is also beneficial to water decision makers.

References

[1] Leete, R., Donnay, F., Kersemaekers, S., Schoch, M., & Shah, M., *Global population and water*, UNFPA report on Population and Development Strategies Series, number 6. UNFPA: New York, 2003.

[2] Wei, S.K. & Gnauck, A., Game theoretic approaches to model water conflicts on a river basin scale. *Modelling and Simulation of Ecosystems*, ed. A. Gnauck, Shaker Verlag: Aachen, pp. 22-40, 2007

[3] Wolf, A.T., Criteria for equitable allocations: The heart of international water conflict. *Natural Resources Forum* 23, pp. 3-30, 1999

[4] Fang, L., Hipel, K.W., & Wang, L.Z., Gisborne water export conflict study. *Proc. of the 3rd Int. conf. on Water Resources and Environmental Research*, ed. G.H. Schmitz, Dresden, Germany, Vol.1, pp. 432-436, 2002

[5] Van der Veeren, R.J.H.M. & Tol, R.S.J., Game theoretic analyses of nitrate emission reduction strategies in the Rhine river basin. *Int. J. Global Environmental Issues* 3(1), pp. 74-103, 2003.

[6] Giglio, R.J. & Wrightington, R., Methods for apportioning the costs of a water resource project. *Water Resourc. Res.* 8, pp. 1133-1144, 1972.

[7] Dinar, A. & Howitt, R.E., Mechanisms for allocation of environmental control cost: Empirical test of acceptability and stability. *J. Environ. Management*, 49, pp. 183-203, 1997.

[8] Heany, J.P. & Dickinson, R.E., Methods for apportioning the costs of a water resource project. *Water Resourc. Res.* 18(3), pp. 476-482, 1982

[9] Young, H.P, Okada, N. & Hashimoto, T., Cost allocation in water resource development. *Water Resourc. Res.*, 18(3), pp. 463-475, 1982.

[10] Lejano, R.P. & Davos, C.A., Cost allocation of multiagency water resource projects: Game theoretic approaches and case study. *Water Resourc. Res*., 31(5), pp. 1387-1393, 1995.

[11] Wang, L.Z., Fang, L. & Hipel, K.W., Water resource allocation: A cooperative game approach. *J. Environ. Informatics* 2(1), pp. 11-22, 2003.

[12] Wei, S.K. & Gnauck, A., Water supply and water demand of Beijing – A game theoretic Approach for modelling. *Information Technologies in Environmental Engineering*, eds. J.M. Gómez, M. Sonnenschein, M. Muller, H. Welsch & C. Rautenstrauch, Springer-Verlag: Berlin and Heidelberg, pp. 525-536, 2007.