Game theory based models to analyze water conflicts in the Middle Route of the South-to-North Water Transfer Project in China

Shouke Wei\textsuperscript{a,b,*}, Hong Yang\textsuperscript{a,1}, Karim Abbaspour\textsuperscript{a,1}, Jamshid Mousavi\textsuperscript{a,c,1}, Albrecht Gnauck\textsuperscript{b}

\textsuperscript{a}Department System Analysis, Integrated Assessment and Modelling, the Swiss Federal Institute of Aquatic Science and Technology (EAWAG), Ueberlandstrasse 133, CH-8600 Dübendorf, Switzerland
\textsuperscript{b}Department of Ecosystem and Environmental Informatics, Brandenburg University of Technology, Konrad-Wachsman-Allee 1, D – 03046 Cottbus, Germany
\textsuperscript{c}Department of Civil Engineering, Amirkabir University of Technology (Tehran Polytechnic), 424 Hafez Avenue, Tehran, Iran

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\textbf{ABSTRACT}

This study applied game theory based models to analyze and solve water conflicts concerning water allocation and nitrogen reduction in the Middle Route of the South-to-North Water Transfer Project in China. The game simulation comprised two levels, including one main game with five players and four sub-games with each containing three sub-players. We used statistical and econometric regression methods to formulate payoff functions of the players, economic valuation methods (EVMs) to transform non-monetary value into economic one, cost-benefit Analysis (CBA) to compare the game outcomes, and scenario analysis to investigate the future uncertainties. The validity of game simulation was evaluated by comparing predictions with observations. The main results proved that cooperation would make the players collectively better off, though some player would face losses. However, players were not willing to cooperate, which would result in a prisoners’ dilemma. Scenarios simulation results displayed that players in water scare area could not solve its severe water deficit problem without cooperation with other players even under an optimistic scenario, while the uncertainty of cooperation would come from the main polluters. The results suggest a need to design a mechanism to reduce the risk of losses of those players by a side payment, which provides them with economic incentives to cooperate.

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1. Introduction

From an economic perspective, water resources are composite assets which provide a variety of services for consumptive and productive activities. However, water quality degradation has been an important cause of water scarcity in countries (Wang et al., 2003; Wei and Gnauck, 2007a). Water resources management on those problems is usually involved with interactive and interdependent stakeholders with contradictory or conflicting interests (Fang et al., 1998, 2002; Van der...
Veeren and Tol, 2003), goals and strategies (Wei and Gnauck, 2007a). Pollutant discharge is an essential but complex issue in water resources management, and this complexity is not only from intricate biochemical processes, but also from different pollutant sources and multi-polluters with conflicting aims. Water quality and quantity conflicts are usually caused by (1) water scarcity due to uneven precipitation, (2) multiple users and pollutant sources discharging waste into water, (3) different degrees of upstream pollutions restricting the water use in downstream catchment, and (4) interbasin water transfer breaking the long-established balance of water quality and quantity in a basin.

To solve water conflicts cause by water scarcity, Donevskaya et al. (2009) proposed some engineering solutions in terms of reducing water losses, increasing water use efficiency and waste water recycling, water conservation, and water transfer, and some other non-engineering measures. However, methods of using water efficiency and waste water recycling are not sufficient to the regions facing extreme water shortage. In addition, interbasin water diversion involves a multidisciplinary problem (Yevjevich, 2001), which usually brings about fundamental issues and conflicts concerning socio-economical, environ-ecological, administrative and legislative problems (Shao and Wang, 2003; Yang and Zehnder, 2005). Besides, different economic and political instruments have been widely used to solve water use conflicts (Dinar and Howitt, 1997; Wang et al., 2003). Water markets approach is one cited frequently in the literature (Burness and Quirk, 1979; Howe et al., 1986; Colby, 1990; Green and O’Connor, 2001; Bhaduri and Barbier, 2003). Water market methods can provide water users with incentives to allocate water and reduce pollutants discharge efficiently, and such market really exists in some countries, such as Australia (Pegram et al., 1992), California (Howe and Goodman, 1995), Chile (Hearne and Easter, 1995), India (Saleth, 1996), and Spain (Reidinger, 1994), etc. However, water market requires defining the original water rights, creating institutional and legal mechanisms, and establishing basic infrastructures for water trade (Holden and Thobani, 1996; Wang et al., 2003) before it can operate well. Waste discharge is a public bad, and every polluter can free-ride others’ achievement of treatment (Wei and Gnauck, 2007b). Free-riding problem will cause market failure. In the absent of market and property right, conflicts between multi-stakeholders competing for water uses are unavoidable (Pethig, 1992; Wei and Gnauck, 2007a).

There are rare water markets in reality and they are not real free market (Dellapenna, 2000). Those economic and political based water conflict solving methods can be summarized into two classes, direct regulations and economic instruments (OECD, 1988; Markandya and Rechardsson, 1992; Wei and Gnauck, 2007a). Direct regulation is also known as the “command and control” strategies, which usually include limitation quotas, standards, laws, etc. Economic and political instruments make use of market mechanism, price incentives, water rights, subsidies, compensation, tradable permits, green taxations, etc. However, environmental resource problems and its interrelationships with economic activities and the dynamic ecosystem are very complex and cannot be solved with simple policy tools (Carraro and Filar, 1995). Command and control strategies usually lack incentive, because it is mainly in virtue of legislation, power or force. Wei and Gnauck (2007a) stated that the existing economic and regulation instruments do not work so well in solving these conflicts. From a technical strategy point of view, multi-objective optimization models have been used early to maximize the overall benefit in order to solve transboundary water conflict in a river basin (Zeng et al., 2001; Yang and Zeng, 2004). In recent years, more advanced and popular multi-objective evolutionary algorithms have been used to solve conflicts objectives in watersheds (Bekele and Nicklow, 2005; Muleta and Nicklow, 2005). In general, however, those optimization measures neglect the real interests and benefits of the stakeholders in the basin, though they can capture the multiple optimal solutions, sometimes called as Pareto optimal solutions.

Game theory is an appropriate approach to model and solve such water conflicts. It was launched by John von Neumann, a great mathematician, and Oskar Morgenstern in 1944. Game theoretical modelling concepts and reasoning have been widely applied in economic, commercial, social, political, biological, and other sciences to help people analyze social and behavioural phenomena. However, the applications of game theory to solve conflicts in water resources management are comparatively few. As for this topic, it was originally applied into the cost distribution in joint water resource projects, i.e. waste water treatment and disposal facilities (Giglio and Wrightington, 1972; Dinar and Howitt, 1997). Bogardi and Szidarovszky (1976) introduced possible application of game theory, especially the oligopol game, in four main areas of water management, and offered solutions for the typical problems in decision analysis. Lewandowski (1979) used a game-theoretic approach to model the behaviour of water users in a quality control problem, and he has proposed a game-theoretic solution to different uses of a water system. Coppola and Szidarovszky (2004) designed a two-person conflicting game to analyze the optimal trade-off between water supply and contamination risk for a municipal wellfield. Salazar et al. (2007) described the application of conflict resolution methods to a two-person conflicts game in groundwater management. Besides, game theory is regularly used to analyze equitable allocation of waste loads to a common receiving medium (Kilgour et al. 1988; Okada and Mikami 1992; Wei and Gnauck, 2007b,c). It was also applied to solve water allocation and pollution problems in transboundary river, including inter-country river (Friskvold and Caswell, 2000; Van der Veeren and Tol, 2003) and intra-country river (Zeng and Yang, 2004; Yang and Zeng, 2004). In game theory, the development of conflict concepts and methods has received increasing attention since the pioneering work of Nash (1950). Based on the axiomatic approaches of Nash, many modified and extended solutions have been introduced. Among those solutions, four particular methods have frequently cited and used in water management in the literature (Coppola and Szidarovszky, 2004; Salazar et al., 2007), including: (1) non-symmetric Nash solution of Harsanyi and Selten (1972); (2) non-symmetric solution of Kalai and Smorodinsky (1975); (3) non-symmetric area monotonic solution of Anbarci (1993); and (4) non-symmetric equal-loss solution of Chun (1988).

China possesses total water resources of 2812.4 billion m³, ranking the 6th in the world (World Bank, 2002; Wei, 2007).
However, due to spatially uneven distribution of precipitation, water shortage has been a prolonged and widespread problem in Northern regions of China (Yang and Zehnder, 2001; Wei, 2007). In order to mitigate the existing water crisis, the engineers in China proposed the South-to-North Water Transfer (SNWT) Projects, including the East Route Project, the Middle Route Project and the West Route Project. The Middle Route Project covers two municipalities and four provinces. It is difficult to manage when water transfer involving such different large regions. This study aimed to establish game theoretical models to analyze water allocation and pollution conflicts existing in the Middle Route of South-to-North Water Transfer Project in China. The main goals of the study include:

- To forecast and analyze water supply, water demand and water deficit in the different sectors in water scarce cities (only Beijing municipality) in northern China,
- To predict and estimate pollutant production, discharge and reduction from the different pollutant sources in the upper basin of the Hanjiang River,
- To evaluate the economic benefits and losses of water diversion and pollutant reduction to the cities in the study area,
- To analyze future uncertainty of the game simulation under different scenarios.

### 2. Material and methods

#### 2.1. Area description

The South-to-North Water Transfer (SNWT) projects in China comprise the Western Route Project (WRP), the Middle Route Project (MRP) and the Eastern Route Project (ERP) (Fig. 1). We focus the study area on the MRP, including Beijing municipality, and the 6 cities in the provinces of Shaanxi, He’nan and Hubei in the upper basin of Hanjiang River (Table 1). The MRP will divert water in 2010 from the Danjiangkou Reservoir in the Hanjiang River Basin for 20 big cities and 100 counties in Beijing and Tianjin Municipalities, He’nan and Hubei provinces (CWRPI, 2005). It covers a total area of about 155,000 km² and crosses about 200 river channels or canals with the total cannal distance of 1246 km. Interbasin water transfer projects to reduce water shortage are not new in China. However, WRP covers two municipalities and four provinces. This project will change the runoff and water level of the rivers, break the long-established balances of benefits of different stakeholders, and cause conflicts. Water transfer action within a region can be effectively managed through the coordination of local government and regional river administration, while water...
transfer involving different regions with such large areas is usually difficult to manage.

The 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, flows through Shaanxi and Hubei provinces and joins the Yangtze River at Wuhan, the capital city of Hubei province. It is about 1577 km long, the longest tributary of Yangtze River; and the basin covers a watershed area of 159,000 km², the second largest river basin in Yangtze River catchment. The Hanjiang River basin belongs to subtropics monsoon area, and it is temperate and moist and annual precipitation is 873 mm. According to the data series of hydrology from 1956–1998, the river has total water resource of 58.2 billion m³ and average annual natural runoff is 56.6 billion m³ (CWRPI, 2005). The river is traditionally divided into three parts: upper, middle and lower rivers. The upper river is from the river source to the Danjiangkou city, the middle river from the Danjiangkou city to Zhongxiang City, and the lower part from Zhongxiang City to the river mouth (Zhang, et al., 2000). This paper only dealt with the upper basin of the Hanjiang River. The upper river is 925 km long, and the upper basin includes part of provinces of Shaanxi, He’nan and Hubei. This part possesses surface water of 36.796 billion m³, groundwater of 10.647 billion m³, and overlap amount is 10.387 billion m³. In the upper basin, the u-shaped Danjiangkou Reservoir is the water source of MRP, covering an area of 1050 km² with a total storage capacity of 17.45 billion m³. The Danjiangkou Reservoir has been deteriorated in recent years, due to great amount of waste discharged into the River without being treated. The water transfer project requires that the reservoir water quality should conform to water class II of Chinese Surface Water Standard II (GB 3838–2002) (SEAPAC and AQSIQC, 2002) before water transfer in 2010. We selected annual average concentrations of BOD₅ (Biological Oxygen Demand after Five Days), DO (Dissolved Oxygen), COD₅ (Permanganate Index), NH₃-N (Ammonia Nitrogen), TP (Total Phosphorus) and TN (Total Nitrogen) during 1995–2004, which cannot conform to the standard of Class II (0.025 mg/L) in 2001 and 2003 in Taocha, but they meet the standard in other years (Fig. 3f). The concentrations of TP reach 0.6 mg/L and 0.06 mg/L, which cannot conform to the standard of Class II (0.025 mg/L) in 2001 and 2003 in Taocha, but they meet the standard in other years (Fig. 3f). However, the concentration of TN cannot conform to the Class II, and it belonged to Classes IV and V (Fig. 3e). The analysis suggests that the water quality deterioration of the Reservoir is mainly reflected by the increase of concentration of TN, and thus this study focuses on TN concentration reduction.

2.4. Game-theoretic approach

Games exist in the situations where the actions of actors (individuals or groups) are interacting and interdependent and the choices of all actors affect the outcome (Schapf, 1997). A game is a metaphor of the rational behaviors of multi-actors in an interacting or interdependent situation, such as cooperating or coalition, conflicting, competing, coexisting, etc. (Wei and Gnauck, 2007a). A country, a region, a group, an individual, organism, abiotic and biotic constituents or even


2.2. Data sources

The data in this study includes climatological and hydrological data (1986–2005), water quality data (1995–2004) environ-ecological data (1994–2005) and socio-economic data (1978–2008). Climatological and hydrological data include precipitation, evaporation, surface water, groundwater, and water flows. Water quality data comprise pollutants concentrations, point pollution sources (industrial waste discharge and urban domestic waste water discharge), waste water reclaim amount, and non-point pollution sources (agricultural fertilizer consumptions, soil erosions, rural domestic satisfactory. The analyzing results illustrate that concentrations of BOD₅ (0.68–2.2 mg/L), DO (7.5–9.4 mg/L), COD₅ (1.4–2.3 mg/L), NH₃-N (0.05–0.24 mg/L), all meet the Class II (4 mg/L) (Fig. 3d). The concentrations of TP reach 0.6 mg/L and 0.06 mg/L, which cannot conform to the standard of Class II (0.025 mg/L) in 2001 and 2003 in Taocha, but they meet the standard in other years (Fig. 3f). However, the concentration of TN cannot conform to the Class II, and it belonged to Classes IV and V (Fig. 3e). The analysis suggests that the water quality deterioration of the Reservoir is mainly reflected by the increase of concentration of TN, and thus this study focuses on TN concentration reduction.
nature proper each can be an actor. The essence of this theory is to study the interaction, strategies and equilibrium of different actors. A game can be defined by set (1), but a normal form game (or strategic game) can be generally described as set (2).

\[ G \triangleq (N, A, V, I, O, E) \]  

where \( G \) – a general symbol for all kind of games, \( N \) – a normal form game (or strategic game), \( A \) – actions (moves), \( V \) – payoffs (or utility), \( I \) – information set, \( O \) – outcomes and \( E \) – equilibrium or equilibria, i.e. NAVI-OE. NAPI are collectively known as the rules of a game and OE are the game results. The main aim of constructing a game model is to define the rules (NAVI) in mathematical language and get the solution from OE.

To analyze and solve the problems by means of non-cooperative and cooperative games, we modelled and simulated the conflicts of pollution (i.e. TN) reduction and water allocation in the study area as a set of games with two levels, including one main game with five players at the first level and four sub-games with each containing three sub-players at the second level. In the game model, we used subscripts ‘\( i \)’ and ‘\( n/1 \)’ to stand generally for every player and every other ‘\( n - 1 \)’ player (or player \( i \)’s opponent in some senses), respectively. In game with sub-games, we also used ‘\( m \)’ and ‘\( j \)’ to refer to every main player and sub-player, and ‘\( mj \)’ to point out which main player a sub-player belongs to, like 11 means sub-player belongs to main player 1 (see Nomenclature). Our game modelling and simulation process can be generally expressed as defining a problem (or conflict) as a game, analyzing the game, setting up game models, analyzing the game models and solving the game. Non-cooperative game modelling approach is used to find out what the real payoff (or utility) of the players, and cooperative game approach is to get the optimal solution. The main aim of studying non-cooperative game is to find the solutions for cooperation.

2.5. Regression model

In order to formulate functions of the input variables and payoffs of the players, statistical and econometric regression methods were used. The linear regression model can be simply expressed by the following equations:

\[ Y_p = b_0 + \sum_{k=1}^{n} \sum_{p=1}^{m} (b_k X_{kp}) + \varepsilon_p \]  

where \( Y_p \) – values of dependent variables in observation \( kp \); \( X_{kp} \) – independent (or explanatory) variables; \( b_k \) – parameters of the equation; \( \varepsilon_p \) – disturb (or error) term. The equation includes two components:

(1) \( b_0 + \sum_{k=1}^{n} \sum_{p=1}^{m} (b_k X_{kp}) \), the non-random component,

(2) \( \varepsilon_p \), the random component.

To use ordinary least squares (OLS) estimation methods, some nonlinear models were transformed into linear ones by logarithm conversions at one side or both sides of the modelling equations. Besides, polynomial regression and vector auto-regression were also applied. Autoregressive (AR) and/or Moving average (MA) terms were included in some model equations to account for serial correlation. In addition, balanced panel data and its related modelling approaches were employed to establish model of the gross agricultural products and nitrogen fertilizer consumptions. The validity of the models was evaluated by comparing predictions with observations.

2.6. Transport process of pollutants

The transporting process of pollutants (W) – total nitrogen (TN) in this study – into the reservoir during a period of time can be classified as (1) producing, (2) entering the rivers, (3) reaching into the reservoir, (4) nitrification/denitrification processing and forming the final concentration in reservoir. Part of pollutants will be decayed due to biochemical and
ecological processes. This process and the annual mean concentration of TN reached in the reservoir can be expressed by Eqs. (4) and (5), respectively:

\[ L_{ra} = \bar{W}_{rt} \kappa_{ra} \lambda_{ra} f_{ra} \]  

\[ C_{rt} = \frac{L_{ra}}{Q_f} \]  

where \( ra \) – subscript presenting human activity in a region; \( L_{ra} \) – load of TN into the reservoir from a certain human activity in a region during time \( t \); \( \bar{W}_{rt} \) – pollutant TN production from a certain human activity in a region during time \( t \); \( \kappa_{ra}, \lambda_{ra}, f_{ra} \) – generally called pollutant transport coefficients, i.e. rate of TN loss, coefficient of TN into the river, rate of TN into the reservoir, as well as rate of TN finally maintaining in the reservoir, respectively; \( C_{rt} \) – average TN concentration into the reservoir during time \( t \); \( Q_f \) – mean water inflow into the reservoir during time \( t \).

Based on the previous studies (Yang et al. 2006, Cheng et al. 2006, Song et al. 2006), the values of nitrogen transport coefficients were defined in Table 2. Urban domestic sewage and industry waste water are transported by pipelines, and they are emitting directly into the local river surface. Therefore, nearly 100% of nitrogen enters regional rivers, and thus rate of loss (\( \lambda \)) from production resource and rate of entering river (\( \lambda \)) are defined as 1. We also defined that the rate of TN maintaining in the reservoir is 1, i.e. no loss in the reservoir. A unit of Pig equivalence was used to measure the livestock and poultry by pig unit based on their annual average nitrogen production. According to the study on the spatial and temporal change of nitrogen and phosphorus produced by livestock and poultry in China (Wu, 2005), it defined that 1 pig
is equal to 1/5 of large animals, 2 goals or sheep, and 30 poultry, respectively, in nitrogen production. Those researches also stated that the average annual nitrogen amounts from a person’s manure and liquid, a pig’s manure and liquid are 1.32 kg a\(^{-1}\), 3.07 kg a\(^{-1}\), 7.58 kg a\(^{-1}\) and 3.93 kg a\(^{-1}\), respectively.

### 2.7. Total nitrogen reduction

Total nitrogen (TN) concentration reduction in the Danjiangkou Reservoir was planned to follow a linear trend to reach the Chinese water quality standard of Class II (0.2 mg/L ≤ TN ≤ 0.5 mg/L) by 2010, and the two main reasons for this consideration are: (1) a straight line is the shortest distance between two points in geometric and mathematic principle; (2) a straight line trend to reduce TN means time-cost saving. The linear trend of upper threshold (C\(_{\text{max}}\)) and lower threshold (C\(_{\text{min}}\)) of TN concentrations during different years (\(t\)), are expressed by Eqs. (6) and (7).

\[
\begin{align*}
C_{\text{max}} &= -0.127t + 255.1 \quad \text{(6)} \\
C_{\text{min}} &= -0.177t + 355.3 \quad \text{(7)}
\end{align*}
\]

### 2.8. Nominal and real values

In the case area, there is a clear time value included in the benefits and losses of players, because pollution reduction (cost) will be processed before water transfer (benefit). Therefore, the payoff values of the players are not at the same time level. In details, the benefits of Beijing obtaining from water diversion will be produced after 2010, while the losses of the cities in the Hanjiang River basin due to reduction pollution for water transfer will be generated before 2010. In this study, we start our pollution reduction from the base 2005, and we only calculate the benefits of Beijing from 2010 to 2015 in order to compare those 6-year benefits to the 6-year losses. In this sense, the future values should be discounted and transformed into the current values. The future values are termed as “nominal values” and the present values as “comparable or real values”. In economics, Consumer Price Index (CPI) is one of widely used deflator to kick out the price inflation and change the nominal values into comparable values. The CPI observation values of Beijing used for the value discount in this study are listed in Table 3, and the discount formula can be expressed as:

\[
D_{\text{pt}} = D_{\text{nt}} \frac{I_t}{I_0} \quad \text{(8)}
\]

where \(D_{\text{pt}}\) = comparable or real value of payoff (\(V'\) and \(U'\)) in year \(t\), \(D_{\text{nt}}\) = nominal value of payoff (\(V\) and \(U\)) in year \(t\), \(p_t\) = Consumer Price Index in year \(t\), \(p_0\) = Consumer Price Index in year 0.

### 2.9. Other methods

We used demand-supply principle (DSP), cost-benefit analysis (CBA) and economic valuation methods (EVMs) to compare the

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### Table 2 – Different transportation coefficients of nitrogen.

<table>
<thead>
<tr>
<th>Nitrogen source</th>
<th>Shaanxi</th>
<th>Hubei</th>
<th>He’nan</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(\xi)</td>
<td>(\lambda)</td>
<td>(\kappa)</td>
</tr>
<tr>
<td>Nitrogen fertilizer</td>
<td>0.10</td>
<td>0.96</td>
<td>0.80</td>
</tr>
<tr>
<td>Soil erosion</td>
<td>0.21</td>
<td>0.81</td>
<td>0.80</td>
</tr>
<tr>
<td>Urban domestic sewage</td>
<td>1.00</td>
<td>1.00</td>
<td>0.80</td>
</tr>
<tr>
<td>Industry waste water</td>
<td>1.00</td>
<td>1.00</td>
<td>0.80</td>
</tr>
<tr>
<td>Animal husbandry</td>
<td>0.10</td>
<td>0.96</td>
<td>0.80</td>
</tr>
<tr>
<td>Rural domestic life</td>
<td>0.10</td>
<td>0.96</td>
<td>0.80</td>
</tr>
</tbody>
</table>

### Table 3 – Consumer Price Index of Beijing used for the value transformation.

<table>
<thead>
<tr>
<th>t</th>
<th>CPI</th>
<th>t</th>
<th>CPI</th>
<th>t</th>
<th>CPI</th>
<th>t</th>
<th>CPI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1978</td>
<td>100.0</td>
<td>187.6</td>
<td>1988</td>
<td>598.2</td>
<td>2008</td>
<td>703.4</td>
<td></td>
</tr>
<tr>
<td>1979</td>
<td>101.8</td>
<td>219.9</td>
<td>1999</td>
<td>601.8</td>
<td>2009</td>
<td>740.4</td>
<td></td>
</tr>
<tr>
<td>1980</td>
<td>107.9</td>
<td>231.8</td>
<td>2000</td>
<td>622.9</td>
<td>2010</td>
<td>783.8</td>
<td></td>
</tr>
<tr>
<td>1981</td>
<td>109.2</td>
<td>259.4</td>
<td>2001</td>
<td>642.2</td>
<td>2011</td>
<td>829.0</td>
<td></td>
</tr>
<tr>
<td>1982</td>
<td>111.2</td>
<td>285.1</td>
<td>2002</td>
<td>630.6</td>
<td>2012</td>
<td>873.4</td>
<td></td>
</tr>
<tr>
<td>1983</td>
<td>111.8</td>
<td>339.3</td>
<td>2003</td>
<td>631.9</td>
<td>2013</td>
<td>914.8</td>
<td></td>
</tr>
<tr>
<td>1984</td>
<td>114.2</td>
<td>423.8</td>
<td>2004</td>
<td>638.2</td>
<td>2014</td>
<td>952.1</td>
<td></td>
</tr>
<tr>
<td>1985</td>
<td>134.4</td>
<td>497.1</td>
<td>2005</td>
<td>647.8</td>
<td>2015</td>
<td>984.6</td>
<td></td>
</tr>
<tr>
<td>1986</td>
<td>143.5</td>
<td>554.8</td>
<td>2006</td>
<td>653.6</td>
<td>2008</td>
<td>703.4</td>
<td></td>
</tr>
<tr>
<td>1987</td>
<td>155.8</td>
<td>584.2</td>
<td>2007</td>
<td>669.3</td>
<td>2009</td>
<td>740.4</td>
<td></td>
</tr>
</tbody>
</table>

*Values from 2009 to 2015 are predictions.
*The values in parenthesis from 2006 to 2008 are predictions used to test the accuracy of the prediction.
*The prediction model is: \(P_t = -6521.67 - 0.79 P_{t-1} - 1.6 P_{t-1}^2 + 3.30t\) with \(R^2 = 0.99\), Adj-\(R^2 = 0.99\), F-statistic = 2148.56, Prob(F-statistic) < 0.000001, *significant at \(p < 0.01\), **significant at \(p < 0.0001\).
outcomes and results of the game modelling. EVMs were also applied to estimate the benefit and loss in monetary term. Various economic valuation methods can be used to quantify economic value of water resources and losses of water pollution, such as Direct market value method (DMVM), Shadow engineering Method (SEM) or Replacement cost approach (RCA), and Opportunity cost or benefits method (OCM/OBM), Cost analysis method (CAM), Hedonic Pricing, etc. (Feng and Wang, 2003; Li and Xiu, 2003, 2004; Wei, 2005). We adopted DMVM to measure the benefits of water transfer, CAM to calculate the losses of nitrogen pollutant reduction, and OCM and OBM to evaluate the losses of Beijing and benefits of cities in the upper river basin of Hanjiang without water transfer.

### 2.10. Scenario design

Four scenarios were designed to analyze the uncertainties of the simulation. The normal modelling and simulation were established based on past data under an assumption of “business as usual”, and they were regarded as the first scenario (SN1). The other three main scenarios were designed according to the possible changes of constrains and input variables in SN1. The second scenario (SN2) is very optimistic, in which the situation is much better than that in SN1 from an economic and environmental perspective. By contrast, the fourth scenario (SN4) is much more pessimistic. The third scenario (SN3) is a coordinated one, whose situations approximately lied between SN2 and SN4. The main descriptions of those scenarios are showed in Table 4. Based on those descriptions of the main scenarios, the assumptions of scenarios were quantified in the Table 5.

### 3. Model

Water conflicts in the study can be briefly stated that R1 will transfer water from the Danjiangkou Reservoir in the Hanjiang River. Water transfer requires the cities (C1, C2, C3, C4, C5, C6) reducing their pollutant (TN) discharge in order to improve the water quality in the Reservoir, while TN reduction will raise cost to those cities (Fig. 4). In this connection, the conflicts concerning water allocation and water pollutant...
reduction in this study area are unavoidable if the interests and benefits are not balanced well.

3.1. Formulating the game model

The water conflicting problem in the study area is simulated as normal (or strategic) form games with two levels, including one big game and 4 sub-games. The mathematic definitions of those games can be expressed generally as follows:

\[
G_T \equiv (G_1, G_T)
\]
\[
G' \equiv (G_1, G'_2, \ldots, G'_m)
\]
\[
G_1 \equiv (N_m, S_m, V_m)
\]
\[
G'_m \equiv (N_{mj}, S_{mj}, V_{mj})
\]

where \(m, j = 1, 2, 3, 4\); and \(m, j = 1, 2, 3, \ldots, n\).

3.1.1. Definition of the players

In the game at the first level, \(R_i\) is defined as main player 1 (\(P_1\)), \(C_1\), \(C_2\) and \(C_3\) main player 2 (\(P_2\)), \(C_4\) main player 3 (\(P_3\)), and \(C_5\) main player 4 (\(P_4\)). In each sub-games, industry, household and agriculture of every main player are defined as sub-players 1, 2 and 3, denoted by \((P_{11}, P_{12}, P_{13})\). They can be expressed as follows:

\[
N_m = \{P_1, P_2, \ldots, P_m\}, \quad m = 1, 2, 3, 4
\]
\[
N_{mj} = \{P_{mj} \mid m \in N_m, j = 1, 2, 3\}
\]

Among them:

\[
P_1 = \{\text{Industry}\}, \quad P_{m2} = \{\text{household}\}, \quad P_{m3} = \{\text{agriculture}\}
\]

3.1.2. Definition of the strategies

To simplify the problems, we defined that every player has only two strategies. Rather, in the main game, \(P_1\) has either strategies of transferring water from other players \((S_{wcr})\) or not transferring water \((S_{wtr})\), i.e. solving water shortage internally; and \(P_2\), \(P_3\) and \(P_4\) have similar two strategies: reducing TN pollution for water transfer \((S_{wtr})\) and not doing so \((S_{wtr})\). In the sub-games 1, the sub-players of main player 1 will choose strategies of struggling for water without considering too much of environment-ecology \((S_{vtr})\) and sharing their imitated water resources considering environment-ecology and increasing water use efficiency \((S_{vtr})\). In the sub-games 2, 3 and 4, the two strategies of the sub-players are (1) to discharge pollutant into reservoir freely \((S_{vtr})\); (2) to reduce the pollutant TN discharge according to their economic abilities \((S_{vtr})\).

3.1.3. Definition of the payoff functions

The payoffs of the main player 1 (\(P_1\)) and his sub-players \((P_{11}, P_{12}, P_{13})\) are the benefits obtained by using water, and therefore their payoff functions can be formulated by their available water and the economic values produced by water use. For other 3 main players and their sub-players, their payoffs are the cost to reduce TN discharge, and thus their payoff functions can be formulated by the TN reduction and the cost to reduce TN. Those payoff functions can be generally expressed by Eq. (17).

\[
V'_i; U'_i = \{ f(Q'_t), \quad m, j = 1, 2, 3, \quad t = \text{superscript stands for time, } V, U - \text{payoff of every player } i \text{ non-cooperative and cooperative game, respectively, } Q'_t - \text{available water of every player } i \text{ during time } t, \ W'_i - \text{pollutant TN reduction by every player.}}\]

3.2. Assumptions

- The games are static and finite with incomplete information;
- All the players are rational, and their aims are to maximize their welfare;
- There is no administrative intervention during game processing, but the game processing is influenced by the current policies;
- The cities in the same administrative regions is willing to cooperate with each other due to the similar interests, i.e. \(C_1\), \(C_2\), and \(C_3\) cooperation with each other; the same for \(C_4\) and \(C_5\);
- Cooperation or non-cooperation of other players excluded from this example will depend on whether players 1, 2, 3 and 4 cooperate or non-cooperate;
- Water demand of each player will keep the same in different hydrological conditions.

3.3. Game simulation processes

The game simulation flow can be illustrated by Fig. 5, which includes 5 games. These five games are divided in two levels. Game 1 is the main game at first level and games 2–5 are the four sub-games at the second level. The main game is named as a benefit-loss game, in which we will compare the benefits and losses of different players under non-cooperation and cooperation. The first sub-game (game 2) is a water obtaining game, where sub-players make decision how to get their water. The other three sub-games (games 2–5) are classed as TN reduction game, where sub-players will decide if they should reduce pollutant TN discharge into the river (Fig. 5). We start the games from the main game, and then game 2, game 3, and so on. In game one, \(P_1\) starts first, and he uses either strategy 1 \((S_{wcr})\) or strategy 2 \((S_{wtr})\). Then \(P_2\) moves and he knows \(P_1\) has two strategies, but does not know which strategy \(P_1\) will use due to incomplete information. Thus he will use his strategy 1 or strategy 2 according to his real situations. \(P_3\) moves next, and then \(P_4\) moves. For each sub-game, we also start from sub-player 1, then sub-player 2 and sub-player 3. In game 1, when
P1 uses strategy of transferring water, and others players reducing pollution for water transfer, the game enters a cooperative game. In game 2, it also enters a cooperative game if sub-players 11–13 all adopt the strategy 2 (SNS). Similarly, games 3–5 each will also enter a cooperative game when sub-players employ their strategy 2 (SPA). All problems in those situations need cooperative methods to solve and get the results. The results in those cooperative situations and reverse situations have more practical values than those in other mixed situations. Those results are the outcome (V1, V2, V3, V4) and (U1, U2, U3, U4) for sub-players 11, 12, 13, 21, 22, 23, ..., 41, 42, 43, 44; S0t = strategy of solving water shortage internally, i.e. not transferring water, S1t = strategy of reducing pollution TN for water transfer, S2t = strategy of non-reducing pollution TN for water transfer, S3t = strategy of sharing their limited water resources considering environ-ecology and increasing water use efficiency; S4t = strategy of emitting pollutant in river freely; S5t = strategy of reducing pollutant TN discharge according to the economic abilities.

**Fig. 5 – A sketch of game simulation process, (a) the main game at first level, (b) sub-game 1, (c) sub-game 2, (d) sub-game 3, and (e) sub-game 4.**

\[
\text{Max}\, \mathcal{V}_t^i = \max_{Q, W_0} \int \mathcal{B}_t^i(Q) - \mathcal{K}_t(W_0) e^{-\alpha t} dt 
\]

where \( i \) – subscript general refers to every player, \( t \) – superscript stands for time (year), \( \mathcal{V}_t^i \) – payoff of every player \( i \) during time \( t \), \( Q \) – available water for player \( i \), \( W_0 \) – pollutant TN reduction by every player \( i \), \( e^{-\alpha t} \) – discount factor, \( \mathcal{B}_t^i(Q) \) – benefit function of every player \( i \) to use available water during time \( t \), \( \mathcal{K}_t(W_0) \) – cost of every player \( i \) to abate pollutant TN during time \( t \). Unlike other study to use interest rate, we used Eq. (8) to make discount or value transformation in this study.

### 3.4. Game solution

#### 3.4.1. A non-cooperative game model

A non-cooperative game solution model for water resources management presents that every player \( i \) maximizes the net benefits, i.e. differences between benefits produced from water usage and the costs charged for waste water reduction or treatment. The model is expressed by Eq. (18).

### 3.4.1.1. Water quantity optimization

Water quantity optimization means that per unit economic value will be produced by consuming minimum unit of water. It also means that consumption per unit of water will produce maximum unit of economic values. It can be expressed by:

\[
\text{Max} \mathcal{B}_t^i(Q) = \sum_{t=0}^{n} \beta_t Q_t^i 
\]
subject to
\[ W_i^t + W_{i-1}^t + R^t - Q_{\text{av}}^t \geq Q_i^t \quad (20) \]
\[ Q_{\text{ws}}^t + Q_{\text{av}}^t + Q_{\text{tr}}^t \leq Q_{\text{td}}^t \quad (21) \]
\[ Q_i^t - Q_{i-1}^t - aQ_i^t - Q_{\text{ws}}^t - E_{\text{ws}}^t \geq Q_i^t \quad (22) \]
\[ 0 \leq R^t \leq Q_i^t \quad (23) \]
\[ Q_i^t \leq \overline{Q}_i^t \leq \underline{Q}_i^t \quad (24) \]
where \( i \) - subscript refer to every player including the main player and sub-player, \( t \) - superscript stands for time (year), \( B(Q_i) \) - benefit function of available water of every player \( i \), \( \beta_i \) - benefit coefficient of water use, i.e. value produced by every player \( i \), \( Q_{\text{td}}^t \) - available water for every player \( i \) during time \( t \), \( Q_{\text{ws}}^t \) - environ-ecological water demand of player \( i \) during time \( t \), \( Q_{\text{av}}^t \) - available water used for environ-ecology of player \( i \) during time \( t \), \( W_i^t \) - surface water resource amount during time \( t \), \( W_i^t - W^t \) resource amount; \( Q_{\text{ws}}^t \) - water demand to keep certain amount of urban water surface during time \( t \), \( \alpha_i \) - water demand to maintain certain area of public green area during time \( t \), \( Q_{\text{av}}^t \) - water demand of newly planned trees during time \( t \), \( R^t \) - reclaimed waste water during time \( t \), \( \alpha \) - coefficient of waste water and sewage back into water during time \( t \), \( Q_{i-1}^t \) - water inflow from upstream controlling (i.e. player \( i \)'s) section \( y - 1 \) in during time \( t \), \( Q_i^t \) - water flow in the observed (player \( i \)'s) section \( y \) during time \( t \), \( E_{\text{ws}}^t \) - evaporation of water surface during time \( t \), \( \overline{Q}_i^t \) and \( \underline{Q}_i^t \) - minimum and maximum of water demand of player \( i \) during time \( t \).

3.4.1.2 Water quality optimization. Water quality optimization means that every player \( i \) minimizes the costs to reduce pollutant (TN) discharge into the water body. It can be expressed as follows:

\[
\text{Min } K_i'(W) = \gamma_w \sum \omega_i = \sum_{y=1}^{m} \left( L_{w,y-1} - \sum_{y=1}^{m} (L_{w,y-1} - 1)(1 - \eta_{w,y}) - L_{w,y} y - 1 \right) \quad (25)
\]
subject to
\[
L_{w,y} y - 1 = Q_{i-1}^t C_{w,y-1} \quad (26)
L_{w,y} y' = Q_i^t C_{w,y} \quad (27)
L_{w,y} y' = Q_i^t C_{w,y} \quad (28)
Q > 0, L > 0, C > 0, \eta \geq 0 \quad (29)
\]
where \( K_i'(W) \) - cost of every player \( i \) to abate pollutant \( W \) (TN) during time \( t \), \( \gamma_w \) - cost coefficient to reduce pollutant \( W \) (TN) of every player \( i \), \( L_{w,y} y' \) - load of pollutant \( W \) in controlling (i.e. player \( i \)'s) section \( y \) during time \( t \), \( L_{w,y} y' \) - load of pollutant \( W \) from upstream controlling (i.e. player \( i \)'s) section \( y - 1 \) during time \( t \), \( L_{w,y} y' \) - controlling load of pollutant \( W \) in player \( i \)'s controlling section \( y \), \( \eta \) - decomposition (assimilation) coefficient of pollutant \( W \) in player \( i \)'s controlling section \( y \), \( C_{w,y} \) - concentration of pollutant \( W \) in player \( i \)'s controlling section \( y \) during time \( t \), \( C_{w,y-1} \) - concentration of pollutant \( W \) from player \( i \)'s controlling section \( y - 1 \) in upstream during time \( t \), \( C_{w,y} \) - controlling concentration (i.e. standard) of pollutant \( W \) in player \( i \)'s controlling section \( y \).

3.4.2. A cooperative game model
The cooperative game model means that all the players cooperate with each other to maximize the overall net benefits. It is expressed by Eq. (30). Every player in cooperative game is to maximize the net benefits which he can obtain from cooperation. It is expressed by Eq. (31).

\[
\text{Max } U_i^t = \sum_{W,t} n \left[ B(Q_i) - K_i'(W) \right] e^{-\alpha dt} \quad (30)
\]
\[
\text{Max } U_i^t = V_i^t + \sum_{W,t} n \left[ (U_i^t \psi) \right] \quad (31)
\]
subject to
\[
U_i^t \geq \sum_{W,t} n V_i^t + U_{i}^t \quad (32)
U_{i}^t \geq 0 \quad (33)
\]
where \( i \) - subscript refer to every player, \( t \) - superscript stands for time, \( U_{i}^t \) - the total benefit obtained from cooperative game during time \( t \), \( B(Q_i) \) - the benefit function of water use in cooperative game during time \( t \), \( K_i'(W) \) - the cost to abate pollutant TN in cooperative game, \( U_i^t \) - pay-off of each player \( i \) in cooperative game, \( V_i^t \) - pay-off of every player \( i \) non-cooperative game, \( U_{i}^t \) - total net benefit obtained from cooperative game, \( \psi \) - distribution factor of cooperative benefit.

4. Results and discussion
4.1. Evaluation of game simulation
The validity of the simulation was evaluated by comparing predictions with observations (data) during 2000 and 2006. To display the compared results of all the values at different sizes in one diagram, scientific notion method was applied to transform all numbers into the form \( a \times 10^b \), the significant \( a \) was defined as any real number between 1 and 10, and three decimal places was set to \( a \) to keep all residuals (differences between observations and predictions) from zero after the transformation. The evaluation results illustrate that forecasts and observation are very close (Fig. 6a) with an average error of 3.6% except one error is 16.51% and another 10.48% (Fig. 6b). Through this evaluation, it is clear that the simulation has a very good ability to reflect reality and can be used for future prediction.

4.2. Water deficit
The simulation results of water deficits of sub-players 11, 12 and 13 in game 2 are displayed in Table 6. In the non-cooperative game, available water for sub-player 11 (Q11) and sub-player 13 (Q13) will decrease from 5.38 \times 10^8 \text{ m}^3 to 4.10 \times 10^8 \text{ m}^3, and 10.46 \times 10^8 \text{ m}^3 to 7.99 \times 10^8 \text{ m}^3, respectively
from 2010 to 2015. In contrast, available water for sub-player 12 showed an increasing trend, from 15.92 × 10^8 m^3 to 17.88 × 10^8 m^3 during the same period of time. In cooperation game, the water amounts obtained by them are less than that in non-cooperation, mainly because the players stop over-using underground and ecological water and share their limited water resources. By comparing the available water in cooperation to that in non-cooperation, it was found that those players will face serious water deficits in the condition of cooperation.

4.3. Nitrogen reduction

The simulation results of nitrogen reductions in games 3–5 are revealed from Tables 7–9. In game 3, players 21, 22 and 23 can produce total nitrogen (TN) of 694.0–514 tons, 40,131.7–40,466.3 tons, and 273,586.4–290,772.4 tons, respectively from 2005 to 2010 in non-cooperative game. In cooperative game, they have to reduce the nitrogen production in order to improve the water quality for water transfer. Comparing the TN productions in non-cooperative to that in cooperative games, it found that players 21, 22 and 23 will reduce, respectively, TN of 163.2–356.2 tons, 9439.4–28,040.0 tons, and 64,350.3–201,482.3 tons from 2005 to 2010 (Table 7). Based on the similar analysis, it revealed that in game 4 sub-players 31, 32 and 33 should reduce, respectively, nitrogen of 89.2–506.2 tons, 3695.0–11,581.8 tons and 15,672.5–51,276.9 tons, during the same period of time (Table 8). In game 5, the results confirmed that players 41, 42 and 43 should reduce, respectively, TN of 45.6–165.8 tons, 1120.7–3247.4 tons and 13,553.3–52,755.2 tons to meet the water quality standard from 2005 to 2010 (Table 9).
4.4. Payoffs

Results of payoffs at nominal prices in game 1 are presented in the Matrix 1. In the matrix, the first column and the second column refer to the payoffs resulting from the simulations of non-cooperative and the cooperative games, respectively. In each column, the first, second, third and fourth numbers refer to the payoffs of players 1, 2, 3 and 4 respectively. The zeros are used to (1) keep the matrix symmetric, (2) state no game played there. These results proved that the non-cooperative game will cost player 1 a total loss of $17.3 \times 10^{11}$ yuan from year 2010 to 2015, but it would yield players 2, 3 and 4 a benefit of $1.1 \times 10^{11}$ yuan. However, compared the overall costs to benefits, there was an overall loss of $16.2 \times 10^{11}$ yuan when each player does not cooperate with the others. In contract, the cooperative game results showed that there is an overall benefit of $16.2 \times 10^{11}$ yuan, though players 2–4 lose $1.1 \times 10^{11}$ yuan. Those nominal values have been transformed into comparative value (real value) (Matrix 2) based on Eq. (8) to make reasonable comparison. Based on those results, the payoffs of players 1 and his sub-players in the years of 2010, 2011, 2012, 2013, 2014 to 2015 have been transferred into the values in years of 2005, 2006, 2007, 2008, 2009 and 2010, respectively. These results calculated at real prices proved that the non-cooperative game will cost player 1 a total loss of $13.6 \times 10^{11}$ yuan during 2010–2015, but it yields players 2–4 a benefit of $1.1 \times 10^{11}$ yuan from 2005 to 2010. However, comparing the overall costs and benefits, there is an overall loss of $12.5 \times 10^{11}$ yuan when each player does not cooperate with the others. In contract, the cooperative game result showed that there is an overall benefit of $12.5 \times 10^{11}$ yuan, though players 2–4 lose $1.1 \times 10^{11}$ yuan (Matrix 2).

Matrix 3 explained the real losses of all sub-players under the game 1. In the matrix, the rows above the line present non-cooperative results and down are cooperative results. From those results, it showed that non-cooperation among players 1, 2, 3 and 4 will cost sub-players 11, 12 and 13 losses of $662.83 \times 10^{8}–1222.25 \times 10^{8}$ yuan, $1230.70 \times 10^{8}–2614.94 \times 10^{8}$ yuan and $24.51 \times 10^{8}–27.74 \times 10^{8}$ yuan, respectively, due to water deficits during 2010–2015. However, sub-players of players 1 and his sub-players in the years of 2010, 2011, 2012, 2013, 2014 to 2015 have been transferred into the values in years of 2005, 2006, 2007, 2008, 2009 and 2010, respectively. These results calculated at real prices proved that the non-cooperative game will cost player 1 a total loss of $13.6 \times 10^{11}$ yuan during 2010–2015, but it yields players 2–4 a benefit of $1.1 \times 10^{11}$ yuan from 2005 to 2010. However, comparing the overall costs and benefits, there is an overall loss of $12.5 \times 10^{11}$ yuan when each player does not cooperate with the others. In contract, the cooperative game result showed that there is an overall benefit of $12.5 \times 10^{11}$ yuan, though players 2–4 lose $1.1 \times 10^{11}$ yuan (Matrix 2).
11–13 can avoid those losses if players 1–4 are cooperative, but cooperation imposes cost to sub-players of 21–23, 31–33, 41–43. The losses of sub-players of 21, 22, 23, 31, 32, 33, 41, 42 and 43 are $0.15 \times 10^8 - 0.32 \times 10^8$ yuan, $39.07 \times 10^8 - 40.18 \times 10^8$ yuan, $38.89 \times 10^8 - 98.50 \times 10^8$ yuan, $0.59 \times 10^8 - 3.36 \times 10^8$ yuan, $11.46 \times 10^8 - 16.98 \times 10^8$ yuan, $6.96 \times 10^8 - 26.04 \times 10^8$ yuan, $0.08 \times 10^8 - 0.29 \times 10^8$ yuan, $38.21 \times 10^8 - 38.41 \times 10^8$ yuan and $3.47 \times 10^8 - 17.83 \times 10^8$ yuan, respectively from 2005 to 2010. On the contrary, the sub-players of 11–13 will have no such losses if players 1–4 are cooperative, but cooperation also imposes cost to the sub-players of 21–23, 31–33, 41–43. For example, the sub-players 21, 22 and 23 will lose $0.15 \times 10^8 - 0.32 \times 10^8$ yuan, $39.07 \times 10^8 - 40.18 \times 10^8$ yuan and $38.89 \times 10^8 - 98.50 \times 10^8$ yuan, respectively from 2005 to 2010. Therefore, all the players will be better off if a side payment is made between them at the end of the cooperative game.

Fig. 7 – Scenarios (SN) of (a) water demand, (b) available water resources, (c) water deficit of player 1 (P1), (d) water deficits of sub-players 11, 12 and 13 (P11, P12, P13) without cooperation with outside players.
Form those comparing results, it is clear that the players should cooperate with each other so as to maximize the overall benefits. However, every player is usually afraid of cooperation, because they face risks and uncertainties of losses when they are not sure if others really want to cooperate. Furthermore, every player can be better off by free riding in non-cooperation. In water scarce area, players can get their water by free riding in terms of overusing groundwater and ecological water. In the Hanjiang River basin, every player can also be better off by free riding others’ achievement of pollution reduction. In a long run, non-cooperation will deteriorate the environment and water quality. Therefore, non-cooperation results in a game of “Prisoners’ dilemma”. The methods to solve the dilemma are usually to design a mechanism to change the rules and drive the players to reach collective rationality. The driving forces usually refer to something like laws, regulations, contracts and other binding agreement. In contrast with those legislation methods, economic methods such as tax, fine, compensation and so on, are also such kinds of driving forces. In this study, reducing waste water and increasing water quality will impose cost to players in the reservoir catchment, but they can create a large benefit to the players in water receiving area. In this sense, all the players will have incentives to cooperate if a mechanism could guarantee to transfer part of the benefits obtained from cooperation to cover the losses of players.

4.5. Scenario simulation

The main comparison results from the water demand game simulation under the four scenarios are illustrated in Fig. 7. The scenario results revealed that, from 2008 to 2015, water demand of player 1 (Fig. 7a) will increase under each of those four scenarios, though the efficiency of water consumption will be highly increased in those scenarios. Player 1 and his sub-players would face shortage problems (Fig. 7c and d), mainly due to increase of ecological water demand. Comparing to other sub-players, player 2 will face most serious water deficits in each of the four scenarios (Fig. 7d). It also found that, due to extremely severe water scarce situation, those players cannot solve their water deficits without cooperation with other players, even under the optimistic scenario 4 ($S_4$), where it is in the wet years ($P = 20\%$), high waste water recycling amount, etc.

The comparing simulation results of TN reduction under the four scenarios are illustrated in Fig. 8. The results showed that, in each of the scenarios, player 2 should take more responsibility to reduce nitrogen production (Fig. 8a), because he is the main polluter discharging more pollutant TN into the reservoir than that of other players. The uncertainty of non-cooperation probably come from this player and his sub-players because they face big loss to reduce their TN discharge based on the payoffs results in scenario 1 (Matrix 2).
From the scenario results of sub-games, it is also clear that sub-players 23, 33 and 43 are the main polluters in games 3, 4 and 5, respectively, because they discharge more nitrogen than that other players do in each of those games under the four scenarios (Fig. 8c and d). Those sub-players will be the uncertainty sources of non-cooperation in those games.

5. Conclusions

This study established game-theoretic simulation models to analyze the problems of water scarcity and nitrogen reduction in the South-to-North Water Transfer Project. The simulation is consisted of two levels, 1 main game with 4 players and 4 sub-games with 12 sub-players. Beijing municipality, Shaanxi (Hanzhong, Ankang and Shangluo cities), Hubei (Shiyian city) and He’nan (Xixia and Xichuan cities) were defined as players 1, 2, 3 and 4, and industry, household and agriculture of those four players as the sub-players 11, 12 and 13, 22 and 23, 31, 32 and 33, and 41, 42 and 43, respectively. The main results revealed that player 1 and its sub-players cannot solve their water deficit problem without cooperation with other players even under an optimistic scenario. Sub-player 12 will face most serious water deficit based on the simulation results of four scenarios. Cooperation with other players is the dominant strategy of those players. Players 2–4 and their sub-players will face costs to reduce pollutant total nitrogen for the water diversion. The uncertainty of non-cooperation might come from player 2 in game 1, and sub-players 3 in the games 2–5. This study also proved that non-cooperation will cause whole society a loss although some players can get benefits. In contract, cooperation brings some players losses, but it will produce much more collective benefits. However, players usually are not willing to cooperate, because they will face risks of losses. This usually results in a game of “Prisoners’ dilemma”. The players are willing to cooperate if a mechanism can guarantee to transfer part of the benefits obtained from cooperation to cover the losses of players. Suggestions on the mechanisms can include: (1) to sign a binding agreement on the beneficial players funding losers to build necessary pollution treatment plan; (2) to transfer water using and controlling right to the losing players; and (3) to include the losses of losers into the water prices for winners. These game simulation results will not only benefit the water users to be better off, but also benefit water administration for decision support on water distribution, water pricing and ecological compensation, etc.

References


A: action (or moves) in a game
B(Q): water benefit function in cooperative game
B_i(Q): water benefit function of player i in non-cooperative game
BOD: biochemistry index; oxygen demand after 5 days (mg/L)
C_{N,i}: TN concentration into reservoir from one human activity in a region (mg/L)
C_{N,y}: concentration of pollutant (TN) in controlling section y (mg/L)
C_{W,y}: concentration of pollutant (TN) in the controlling section y (mg/L)
CODmn: permanganate index (mg/L)
C_{max}: upper threshold of TN concentrations (mg/L)
C_{min}: lower threshold of TN concentrations (mg/L)
D_i: nominal value of payoff (V and U) (10^8 yuan)
D_y: real value of payoff (V and U') (10^8 yuan)
DO: dissolved oxygen (mg/L)
e^{-g}: discount factor
E: game equilibrium
E_{vol}: evaporation of water surface (mm)
G: game; G_i: first level game, sub-game respectively
G_{m}: main player m’s sub-game
I: information set of a game
K(W): cost function to abate pollutant (TN) in cooperative game (10^8 yuan)
K_{N,y}: cost function of player i to abate pollutant in non-cooperative game (10^8 yuan)
L_{v,y}: limit of pollutant load in section y (tons)
L_{w,y}: load of TN into the reservoir from one human activity in a region (mg/L)
L_{w,y}: load of pollutant (TN) in section y (tons)
L_{w,y}: load of pollutant W from upstream controlling section y – 1 (tons)
M: set of players
M_{n}: main game, M_1: sub-game
N: set of players
N_{m}: set of main players, sub-players
NH_3-N: ammonia nitrogen (mg/L)
O: game outcome
P_{w,y}: main player, sub-player
P_{w,y}: consumption price index (CPI) in time t, t'
Q_{w,y}: water used for environ-ecology (10^8 m^3)
Q_{w}: water inflow into the reservoir (10^8 m^3)
Q_{w,y}: available water of every player in non-cooperative, cooperative game (10^8 m^3)
Q_{w,y}: water deficit of player i (10^8 m^3)
Q_{w,y}: maximum water demand of player i (10^8 m^3)
Q_{w,y}: minimum water demand of player i (10^8 m^3)
Q_{w,y}: water flow from upstream section y – 1 (10^8 m^3)
Q_{w,y}: water flow in the section y (10^8 m^3)
Q_{w,y}: water demand to keep certain water surface (10^8 m^3)
Q_{w,y}: water demand of public green area (10^8 m^3)
Q_{w,y}: water demand of newly planed trees (10^8 m^3)
R: reclaimed water (10^8 m^3)
SN: scenarios
S: strategy profile of a game
S_m, S_{w,y}: strategy profile of main player, sub-player
SN: total nitrogen (mg/L)
U_{m}, U: payoff, real payoff of player i in cooperative game (10^8 yuan)
V: payoff (or utility) in a game
V_{m}, V: payoff, real payoff of player i in non-cooperative game (10^8 yuan)
V_{m,y}, V_{w,y}: payoff of main player, sub-player (10^8 yuan)
V_{w,y}: payoff of player i in non-cooperative game (10^8 yuan)
V_{w,y}: payoff of main player, sub-player (10^8 yuan)
W_{m,1}: ground surface water resources (10^8 m^3)
W_{m,2}: groundwater resources (10^8 m^3)
W_{m,3}: surface water resources (10^8 m^3)
W_{m}: pollutant TN production of player i in non-cooperative, cooperative game (tons)
W_{m,y}: pollutant TN reduction of player i (tons)
W_{m,y}: pollutant TN produced from a certain activity in a region (tons)
X_{k,p}: independent (or explanatory) variables
Y_{i,p}: dependent variablesGreek symbols
\alpha: coefficient of waste water back into water
\beta: parameter in linear equation
\gamma: benefit coefficient
\delta: cost coefficient to reduce pollutant (TN)
\psi: distribution factor of cooperative benefit
\epsilon: loss coefficient of TN from production source
\lambda: coefficient of TN into river
\kappa: coefficient of TN into reservoir
\phi: coefficient TN finally maintaining in reservoir
\sigma: assimilation coefficient of pollutant
\epsilon_{y}: disturb (or error) termSubscripts and superscripts
ra: one certain human activity in a region
k, p: observation numbers
i, j: every player, other n – 1 player
m, j: every main player, sub-player in sub-game
m_j: which main player a sub-player belongs to
W: referring to pollutant (TN in this study)
y, y – 1: lower, upper stream controlling sections