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Optimal Multi-Sectoral Water Resources Allocation Based on Economic Evaluation Considering the Environmental Flow Requirements: A Case Study of Yellow River Basin

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Abstract: Competitions and disputes between various human water sectors and environmental flow of the river are exacerbated due to the rapid growth of the economy in Yellow River basin as well as the limited supply of available water resources in recent decades. It is necessary to implement rational and effective management and allocation to alleviate the pressure of water shortage. In order to promote economic development and maintain the ecological balance of the river, both the water allocation to the river environmental system and different human needs should be of concern when making the allocation polices. This study developed a water allocation model based on Nash–Harsanyi bargaining game theory for optimal water resources allocation among agricultural, industrial, domestic, public, and urban ecological water (watering for urban green space) sectors while ensuring the environmental flow requirements of lower reaches. A comprehensive economic evaluation framework is built to assess the economic benefits of different water uses that were taken as the basis of water allocation model. The annual environmental base flow is 7.50 billion m^3 in the lower reaches of Yellow River. Moreover, the optimal annual allocations for agricultural, industrial, domestic, public, and urban ecological water use sectors are estimated as 33.7, 6.42, 3.96, 1.75 and 2.68 billion m^3, respectively.

Keywords: optimal water allocation; environmental base flow; economic values; asymmetric Nash bargaining game model

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1. Introduction

With the development of social economy and population growth, the trade-offs between human society's water demand and its limited water resources have become increasingly prominent [1], which has intensified conflicts and rivalry between different sectors of water use as well as regions. Water is also facing increasing pressure due to the uneven temporal and spatial distribution and the impacts of climate change [2–6], and several regions in the world are dealing with increasing serious problems with water shortages [7–14]. Solving the issue of water scarcity relies not only on the availability of water supplies, but also on rational, empirical, and effective management and allocation [15–17]. Meeting diverse human needs and ensuring environmental requirements to achieve long-term sustainability is the core theme of water resource management and allocation [18]. It is therefore important to take both the needs of different sectors of human society and environmental requirements of river ecosystems into consideration in the allocation of water resources. In the past few decades, in order to proceed with the equal, effective and sustainable use of water resources, research on water resources allocation has drawn more and more attention [19–26].

Economic evaluation can help identify how best to allocate the available water resource among different competitive sectors to optimize the economic benefits when there are inadequate water supplies [27,28]. It can lay the foundation for reaching a consensus on sharing the limited water supplies between different demand sectors to help achieve a balance between water supply and demand [29]. Regarding the evaluation of the economic value of different water sectors, existing research has focused more on how to measure the economic value of agricultural and industrial water use [10,30–37], while fewer discussions have been conducted on domestic (public) water sectors as well as urban ecological water sector [38,39].

As for the agricultural and industrial sectors, cost-benefit method and Cobb–Douglas (C–D) production function are two general approaches for evaluating the economic value of water use. The cost-benefit method assesses the value of agricultural and industrial water by the difference between the income of products (e.g., various crops and electricity) and water use costs as well as production costs of other supplies [40–44]. Nevertheless, this kind of method is susceptible to the limitation of data availability as it has relative high data requirements. However, the C–D production function is widely used to represent the amount of output that can be produced by multiple inputs including water use and non-water supplies; meanwhile, the marginal value of unit water for different sectors can be further evaluated to represent the economic value of different sectors [10,36,37,39,45]. Domestic water use is essential in terms of human needs because domestic water uses such as drinking, food preparation and hygiene are critical to daily life. However, economic evaluation of domestic water is absent from the large-scale literature. Some studies on water allocation have simply used water prices and water supply costs to measure the economic value of domestic water [42,46,47], whereas what they measured is not the value of water used by households, but the revenue of enterprises on water. Since it is difficult to directly observe the economic value of domestic water use, alternative non-market valuation methods are necessary to be developed to reveal and evaluate the value of domestic water [27,29,48]. There are some studies which carried out questionnaire surveys and employed a contingent valuation approach to assess people's willingness to pay for domestic water use [49,50] for some small-scale areas (e.g., communities, cities). Furthermore, the value of domestic water is generally evaluated by the economic surplus derived from demand functions by econometric estimations [27,48]. In addition, owing to the relatively small amount of public water and urban ecological water, these two sectors have not been paid much attention to within the research of water allocation, and there was less research on how much economic value they can produce. Therefore, a comprehensive evaluation framework of economic values in agricultural, industrial, domestic, public, and urban ecological water sectors will be built in this study to establish the relations that can be adopted to represent the generated economic benefits and water inputs for different sectors.

Yellow River basin in China is taken as the target area in this study, based on the evaluation of the economic benefits; water allocation among five water sectors in Yellow River basin will be fully taken into consideration, while most existing studies mostly focused on water allocation between administrative regions [11,51–56], or focused on one or two sectors such as agriculture and industry [57–59]. The lower reaches of the Yellow River experienced the phenomenon of river cut-off continuously as the result of excessive and irrational development by humans, which severely impaired the ecological balance of the river in the 1990s. Therefore, both the ecological environment and human water uses are supposed to be highly concerned when implementing water allocation in Yellow River basin. A certain amount of water is intentionally preserved in the river channel to sustain the functions and health of a river ecosystem's named environmental base flow. The existing research often conducted separate discussions and studies in Yellow River basin on water allocation to the river's environmental system or human needs, with little regards to environmental flow requirements when allocating water to sectors of human demands [11,53,54,59–63]. Therefore, the optimal allocation of water resources among different water sectors in this study will be discussed while ensuring environmental flow requirements.

The issue of the effective and rational allocation of available water resources in this study is essentially a game of resources between different water sectors. A variety of methods and models were applied in the allocation of water resources, among which approaches based on game theories are a kind of effective method for implementing water allocation among different water sectors [20,24,26,59,64,65]. In terms of methods based on game theories, the behaviors of different rational decision-makers are taken into consideration and the different interests of multiple decision-makers can be identified, which reflect the equilibrium of the direct interactions among multiple rational decision-makers. The Nash–Harsanyi bargaining game model [66–68] is employed in this study which is applied to resolve resource sharing issues among different users that have overlapping demands on available resources in a more sustainable way.

Based on the above discussions, this study aims to answer three research questions: (1) How much economic benefits can be produced by water inputs for agricultural, industrial, domestic, public, and urban ecological water sectors, respectively? (2) At least how much environmental base flow should be maintained in the river channel of lower reaches of Yellow River? (3) What is the optimal water allocation scheme among five water sectors? To this end, this study firstly established a comprehensive evaluation framework to assess the economic values of different water use sectors, and an optimal water allocation model based on Nash–Harsanyi bargaining game theory was developed to implement water allocation for different water sectors while considering the environmental base flow requirements in the downstream of Yellow River. Section 2 describes the policies of the study area, Section 3 introduces the methodologies, Section 4 shows the results and discussions. Section 5 summarizes the conclusions and some implications.

2. Study Area

Yellow River, the second largest river in China, is an important source of water for northwestern and northern China. It originates from Tibetan Plateau, flows through nine provinces of Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shanxi, Shaanxi, Henan, and Shandong and runs into the Bohai Sea at last (Figure 1). The per capita river runoff in the Yellow River is 473 cubic meters which is less than 1/4 of the average number of the country, and feeds both 15% cultivated land and 12% of water requirements of people in China [54]. An increasing water scarcity is faced in Yellow River basin due to rising water consumption due to the fast-growing economy and rapidly urbanizing population. Hence the Yellow River basin has become one of the areas which faces one of the most significant water resource shortage problems in China. Therefore, the limited available water should be managed efficiently to maintain sustainable development.

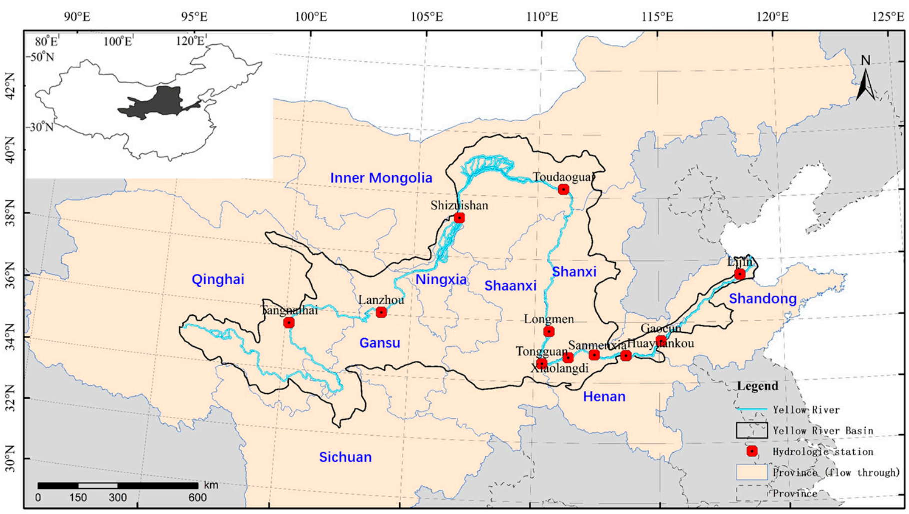


Figure 1. The location and administrative regions of Yellow River basin.

The average amount of total water resources of Yellow River is about 55.9 billion m^3 year^{-1} for nearly the past 20 years which include surface water, groundwater, water storage in reservoirs and so on, and the total amount of water resources in most years is between 50–70 billion m^3 year^{-1} (shown in Figure 2) [69]. According to the consumption types identified in the Yellow River basin, the multiple demands are centered on the agricultural, industrial, domestic, public, and urban ecological water sectors. Water use competition has intensified among different water sectors as well as several provinces along the Yellow River.

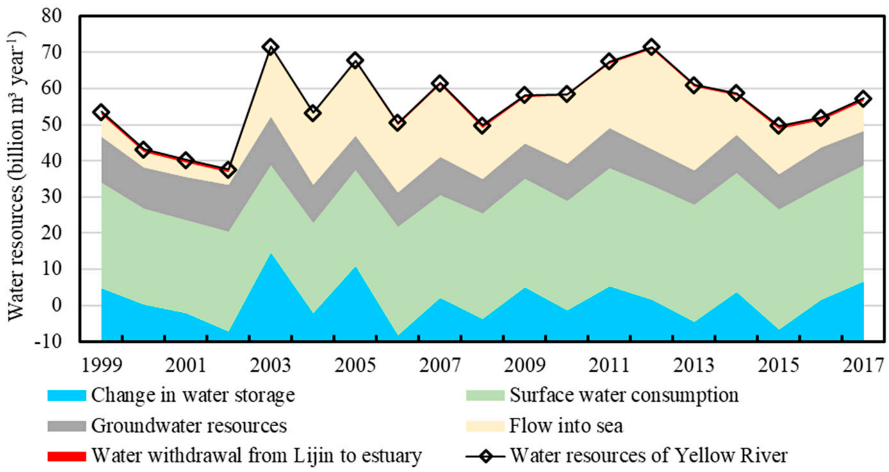


Figure 2. The total water resources of Yellow River.

Due to the economy in the Yellow River basin which boosted rapidly in the 1990s, the provinces located in the upper reaches took water aimlessly and unrestrainedly, causing the downstream rivers to cut-off in 22 of the 28 years from 1972 to 1999 [69]. In order to solve this problem, in order to cope with the sharp contradiction between the supply and demand as well as maintain the healthy ecosystem of the river, China State Council authorized the Yellow River Conservancy Commission (YRCC) to uniformly regulate the water volume of the Yellow River in the late 1990s [70]. China State Council announced the first Chinese major rivers diversion plan—The Yellow River Water Diversion Scheme (Scheme 1987) in 1987. The Scheme allocated a total volume of 58 billion m^3 a year of water to the provinces along the river and the ecosystem of Yellow River. It clarified the quotas of available water among administrative regions, which has a positive impact on the rational use of water resources in the Yellow River and has served as the basis for formulating water dispatching plan and water consumption index of each province to date. After that, the "Yellow River Water Dispatch Rules" came into effect in 2006, and the goal of these rules was to first meet the domestic water needs of urban and rural residents, rationally arrange water for agriculture, industry, and the ecological environment to prevent the Yellow River from drying up [71]. In 2013, the "Comprehensive Plan for the Yellow River Basin" was approved, proposing future control of the environmental flow at the Lijin (the last hydrological station in the downstream of the Yellow River) section and strengthening water conservation in agriculture, industry, and urban life in the future [72]. Strict management and reasonable allocation of water resources are significant issues that have long been concerned and discussed in the Yellow River basin. However, there were relatively few related policies and research on the optimal allocation among different water sectors. In this study, the water use sectors include agricultural, industrial, domestic, public, and urban ecological water sectors. The agricultural water sector includes the irrigation of farming fields, forestry and orchards, grassland, and replenishment of fishing farms. For industrial sector, not only cooling water in thermal power plants, but also other water uses, such as manufacturing, washing and purification in the production process of industrial enterprises, are considered. Regarding the urban ecological water use, it is mainly used for the irrigation of green space in cities. Moreover, ensuring environmental flow in lower reaches for maintaining the sustainable development of the river is an issue that should be continuously concerned for the rational water resources allocation of the Yellow River.

3. Materials and Methods

3.1. A General Framework

The optimization framework for the design and planning of the Yellow River's water resources allocation system is illustrated in Figure 3. Since the total water demands from different users are larger than the supply of available resources, efficient water allocation can balance supply and demand and ensure an equitable share between the needs of different water sectors. Firstly, the minimum water demands of each province for different sectors needed to be satisfied when allocating water in order to ensure minimum production and people's livelihood. Secondly, an economic evaluation framework is developed to determine the economic benefits when water is allocated to agricultural, industrial, domestic, public, and urban ecological water sectors. Thirdly, before determining the available water resources that can be allocated, it is necessary to define the environmental base flow of the lower Yellow River, how much water should be remained in the river to maintain the ecological balance of the river, and then estimate the water resources that can be used for human sectors. Finally, using Nash–Harsanyi bargaining game theory with considerations on environmental and social-economic constraints, the optimal water allocations maximizing the economic benefits are estimated.

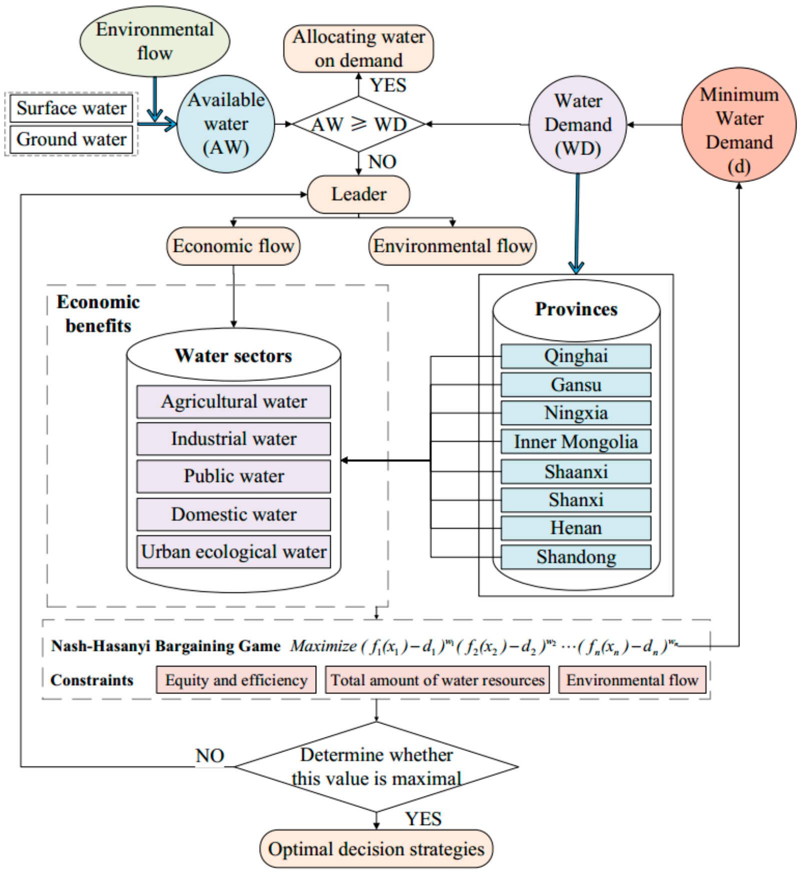


Figure 3. The framework for the design and planning of the Yellow River's water resources allocation.

3.2. Methods Evaluating the Values of Five Water Sectors

An evaluation framework for estimating the economic value of five water sectors is shown in Figure 4. The specific water usage and categories covered by each sector in this study are illustrated.

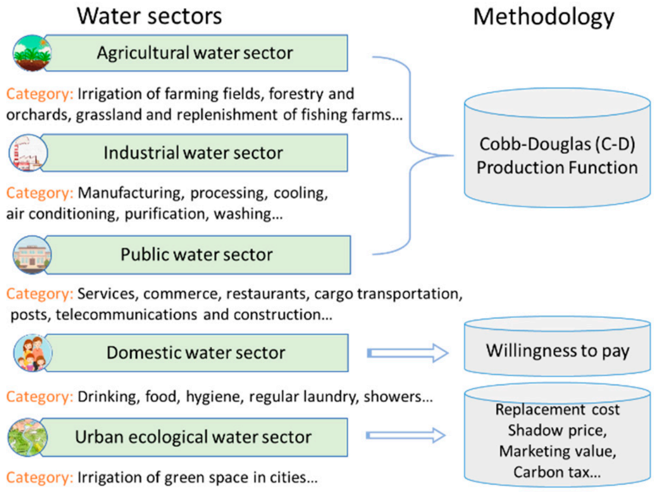


Figure 4. Evaluation framework for estimating the economic value of five water sectors.

3.2.1. Agricultural, Industrial, and Public Water Sectors

We developed Cobb–Douglas (C–D) Production Function for these three sectors to obtain the relations of economic benefits and water supplies. The C–D production function is often used as a utility function; it is widely used to represent the amount of output that can be produced by multiple inputs (including water input and non-water supplies). Regarding the construction of the C–D production function, the outputs of three sectors are represented by added value of these three sectors, respectively. The selected input factors of the agricultural sector include water, labor, fertilizer, investment in fixed assets, and machinery power shown in Equation (1). For industrial sector, the input factors are labor, investment in fixed assets, coal consumption, and water following Equation (2). For public water sector, urban population, water, investment in fixed assets, and wage income are the inputs shown in Equation (3). The panel data from 2005 to 2016 of eight provinces through which the river mainly flows was used for building the C–D production functions. It is worth noting that the total water withdrawal of the agricultural sector in the model is derived from the annual precipitation plus the irrigation water [35,73,74].

$$YA_{it} = A_0 \cdot F_{it}{}^{\beta_1} \cdot FA_{it}{}^{\beta_2} \cdot LA_{it}{}^{\beta_3} \cdot WA_{it}{}^{\beta_4} \cdot M_{it}{}^{\beta_5} \quad (1)$$

$$YI_{it} = A_1 \cdot LI_{it}{}^{\sigma_1} \cdot FI_{it}{}^{\sigma_2} \cdot C_{it}{}^{\sigma_3} \cdot WI_{it}{}^{\sigma_4} \quad (2)$$

$$YP_{it} = A_2 \cdot P_{it}{}^{\alpha_1} \cdot FP_{it}{}^{\alpha_2} \cdot I_{it}{}^{\alpha_3} \cdot WP_{it}{}^{\alpha_4} \quad (3)$$

where i represents province; t means in year t. YA, YI, YP are the utilities of agricultural, industrial, and public water sectors, respectively, and A_0, A_1, A_2 are the constants of three functions, respectively. F, M, C, P, I represent fertilizer, machinery power, coal, urban population, and income, respectively. WA, WI, WP indicate the water withdrawals of three sectors; FA, FI, FP refer to the investment in fixed assets of three sectors; the labor of agricultural and industrial sector are represented by LA, LI and α_i, β_i, σ_i are the elasticities. The model coefficients A_0, A_1, A_2, α_i, β_i, σ_i are estimated from Equations (4), (6) and (8).

The economic value of water for agricultural, industrial, and public water uses are estimated by isolating the marginal contribution of water to the total output value [10,36,37,39,45]. The marginal value can be obtained by the partial derivative of the production function with respect to water for three water use sectors following Equations (5), (7) and (9).

$$\ln YA_{it} = \ln A_0 + \beta_1 \ln F_{it} + \beta_2 \ln FA_{it} + \beta_3 \ln LA_{it} + \beta_4 \ln WA_{it} + \beta_5 \ln M_{it} \quad (4)$$

$$MPA_t = \frac{\partial \ln YA_t}{\partial \ln WA_t} \cdot \frac{YA_t}{WA_t} = \beta_4 \frac{YA_t}{WA_t} \quad (5)$$

$$\ln YI_{it} = \ln A_1 + \sigma_1 \ln LI_{it} + \sigma_2 \ln FI_{it} + \sigma_3 \ln C_{it} + \sigma_4 \ln WI_{it} \quad (6)$$

$$MPI_t = \frac{\partial \ln YI_t}{\partial \ln WI_t} \cdot \frac{YI_t}{WI_t} = \sigma_4 \frac{YI_t}{WI_t} \tag{7}$$

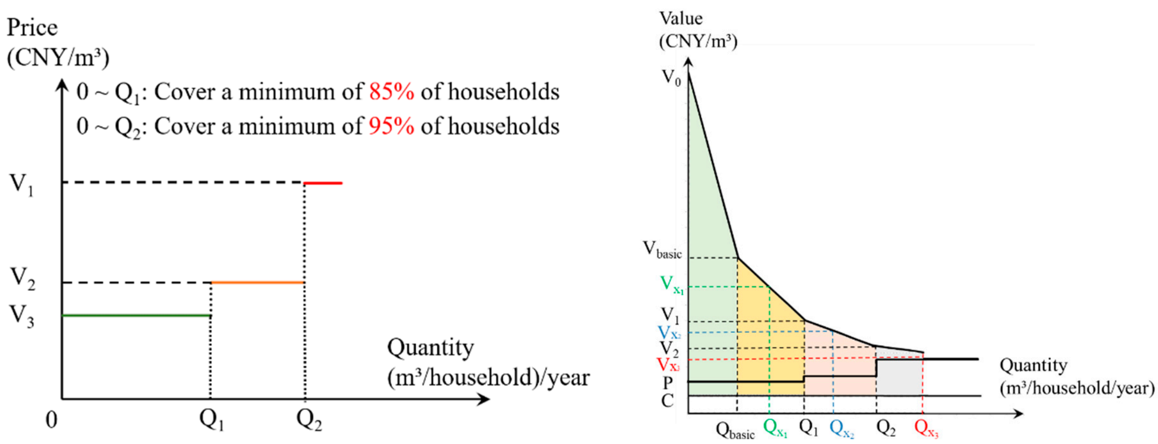
$$\ln YP_{it} = \ln A_2 + \alpha_1 \ln P_{it} + \alpha_2 \ln FP_{it} + \alpha_3 \ln I_{it} + \alpha_4 \ln WP_{it} \tag{8}$$

$$MPP_t = \frac{\partial \ln YP_t}{\partial \ln WP_t} \cdot \frac{YP_t}{WP_t} = \alpha_4 \frac{YP_t}{WP_t} \tag{9}$$

where MPA_t MPI_t MPP_t represent the marginal value of unit water use of agricultural industrial and public sectors in year t.

3.2.2. Domestic Water Sector

Block water pricing policy has been implemented in Chinese households in order to encourage people to save water [75]. Three block pricing policy shown in Figure 5a is adopted by most provinces; in general, it means the more water use, the higher water unit price. At least 85% of total families' water use is covered in the volume of first block and 95% is within the second block. Domestic water sector is different from other sectors, since water is a final good, it can be valued by the economic surplus derived from the demand function using willingness to pay of household and water utility's revenue [27,29]. The approach is to build average n-parts demand function for households in Yellow River basin illustrated in Figure 5b considering the water categories (Table 1) and the block water pricing policy (Figure 5a), since the households' willingness to pay for water decreases with the increase of quantity and block water price. The first part of the demand function corresponds to basic water requirements, which are very highly valued (e.g., drinking), therefore the boundary of this part is determined by the volume of basic water requirements. The second part corresponds to intermediate needs (e.g., regular laundry) which are less valued than use of the first category, and the boundary is the volume of first block defined by block water pricing policy. The following parts of demand function corresponds to least-valued supplementary consumption, such as further indoor uses (e.g., leisure bath) or outdoor uses (pool, fountain, etc.), and the boundary between the third and fourth part is determined by the volume of second block setting by the block water pricing policy. The values of parameters of different parts of demand function will refer to the existing studies and related government reports which will be introduced in Section 3.5. At the end, the economic value of per household water use is the economic surplus of the demand function which is represented by the sum of the value of colored areas in Figure 5b.



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

Figure 5. (**a**) Block water pricing policy; (**b**) General structure of the n-part demand function. P_i is the water price of ith block; Q_i is the water volume of ith block; C is the cost of water; V_i is willingness to pay corresponding to the water volume Q_i; Q_{basic} is the volume of basic requirements; Qx_i is the allocated water.

Table 1. Categories of households' water use.

Categories	Water Use
Basic water requirements	Drinking, food, and hygiene (e.g., hand washing); highly valued
Intermediate needs	Additional hygiene (regular laundry, showers, etc.); less valued than the first category.
Supplementary consumption	Further indoor uses (e.g., leisure bath) or outdoor uses (lawn watering, pool, fountain, etc.); least valued

Source: [27].

3.2.3. Urban Ecological Water Use Sector

The urban ecological water is used for irrigating the green space in cities, and the value could be assessed by ecological service functions' value of green space in cities [76,77]. The main ecological service functions of green space are water conservation, gas regulation, cooling (temperature reduction), purification, noise reduction, and culture and recreation [78,79]. The method of estimating the values of these functions mainly include the replacement cost, shadow engineering method, marketing value, and carbon tax [76–83].

Water conservation function: The value can be estimated by shadow engineering method following Equation (10). It is represented by the product of the amount of water that can be conserved by green space and the unit cost of the reservoir capacity.

$$Y_W = A \cdot P \cdot \lambda \cdot F_W \tag{10}$$

where Y_w is the value of green space for water conservation; A is the area of green space; P is the precipitation; λ is the coefficient of water conservation; F_w is the cost of reservoir unit capacity.

Gas regulation and purification function: It mainly includes CO_2 fixation, O_2 release, NO_x, SO_2 absorption, and dust retention functions. Regarding CO_2 fixation function, the internationally accepted carbon tax method is used to estimate the value following in Equation (11). The value of O_2 release can be assessed by the shadow price of producing industrial oxygen shown in Equation (12). Concerning the purification function, replacement cost method can be adopted, and the treatment costs of removing the pollutant gas and dust are used to evaluate the value of purification in Equation (13).

$$Y_C = A \cdot Q_C \cdot T_C \tag{11}$$

$$Y_C = A \cdot Q_C \cdot T_C \tag{12}$$

$$Y_P = A \cdot \sum_{i=1}^{3} (Q_i \cdot P_i) \tag{13}$$

where Y_C, Y_O, Y_P are the values of green space for CO_2 fixation, O_2 release and purification functions; Q_C, Q_O are the carbon fixation and oxygen release per unit area of green space; T_C is the tax rate of carbon; P_O is the average price of industrial oxygen in China. Q_i is the SO_2, NO_x and dust absorption per unit area of green space; P_i is the treatment cost of SO_2, NO_x and dust.

Cooling (temperature reduction) and noise reduction function: Green space in cities can alleviate the urban heat island effect and reduce noise. The cooling function can be assessed by the value of electricity consumed by the air-conditioning operation to achieve the same cooling effect following Equation (14). Regarding noise reduction function, the value can be represented by the afforestation cost with the same effect shown as Equation (15)

$$Y_M = A \cdot D_M \cdot M \cdot G \cdot P_G \cdot 24 \tag{14}$$

$$Y_J = A \cdot B \cdot C \cdot \lambda \tag{15}$$

where Y_M, Y_J are the values of green space for cooling and noise reduction; A is the area of green space; D_M is the cooling days; M is the number of air conditioners per unit area; G is the power of air conditioner; P_G is the price of electricity; B is the wood accumulation per unit area of mature forest; C is the average afforestation cost in China; λ is ratio of noise reduction value to afforestation cost.

Culture and recreation function: The value of green space for culture and recreation function is evaluated by the area of park green space and cultural value per unit area, which are referred to [84,85].

3.3. Method of Quantifying Monthly Naturalized Flow and Environmental Base Flow

The observed discharge of the river at the hydrological station is the flow measured after taking human water withdrawals, therefore, the naturalized flow can be derived by the observed discharge plus the human water withdrawal shown in Equation (16). Human water withdrawals in the downstream of Yellow River represented in Equation (17) mainly includes water use in productive activities such as agricultural and industrial water withdrawal, and household water withdrawal for the residents' daily life as well as public water withdrawal and urban ecological water withdrawal. Moreover, the industrial water withdrawal in this study refers to the new water withdrawal, which does not include the reuse of water within enterprises, return flow of once-through cooling water, and so on.

$$D_n = D_o + W_H \tag{16}$$

$$W_H = W_a + W_i + W_h + W_p + W_e \tag{17}$$

where D_n is the naturalized flow; D_o is the observed discharge; W_H is the human water withdrawal; W_a, W_i, W_h, W_p, W_e are the human water withdrawal of agricultural, industrial, domestic, public, and urban ecological sectors.

In order to evaluate monthly naturalized flow, since the statistical data released are all annual data, it is better to assess the monthly water withdrawals of different human water sectors. For the agricultural sector, due to the impact of the natural environment and crop growth cycle, the monthly water withdrawal pattern is different for reasons, and it is not appropriate to allocate the annual water withdrawal evenly to each month. The H08 hydrological model [86–89] can evaluate the monthly pattern of agricultural water withdrawal, and the statistical annual agricultural water withdrawal data can be converted into monthly agricultural water withdrawal using this pattern. However, for industrial, domestic, and other sectors, it can be assumed that the average monthly water withdrawal is equal owing to the stable advancement of production activities and regular people's lives.

The environmental base flow is necessary to maintain the health of rivers in the development and utilization of river water resources. Since long-term series of monthly naturalized flow can be evaluated as in the above section, the Tennant method [90], which is one of the most used methodologies to calculate environmental base flow, is adopted in this study. To be specific, the monthly environmental base flow can be derived by the average naturalized flow of each month of the long-term years multiplied by the specific percentage, and 30% [59,91] is taken in this study and to further obtain annual environmental base flow following Equation (18).

$$E = \sum_{i=1}^{12} (M_i \cdot N_i) \tag{18}$$

where E is the annual environmental base flow of the river (m^3); M_i is the average flow of the ith month of the long-term years (m^3); N_i is the percentage of environmental base flow in month i (%), which is 30% in this study.

3.4. Water Allocation Model: Asymmetric Nash–Harsanyi Game Model

The asymmetric Nash–Harsanyi game model is employed to allocate water among agricultural, industrial, domestic, public, and urban ecological water sectors in this study. Nash [66] proposed the two-person Nash bargaining game model, which has a great potential for finding win–win solutions towards sharing limited water resources and obtaining optimal economic benefits. The two-person Nash bargaining game model was extended to the n-person Nash–Harsanyi bargaining game model by Harsanyi [67,68]. The objective function of Nash–Harsanyi bargaining game model aims to maximize the overall benefits of agricultural, industrial, domestic, public, and urban ecological water sectors using bargaining and cooperation, while ensuring the minimum water demand of five sectors. It can help optimize the total economic benefits of the entire river basin. According to whether the bargaining weights are the same for each decision-maker, it can be divided into symmetric and asymmetric bargaining models. The asymmetric Nash–Harsanyi game is a cooperative game while also considering the importance of different players. It is about how the decision-makers interact to achieve a binding cooperation agreement, thereby maximizing the overall benefit [24,65,92] shown as (19)–(23).

$$Maximize(f_1(x_1) - d_1)^{w_1}(f_2(x_2) - d_2)^{w_2}(f_3(x_3) - d_3)^{w_3} \cdots (f_n(x_n) - d_n)^{w_n} \tag{19}$$

$$f(x_i) \geq d_i \; i = 1, 2, 3, \ldots n \tag{20}$$

$$d_i = \text{const} \tag{21}$$

where x_i is the water allocated to decision-maker i; $f(x_i)$ is the utility derived from water allocated to decision-maker i; d_i is the utility of minimum water demand of different sectors; w_i is the bargaining weight; i is different water use sector.

The symmetric Nash–Harsanyi game is a special case of the asymmetric Nash–Harsanyi game theory, when $w_1 = w_2 = w_3 = \ldots = w_n$ in Equation (22). However, in addition to achieving the maximization of economic benefits, it is also necessary to consider factors such as the importance of different sectors such as the water claims of different water users. Therefore, the bargaining weights of different players should be different based on equity and efficiency principle.

$$\sum_{i=1}^{n} w_i = 1 \tag{22}$$

The total allocated water in the basin should be less than or equal to the amount of water available for allocating following Equation (23).

$$\sum_{i=1}^{n} x_i \leq R_A \tag{23}$$

where R_A is available water resources that can be used for allocation.

The bargaining weights based on equity and efficiency principle [24,93] are described as follows in Equations (24)–(27).

$$w_i = \eta\delta_{1i} + (1 - \eta)\delta_{2i} \tag{24}$$

$$\delta_{1i} = \frac{r_i - I_i}{\sum\limits_{i=1}^{n}(r_i - I_i)} \tag{25}$$

$$\beta_i = 1 - \frac{D_i - \frac{1}{n}\sum\limits_{i=1}^{n} D_i}{\frac{1}{n}\sum\limits_{i=1}^{n} D_i} \tag{26}$$

$$\delta_{2i} = \frac{\beta_i}{\sum\limits_{i=1}^{n} \beta_i} \tag{27}$$

where δ_{1i} is the bargaining weight for follower i based on equity principle; η is the ratio of the equity principle; δ_{2i} is the bargaining weight for follower i based on efficiency principle;

$(1-\eta)$ is the ratio of the efficiency principle; β_i is the water use correction coefficient for follower i; D_i is the integrated water utility for follower i.

3.5. Data

Multiple indicators are included in the dataset of this study. The water withdrawal of five sectors refer to National Bureau of Statistics [94]. The data of other variables which related C–D production functions of agricultural, industrial, public sectors (e.g., added value, investment in fixed assets, fertilizer, labor, machinery power, wage income) are collected from *Compilation of agricultural information* [95], *Industrial Statistics Yearbook* [96], and *China Urban Construction Yearbook* [97]. For the domestic sector, the block water price of eight provinces is acquired based on government documents of block water pricing policies [98] and from "China Water Price Network" [99], and other variables such as basic water requirements and willingness to pay are obtained through the survey of the literature research [27,100–104]. For the ecological sector, the variables of urban green space, water conservation, cost of carbon fixation, price of industrial oxygen and electricity, value of culture and recreation, and treatment cost of SO_2, NO_x and dust are from China Statistical Yearbook [94], Yellow River Water Resources Bulletin [69], and literature surveys [66,83,84]. Besides, the observed discharge at Lijin station and the human water withdrawals of agricultural, industrial, domestic, public, and urban ecological sectors of lower reaches of Yellow River is obtained from Yellow River Water Resources Bulletin [69].

4. Results and Discussions

4.1. Economic Benefit of Five Water Use Sectors

The results of marginal value of three water sectors following Equations (5), (7) and (9) are shown in Figure 6. The economic value of unit water resource of three water sectors has removed the effects of inflation (2005 is selected as the base year). It can be found that the economic value of unit water in agricultural, industrial, and public water sectors has generally maintained a growing trend. Despite food crops having relatively low economic value, they are indispensable for human survival. Specifically, the economic value of unit agricultural water use increased from 2.12 CNY/m^3 in 2006 to 3.95 CNY/m^3 in 2016. Besides, the economic value of industrial water is greater than that of the agricultural sector due to high output value for industry, the average value of unit water resources in the past 10 years is 33.8 CNY/m^3, and its economic value has reached 45.1 CNY/m^3 in 2016. As for the public sector, since the water is served for the tertiary industry and construction industry, relatively less water can produce higher economic value, therefore, the economic value is greater than that of the industrial sector. The average value of unit water from 2006 to 2016 was 80.5 CNY/m^3, with its economic value reaching 94.4 CNY/m^3 in 2016.

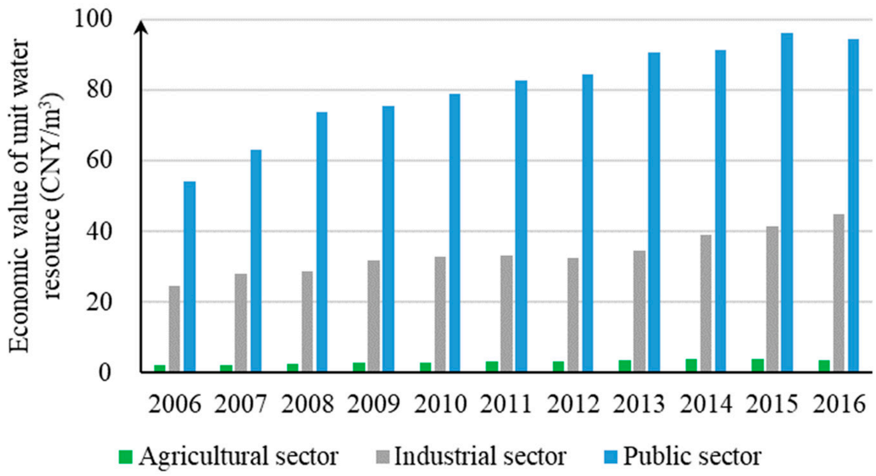


Figure 6. Economic value (marginal value) of unit water resource of agricultural, industrial, and public water use sector.

The average household's demand function in Yellow River basin is represented in Figure 7, and the values which include the respective volume limits and the corresponding willingness to pay (WTP) of different parts of demand function are illustrated in Figure 7. The average basic water requirement per household which denotes the first part of demand function is 57 m^3 per year, and the WTP at the lower and upper bound volumes of the first part is 600 and 50 CNY/m^3. The volume of second and third part of demand function is 57~143 and 143~227 m^3, respectively, with the WTP at the corresponding boundary volumes being 30 and 18 CNY/m^3 as shown in Figure 7. Since the economic value of domestic water use is assessed by the economic surplus of average household's demand function, hence the generated economic value will vary with the amount of water allocated. For instance, if the average water use per household is 101.3 m^3 in 2010, the economic value will be 20.1 thousand CNY. Regarding urban ecological water use sector, the economic values are determined by the values of different ecological functions of irrigated green space in cities (Figure 8). Among these functions, the values of cooling as well as cultural and recreation functions are relatively higher than others, which are 9.07 and 6.13 CNY/m^3, respectively. As for water conservation, gas regulation, purification, and noise reduction functions, the values are 1.95, 2.19, 3.16, 1.22 CNY/m^3, respectively. Consequently, the total value of all ecological functions for urban ecological water use is approximately 23.7 CNY/m^3.

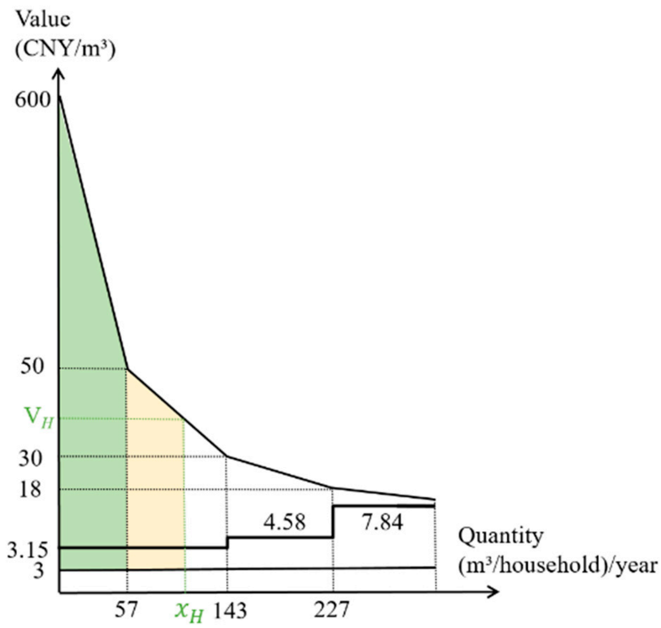


Figure 7. The demand function of households.

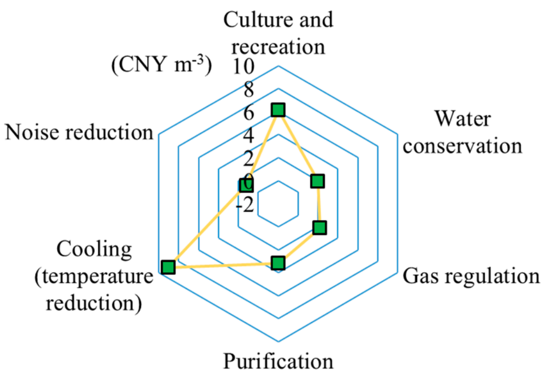


Figure 8. Economic values of urban ecological water use.

4.2. Monthly Naturalized Flow and Environmental Base Flow

This study picked up the seasonal pattern of irrigation withdrawal of H08 model, then proportionally estimated the monthly water withdrawal based on total volume of the statistics of years, and obtained the monthly results from 1999 to 2017 shown in Figure 9. For the seasonal pattern in the downstream, the water withdrawal from Huayuankou to Lijin station is concentrated from June to October, with the largest water withdrawal being more than 1200 m^3/s. The maximum monthly agricultural water withdrawal in most years is above 900 m^3/s, but the monthly flow did not exceed 200 m^3/s in 2002 which was very dry. The monthly naturalized flow is the sum of the human water withdrawals and the observed discharge shown in Figure 10. It can be seen that in terms of water withdrawals, the agricultural sector is the dominant sector from June to October, while the industrial and domestic sectors are the dominant sectors from November to May. The naturalized flow also has seasonal changes during the year, with wet season from June to October, and its average flow range is between 1000 and 2500 m^3/s. The monthly maximum flow in wet years can even reach 3500 m^3/s, and the flow in the dry season is mostly less than 500 m^3/s.

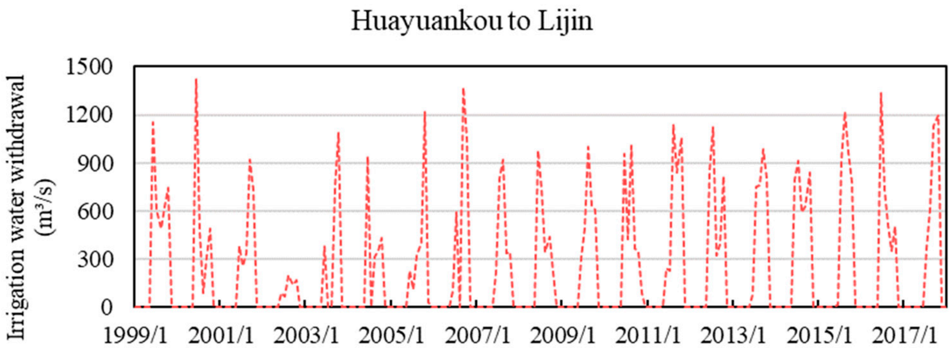


Figure 9. Monthly irrigation withdrawal from Huayuankou to Lijin station.

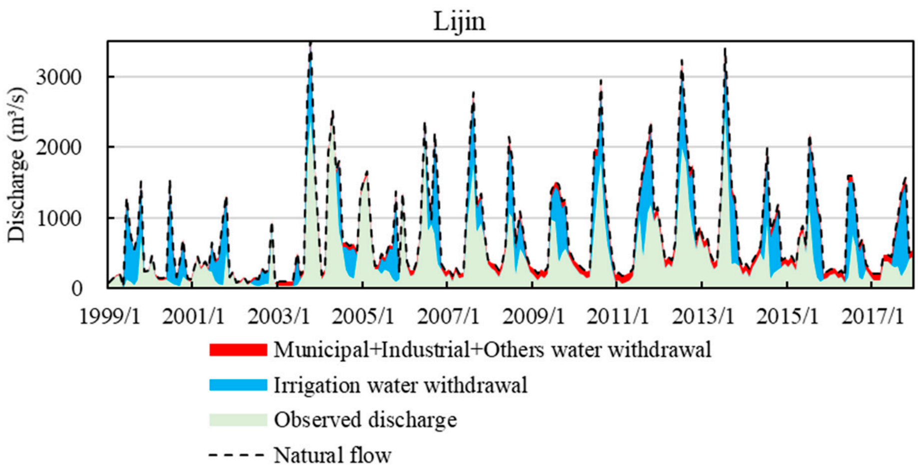


Figure 10. Monthly naturalized flow at Lijin station.

The environmental base flow and available water resources that can be allocated are shown in Figures 11 and 12. The monthly environmental flow at Lijin station is unevenly distributed during the year, the peaks of the environmental base flow occur from June to July and September to October, with the flows exceeding 300 m^3/s, while the flows in the remaining months are approximately stable between 100–200 m^3/s. The total amount of environmental base flow is about 7.50 billion m^3 a year. Furthermore, the available water resources that can be used for the allocation of five human water sectors are obtained based on the total water resources of Yellow River minus the annual environmental base flow in lower reaches illustrated in Figure 12, with the average volume approximately 51.5 billion m^3 a year from 2005 to 2017.

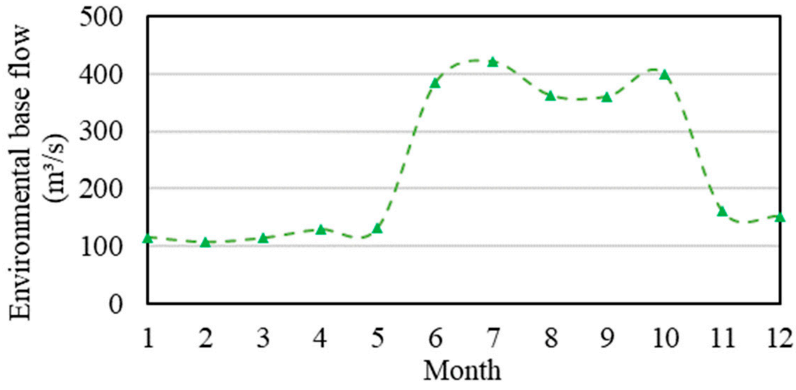


Figure 11. Monthly environmental base flow.

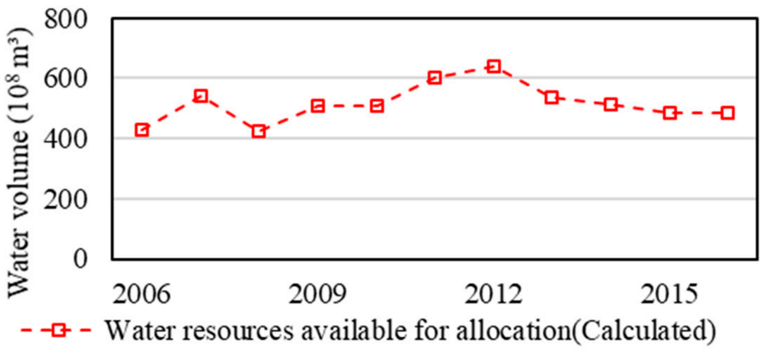


Figure 12. Available water allocation resources.

4.3. Water Allocation between Five Water Sectors

The bargaining weights under symmetric and asymmetric bargaining solution are shown in Figure 13. The results under asymmetric which considered the different importance of water sectors are based on the principles of equity and efficiency. The asymmetric weight of agricultural sector is 0.55 bigger than that of symmetric bargaining weight, while for industrial, public, domestic, and ecological water sectors, it is 0.16, 0.07, 0.13, and 0.09, respectively. Therefore, emphases should be placed on allocating water to the agricultural, industrial, and domestic sectors on the basis of achieving the maximization of economic benefits.

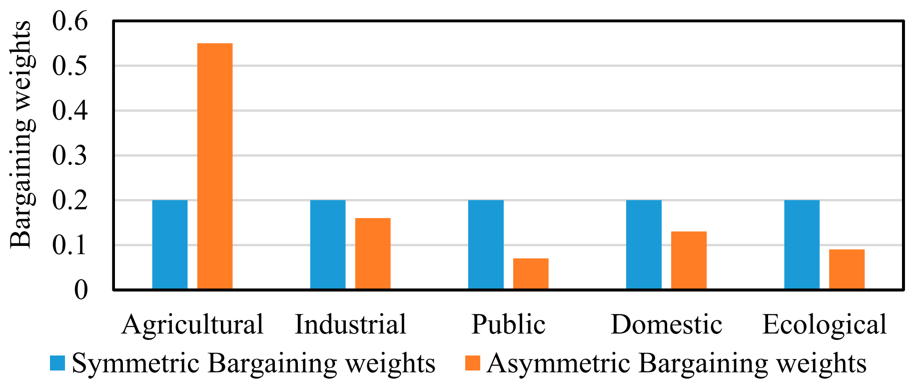


Figure 13. Bargaining weights of five water use sectors.

Figure 14 shows the results of the optimal water allocation in 2016 under symmetric and asymmetric Nash–Harsanyi bargaining game model. The change of the result of asymmetric bargaining solution relative to the result of symmetric bargaining (green bars) are assessed in detail. Water withdrawals in statistics can be regarded as the reference amount of the actual allocation value in 2016. Figure 15 shows the water shortage between the allocation results under symmetric/asymmetric Nash–Harsanyi bargaining game model and actual water allocation in 2016. A positive value indicates the water shortage between the allocated results and the actual water allocation, while the negative values indicate that the amount of allocated water should be saved compared with the actual water allocation. As a matter of fact, the results under symmetric bargaining solution depend entirely on the maximization of economic values of agricultural, industrial, public, domestic, and urban ecological water sectors. Specifically, since the economic value produced by unit agricultural water is the smallest in contrast with other sectors, the agricultural sector obtained less water compared to its demand under the goal of maximizing total economic benefits of five sectors, while the domestic, public, and urban ecological sectors with higher value of unit water can get more water.

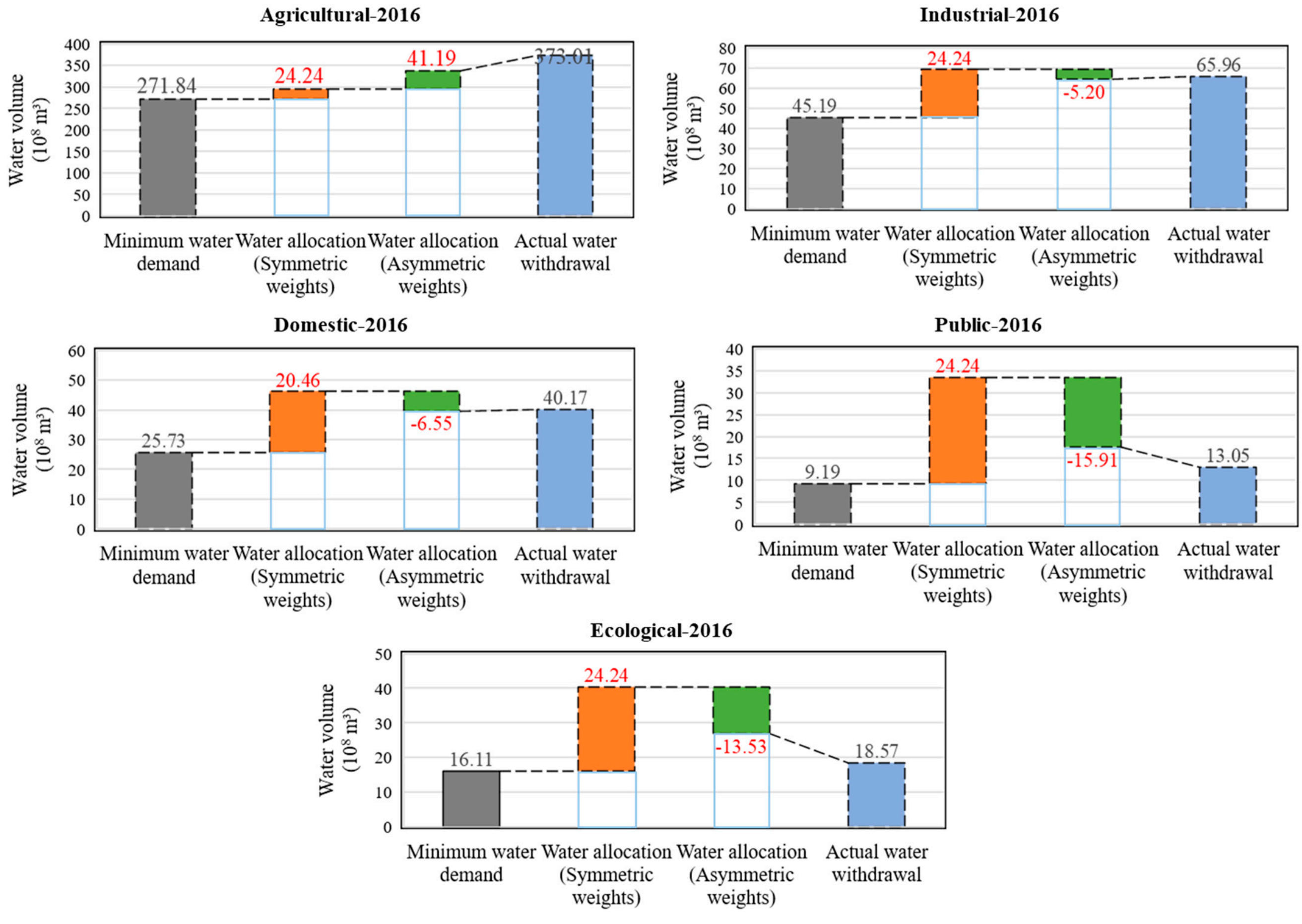


Figure 14. Results of water allocation in 2016 (symmetric and asymmetric).

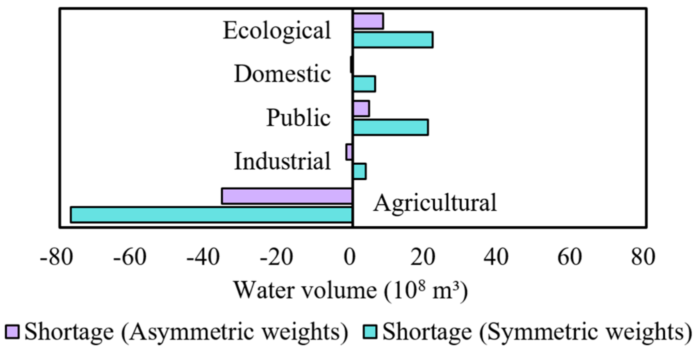


Figure 15. Water shortage between the allocated results and the actual allocation in 2016.

However, for the asymmetric bargaining solution, it also considers the different importance among water sectors based on the principles of equity and efficiency, which makes the allocation results more reasonable. It can be found that compared with the allocation under symmetric bargaining solution, the amount of water allocated to agriculture under asymmetric bargaining solution increased by 4.20 billion m^3 a year and the allocation value is 33.7 billion m^3 in 2016. This is because the asymmetric bargaining weight of the agricultural sector is 0.35 larger than the weight under the symmetric model. The allocation results of industrial, domestic, public, and urban ecological sector under asymmetric bargaining model decreased by 0.52, 0.65, 1.59, and 1.35 billion m^3 compared with those under the symmetric model, with the values of 6.42, 3.96, 1.75, and 2.68 billion m^3 in 2016, respectively. Besides, Figure 15 donates that under symmetric and asymmetric Nash–Harsanyi bargaining game model, the agricultural sector should save 7.70 and 3.70 billion m^3 compared with actual water allocation, respectively. It indicates that the agricultural sector should further improve irrigation efficiency to save water so that more water can be allocated to other sectors, thereby creating higher economic value for the entire society. The actual water allocation of the public and urban ecological sector is lower than that of the results of optimal water allocation under asymmetric Nash–Harsanyi bargaining game model, which means that water resources distributed to these two sectors were insufficient as shown in Figure 15.

It is recognized that the relationship between economy and environment should be managed well in the development of society to realize the coordinated development of economy and environment. Protecting the natural ecosystem of rivers should be the foundation for fulfilling various human needs for water supplies. Therefore, this study took both different human needs for water resources and environmental flow requirements of river into account when assessing the optimal water allocation. As the results showed, at least an average of 7.50 billion m^3 of water should be maintained in the river channel every year to sustain the balance and health of the river's ecosystem, and how the remaining water resources should be allocated to different water sectors are shown in Figure 14. Besides, Figure 16 also shows the amount of water that will be allocated to each sector if the environmental base flow is not considered. It can be found that the allocation results among agricultural, industrial, domestic, public, and urban ecological water sectors are 38.6, 7.65, 4.57, 2.09, and 3.17 billion m^3, respectively. Compare the allocation of water including environmental base flow, most of the water is allocated to the agricultural sector, which is 4.82 billion m^3 a year, and the water allocation for other sectors is also relatively increased. Among them, the second largest increase is in the industrial sector, being 1.23 billion m^3. Moreover, the increases in domestic, public, and urban ecological sectors are 0.61, 0.34, and 0.51 billion m^3, respectively.

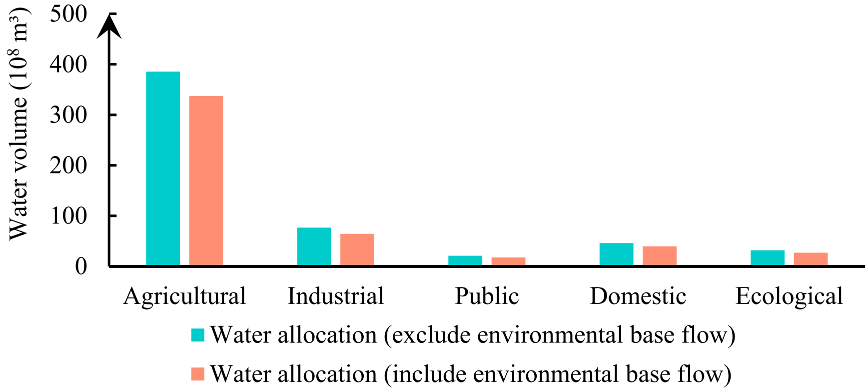


Figure 16. Comparison of water allocation with or without environmental base flow.

5. Conclusions

Effective and scientific water allocation among various sectors of human water usage as well as a river's ecological environment is of great importance for promoting the growth of human society and preserving the ecological health of large rivers. River managers need to pay attention to the economic development and ecological balance at the same time when formulating water allocation policies. Therefore, both the water allocation to the river's environmental system and different human needs are considered in this study. The evaluation of the economic value of various water uses can provide a basis for the allocation of limited water supplies. Moreover, the importance of different water sectors should be considered in combination with the principle of equity and efficiency when performing water resource management and allocation. On the basis of maintaining the environmental base flow of the river, the cooperation game can help different players maximize additional benefits, thereby facilitating the growth of the entire river basin. Accordingly, this study established a comprehensive economic evaluation framework to determine the economic benefits produced by agricultural, industrial, domestic, public, and urban ecological water sectors. The monthly naturalized flow and environmental base flow of the lower Yellow River were then assessed by integrating the H08 model's monthly patterns of agricultural water withdrawal. An asymmetric Nash–Harsanyi bargaining game model was developed to implement water allocation among five water sectors in Yellow River basin based on the economic benefits under the constraints of environmental flow requirements.

In regard to the economic benefits of water uses in five sectors, due to the large amount of water use but low crop income, the economic benefit per unit of agricultural water use is the lowest, with the value being 3.95 CNY/m^3 in 2016. Although the industrial output value is high, the contribution of water to industrial production is relatively small, and the economic value is 45.1 CNY/m^3 in 2016. As for the domestic sector, the average economic value is up to 200 CNY/m^3 in 2016 since domestic water is an indispensable necessity for human life. Regarding the public sector, water withdrawal is mainly used in the service industry and construction industry, and the output value is higher than that of agriculture and industry sectors, hence the marginal value of public water is higher than that of two sectors which is equivalent to 94.4 CNY/m^3. Besides, the evaluated economic value for urban ecological water use is 23.7 CNY/m^3.

With respect to the environmental flow of a river's ecosystem, the amount of annual environmental base flow is 7.50 billion m^3 in the downstream of Yellow River. Furthermore, the average available water resources that can be allocated to human uses were 56.0 billion m^3 in 2016. This study addresses both the water allocation scheme under the symmetric and asymmetric Nash–Harsanyi bargaining game model for five water sectors. The asymmetric bargaining game solution not only aims at optimizing economic benefits, but also considers the importance of different sectors compared to symmetric bargaining game, as the bargaining weight of agricultural sector is 0.55 which is much higher than that of under symmetric bargaining solution. The optimal water allocation results in 2016 among agricultural, industrial, domestic, public, and urban ecological water sectors are 33.7, 6.42, 3.96, 1.75, and 2.68 billion m^3, respectively. Compared with the actual water allocation of five sectors, the optimal allocation of industrial and domestic sector is similar with the actual allocation, and the agricultural sector should save 3.7 billion m^3 water and further allocate to public and urban ecological water sectors to maximize the total benefit of water use in the basin. Specifically, river basin management agencies should encourage the application of agricultural water-saving technologies, and provide more water-saving subsidies and technical support. Moreover, the additional public and ecological benefits generated by the saved water can be used as a source of investment in water-saving technologies for the agricultural sector, thereby forming a virtuous circle of economic benefits among different sectors. At the same time, they should actively cooperate with provincial-level administrative units to improve the irrigation water quota system based on the existing basis as well as the water price rules for encouraging farmers to actively achieve water-saving goals. In addition, it is necessary to strengthen the supervision and measurement of water withdrawal in the whole basin to realize the designed targets of water use.

As the demand for water resources in the provinces along the Yellow River continues to grow in the future, the allocation of water resources will face new challenges. The existing water allocation plan only considers the allocation of surface water, while the joint dispatch of surface water and groundwater needs more attention. The developed model can be used as a tool to analyze different scenarios for further analysis and the model results can assist policy-makers in proposing improved water allocation policies and plans as well as increase economic efficiency of water use in the basin. Besides, the government emphasizes the construction of ecological environment, and the existing water allocation plans need to be improved to meet the future needs both for human use and the river's ecological environment. However, the current unified management and regulation of the Yellow River basin's water resources is still mainly based on administrative means, while legal means, economic means, and scientific and technological means are obviously lagging, and more support from policies and laws is needed. Based on the environmental base flow of this study, sensitivity analysis of environmental flow requirements can be further carried out to discuss the water allocation between different sectors under the circumstances of environmental flow changes, as well as provide reference and basis for policy-makers.

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Conflicts of Interest: The authors declare no conflict of interest.

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