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Ecological Compensation Standard of a Water-Receiving Area in an Inter-Basin Water Diversion Based on Ecosystem Service Value and Public Willingness: A Case Study of Beijing

Zhuoyue Peng *, Hao Wu, Maohua Ding , Min Li, Xi Huang, Rui Zheng and Lin Xu

College of Hydraulic Science and Engineering, Yangzhou University, Yangzhou 225009, China; wu_hao@yzu.edu.cn (H.W.); jiaotongdmh@sina.com (M.D.); limintju@126.com (M.L.); huangxi618@sina.com (X.H.); zhengrui199912@163.com (R.Z.); xl15885150493@sina.com (L.X.)

* Correspondence: pengzhuoyue123@sina.com; Tel.: +86-178-5197-5816

Abstract: Ecological compensation has recently gained significant attention as an economic incentive promoting natural resource management. However, there remain several challenges to its application. A key issue is the lack of a method clearly define the standard of ecological compensation. This study established an accounting methodology for the ecological compensation standard for the water-receiving area in an inter-basin water diversion in China. Beijing, a major water-receiving area of the South-to-North Water Diversion Project, was used as an example of the application of this approach. First, the evaluation index of ecosystem service value of the water-receiving area was selected, then, emergy theory was used to calculate the increment of ecological service value based on the characteristics of each indicator. The ecological service value due to the project was calculated to be 3.898 billion RMB, while the willingness-to-pay by the public was estimated at 915 million RMB. Therefore, the increment of ecological service value was the highest standard of compensation, and the public's willingness-to-pay was the lower limit of ecological compensation. The final compensation standard can be determined through negotiation between suppliers and beneficiaries under the leadership of relevant governments and water-transfer authorities. Thus, this study aimed to provide a scientific basis for the construction of diversified ecological compensation mechanisms and promote sustainable development of the region.

Keywords: ecological compensation; ecological compensation standard; ecosystem service value; willingness to pay; emergy theory; south-to-north water diversion project



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1. Introduction

During rapid development of the global economy, the disequilibrium between the population, economy, resources and the environment is very severe. In the management of inter-basin water transfers, the utilization and protection of water resources remain poorly coordinated. Because economic and social welfare of water-receiving areas continue to develop, [1], and the development of the water-transfer areas is restricted due to ecological protection, social harmony and public security are threatened. The implementation of inter-basin ecological compensation is an effective means to solve these problems [2]. Due to the need for coordinated development of the ecology and social economy in water-receiving areas, it is particularly important to establish an ecological compensation mechanism in the water-receiving area of an inter-basin water-transfer diversion.

Ecological compensation can be implemented to meet both economic and environmental objectives and demands. The basic concept is that the beneficiaries of ecological services should compensate the providers, to regulate the relationship between social development and ecological protection through economic means. This could enable ecological protection and restoration to form a virtuous circle [3–5]. Despite significant achievements in ecological compensation, some deficiencies remain in design and implementation, wherein the key

issue is the compensation standard [6]. The quantification of the ecological compensation standard is crucial for the establishment of a mechanism for ecological compensation, which is not only directly related to the feasibility and effects of ecological compensation, but also provide a reference for governments to conduct negotiations in market transactions.

At present, the standard of ecological compensation is mainly determined by three considerations. First, the ecosystem service value of the water-receiving area, generated by the ecosystem and provided to the beneficiaries. Second, the cost that ecological beneficiaries are willing to pay, and finally, the direct investment and opportunity cost of the water-transfer areas. Since the compensation costs of water-transfer areas should be borne by multiple water-receiving areas, the determination of ecological compensation standards for water-receiving areas mainly considers the ecosystem service value of water-receiving areas and the willingness-to-pay of ecological beneficiaries.

The valuation methods of ecosystem services mainly include the following three approaches: (1) socio-economic value assessment: The market-value method was used to calculate the value of ecological services provided by the upstream region of the basin to the downstream region [7]. The basis of this method is a well-developed and standardized natural resource market. However, the water resource market in China remains poorly developed, and therefore the market price method cannot be effectively applied. Other methods include opportunity cost methods [8], water supply input accounting methods [6], computable general equilibrium models [9], among others. As these assessment methods are traditional economic methods, they do not consider the ecological background of value generation and therefore are not applicable to ecological economic problems. (2) Emergy theory: The emergence of emergy theory enabled researchers to quantitatively evaluate the ecological environment within a unified measurement standard. Emergy theory provides the link between ecology and economics by synthesizing energy flow, material flow, monetary flow and their interconversions [10]. Emergy theory has been widely used in analyses of watershed environmental resources, environmental policies, environmental management, and development models [11,12]. (3) Other methods: Assessments of ecological footprints provide a clear accounting of the excessive consumption of capital and the relative pressures on a country's, or region's, carrying capacity [13]. However, the calculation parameters of ecological footprint model are not sufficiently flexible. Most directly refer to the results of classical studies, which cannot reflect the particularity of a study area. Furthermore, such models overly emphasize the productivity and quantity of land and give insufficient attention to the function and quality of water resources [14]. In China, the compensation standard of Xin'an River, Poyang Lake and Taihu Lake were calculated using the water quality method, with models based on water quality and quantity of transboundary sections reflecting the property rights of water resources. However, most studies focus on the compensation of external benefits (losses) brought by one aspect of water quantity or water quality, failing to take water quality and quantity sufficiently into account, and failing to reflect the influence of human activities and natural factors on water resources of transboundary sections [15]. Ecosystem service value assessment is an important reference for the formulation of ecological compensation standards in water-receiving areas [16]. Some researchers and research institutions believe that it is the highest standard of ecological compensation, but this method of calculation does not incorporate the willingness to pay (WTP) of the recipients. Consequently, the research results are unable to guide policy making because they are far beyond the ability and willingness of the beneficiaries to pay the compensation.

WTP is the amount of economic compensation that a water-receiving area is willing to pay for the services provided by a water-transfer project, which is closely related to the social characteristics of stakeholders in the water-receiving area, their understanding of the project, and their personal income level. Kerr [17] believed that the WTP of ecological service users for watershed ecological compensation was an important theoretical basis for establishing social and economic links between the upper and lower reaches of the watershed. Hecken et al. [18] investigated the WTP of the downstream residents in Matiguás

area of Nicaragua for obtaining clean water and found that the downstream residents had a higher WTP than upstream.

In recent years, China's ecological compensation policy for inter-basin water diversion projects has primarily relied on the limited transfer payment from the government, rather than compensation between water-receiving and water-transfer areas. For example, the city of Zhangzhou calculated the compensation standard according to revenue and water consumption, through the county government in the lower reaches of the river basin, and municipal financial support. In the Beijing-Hebei region, the project of "returning rice to drought," a subsidy given by the municipal government to farmers to obtain water, reflected the value of water resources and the willingness of farmers to be compensated. However, the evaluation of water resources in this project was inadequate, and only unified standards were used to subsidize farmers, leading to insufficient evaluation of the water-transfer price and low satisfaction of farmers. This causes the water-transfer areas to incur a high cost for protecting water resources, which seriously affects the progress and sustainability of local economic development.

In this study, we developed an ecological compensation standard model by establishing an accounting framework and methodology. The main contributions of this work can be summarized as follows:

1. The flow of water resources from the water-transfer area to the water-receiving area has resulted in an increase of ecosystem service value. The evaluation index of ecosystem service value of the water-receiving area was determined by comprehensively considering the local characteristics, engineering characteristics, socio-economic development, natural environmental conditions, and other factors, of the study area, and combining these with expert opinions. Emergy theory was then used to calculate the increment of ecosystem service value in the water-receiving area.
2. The WTP of the public in Beijing was obtained by the contingent valuation method (CVM), taking into account the economic affordability of the public of the water-receiving area (i.e., Beijing).
3. The ecological compensation standard can be decided based on the increment of ecosystem service value of the water-receiving area and public payment after consultation between the ecological function providers and beneficiaries under the leadership of the relevant government and management authority.

In this paper, the emergy theory, used to evaluate the increment of ecosystem service value in the water-receiving area, is presented. The CVM was adopted in this study to obtain the WTP of the public in water-receiving areas, taking into account the economic affordability of the public of the water-receiving area (i.e., Beijing). The ecological compensation standard was then obtained, based on the value of the ecosystem service value and public-WTP. Last, suggestions for further improvement are provided.

2. Materials and Methods

2.1. Study Area

The South-to-North Water Diversion Project (SNWDP) in China is the largest and longest water-transfer project in the world. The middle route of the SNWDP, with a total length of 1277 km, primarily mitigates water shortage in more than 20 large and medium-sized cities along the route, including Beijing, Tianjin, Shijiazhuang, and Zhengzhou (Figure 1). Beijing is not only the political and cultural center of China, but also a famous ancient capital and a modern international metropolis, with a total area of 16,700 km². In the past, water availability was a restrictive factor affecting the economic development and environmental conditions of Beijing [19,20]. Before water from the SNWDP was diverted to Beijing, the city relied on excessively exploited underground water sources [21]. Over the past six years, Beijing has cumulatively received over 6 billion m³ of water, benefiting 13 million residents. The water-receiving area has clean water resources and generates large socio-economic benefits. Therefore, there is an urgent requirement to clearly define

the ecological compensation standard, promote the horizontal compensation relationship between the demand and transfer areas, and promote sustainable development.



Figure 1. Middle Route of the south-to-north water diversion project.

2.2. Emergy Analysis

The increment of ecosystem service value of the water-receiving area refers to the increasing amount of ecological and environmental functions generated by the ecosystem on the basis of the original functions after the water diversion. We explored the composition of the ecological and environmental value of the water diversion project and applied a quantitative calculation to each sub-value based on emergy theory [22,23]. The basis for calculating the emergy value of the ecosystem is the emergy system diagram (Figure 2), which schematically represents the energy flow, transformation, and interactive relationships of water resource systems in water-transfer projects. The emergy transformity is the key factor in emergy value analysis, which provides data required for accurate calculation of the emergy value. Furthermore, the Emdollar ratio relates the ecological and environmental settings to social economy, transforming natural resources into the monetary value of social and economic systems, and helps achieve specific and easily-understood results.

2.2.1. Emergy Diagram

The value of ecosystem services was obtained from the perspective of ecological economics and emergy theory [22] was used to calculate the value of each ecosystem service index. The water resources system of the water diversion project is a part of the natural–artificial composite water circulation system. The emergy system diagram of the receiving area of the water-transfer project is shown in Figure 2, indicating the relationship between the main energy supply, material input, and output of the water-receiving project, representing the process of various energy flows, transformations, and storage. We used the Delphi method to select the ecosystem service indices that indicated the increment of ecosystem service value in Beijing due to the SNWDP, using the characteristics of the research area and the structure of the ecological and environmental setting of the receiving

areas. According to the characteristics of each index, the energy/monetary value of each index was calculated.

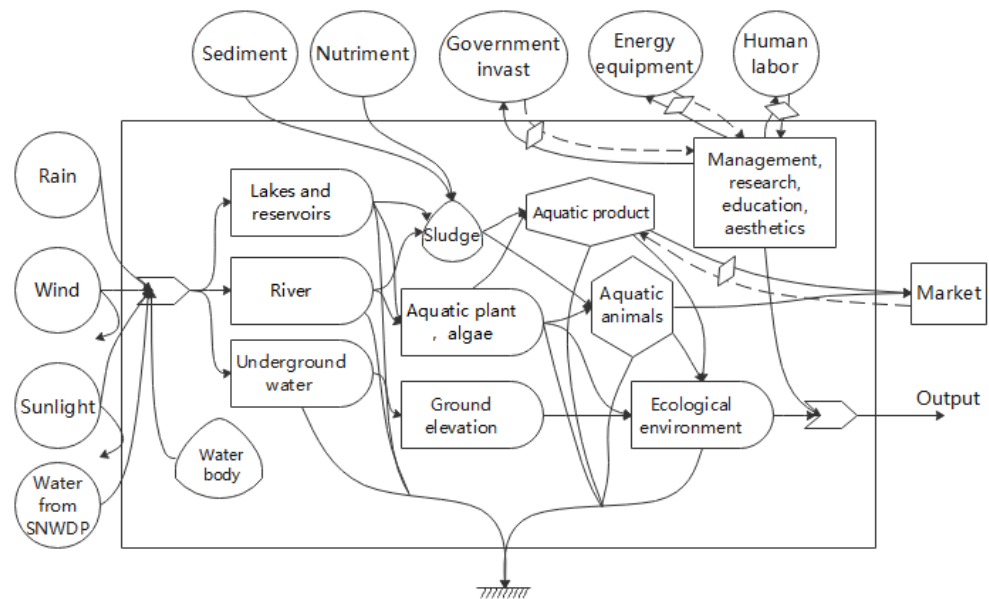


Figure 2. System diagram of the energy flows of water-receiving area.

2.2.2. Emdollar Ratio

We obtained Beijing’s ecological economic energy table using the “Beijing Statistical Yearbook”, “Beijing Water and Soil Conservation Bulletin,” and other relevant data. The total energy of Beijing City in 2015 was 9.77×10^{23} sej (Table 1), including the energy of renewable resources, non-renewable resources, and imports. The 2015 gross domestic product (GDP) of Beijing was RMB 2301.46 billion and therefore the conversion ratio of USD/RMB in 2015 was 6.39. Consequently, the Emdollar ratio of Beijing in 2015 was 2.71×10^{12} sej/\$.

Table 1. Energy synthesis table of resource and economic flows of Beijing in 2015.

Type	Item	Raw Data	Solar Transformity (sej/J or sej/g or sej/\$)	Solar Energy (sej)
Renewable Resources	Sunlight (J)	6.91×10^{19}	1	6.91×10^{19}
	Wind (J)	4.86×10^{16}	2450	1.19×10^{20}
	Rain, geopotential (J)	6.55×10^{14}	47,000	3.08×10^{19}
	Rain, chemical (J)	2.97×10^{16}	30,500	9.06×10^{20}
	Earth cycle (J)	3.12×10^{16}	5.80×10^4	1.81×10^{21}
Non-renewable Resources	Water from SNWDP (m ³)	7.55×10^8	8.50×10^{11}	6.42×10^{20}
	Coal (J)	2.68×10^{17}	6.69×10^4	1.79×10^{22}
	Soil losses (g)	3.19×10^{12}	1.71×10^9	5.45×10^{21}
Imports	Goods (\$)	5.47×10^{10}	6.92×10^{12}	3.79×10^{23}
	Services (\$)	8.12×10^{10}	5.85×10^{12}	4.75×10^{23}
	Energy sources (J)	9.00×10^{17}	8.81×10^4	7.93×10^{22}
Summary	Tourism (\$)	4.61×10^9	3.80×10^{12}	1.75×10^{22}
				9.77×10^{23}

Notes: Solar transformity refers to Handbook of emergy evaluation, Folio #1 [22]; Handbook of emergy evaluation, Folio #2 [23]; Environmental accounting: emergy and environmental decision making, Emery analysis of Chinese society 1980–2005, systems ecology reports [24]. Imported goods include food, pulp, synthetic rubber, cotton, clothing, machinery, and parts for construction and mining, motors and generators, and electrical circuits. Imported energy sources include minerals and fuel oil. Tourism primarily refers to international tourism.

2.2.3. Emergy Assessment of Each Index

Water Supply

Water supply is the primary function of water resources, as they provide local, domestic, and industrial water. Its emergy can be calculated as:

$$E_{Mw} = Q_W T_W \quad (1)$$

where E_{Mw} is the emergy of water supply, Q_W is the total volume of water supply, and T_W is the emergy transformity of surface water.

In 2015, the SNWDP provided 686 million m^3 of water to domestic industry, and the emergy transformity of surface water was 8.50×10^{11} sej/ m^3 [22]; the resulting emergy of water supply was 5.83×10^{20} sej.

Water Regulation and Storage

Reservoirs and groundwater storage can regulate water volume and store water resources, which play a vital role in maintaining the structure, function, and ecological processes of water ecosystems. The emergy of water resource regulation and storage was calculated from:

$$E_{Ms} = Q_s T_n \quad (2)$$

where E_{Ms} is the emergy of water resource regulation and storage, Q_s is the total amount of water resource regulation and storage, and T_n is the emergy transformity of storage water.

In 2015, the natural water supply of Beijing central city was 0.7 billion m^3 . Because of the SNWDP, groundwater reserves increased by 202 million m^3 , and the emergy transformity of storage water was 1.64×10^{11} sej/ m^3 [22], equivalent to 4.46×10^{19} sej.

Net Primary Productivity and Biomass

All of the different areas within the water-receiving region need to be classified and analyzed. The emergy of net primary productivity and biomass was calculated from:

$$E_{Mp} = Q_p T_t \quad (3)$$

where E_{Mp} is the emergy of net primary productivity and biomass, Q_p is the total amount of net primary productivity and biomass, and T_t is the emergy transformity of net primary productivity and biomass.

The emergy transformity of net primary productivity is 5.78×10^7 sej/g, and the emergy transformity of biomass is 5.11×10^6 sej/g [25]. The average net primary productivity of lakes and rivers is 500 g/ m^2 /a and the biomass is 10^3 g/ m^2 [26]. The water surface area considered here was the increased water surface area in Beijing due to the SNWDP, including Daning storage reservoir, TuanCheng lake basin, and TuanCheng open channel. The water area calculated using the relevant data and Google Earth was 1.77 km^2 . Data from the Miyun Reservoir Management Office showed that the water area of Miyun Reservoir expanded from 74 km^2 before the SNWDP to 114 km^2 , with an added water area of 41.77 km^2 . The emergy of net primary productivity increased by 1.21×10^{18} sej, while the emergy of biomass increased by 2.14×10^{17} sej.

Prevention of Land Subsidence

Land subsidence refers to the reduction of ground elevation due to the combined action of natural and manmade factors. It is characterized as a slow and delayed reaction, and the rate of subsidence is measured in millimeters. These slow and degenerative geological disasters have a long formation cycle, generate a wide range of impacts, and are not easily detected; they are also not easily recoverable. Moreover, several factors affect land subsidence, but the overexploitation of groundwater is a primary cause in northern China. Thus, excessive exploitation of groundwater has resulted in land subsidence in numerous large and medium-sized cities, including Beijing, Shanghai, and Tianjin. If existing reserves

of groundwater undergo further exploitation, multiple economic losses may occur due to land subsidence, and the sum of these losses can be regarded as the indirect economic value of groundwater to prevent land subsidence. The emergy of preventing land subsidence can be calculated from:

$$E_{Mg} = Q_g T_g \quad (4)$$

where E_{Mg} is the emergy of preventing land subsidence, Q_g is the increased groundwater reserves, and T_g is the emergy transformity of underground water.

Land subsidence surveys and monitoring data of the North China Plain in 2010, estimated that the direct losses caused by land subsidence in Beijing amounted to 4.4794 billion RMB, the indirect losses accounted for 3.975 billion RMB, generating a total economic loss 8.4544 billion RMB. The multi-year storage variable of groundwater was estimated to be 7.766 billion tonnes. Due to the south-to-north water diversion, groundwater reserves increased by 432 million m^3 and the emergy transformity of underground water is 3.38×10^{11} sej/ m^3 [27]; therefore, the emergy was 1.46×10^{20} sej.

Biodiversity

Biodiversity value refers to the value of maintaining the stability of the number and composition of species and providing biological carriers for material circulation and energy flow in the system [28]. The emergy of maintaining biodiversity can be calculated from the following:

$$E_{Mb} = Q_b T_b \quad (5)$$

where E_{Mb} is the emergy of maintaining biodiversity, Q_b is the number of biological species in the study area, and T_b is the emergy transformity of biological species.

Wetlands provide an environment for the breeding and growth of fish, aquatic plants, waterfowl, and other animals and plants, which is conducive to the protection and support of biodiversity and represents the biodiversity value of the SNWDP in Beijing. According to the average solar emergy of each species (1.26×10^{25} sej/species) [29], the emergy was calculated by multiplying the average solar emergy of each species with the proportion of the study area expressed as a fraction of the surface area of the Earth (5.21×10^8 km^2).

A total of 49 species of fish, comprising economic fish, including grass carp, silver carp, *Bighthys nobilis*, rainbow trout, male gurnard, and megalobrala, and 43 species of native wild fish belonging to 6 orders, 12 families, and 36 genera, were identified in natural and semi-natural water bodies in Beijing [30].

12 kinds of aquatic plants (including floating, emergent and submerged plants) were identified in the Miyun Reservoir [31] and 15 species of benthic fauna were also identified in Miyun Reservoir, including 7 families and 71 genera of phytoplankton and 71 species of zooplankton [32].

91 species of birds, including seven species under first-class national protection (for example, golden eagles and the IUCN endangered species of white crane), and multiple national level 2 protected animals, including green-winged teal, and white-tailed eagle, have been identified in the Miyun Reservoir through field surveys.

In summary, there are approximately 309 species, and the calculated emergy of maintaining the biodiversity was 3.12×10^{20} sej (Table 2).

Ecological Replenishment of River Water

Artificial water replenishment in lakes and wetlands through water diversion and other engineering measures can dilute and purify water to improve the environment. The emergy of river ecological replenishment (E_{Mr}) can be calculated as the product of the volume of artificial water replenishment and the emergy transformity:

$$E_{Mr} = Q_r T_r \quad (6)$$

where E_{Mr} is the emergy of river ecological replenishment, Q_r is the volume of artificial water replenishment, and T_r is the emergy transformity of water replenishment.

Table 2. Emergy value of maintaining biodiversity.

Category	Species	Emergy Transformity (sej/Species)	Emergy (sej)
Fish	49	1.26×10^{25}	4.95×10^{19}
Aquatic plants	12	1.26×10^{25}	1.21×10^{19}
Phytoplankton	71	1.26×10^{25}	7.17×10^{19}
Zooplankton	71	1.26×10^{25}	7.17×10^{19}
Benthic animals	15	1.26×10^{25}	1.52×10^{19}
Birds	91	1.26×10^{25}	9.19×10^{19}
Sum	309		3.12×10^{20}

The emergy transformity was determined according to the source of water replenishment. If water replenishment occurred from surface water, the emergy transformity of surface water was used; if water replenishment was from reclaimed water, the emergy transformity of reclaimed water was used.

The water from the SNWDP replenished 225 million m³ of urban rivers and lakes, including Lugou Xiaoyue Lake and Garden Expo Park, restoring the beauty of Lugou Xiaoyue. The surplus water of Miyun Reservoir was approximately 170–320 million m³ for ecological replenishment of the North Canal and Chaobai River. For the calculation, 250 million m³ was taken as the ecological water replenishment, and the surface emergy transformity was 8.50×10^{11} sej/m³, and the emergy of ecological replenishment was 2.13×10^{20} sej.

Climate Regulation

The value of climate regulation primarily refers to the influence of atmospheric humidity and temperature on water surface evaporation. The emergy of climate regulation was calculated from the following:

$$E_{Mt} = Q_t T_t \quad (7)$$

where E_{Mt} is the emergy of climate regulation, Q_t is the heat absorbed by evaporation from the water surface, and T_t is the emergy transformity of water vapor. Table 3 presents the partial emergy transformity of surface water vapor based on altitude.

Table 3. Emergy transformity of surface water vapor at specific elevations.

Elevation (m)	Emergy Transformity (sej/J)
0	12.2
990	21.4
1950	25.1
3010	42.7
4200	113.0
5570	176.0

Average annual evaporation from Beijing is 1100 mm. Based on the calculation of net primary productivity in Section 3, the increase in water surface area arising from the water diversion project was 41.77 km², and the amount of evaporated water was 4.59×10^7 m³. The heat of vaporization of water at 100 °C and one standard atmospheric pressure was 2260 KJ/kg. Therefore, the heat absorbed was 1.04×10^{14} KJ.

Because the altitude of the plain in Beijing is 20–60 m and that of the mountain is 1000–1500 m, the average altitude is 43.7 m and the emergy transformity at 43.7 m is 12.20 sej/J. Thus, the emergy of climate regulation was 1.27×10^{18} sej.

Water Purification

Through a series of biochemical and physical processes, including filtration, dilution, diffusion, adsorption, oxidation, and decomposition, water bodies can effectively degrade and remove the waste discharged by humans to the natural environment. Assuming the water pollutant content in the upstream section as M_1 (g/m³ or mg/L), and that in the downstream section as M_2 (g/m³ or mg/L), the difference between the upstream and downstream can be regarded as the purification effect of a water body on pollutants. The energy consumed by pollutants in water purification is equal to the difference between the energy of the upper and lower water bodies, which is defined as the energy of water purification (E_{Mj}), calculated using the following:

$$E_{Mj} = E_{M1} - E_{M2} = M_1 \tau_1 - M_2 \tau_2 \quad (8)$$

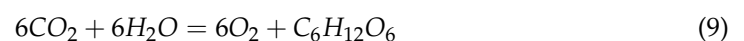
where M_1 and M_2 are the contents of pollutants in the upper and lower water bodies, respectively; τ_1 and τ_2 are the energy transformities of pollutants in the upper and lower water bodies, respectively; and E_{M1} and E_{M2} are the energy of the upper and lower water bodies, respectively. The water from the SNWDP in Beijing is a high-quality water source. After entering the water bodies of rivers and lakes in Beijing, the self-purification capacity and environmental quality of the rivers and lakes are significantly improved. Due to limited data, Daning Reservoir was selected for this calculation. Gao [33] showed that the Daning Reservoir had the highest annual average NH₃-N content in the upstream section (0.13 mg/L), while the annual average NH₃-N content in the downstream section was comparatively low (0.10 mg/L), and the NH₃-N removal rate was 23%. Nitrification of NH₃-N content occurred, as indicated by the water quality index in the water transfer. The annual average total nitrogen (TN) content of the upstream section was 1.92 mg/L, and the annual average TN content of the downstream section was 0.95 mg/L. The hardness of tap water decreased from 380 mg/L to 120–130 mg/L, and the energy of water purification was 2.74×10^{20} sej (Table 4).

Table 4. Energy values for water purification.

Parameter	Difference (mg/L)	Energy Transformity (sej/g)	Energy Value (sej)
NH ₃ -N	0.03	2.80×10^9	8.90×10^{16}
TN	0.97	3.80×10^9	3.91×10^{18}
Hardness	255	1.00×10^9	2.70×10^{20}
Sum			2.74×10^{20}

Carbon Fixation and Oxygen Release

Aquatic plants absorb CO₂ from the atmosphere through photosynthesis and release O₂, and their tissues can store organic materials produced by photosynthesis. A large amount of carbon is stored when soil organic matter accumulated in peat bogs, influencing carbon fixation and storage. Therefore, the water ecosystem can significantly buffer the increase in CO₂ concentration. Photosynthesis can be summarized as follows:



Thus, the energy is calculated as follows:

$$E_{M_{CO_2}} = Q_{CO_2} T_{CO_2} \quad (10)$$

$$E_{M_{O_2}} = Q_{O_2} T_{O_2} \quad (11)$$

where $E_{M_{CO_2}}$ and $E_{M_{O_2}}$ are the energy of carbon fixation and oxygen release, respectively; Q_{CO_2} and Q_{O_2} are the amounts of CO₂ and O₂ respectively; and T_{CO_2} and T_{O_2} are the energy transformities of CO₂ and O₂, respectively.

From the photosynthesis of plants given by Equation (9), it is known that plants can fix 1.47 g CO₂ and release 1.06 g O₂ for every 1 g of dry matter produced. The calculated net primary productivity was 2.09×10^{10} g (dry weight) and therefore the amount of fixed CO₂ was 3.07×10^{10} g, and the amount of released O₂ was 2.21×10^{10} g. Furthermore, the emergy transformation of CO₂ is 3.78×10^{10} sej/kg, and the emergy transformity of O₂ is 5.11×10^{10} sej/kg; thus, the value of carbon fixation and oxygen release was 2.29×10^{17} sej.

Recreational Value

The recreational value of water is primarily embedded in two aspects. The first is the aesthetic value, which includes the water body and the landscape along the river, including canyons, waterfalls, and rapids. The second is the entertainment value, including boating, swimming, rafting, fishing and hunting, camping, hiking, photographing, and picnicking along the riverbank. These not only provide a place for rest and entertainment but also add to the spiritual value for humans. Therefore, the value of water recreation can be measured by the income of the tourism sector, which is affected by infrastructure, geographical location, resident income, and natural conditions around the water source. According to Liu Qing [34], water-related tourism accounts for 12.3% of tourism revenue. The emergy of recreation can be calculated from the following:

$$E_{My} = I \times 12.3\% \times EDR \quad (12)$$

where E_{My} is the emergy of recreation and EDR is the Emdollar ratio of the region.

The relevant scenic spots benefiting from the SNWDP are presented in Table 5.

Table 5. Water scenic spots impacted by the SNWDP in Beijing.

Scenic Spot	Water Landscape	Activity	Mode of Payment
Ming Tombs Reservoir	Ming Tombs Reservoir	Sightseeing, yacht	Tickets
Shidu Scenic Spot	Juma river	Sightseeing, yacht	Tickets
Garden Expo Park	Yongding river	Sightseeing	Tickets
Summer Palace	Kunming Lake	Sightseeing, boating	Tickets
lugou Bridge	Lugouxiaoyue	Sightseeing	Tickets
Yuyuantan Park	Yuyuantan	Sightseeing, boating	Tickets

According to the Beijing Tourism official website, there are 292 scenic spots in Beijing, comprising 32 scenic spots of 5A (The quality level of scenic spots in China can be divided into five levels, from high to low: 5A,4A,3A,2A and 1A), 82 scenic spots of 4A, 114 scenic spots of 3A, 56 scenic spots of 2A, and 8 scenic spots of 1A. In 2015, the tourism revenue of Beijing was 72.211 billion RMB, and therefore revenue of scenic spots impacted by the SNWDP in Beijing was 1.484 billion RMB (12.3 % of the total) and, from Equation (12), the recreational emergy was 7.74×10^{19} sej.

3. Results

3.1. Increment of Ecosystem Service Value

The increment of ecosystem services attributable to the SNWDP in Beijing are shown in Table 6, with a total value of \$610 million. The exchange rate was 6.39 RMB to the US dollar in 2015, which was calculated as 3.898 billion RMB.

3.2. WTP of Residents

A CVM was adopted to construct a hypothetical market scenario, using a questionnaire survey to obtain the WTP of stakeholders, with respect to the provision of ecological services. WTP is closely related to the social characteristics of stakeholders in the water demand area, their understanding of the project, and their personal income level. The WTP

of the users of ecosystem service is an important theoretical basis for establishing the social and economic relationship between the upstream and downstream of the “watershed”.

Table 6. Ecosystem service emergy-currency value of SNWDP in Beijing.

Item	Raw Data	Emergy Transformity	Emergy (sej)	USD (\$)	Proportion (%)
Water supply	$6.86 \times 10^8 \text{ m}^3$	$8.50 \times 10^{11} \text{ sej/m}^3$	5.83×10^{20}	2.15×10^8	35.26
Water regulation and storage	$2.72 \times 10^8 \text{ m}^3$	$1.64 \times 10^{11} \text{ sej/m}^3$	4.46×10^{19}	1.65×10^7	2.71
Net primary productivity	$2.09 \times 10^{10} \text{ g}$	$5.78 \times 10^7 \text{ sej/g}$	1.21×10^{18}	4.46×10^5	0.07
Biomass	$4.18 \times 10^{10} \text{ g}$	$5.11 \times 10^6 \text{ sej/g}$	2.14×10^{17}	7.90×10^4	0.01
Prevent land subsidence	$4.32 \times 10^8 \text{ m}^3$	$3.38 \times 10^{11} \text{ sej/m}^3$	1.46×10^{20}	5.39×10^7	8.84
Biodiversity	309 spices	$1.26 \times 10^{25} \text{ sej/spices}$	3.12×10^{20}	1.15×10^8	18.86
Ecological replenishment of river	$2.5 \times 10^8 \text{ m}^3$	$8.50 \times 10^{11} \text{ sej/m}^3$	2.13×10^{20}	7.86×10^7	12.89
Climate regulation	$1.04 \times 10^{14} \text{ KJ}$	12.20 sej/J	1.27×10^{18}	4.69×10^5	0.08
Water purification	NH ₃ -N, TN, Hardness		2.74×10^{20}	1.01×10^8	16.57
Carbon fixation and oxygen release			2.29×10^{17}	8.45×10^4	0.01
Recreational value	$1.484 \times 10^9 \text{ RMB}$	$2.71 \times 10^{12} \text{ sej/\$}$	7.74×10^{19}	2.86×10^7	4.69
Sum				6.10×10^8	100.00

The questionnaire survey on WTP of residents for water reserves impacted by the SNWDP in Beijing had three components: the social identity of the respondents, background knowledge, and WTP. The first part involved collecting relevant social background information, including age, sex, educational background, income, occupation, and residence type. The second part consisted of investigating the knowledge of the individuals surveyed regarding the SNWDP and water reserves. The third part aimed to determine each individual’s WTP. The questionnaire was designed with reference to previous applications and advice from experts and engineers. The survey used a computer-assisted telephone interviewing system to interview permanent residents of Beijing aged 20 to 70 years and who had resided in the city continuously for over half a year.

A total of 906 data samples were obtained, of which 776 were valid. Excluding 0 WTP, respondents willing to pay 6–20 RMB constituted the largest percentage (25.77%). Those willing to pay 21–100 RMB constituted 24.36% and those willing to pay over 100 RMB constituted the smallest percentage (3.4%). The average sum that people were willing to pay was 42.15 RMB. The permanent resident population of Beijing was 21.705 million in 2015 (Statistical Yearbook of Beijing) and therefore the annual WTP of residents for the water resources reserve of the SNWDP was 915 million RMB. Relevant research results have been previously reported by Peng et al. [35].

4. Discussion

Figure 3 shows the proportional value of each ecological and environmental index to the total ecosystem service value. The total value of ecosystem services attributable to the SNWDP in Beijing was very large. The value of water supply was the largest, accounting for 35.26% of the total, followed by biodiversity (18.86%). The proportion of the value attributable to climate regulation, net primary productivity, carbon sequestration, oxygen release, and biomass, were less than 0.1%, which indicated that the SNWDP positively influences the water supply function and the maintenance of biodiversity in Beijing, while having minimal impact on climate regulation, net primary productivity, carbon sequestration, oxygen release, and biomass accumulation. The indices directly related to the volume of water transferred were water supply, water purification, ecological replenishment of rivers, water regulation and storage, prevention of land subsidence, and these accounted for 76.27% of the total eco-environmental value. Therefore, the volume

of water transferred played a decisive role in the value of ecosystem services. Beijing has a wide variety of animals and plants, and the diversion of water from the SNWDP will provide favorable conditions for maintaining biodiversity. The small amount of climate regulation, carbon fixation and oxygen release may be related to local environmental governance and global warming. From the perspective of recreational value, as a tourist city, the SNWDP water has recreated many valuable tourist attractions of Beijing, and income from tourism will increase annually and this proportion will also continue to rise.

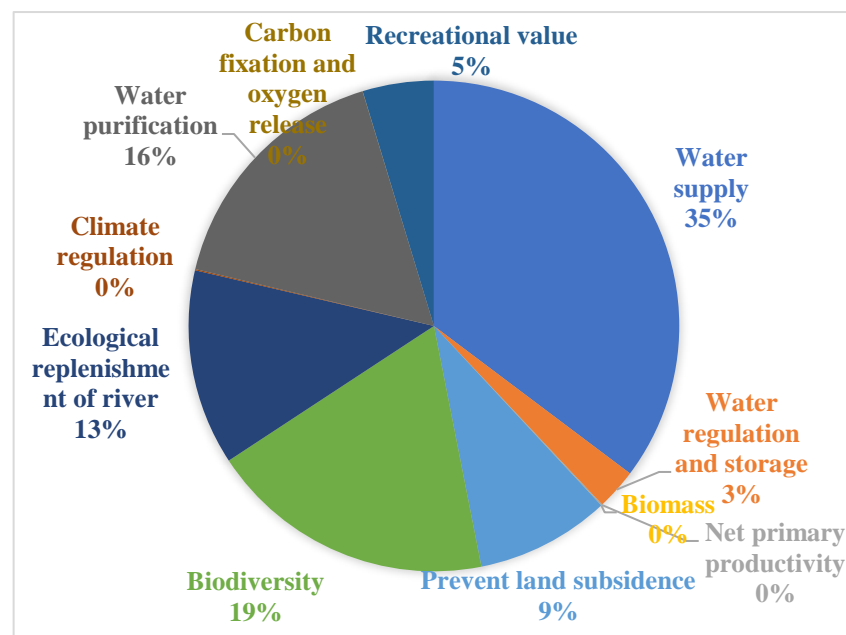


Figure 3. Proportion of each ecological environment index value in the total eco-environmental value.

The Emdollar ratio of Beijing in 2004 was 1.16×10^{13} sej/USD [36], and in 2005 was 4.48×10^{12} sej/USD [37]. We found that the Emdollar ratio in 2015 was 2.71×10^{12} sej/USD. Thus, the Emdollar ratio of Beijing has declined and was similar to that of developed countries, which is possibly related to the increasing value of imported goods, rapid growth of the GDP of Beijing, and the exchange rate of RMB. The Emdollar ratio of Beijing was smaller than that of cities in the Yangtze River Delta and Pearl River Delta in China [37], which demonstrates the development potential and highlights the potential for new development opportunities, along with large-scale investment.

The contradiction between water supply and demand in Beijing was the most prominent in the years before the SNWDP entered Beijing in 2014. The value of water resource ecosystem services in Beijing in 2008 was evaluated by Meng [38], which totaled 287.073 billion yuan. This study shows that after the SNWDP was put into operation in 2015, the increment of ecosystem service value was 3.898 billion RMB, an increase of about 1.4%, which is not a big increase, which may be related to the water transfer project just started operation. Because the middle route of the SNWDP officially started transferring water to Beijing on 27 December 2014, the time period of water transfer has been from 2015 to the present. Consequently, this study evaluated the water resource value in 2015 and did not develop a long-term series of water resource value assessments and prediction. As a national strategic project, the middle route of the SNWDP will continue for a long time and the amount of water transferred will also vary annually. Consequently, we plan to evaluate the annual water resource value of the SNWDP in Beijing.

The increment of ecosystem service value in Beijing due to the SNWDP was 3.898 billion RMB, while the WTP by the public was 915 million RMB. The public's WTP was much lower than the increment of ecosystem service value. As the survey of WTP is always undertaken in a certain geographical area, its results are closely related to the political

system, economic level, environmental awareness, environmental management mode, and supply mode of public goods in the surveyed area [39,40]. The practice of CVM in China is not widespread, especially in aspects of national measures and public facilities. The public has no experience in being consulted about public facilities and the WTP value obtained was relatively low [41]. Public awareness should be enhanced so that the public can truly understand the current status of water resources and the significance of the SNWDP project. Previous field investigations and regarding ecological compensation on the water-transfer area of SNWDP in 2010 demonstrated that the weighted minimum willingness-to-accept (WTA) to urban residents was 328 RMB/month, and the weighted minimum WTA to farmers was 342 RMB/month [42]. How to balance the differences between WTP and WTA is the direction of our group's next research on ecological compensation.

5. Conclusions

Our analysis demonstrated that the increment of ecosystem service value in Beijing due to the SNWDP was 3.898 billion RMB, while the WTP by the public was 915 million RMB. Therefore, the increment of ecosystem service value was the highest standard of compensation, and the public's WTP was the lower limit of ecological compensation. The public's WTP was significantly lower than the increase in ecological environment value. Therefore, Beijing's ecological compensation should be based on government compensation and supplemented by public compensation. Subsequently, the compensation standard can be established through negotiation between the suppliers and beneficiaries under the guidance of the relevant government and administrative agencies.

The following are suggestions to further improve the mechanism of ecological compensation.

1. Constructing an incentive mechanism for ecological compensation: incentives should be established for market entities and to encourage the public to participate in ecological compensation. Water-receiving areas should encourage industries that benefit from improved water quality. Such companies should share compensation to ease the financial pressure on governments. Furthermore, they should provide policy support or financial incentives to public organizations that actively participate in ecological compensation on the basis of obtaining ecological benefits.
2. Reducing the need for compensation in water-receiving areas: A focus on advantages of advanced industries and talents is required and the water-transfer areas should be assisted to reduce maintenance costs. The adjustment of industrial structures requires acceleration and industries with high water consumption and low output value should be regulated. A circular economy should be encouraged and the use of unconventional water resources should be extensively studied, with efforts made to develop and seek alternative water sources.
3. Establish a multi-subject regulatory evaluation system: public disclosure of financial status, the construction of public goods and achievements, and other measures should be implemented to enhance public trust, improve supervision and strengthen the audit and supervision duties of financial and audit departments. The compensation process should be regularly evaluated to protect the interests of the object of compensation and to verify the compensation standard. The results of ecological compensation evaluation and environmental monitoring can be included in the performance appraisal of the government.

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