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Urban Ecological Compensation Through Water Resource Ecological Footprint

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Abstract: To accelerate the exchange of water rights between regions and address the uneven costs of water resource ecological protection among different districts in urban areas, it is essential to make an analysis of regional water resource ecological compensation responsibilities. Establishing a rational standard for ecological compensation based on water resources remains a key method for quantifying the ecological value of water resources. In this study, all districts within a national central city in southwestern China were divided into four functional zones as the research subjects. The water resource ecological footprint method was employed to calculate the water ecological footprint of each zone. The ecological carrying capacity was utilized as the benchmark to determine the water resource ecological deficit or surplus, and the corresponding ecological monetary value of water resources was estimated. The results indicated that the city, as a whole, exhibited a water resource ecological surplus, with a monetary value of 5.088 billion CNY. The western zone, a key urban development area, recorded the highest water resource ecological footprint and the largest ecological deficit. In contrast, the northeastern zone, abundant in water resources, presented the highest water resource ecological surplus, with a monetary value of 9.196 billion CNY. Compensation amounts for the central-eastern and western zones were calculated as 4.169 billion and 7.661 billion CNY, respectively. These findings align with the local water resources' sustainable utilization conditions. The relationship between regional economic development, water conservation, and sustainable development was further analyzed in this study, proposing a water resource ecological compensation model with certain districts and counties as beneficiaries.

Keywords: Water resources compensation; Ecological footprint; Water ecological compensation; Ecological carrying capacity of water resources

1. Introduction

An allocation-based model was historically adopted for water resources in China's planned economy system, where the price of water did not reflect its natural capital attributes. Ecological compensation serves as a public policy aimed at rectifying the distorted relationship between ecological environmental protection and economic interests through governmental and market mechanisms. It facilitates the adjustment of benefits concerning the value of ecosystem services, ecological protection costs, and opportunity costs for development among various levels of government, regions, and stakeholders in ecological protection (Li et al., 2022). Allen & Feddema (1996) posited that ecological compensation serves as an environmental protection measure, which compensates for damages, safeguards rights, and introduces market mechanisms alongside sustainable development principles to offset the ecological damage caused by economic activities. This approach not only aids in restoring degraded ecosystems but also fosters positive interactions between the economy and the environment. Given that water resources constitute a crucial component of the ecological environment, ecological compensation can play an active role in protecting these resources. Within this context, it becomes essential to explore the ecological properties of water, rationally utilise natural water capital, and propose water resource compensation schemes that align with market-driven mechanisms. Costanza et al. (1997) emphasised that determining ecological compensation standards is a critical factor in watershed ecological compensation. The determination of compensation standards necessitates consideration of multiple factors, including the complexity of ecological restoration and the time costs involved. Consequently, the key to resolving these challenges lies in the rational and effective assessment and valuation of water resources' ecological value.

In the 1990s, Canadian ecological economists Rees (1992) and Wackernagel & Rees (1998) introduced the concept of the ecological footprint. Soltani et al. (2021), Kibria (2023), and da Silva et al. (2021) analysed the application and variation of the ecological footprint under various environmental conditions at national and provincial levels. Hoekstra & Hung (2003) further proposed the water footprint concept, evaluating human consumption of water resources from a consumption perspective and linking resource consumption with consumption patterns. The ecological footprint concept was incorporated into water resource accounting, defining the water footprint as the amount of water required for all products and services consumed by a known population within a specific period. This approach, based on virtual water, incorporates water resources into the calculation, providing a novel quantitative framework for assessing sustainable water resource use. Building on the ecological footprint concept and methodology, Zheng et al. (2020) and Zhang & Zhu (2022) calculated and analysed regional water resource carrying capacities. These studies have connected economic development with water resource consumption, offering insights into how regional water resources can be utilised scientifically. However, the traditional ecological footprint model predominantly focuses on the biological productivity of water resources while neglecting the ecological functions of water, including water quantity and quality. Kissinger & Haim (2008) contributed to deepening the study of the relationships among agriculture, the environment, and the economy by establishing a farmer's ecological balance account. This account compares improved and quantified ecological footprints with biological carrying capacities to assess the positive and negative profit effects of crops. Some scholars have also gradually incorporated the impact of pollution as an ecological factor into ecological footprint calculations. In recent years, the improved ecological footprint model has increasingly been applied to studies on water resource development and utilisation. In addition, this methodology has also been employed to study trends in water resource development.

Despite the research linking economic development and water resource sustainability, quantifying ecological gains and losses and proposing compensation policies reflecting the ecological service value of water resources remains an ongoing challenge. Pagiola et al. (2005) analysed data from the Nicaragua Forest Pasture Project, quantifying ecological compensation standards, thus providing valuable practical experience. Lv et al. (2023) proposed a compensation standard for watershed ecological services, suggesting that the value of residual ecosystem services provided by upstream regions should serve as the lower limit for compensation, while the value of actual usage by downstream regions should be the upper limit. With regard to compensation policies, administrative orders remain the primary strategy, offering advantages such as timeliness, simplicity of operation, and significant influence through legislative or policy documents (Imperial, 2005). Yalew et al. (2021) pointed out the limitations of the Sustainable Development Goal (SDG) indicator evaluation system for resource sharing in cross-regional watershed systems. Using the Nile Basin as a case study, they constructed a more equitable water resource management system through ecological compensation. Kazemi et al. (2021) studied the Sefidrud River Basin in Iran, constructing a multi-objective water resource optimisation allocation model involving all water departments across eight provinces. In the context of China, calculating ecological compensation based on watershed boundaries does not align with the administrative requirements of provinces and cities, often resulting in unclear responsibilities and difficulties in practical implementation.

In this study, a national central city located in southwestern China was selected as the research area. This city, covering less than 1% of the national land area, supports 1/50 of the country's population and generates 1/40 of the national economy. The city experiences a subtropical monsoon humid climate, characterised by rich plant diversity, numerous rivers, and nature reserves, and is considered an ecologically fragile area of significant ecological importance within China. Several scholars have analysed and predicted the water resource carrying capacity of different counties in this region at various times (Li, 2012; Zhou, 2019). Most studies related to this region have only proposed trends in ecological or water resource ecological surpluses and deficits, without addressing the monetary value involved in the practical implementation of ecological compensation. An improved water resources account was established in this study to calculate the water resource ecological footprint of each county within the city. By combining the water resource ecological footprint with the carrying capacity of each county, the ecological surplus and deficit of water resources were determined. Regions with an ecological surplus serve as recipients, while regions with an ecological deficit act as compensators. These values were quantified in monetary terms, providing a reference for the compensation amounts that compensating regions should pay to recipient regions. The objective is to offer data support and reference points for the effective implementation of water resource ecological compensation policies.

2. Study Area and Method

2.1 Study Area

The research area selected for this study is a central city in southwestern China, situated at the geometric centre of the continental plate. It lies at the junction of the developed eastern region and the resource-rich western region, covering a land area of 82,400 square kilometres with a population of approximately 32 million. This city holds a strategic position in China's Western Development Plan and its broader modernisation agenda. It is characterised by a complex urban-rural dichotomy, combining features of a large city, vast reservoir areas, mountainous regions, rural expanses, and ethnic minority areas. The region faces pronounced structural contradictions between urban and rural development, uneven regional growth, and substantial ecological construction and environmental protection challenges, making it ecologically representative and typical. Geographically, the city is located in the transition zone between the Qinghai-Tibet Plateau and the Yangtze River's middle and lower reaches, with terrain descending gradually from the Yangtze River valley from north to south. The area experiences a mid-subtropical humid monsoon climate, with numerous rivers throughout its territory. There are 207 rivers with a basin area exceeding 100 square kilometres. The annual average precipitation is relatively abundant, ranging from 1,000 to 1,350 mm across most regions.

Table 1. Statistics of functional zone division (2022)

Functional Zone	District/ County No.	Area (km^2)	Resident Population (10,000 Persons)	GDP (0.1 Billion CNY)	Regional Water Resources (0.1 Billion m^3)
Central-eastern zone	1	23	57.55	1561	0.05
	2	103	43.56	339	0.2
	3	221	94.54	1603	0.64
	4	396	148.56	1107	1.37
	5	431	153.56	1764	1.3
	6	262	96.93	922	0.78
	7	751	84	742	3.11
	8	1457	225.42	2297	3.77
	9	1823	119.55	1022	6.33
Western zone	10	2941	111.52	1504	10.16
	11	1421	68.75	919	3.77
	12	3216	135.38	1330	12.97
	13	2343	123.4	1000	8.51
	14	1579	114.68	1203	4.35
	15	2589	62.24	421	13.42
	16	2747	100.66	771	11.68
	17	1434	83.44	817	3.29
	18	1585	68.11	559	3.89
	19	1341	68.80	734	4.46
	20	1077	66.80	817	2.26
	21	915	76.30	921	2.79
Northeastern zone	22	3453	156.43	1118	15.70
	23	1888	64.30	577	9.38
	24	3289	19.85	66	22.88
	25	2899	55.30	391	8.30
	26	1517	64.61	531	4.21
	27	2187	71.53	508	8.93
	28	3964	119.95	662	26.83
	29	3636	92.62	558	17.74
	30	4098	74.42	395	8.87
	31	2955	46.35	222	12.58
	32	4015	38.78	124	35.79
Southeastern zone	33	2390	49.24	282	9.31
	34	2892	35.76	266	14.30
	35	3014	38.69	209	17.45
	36	2453	49.74	358	13.68
	37	5168	60.67	232	29.77
	38	3897	52.38	282	18.64

In addition, this city serves as an essential "green ecological barrier" in the upper reaches of the Yangtze River, ensuring the future development of the Yangtze River industrial belt and acting as a core area for water resource protection. The city also houses China's largest artificial wetland, and the reservoir and surrounding mountainous areas are rich in forest resources. It is a vital ecological functional zone for soil conservation and a key water source forest area in the upper reaches of the Yangtze River. These unique geographic features and natural conditions establish the city's crucial ecological position within the Yangtze River Economic Belt. Its role in constructing an ecological barrier in the upper Yangtze River is of paramount importance for ensuring sustainable, healthy, and coordinated development of the mid- and downstream regions of the Yangtze River, directly affecting the ecological security of downstream areas. Consequently, the city's 38 districts and counties were divided into four functional zones for analysis in this study: the central-eastern zone, the western zone, the northeastern zone, and the southeastern zone. The central-eastern zone consists of nine districts and counties, the western zone of twelve, the northeastern zone of eleven, and the southeastern zone of six. Statistical calculations for the functional zones are presented in Table 1.

2.2 Research Method

In domestic research on the ecological compensation amounts for watersheds and regions, scholars have primarily applied methods such as the ecosystem service function value method, total ecological protection cost method, water resource value method, contingent valuation method, and water quality compensation method. However, most of these studies have typically focused on water quality, water supply, and compensation for developmental rights, failing to account for the actual ecological service value of water resources. The ecological footprint, as a well-established quantitative indicator for sustainable development, has been widely applied globally due to its simple calculation process, clear results, and strong applicability, resulting in numerous significant findings. Nonetheless, certain limitations are inherent in this model. In this study, an improved water resource ecological footprint method was employed to calculate the water ecological footprint of different functional zones within the city. The calculation results of the water resource ecological carrying capacity were used as a benchmark to determine water resource ecological deficits or surpluses, and the corresponding ecological monetary value was then computed.

2.2.1 Ecological footprints of water resources

Based on the concept of the ecological footprint model, a water resources account was established in this study, which includes three sub-accounts: ecological footprints of aquatic products, freshwater, and water pollution. The aquatic product ecological footprint reflects the consumption of water resources for the production of freshwater products (mainly freshwater fish). The freshwater ecological footprint indicates the consumption of freshwater resources (particularly surface water) during human activities, including domestic use, industrial production, and agricultural activities. The water pollution ecological footprint reflects the consumption of water resources required for pollutant dilution and sewage purification within river systems. The classification of the water resources accounts is presented in Table 2.

Table 2. Classification of water resources accounts

Sub-Account	Accounting Item	Type of Bioproductive Land
Aquatic product ecological footprint	Aquatic products (primarily fish)	Water area
Freshwater ecological footprint	Water consumption for domestic, industrial, and agricultural use	Water resource land
Water pollution ecological footprint	Water required for diluting and purifying wastewater that does not meet functional zone water quality standards	Water resource land

The formula for calculating the water resource ecological footprint is as follows:

$$EF_w = N \times ef_w = N \times a_w \times \frac{A_{fiw} + A_{frw} + A_{waw}}{P_w} \tag{1}$$

where, EF_w represents the water resource ecological footprint (hm²); N denotes the total population; ef_w refers to the per capita water resource ecological footprint (hm²/person); a_w is the equivalence factor; A_{fiw} is the total aquatic product output (t); A_{frw} represents the total freshwater consumption (m³); A_{waw} indicates the water volume required for pollution dilution and purification (m³); P_w represents the national average water resource productivity, set at 2,912 m³/hm².

Based on the calculation method for ecological footprint equivalence factors across different regions of China proposed by Liu & Li (2010), the equivalence factor for water resources was revised according to the characteristics of the study area. The revised values are presented in Table 3.

Table 3. National hectare equivalence factor for water resources

Land Type	Arable Land	Forest Land	Pasture Land	Water Area	Built-up Land	Energy Land
Equivalence factor	1.74	1.41	0.44	0.35	1.74	1.41

Based on the national hectare equivalence factor for arable land, the equivalence factor for the water resource ecological footprint was determined by comparing the added value generated per unit area of arable land with that produced by water resources per unit area. In 2022, the hectare yield of grain from arable land in China was 5,802 kg, with an approximate price of 2.5 CNY per kilogram, resulting in a total yield value of 14,505 CNY per hectare. Using an added value of 54.2% of total output, the gross domestic product (GDP) generated by one hectare of arable land was calculated to be 7,863 CNY. Under the assumption of unchanged conditions, the GDP generated by water resources per unit area can be computed using the Cobb-Douglas production function. The elasticity coefficient of water resources for GDP growth is 0.128, indicating that a 1% increase in water consumption corresponds to a 0.128% increase in GDP. According to the GDP and total water consumption in 2022, each cubic metre of water contributed 11.7 CNY to GDP growth. The amount of usable water resources per unit area of land in China is approximately 1,042 m³/hm², leading to a GDP output of 12,188 CNY per hectare of water resources, which is 1.55 times the GDP output of arable land (7,863 CNY per hectare). Given that the equivalence factor for arable land is 1.74, the national equivalence factor for water resources was determined to be 2.70.

2.2.2 Ecological carrying capacity of water resources

Water resource ecological carrying capacity refers to the capacity of a water resources system within a given region to support the sustainable development of the region's socio-economic environment, under specific historical, economic, and social development conditions, as well as particular management technologies and institutional frameworks (Lv et al., 2023).

The calculation model for water resource ecological carrying capacity is as follows:

$$EC_w = N \times AEC_w = \pi \times \psi \times a_w \times (Q/P_w) \tag{2}$$

where, EC_W represents the water resource ecological carrying capacity (hm²); N denotes the population; AEC_w refers to the per capita water resource ecological carrying capacity (hm²); π is the reasonable development and utilisation rate of water resources; Ψ is the regional water resources yield factor (set to 1.98 for this study); a_w represents the water resources equivalence factor; Q refers to the total regional water resources volume (m³); P_w is the national average water resources production capacity (m³/hm²).

Not all water resources within a region can be entirely allocated to socio-economic development; a sufficient quantity must be reserved to maintain the natural system's ecological functions. According to research, 60% of a region's water resource carrying capacity should be reserved for maintaining the ecological environment and biodiversity to ensure ecological balance. Therefore, the value of π was set to 0.4 in this study.

By comparing the water resource ecological footprint and ecological carrying capacity within each functional zone, it is possible to determine whether the water resources of each zone are in a state of ecological deficit or surplus. This comparison serves as an indicator of the sustainable utilisation of water resources in each functional zone. The calculation formula is as follows:

$$Erd = EC_w - EF_w \tag{3}$$

When $Erd<0$, the water resource development in the functional zone is in a state of ecological deficit, meaning the level of development exceeds the water resource carrying capacity. This indicates that water resource development and utilisation in the zone are unsustainable or excessive, potentially leading to ecological damage. In such cases, external water sources may be required to sustain development within the zone. When $Erd>0$, the water resource development in the functional zone is in a state of ecological surplus, meaning the development intensity is less than the ecological carrying capacity. This indicates that water resource development and utilisation are sustainable and in a positive feedback cycle. The water resources available within the functional zone not only ensure a healthy ecological environment but also provide a surplus that can support further socio-economic development.

2.2.3 Estimation of the monetary value of water resources ecology

The monetary value of ecosystem services was determined using the Constanza-Xie Gaodi method. Based on the "Equivalent Value Factor Table for Ecosystem Services in China's Terrestrial Ecosystems" proposed by Xie Gaodi, and using relevant statistical data from the *China Statistical Yearbook*, the current economic value of one ecological value equivalent in China was calculated as 3,452 CNY. The calculations are shown in Table 4.

Table 4. Estimation of the monetary value of one ecological value equivalent (2022)

National Grain Production (10000 t)	Grain Cultivation Area (1000 hm²)	Yield Per Hectare (kg/hm²)	Average Purchase Price (CNY/kg)	Economic Value Per Ecological Value Equivalent (CNY/Equivalent)
68652.8	118332	5802	3.5	3452

The ecological monetary value of water resources was calculated based on the overall ecological equivalent and ecological carrying capacity of the city under study. By multiplying one ecological value equivalent by the total ecological equivalents of all accounts requiring compensation within the city, the total monetary value of the city's ecosystem services was obtained. Dividing this total by the city's ecological carrying capacity for the same year yielded the monetary value per unit area of ecological carrying capacity. Based on this calculation, the ecological monetary value of water resources for each administrative unit was determined to be 2,476 CNY.

3. Results and Analysis

3.1 Calculation of the Ecological Footprint of Water Resources in the Study City

The calculated results for the water resource ecological footprint of each functional zone, based on the aforementioned method, are presented in Table 5. The calculation results for the water resource ecological footprint of the administrative units within each functional zone are shown in Figure 1.

Table 5. Results of the calculated ecological footprint of water resources (unit: national hm^2)

Functional Zone	Aquatic Product Ecological Footprint	Freshwater Ecological Footprint	Water Pollution Ecological Footprint	Total Water Resource Ecological Footprint
Central-eastern zone	68904	1501407	704146	2274457
Western zone	415511	3220674	2170094	5806280
Northeastern zone	176755	1495975	1363853	3036583
Southeastern zone	20960	589301	714987	1325249

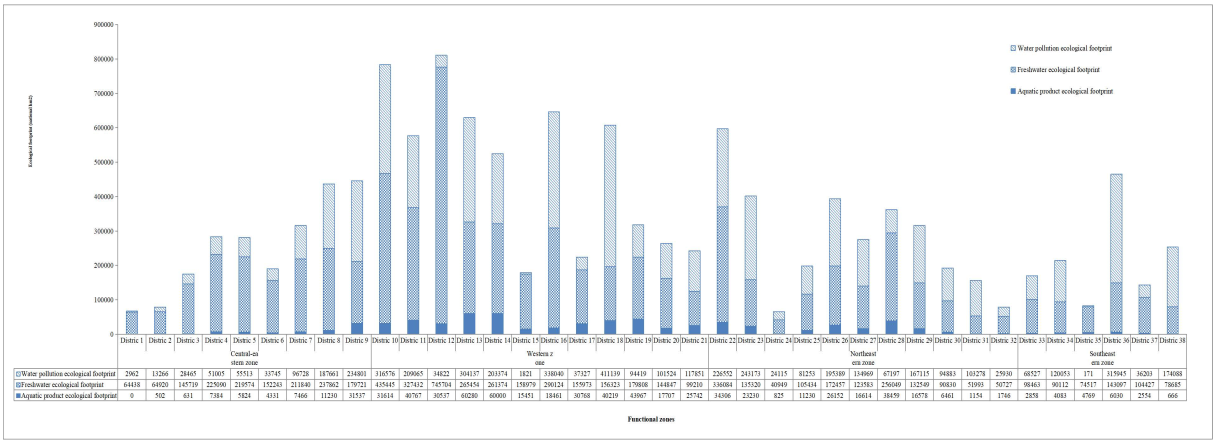

Figure 1. Results of the calculated ecological footprint of water resources for functional zones and administrative units

Based on the calculation results, the total ecological footprint of water resources in the western zone is the highest, accounting for 47% of the total ecological footprint in the entire study area. This is followed by the northeastern zone, contributing 24%, the central-eastern zone with 18%, and the southeastern zone with 11%. This distribution is closely related to the population size and the level of development in the western zone. The total permanent population in the western zone has reached 10.8 million, making it the zone with the highest degree of water resource development and utilisation. Furthermore, the concentration of population has placed significant pressure on water pollution control in the area. The substantial economic development in the western zone has also led to an increased demand for water resources. Compared to the other zones, there is still room for improvement in the efficient and intensive utilisation of water resources in this zone.

3.2 Calculating Ecological Carrying Capacity of Water Resources

Using relevant socio-economic data from the *Statistical Yearbook* and the *Statistical Yearbook of Land and Resources*, the water resource ecological carrying capacity of different administrative units within each functional zone of the study area was calculated. The results for the functional zones are presented in Table 6, and the results for the administrative units are shown in Figure 2.

Table 6. Results of calculated ecological carrying capacity of water resources

Functional Zone	Ecological Carrying Capacity of Water Resources (National hm^2)
Central-eastern zone	590828
Western zone	2712001
Northeastern zone	6750641
Southeastern zone	4443849

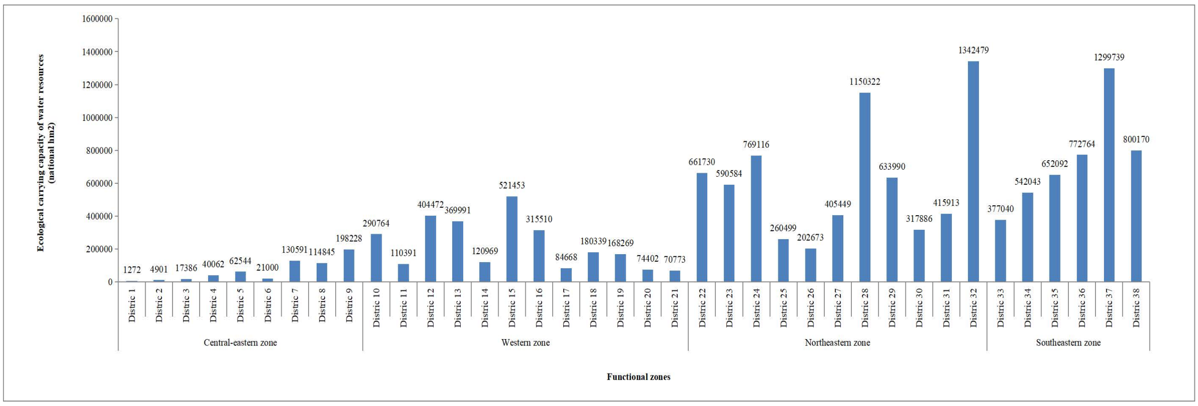

Figure 2. Results of calculated ecological carrying capacity of water resources for functional zones and administrative units

The results indicate that the water resource ecological carrying capacity of the northeastern zone is significantly higher than that of the other zones, which is consistent with the actual conditions of the region. This zone is an ecological functional area, surrounded by mountains, with a relatively low population density and an extensive network of water systems. The central-eastern zone has the weakest water resource ecological carrying capacity among the four zones. This is attributed to the smaller size of the area and its status as the core urban development zone, characterised by high-intensity development, which limits its water resource ecological carrying capacity.

3.3 Ecological Deficit/Surplus of Water Resources and Corresponding Monetary Value

The calculated results for the ecological deficit/surplus of water resources and the corresponding monetary values for the functional zones and administrative units of the study area are presented in Table 7 and Figure 3.

Table 7. Ecological deficit/surplus of water resources and corresponding monetary value

Functional Zone	Ecological Deficit/Surplus of Water Resources (National hm^2)	Corresponding Monetary Value (0.1 Billion CNY)
Central-eastern zone	-1683629	-41.69
Western zone	-3094279	-76.61
Northeastern zone	3714058	91.96
Southeastern zone	3118600	77.22
Total	2054750	50.88

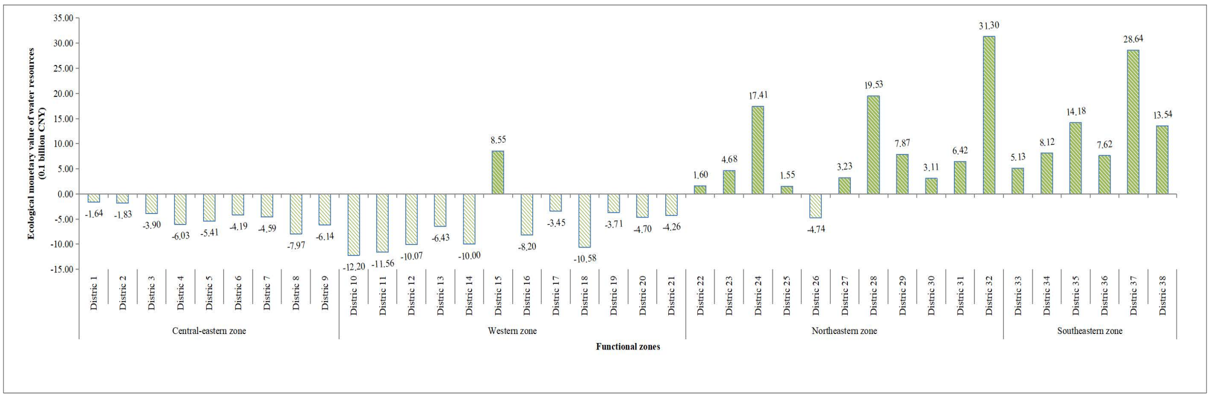

Figure 3. Distribution of ecological monetary values of water resources for functional zones and administrative units

It can be observed that the study city, overall, is in a state of ecological surplus with respect to water resources, with a total ecological surplus of 2.05 million hm^2 and a monetary value of 5.088 billion CNY. The development and utilisation of water resources are sufficient to meet industrial demands. However, the central-eastern zone has an ecological deficit, equivalent to a monetary value of 4.169 billion CNY, while the western zone also experiences an ecological deficit, with a corresponding monetary value of 7.661 billion CNY. In contrast, the northeastern zone shows an ecological surplus, with a monetary value of 9.196 billion CNY, and the southeastern zone has an ecological surplus valued at 7.722 billion CNY.

4. Discussion and Conclusions

4.1 Discussion

When comparing the ecological footprint calculations for the three sub-accounts across the functional zones, it was found that the aquatic product ecological footprint accounts for less than 10% in all zones. Therefore, aquatic products are not the primary factor contributing to water resource imbalances in the study area. The degree of dependence on water resources varies across the four functional zones. In the southeastern zone, the water pollution ecological footprint accounts for 54% of the total water resource ecological footprint, making it the only zone where the water pollution ecological footprint holds the largest share. Water pollution is thus a critical issue for the future development of this zone, necessitating enhanced control of pollutants entering rivers, adjusting the industrial structure, and reducing the introduction of industries that may cause water pollution to prevent water shortages caused by contamination. In the central-eastern zone, the freshwater ecological footprint accounts for 66%, while the water pollution ecological footprint accounts for 31%, aligning with the zone's characteristics of high population density and increased government attention to water environment and ecological management in urban areas. In the western zone, the freshwater ecological footprint represents 55%, and the water pollution ecological footprint accounts for 37%, with urban expansion, population growth, and industrial development being the primary factors influencing water resource demand in this zone. In the northeastern zone, the freshwater and water pollution ecological footprints are nearly equal, accounting for 49% and 45%, respectively, indicating a relatively balanced distribution of water resources.

Further attention should be given to the western zone, which has the highest ecological footprint of water resources. The three administrative units with the highest water resource ecological footprint in this zone are district 12, accounting for 18%, district 10, accounting for 17%, and district 13, accounting for 14%. Together, these three administrative units contribute nearly 50% of the total water resource ecological footprint in the western zone's 13 counties and districts. The increasing water demand places pressure on other counties in the western zone, highlighting the need to ensure coordination between different counties and districts when allocating regional water resources. District 12's freshwater ecological footprint reached 745,704.38 hm^2, accounting for 92% of the zone’s water resource ecological footprint, indicating an increased risk in the sustainable development of water resources. It is essential to consider water conservation, especially regarding freshwater resource utilisation, in regional development planning.

When comparing the ecological surplus and deficit of water resources across the functional zones, the central-eastern zone, as a maturely developed area, exhibits an overall ecological deficit in water resources, indicating unsustainable utilisation. However, since this zone is primarily urban, it ranks first among the four zones in terms of economic capacity. In addition to increased government investment in water resource protection, the awareness of water conservation among the public is gradually improving. As a result, the deficit in this region is not as severe as in the western zone. The western zone experiences the most significant ecological deficit in water resources among the four zones. This region is an emerging development area and represents the future direction of urban expansion, with an economy in a growth phase. Industrial development in this zone demands more from water resources. Due to the zone’s own water resource limitations, its ecological carrying capacity does not hold a competitive advantage among the zones. Therefore, for the zone’s socio-economic development to continue, water resource transfers and treatment must be coordinated alongside ecological compensation efforts. The northeastern zone demonstrates the highest ecological surplus in water resources among the four functional zones. Water resource development in this area is significantly lower than in other regions, and protection efforts are more robust. The Yangtze River’s main stream flows through this region, ensuring abundant water resources. The water resources within the zone are more than sufficient to support current development, and the current industrial layout has achieved a positive cycle of sustainable water utilisation. All six administrative units in the southeastern zone are in a state of water resource ecological surplus. To maintain this surplus, the current industrial development model must be preserved.

The three administrative units with the highest ecological surplus of water resources in the study city are districts 33, 38, and 39. These districts can assume greater ecological functions in the city’s ecological protection and water ecological civilisation efforts, providing more high-quality water resources. However, protecting the environment inevitably limits economic development. These three districts were the last impoverished counties in the city to overcome poverty, and in the context of regional water resource ecological compensation, they should act as recipients to compensate for the absence of other industries. The three administrative units with the highest water resource ecological deficit are districts 11, 10, and 19. The governments of these units should focus on the efficient and economical use of water resources during economic development. While introducing water transfers, they should act as compensators to address the deficit in water resource ecological capital. Compared with previous research, this study treats each district and county within the study city as an independent research unit, free from the limitations of watershed boundaries. The water ecological footprint was analysed to assess the utilisation of water resources, addressing issues related to aquaculture, freshwater utilisation, and water environment improvement in each district/county. This approach provides a direction for water-saving and efficient water use in each district/county. Additionally, the ecological value of water resources was monetised, offering a more robust basis for setting compensation standards and facilitating better implementation of water resource ecological compensation policies.

4.2 Conclusions and Recommendations

(1) The southeastern zone must enhance its water pollution prevention capabilities while maintaining the current industrial model. This will ensure sufficient water resources while optimising water quality standards.

(2) The northeastern and southeastern zones have missed many opportunities to develop non-agricultural industries, especially in the industrial sector, thereby restricting their regional development. Consequently, the central-eastern zone and western zone should allocate funds for horizontal ecological compensation to the northeastern and southeastern zones. Ecological compensation should be prioritised based on the ecological footprint of each district and county. Areas providing "ecological service output," or regions with a water resource ecological surplus, should be prioritised for receiving compensation. Regions with higher economic development and greater "ecological service consumption" should be prioritised for paying ecological compensation.

(3) The monetary value of the water resource ecological deficit was calculated, with the central-eastern zone showing a deficit of 4.6 billion CNY and the western zone a deficit of 6.7 billion CNY. This provides a reference for future water resource ecological compensation standards.

(4) Local governments may optimise regional water resource allocation based on the three areas identified in this study: Aquaculture, freshwater utilisation, and water environment improvement. Counties and districts with a water resource ecological footprint deficit indicate that water resource utilisation is unsustainable. These areas should be a priority for local governments. Future research on historical ecological footprints and predictions of future footprints could be used to assess water resource utilisation issues in these counties. In areas with deficits, local water authorities should focus on the scientific management of water resources, promote high-tech solutions for water conservation, cleaner production, and pollution control, and improve the efficiency of water resource utilisation. By adjusting the industrial structure and transforming production and consumption patterns, a more scientific and rational water usage framework should be explored.

(5) Future ecological compensation for water resources in the study area should also focus on human activities related to water, such as soil and water conservation, water source protection, floodwater utilisation, and wetland conservation. To ensure fair utilisation of water resources across districts and counties, and to share the responsibility of protection, pilot ecological compensation projects could be considered. These could involve districts 11, 10, and 19 as compensators, while districts 33, 38, and 39 would serve as recipients.

(6) In the process of economic development and construction in China, city governments play a managerial role in the governance of districts and counties. This is an objective reality. However, there are cases where local governments may lack sufficient regulatory oversight during industrial upgrades in these districts and counties, which creates challenges in fully implementing the compensation mechanism. To address these issues, several policy recommendations are provided to enhance the effective implementation of ecological compensation. The regulatory model should be tailored to local conditions, and a reasonable system of rewards and penalties should be established. When determining compensation amounts, the city government should consider the specific circumstances of each district and county and adopt a phased approach to gradually increase water resource ecological compensation fees. Moreover, introducing water resources-related assessment systems within the government is encouraged to motivate district and county governments to proactively implement ecological compensation measures.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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