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Cross-Boundary Watershed Eco-Compensation Based on Water Quantity and Quality from Both Production and Consumption Perspectives

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Abstract: Eco-compensation has become an important policy instrument for integrated watershed management in China. However, quantitative approaches that jointly consider water quantity and quality from both production and consumption perspectives remain limited, constraining the systematic development of eco-compensation standards. This study proposes a funding allocation framework based on Water Yield Equivalent (WYE) and Water Consumption Equivalent (WCE) indicators incorporating both water quality and quantity, and applies it to the upper Miyun Reservoir watershed. Compensation funds were calculated for nine counties in 2000, 2008, and 2013. The results show substantial spatial differences in WYE and WCE, resulting in differentiated compensation responsibilities and receipts. Under the baseline scenario, Miyun County received the highest compensation in 2008 (RMB 198 million), whereas Chicheng County incurred the highest compensation payment in 2000 (RMB 135 million). Further comparison with local fiscal revenue indicates that the ratio of compensation funds to fiscal revenue reflects the potential relative fiscal incentive or constraint of the eco-compensation scheme on local governments. In 2013, Yanqing County had the highest ratio under the baseline scenario, at 12.76%, which increased to 22.59% under the South-to-North Water Diversion Project (SNWDP) water price scenario. Overall, jointly accounting for water quantity, quality, production, and consumption provides a quantitative basis for differentiating compensation responsibilities and benefits across counties. For the Miyun Reservoir watershed, future eco-compensation policies could further integrate water resource protection and pollution reduction requirements to establish differentiated compensation standards, thereby improving the coordination between the compensation mechanism and watershed water resource management objectives.

Keywords: eco-compensation; payment for ecosystem services; Water Yield Equivalent indicator; water consumption equivalent indicator; case study

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1. Introduction

Watershed eco-compensation has increasingly become an important policy instrument for integrated watershed management in China [1,2]. In recent years, this mechanism has evolved from early pilot programs toward institutionalization and watershed-scale coordinated governance. The number of pilot projects increased from 2 in 1999 to approximately 67 in 2020 [3], with a gradual transition from localized experiments to basin-wide implementation. By 2026, more than 30 cross-regional horizontal eco-compensation mechanisms had been established across 24 provinces [4]. Meanwhile, under the framework of the "15th Five-Year Plan", the government has further emphasized perfecting diversified eco-compensation mechanisms and strengthening systematic watershed governance, providing policy support for the continuous deepening of the watershed eco-compensation system [5]. Against this backdrop, China has progressively developed a multi-tier eco-compensation framework consisting of vertical, horizontal, and hybrid compensation mechanisms. Within this framework, intergovernmental fiscal transfers continue to serve as a primary implementation approach [6,7].

However, as the scale of compensation expands, increasing pressure is placed on fiscal sustainability. At the same time, the lack of standardized methods for determining compensation levels often leads to substantial discrepancies in compensation estimates within the same watershed, which in turn generates stakeholder disagreements and increases transaction costs [8]. Therefore, developing compensation standards that are equitable, effective, and operational has become a critical challenge in watershed eco-compensation practice [9,10].

Existing studies have explored approaches to establishing eco-compensation standards from multiple perspectives, such as conservation costs [11,12], willingness to pay [13,14], and costs caused by water pollution [15–17]. Although these studies offer critical foundations for estimating compensation funds, the existing approaches still exhibit two notable limitations. First, water quantity and water quality—despite being inherently interconnected and highly interactive key elements—have not yet been genuinely integrated into a unified quantitative benchmark [18–20]. Previous watershed assessments have primarily focused on either aspect in isolation [21–23]. Even in studies that attempt to combine both, they typically treat them as independent evaluation modules, rarely synthesizing them into a single comprehensive indicator [12,16,24,25]. More critically, existing comprehensive evaluation methods for water quality and quantity often lack "linear additivity" and fail to satisfy the principle of water mass balance [26]. This deficiency leads to inconsistencies in accounting results when aggregating across spatial scales or delineating administrative boundaries. Secondly, the existing compensation mechanisms fail to adequately characterize the entire "water yield–water consumption" process within watersheds. In reality, watershed ecosystem services are reflected not only in the water consumption by downstream areas but are also closely tied to the water supply generated by upstream regions through natural processes such as precipitation and runoff. Current mechanisms predominantly focus on the terminal water consumption or disparities in pollution discharge within a given jurisdiction [27,28], frequently overlooking the natural, background water yield contributions from upstream area. Consequently, they fail to fully reflect the differentiated contributions of upstream and downstream regions to water supply and conservation, making it difficult to coordinate effective water allocation across the watershed [29,30]. Although some recent studies (e.g., Xu et al., 2021 [23]) have begun to incorporate both water yield and water consumption into watershed compensation schemes, their perspectives remain largely confined to traditional natural hydrological processes. They overlook the reality that in human-dominated watersheds, treated wastewater discharge (i.e., reclaimed water) has become an indispensable physical component constituting the actual regional water yield. Therefore, relying solely on natural water yield processes is inadequate to fully capture a region's comprehensive water supply capacity.

Consequently, existing research generally still lacks a unified analytical framework capable of integrating both water quantity and water quality, whilst taking into account both water production and consumption. To fill this research gap, this study proposes a new framework to formulate eco-compensation standards and fund allocations in watershed eco-compensation schemes through three steps: (1) defining how much each county within the watershed should pay to the collective eco-compensation fund based on water tariffs and their Water Consumption Equivalent, considering their agricultural, industrial, domestic water uses and pollutant discharge; (2) defining how much each county within the watershed should receive from the collective eco-compensation fund based on water tariffs and their Water Yield Equivalent considering both precipitation and treated wastewater discharge; (3) if total eco-compensation fund payment exceeds total eco-compensation fund to be received, excessive eco-compensation fund can be used for ecological protection purposes in the watershed. By integrating water quantity, water quality, water yield, and water consumption into a unified and additive accounting framework, this study aims to provide a more transparent, objective, and mass-balance-based quantitative methodology. This approach facilitates the formulation of watershed eco-compensation standards, the identification of ecological responsibilities, and the inter-jurisdictional allocation of compensation funds.

2. Study Area and Methods

2.1. Case Study Area

Located in the mountainous northern part of Miyun County, Miyun Reservoir is the largest reservoir in Northern China, with a maximum capacity of 4.375 billion m^3 and an annual water supply capacity of 480 million tons [31]. In an average year, Miyun Reservoir provides 60% of Beijing's drinking water, and its water quality and quantity directly affect the capital city's drinking water security. The Miyun Reservoir watershed (40°19′–41°38′ N, 115°25′–117°35′ E) is formed by the confluence of two inlet rivers, i.e., the Chao River and Bai River [32], covering an area of 15,788 km^2 [20] (Figure 1). The watershed covers three counties in Beijing, i.e., Miyun, Huairou and Yanqing, with a total area of about 3476.7 km^2 and six counties in Hebei, i.e., Chicheng, Fengning, Luanping, Xinglong, Guyuan, and Chongli, with a total area of 11,892 km^2 [32]. The South-to-North Water Diversion Project (SNWDP) also started to transfer water to Miyun Reservoir since September 2015, with a cumulative water transfer of 53.38 million m^3 by the end of that year [33]. Regarding the industrial structure, heavy industries have been largely phased out within the region. In terms of pollution conditions, total phosphorus (TP) concentrations in the reservoir already meet drinking water standards. However, total nitrogen (TN) has persistently exceeded target levels, constituting the main water environmental pressure. Therefore, TN is the dominant pollutant in the study area.

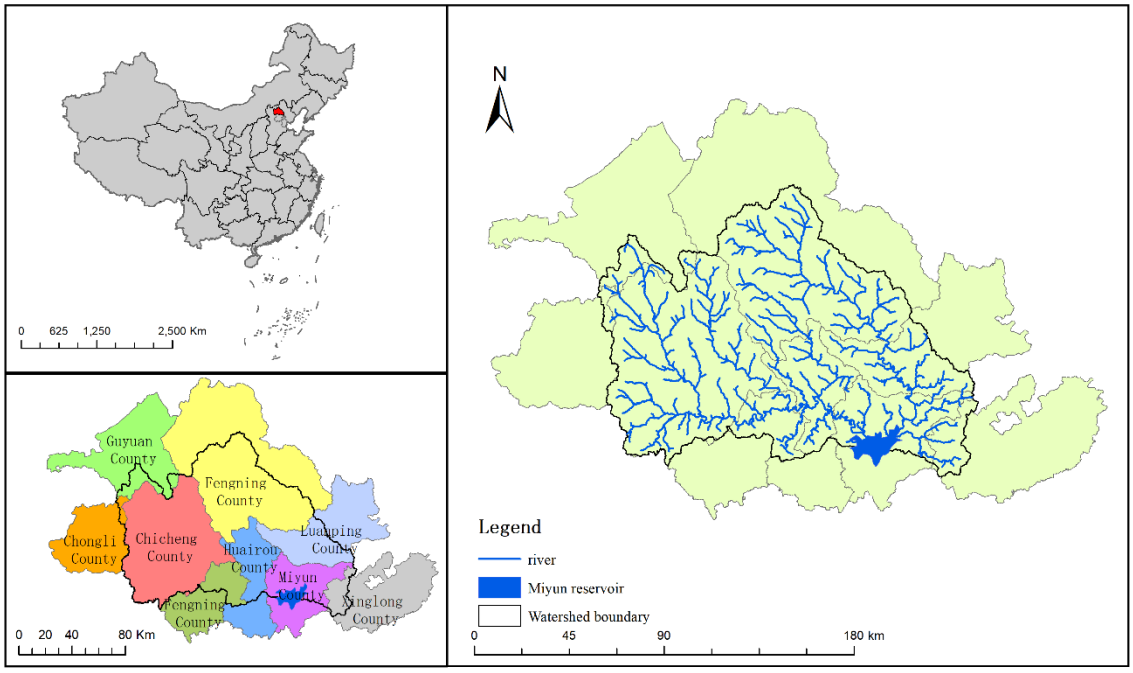


Figure 1. Map of the study area.

2.2. Data Sources

Inflow data for the Miyun Reservoir were obtained from records maintained by the Reservoir Management Office. Water withdrawal refers to the amount of water withdrawn from the watershed for agricultural, industrial and domestic uses, which includes two components: water consumed and water returned to the natural water systems. Industrial water withdrawal can be estimated based on county-level statistics on industrial GDP and water withdrawal intensity per unit of GDP. Domestic water withdrawal can be estimated based on county population data and daily water use per capita. Agriculture water withdrawal is based on irrigation data. The water resource fee is calculated according to the water tariff in Beijing. The SNWDP water tariff in different years is discounted using the annual average of the one-year interest rate of the People's Bank of China in that year. Water consumption coefficients, i.e., proportion of water consumed among water withdrawn, in different counties can be obtained from the "Hebei Province Water Resources Bulletin", "Beijing Water Resources Bulletin", "Second National Pollution Source Census Bulletin" and "Second Hebei Provincial Pollution Source Census Bulletin".

2.3. Research Methodology

The proposed methodological framework builds upon a Water Yield Equivalent Indicator (Section 2.3.1) and a Water Consumption Equivalent Indicator (Section 2.3.2). Both indicators have incorporated water quantity and

quality. Within a cross-boundary eco-compensation scheme, jurisdictions within the same watershed would make payments according to their respective Water Consumption Equivalent while would get compensation based on their respective Water Yield Equivalent. The Fund allocation methods are then outlined in Section 2.3.3.

2.3.1. Water Yield Equivalent (WYE)

The Water Yield Equivalent (WYE) indicator is developed based on a water quality and quantity for Water Yield Equivalent assessment indicator that we established in our previous study [26]. The Water Yield Model in InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs, version 3.10.0) model is used, following Sharp et al. (2015) [34]. Annual water yield $Y(x)$ for each grid on the landscape *x* can be calculated according to Equation (1):

$$Y(x) = \left(1 - \frac{AET(x)}{P(x)}\right) \times P(x) \quad (1)$$

where Y(*x*) denotes the annual water yield in grid *x*; AET(*x*) represents the annual evapotranspiration from grid *x*; P(*x*) refers to the sum of annual precipitation and annual irrigation in grid *x*. Detailed description of the water yield module can be found in Sharp et al. (2015) and Sharp (2020) [34,35].

Based on the linear additive indicator proposed in Cao et al. (2021) [26], water resource equivalents are calculated by combining water quantity and quality according to Equation (2):

$$WYE = \left(1 + \frac{Cs - C}{Cs}\right) \times Q \quad (2)$$

where WYE is the Water Yield Equivalent (m^3); *C* represents the actual concentration of the pollutant (TN) in the water body (mg/L); *Cs* represents the required TN concentration in treated water discharge (0.5 mg/L), according to China's Environmental Quality Standards for Surface Water (GB 3838-2002), which corresponds to the Class II standard for lakes and reservoirs [36]; *Q* stands for water quantity (m^3).

2.3.2. Water Consumption Equivalent (WCE)

Water consumption equivalent includes two components: (1) water withdrawals for agricultural, industrial, urban and rural domestic uses; (2) for industrial and domestic water uses, WCE additionally accounts for the water required to dilute pollutants discharged in wastewater. This water volume is calculated based on TN concentrations, because TN is the dominant pollutant in the study area and total phosphorus (TP) concentrations in the reservoir already meet drinking water standards [26]. WCE in upstream jurisdiction can be calculated according to Equations (3)–(5). WCE for domestic uses is calculated using the same approach as in Equation (5).

$$WCE = WCE_{agr} + WCE_{indu} + WCE_{house} \quad (3)$$

$$WCE_{agr} = WIE_{agr} \quad (4)$$

$$WCE_{indu} = WIE_{indu} + DE_{indu} \quad (5)$$

where WCE denotes Water Consumption Equivalent (m^3); WCE_{agr}, WCE_{indu} and WCE_{house} are the Water Consumption Equivalent of agriculture, industry and household domestic uses respectively in the upstream jurisdiction (m^3); WIE_{agr} and WIE_{indu} are agricultural and industrial water withdrawals respectively in the upstream jurisdiction (m^3); DE_{indu} represents the industrial wastewater discharge equivalent in the upstream jurisdiction (m^3).

Water withdrawal equivalent is used to integrate water withdrawals for agricultural irrigation, industry, urban and rural households, as well as wastewater discharge equivalent from industries as well as urban and rural households. Equations (6)–(8) can be used in terms of incorporating industrial wastewater as an example:

$$WIE_{indu} = \left(1 + \frac{Cs - C_0}{Cs}\right) \times V_{indu,WI} \quad (6)$$

$$DE_{indu} = -\left(1 + \frac{Cs - C}{Cs}\right) \times V_{indu,DR} \quad (7)$$

$$V_{indu,DR} = V_{indu,WI} \times (1 - \eta) \quad (8)$$

where $V_{indu,WI}$ is water withdrawn from the watershed for industrial production in the upstream jurisdiction (m^3); $V_{indu,DR}$ is the amount of wastewater discharged into the watershed from industries in the upstream jurisdiction (m^3); η represents the industrial water consumption coefficient; C represents the actual concentration of the pollutant (TN) in the water body (mg/L); C_0 represents the actual TN concentration of the water source from which the industrial water is withdrawn (mg/L). In this study, C_0 is set to zero because industrial water withdrawal is assumed to originate from groundwater, and the corresponding background TN concentration is assumed to be negligible. The difference between C_0 and C reflects the pollutants introduced during water use rather than pollutants contained in the withdrawn water.

2.3.3. Eco-Compensation Fund Allocation

$$\text{TNP(or TNI)} = TI - TO = f(\text{water,Sup}) - g(\text{water,Dmd}) \tag{9}$$

$$f(\text{water,Sup}) = \beta \times T \times P \tag{10}$$

$$g(\text{water,Dmd}) = \alpha \times T_1 \times P \tag{11}$$

$$T = T_1 + T_2 \tag{12}$$

where TNP(or TNI) is the net payment (or net income); TI (or TO) is compensation received (or paid) for the provision (or consumption) of water resources; $f(\text{water,Sup})$ and $g(\text{water,Dmd})$ is a function of the amount of compensation to be received or paid for the provision or consumption of water resources; α is the water consumption rate reflecting water demand level; β is the water yield rate indicating regional water yield level; T is the total Water Yield Equivalent in the upstream jurisdiction (m^3); T_1 is the total water consumption equivalent in the upstream jurisdiction (m^3); T_2 is the total water supply from upstream jurisdiction to downstream jurisdiction; P represents the residential water tariff in Beijing (yuan/m^3); Water consumption rate α and water yield rate β can be calculated according to Equation (13):

$$\alpha = \frac{\text{WCE}_R}{\text{WCE}},\ \beta = \frac{\text{WYE}_J}{\text{WYE}} \tag{13}$$

where WCE is water consumption equivalent (m^3); WCE_R is the water consumption equivalent of upstream county R (m^3); WYE is the Water Yield Equivalent (m^3); WYE_J is the Water Yield Equivalent of upstream county J (m^3).

The overall calculation procedure for watershed eco-compensation funds is summarized in Figure 2. The framework links water yield and quality assessment to WYE, water use and pollution pressure to WCE, and subsequently determines the direction and magnitude of compensation based on the net balance between the two equivalents.

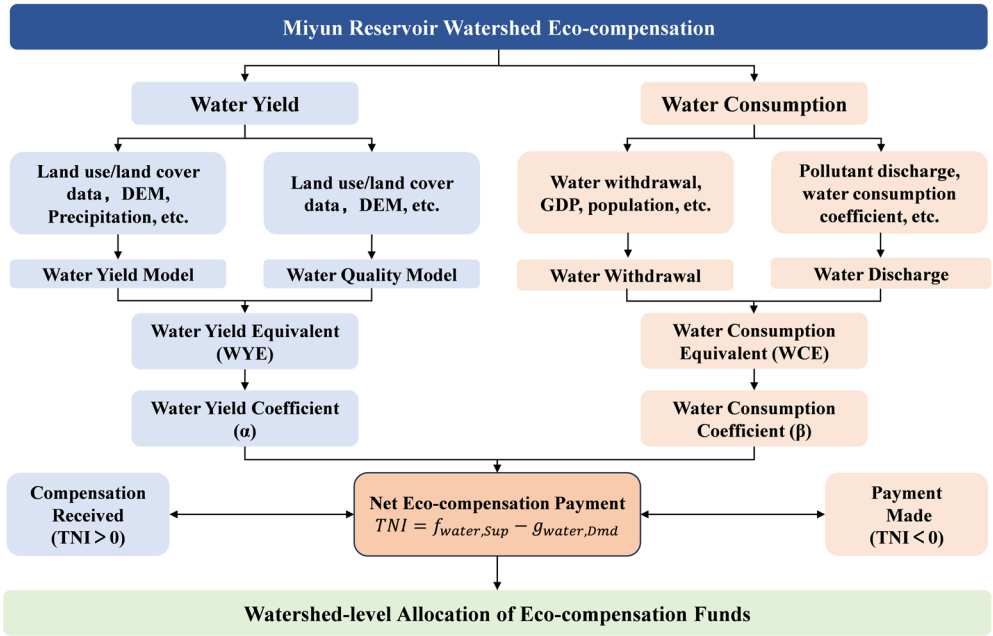


Figure 2. Calculation flowchart of the watershed eco-compensation framework.

2.3.4. Scenario Design and Parameter Substitution

Based on the baseline model described above, two key scenarios were developed to examine the impacts of environmental obligations and economic costs on eco-compensation standards:

(1) Ecological Water Requirement Scenario

To ensure fairness in transboundary compensation, upstream regions are required to prioritize the maintenance of local river health before supplying water to downstream areas. Following the Tennant Method, a flow level of approximately 30% of the multi-year average discharge is generally considered sufficient to maintain a good ecological status [37]. Accordingly, this study defines 30% of the total water yield in each county as a non-tradable ecological water requirement, which is deducted when calculating the net Water Yield Equivalent. Because this study conducts eco-compensation accounting at the county administrative scale, continuous streamflow observation data at county boundaries are unavailable. However, on a long-term temporal scale, the multi-year average water yield closely approximates natural streamflow. Therefore, we adopted the long-term average water yield as a reliable proxy for streamflow and applied the 30% threshold to estimate the minimum ecological water requirement. Consequently, 30% of each county's water yield is defined as the non-tradable "statutory ecological water demand", which is deducted when calculating the net Water Yield Equivalent.

(2) Alternative Water Pricing Scenario

In addition to the baseline water price, this study introduces the water price of the South-to-North Water Diversion Project (SNWDP) supplied to Beijing as an alternative pricing scenario. Because the SNWDP provides a tangible alternative water source for Beijing, its price effectively serves as a reference for the opportunity cost of replacing locally conserved water with inter-basin transfers. Under this scenario, the SNWDP price does not represent an actual eco-compensation payment between upstream and downstream counties. Rather, it acts as a proxy for the economic value of water within a hypothetical substitution framework, aiming to evaluate the replacement cost incurred if local water conservation functions degrade and must be supplemented by transferred water. By replacing P in Equations (10) and (11) with P_{SNWDP}, the potential impacts of different pricing mechanisms on fiscal revenues of upstream counties are assessed.

3. Results

3.1. Water Yield Equivalent

Eco-compensation funds to be received are calculated based on Water Yield Equivalent results, which can be derived from the work of Cao et al. (2021) [26] for the Miyun Reservoir watershed. Variations in natural water yield and anthropogenic TN generation lead to differences in Water Yield Equivalents among counties (Figure 3). Spatially, the Water Yield Equivalent generally exhibits a geographic pattern of being higher in the southeast and lower in the northwest. Temporally, its peak values also demonstrate certain fluctuations; the maximum regional Water Yield Equivalent reached 854.79 in 2008, exceeding the 796.34 recorded in 2000 and the 832.85 in 2013. Although natural water yield is mostly climate-related and thus outside of human control, reducing TN losses from improved fertilizer and pesticide application can increase Water Yield Equivalent effectively, thus resulting in higher amounts of eco-compensation funds to be received.

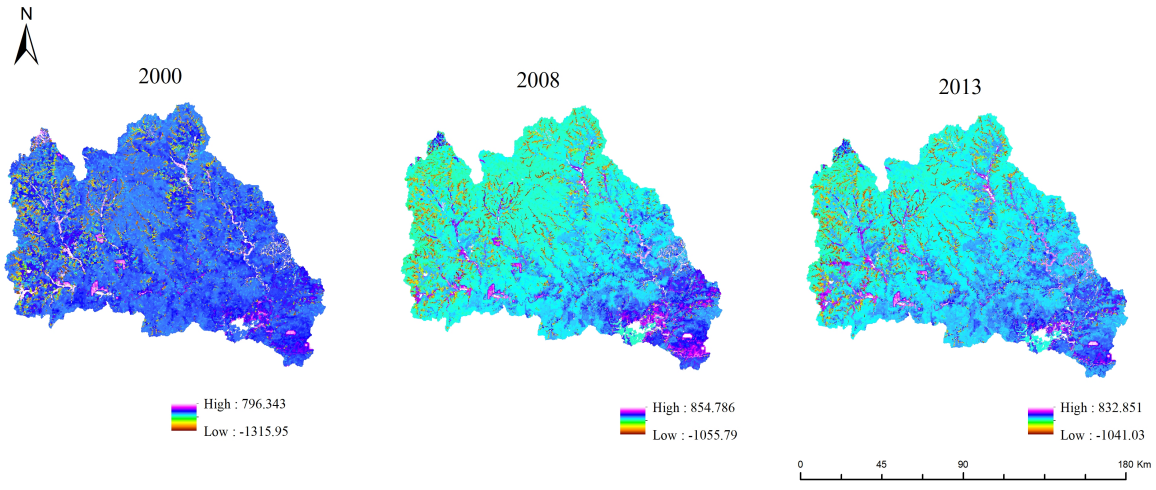


Figure 3. Water Yield Equivalent by county in different years.

3.2. Water Consumption Equivalent

According to our results, Water Consumption Equivalent in the Miyun watershed has more than tripled from 1.5 billion m^3 in 2000 to 4.9 billion m^3 in 2013 (Figure 4). Moreover, industrial water consumption equivalents have gradually taken over increasing proportions replacing domestic water consumption equivalents, presumably due to increased industrial activities with economic growth while relatively stable population. Therefore, upstream counties should pay further attention to manage industrial water consumption equivalents by improving industrial water efficiency and reducing industrial water pollution discharges.

Our results show that total Water Consumption Equivalents in Huairou County and Miyun County are the highest, due to their larger populations and therefore higher domestic water consumption equivalents as well as higher growth rates of industrial water consumption equivalents.

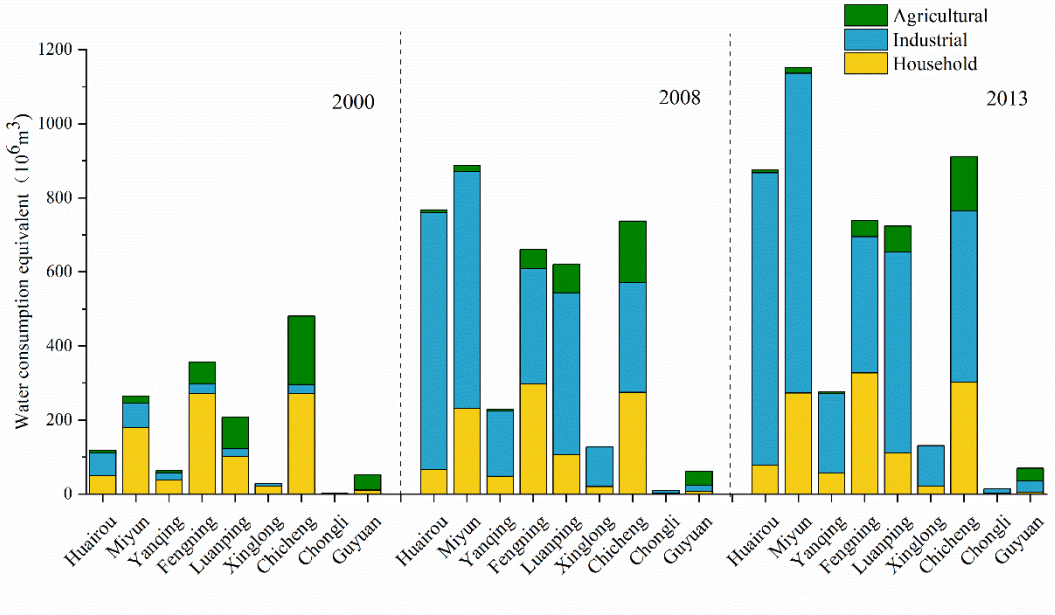


Figure 4. Water consumption equivalents by county in different years.

Our study results show that TN load in the Miyun Watershed amounted to 2280.06 tons in 2008. By converting the TN load into an annual average TN concentration based on the actual water yield for the same period, the resulting concentration was 4.8% higher than the measured concentration reported by Geng, Li, et al. (2015) and Geng, Zhang, et al. (2015) [38,39] at 3 mg/L, indicating that our results are within the reasonable range. Given the multiple sources of uncertainty inherent in watershed-scale nutrient load estimation, including input statistics, pollutant generation and discharge coefficients, and spatial aggregation effects, a deviation of less than 5% can generally be considered reasonable and acceptable for regional environmental accounting studies. However, owing to the lack of comparable observational data for 2000 and 2013, the present study cannot be further validated using a continuous time series. Therefore, the current validation should be regarded primarily as a consistency check against existing literature estimates rather than as a comprehensive and systematic model calibration.

3.3. Allocation and Scenario Analysis of Watershed Eco-Compensation Fund

3.3.1. Baseline Allocation

Unlike conventional eco-compensation mechanisms, in which downstream beneficiaries typically compensate upstream areas for watershed protection, this framework integrates the polluter pays principle with ecosystem service compensation. It achieves this by jointly considering each jurisdiction's Water Yield Equivalent and water consumption equivalent. The direction and magnitude of compensation are determined by their net balance: a jurisdiction with a higher water consumption equivalent than Water Yield Equivalent becomes a net payer, whereas one with a higher Water Yield Equivalent receives compensation. The resulting compensation amounts represent model-based outcomes derived from historical water resource and pollution conditions and should not be interpreted as evidence of actual compensation policies implemented during the study period.

Based on the allocation mechanism and the baseline water price, compensation funds across the counties in the Miyun Reservoir watershed exhibited substantial spatial and temporal variations. The total compensation funds

for the Miyun Reservoir Watershed increased from RMB −236 million in 2000 to RMB 378 million in 2008, but slightly decreased to RMB 350 million in 2013 (Figure 5). In terms of the spatial flow of compensation, upstream counties paid more to downstream counties in 2000. By contrast, downstream counties made larger payments to upstream counties in 2008, as upstream counties lowered their water uses and water pollution throughout the period and thus effectively increased their Water Yield Equivalents. Miyun and Luanping counties received higher compensation funds than other counties due to their higher Water Yield Equivalents although their Water Consumption Equivalents do not differ significantly from other counties. Chicheng County has the highest net payment due to its large amount of non-point source pollutants and therefore negative Water Yield Equivalents.

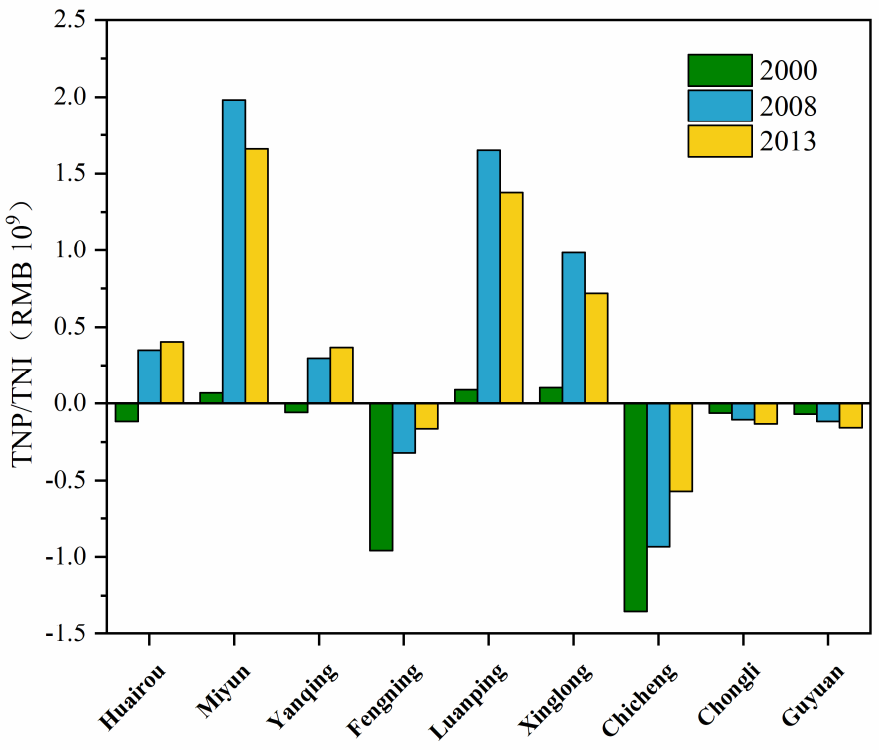


Figure 5. Eco-compensation funds based on Water Yield Equivalents and water resource fees by county.

3.3.2. Allocation Considering Ecological Water Requirements

The minimum ecological water requirement is the minimum threshold of ecological water requirement that is needed to provide suitable habitat for ecosystems [40]. In the above calculation, no ecological water requirement is considered. Current international practices have used 20% to 40% of the stream flows for ecological requirements and a previous study on Chinese rivers has suggested that 30% of the flows are needed to support ecosystem habitats [41], therefore we applied 30% of the water yield as Ecological Water Requirement in our analysis to demonstrate the impacts of incorporating ecological water requirements. Based on the calculated Water Yield Equivalents, the total eco-compensation funds increased from RMB −451 million in 2000 to RMB −16 million in 2008, but declined to RMB −102 million in 2013 (Figure 6). Compared with the baseline scenario, incorporating a 30% ecological water requirement reduced the total eco-compensation funds in all three study years. This fluctuation is primarily attributed to a decrease in water yield under the ecological baseline while the pollution load remained unchanged, which consequently reduced the water resource production equivalent.

3.3.3. Allocation Based on Alternative Water Sources

An alternative water source for Beijing is from SNWDP. However, using the SNWDP water price, eco-compensation funds would increase from RMB −511 million in 2000, to RMB 619 million in 2008, and RMB 620 million in 2013 (Figure 7), substantially higher than the compensation payments to upstream counties in the Miyun Reservoir watershed.

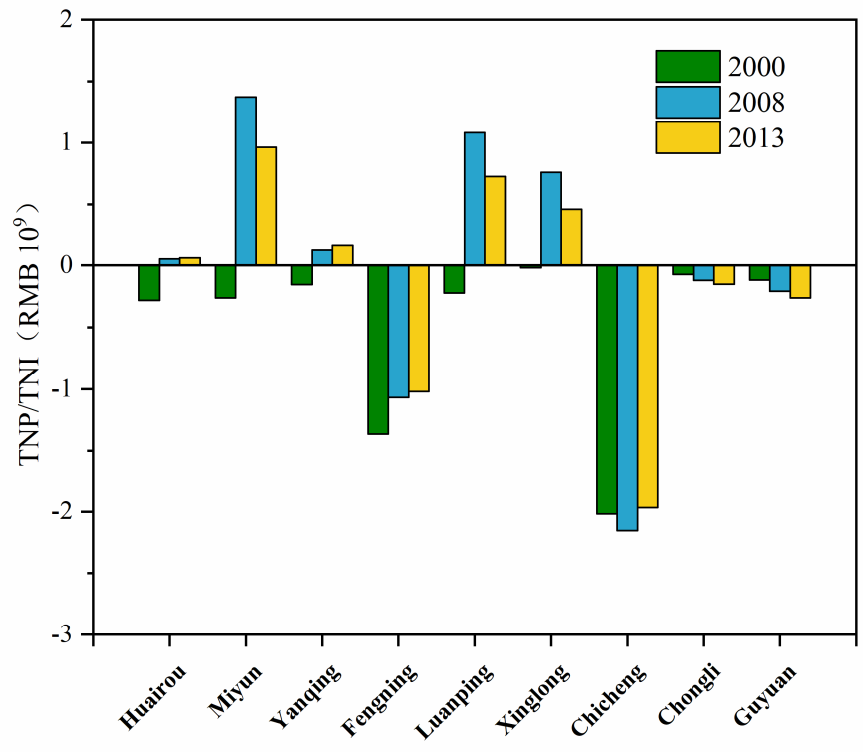


Figure 6. Eco-compensation funds considering ecological water requirements.

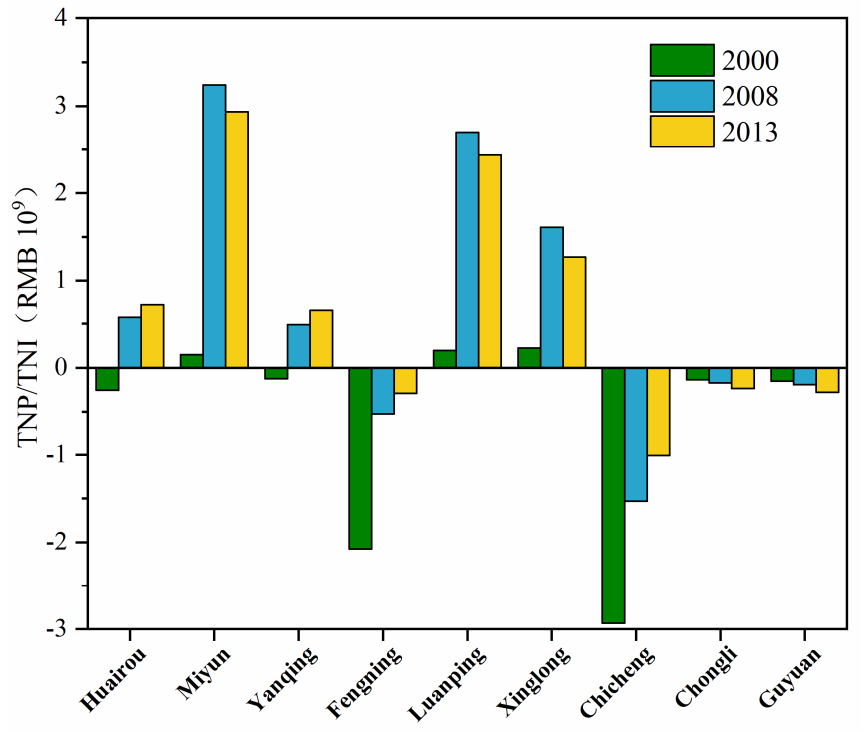


Figure 7. Eco-compensation funds based on SNWDP price by county.

We further evaluated the proportion of eco-compensation funds in county fiscal revenues under both the water resource fee scenario and the alternative SNWDP water pricing scenario (Figure 8). Under the water resource fee scenario, eco-compensation funds accounted for the largest proportion of Yanqing County's fiscal revenue, reaching 12.76%. When the SNWDP water tariff was applied, this proportion increased to 22.59%, indicating that higher opportunity costs of alternative water supply would substantially enhance the compensation intensity. Without effective eco-compensation incentives, local governments may have weaker economic incentives to avoid resource depletion and pollution-intensive development.

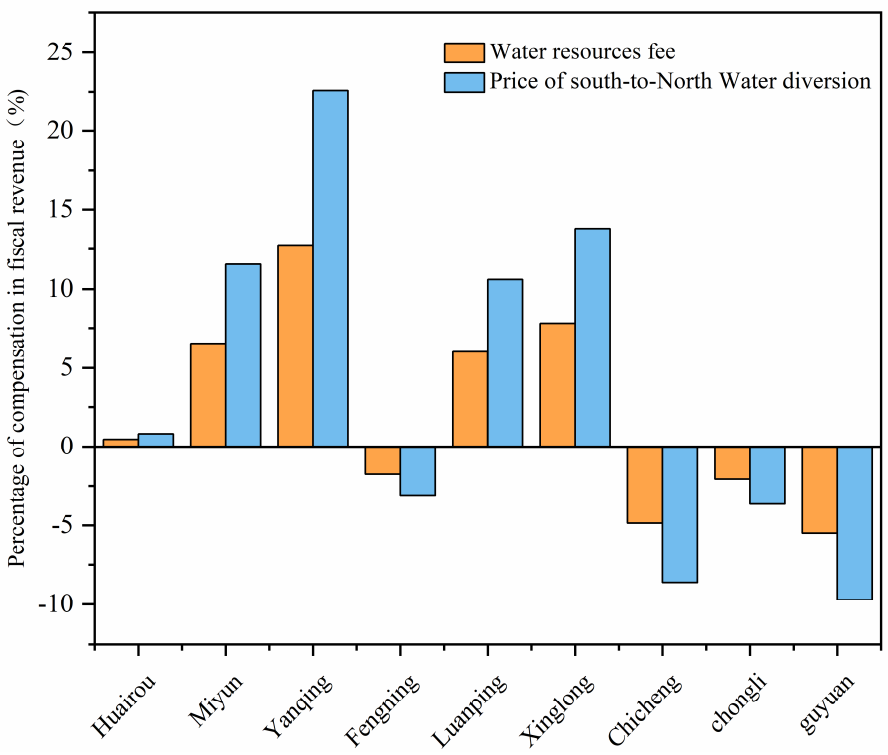


Figure 8. Percentage of eco-compensation funds in fiscal revenue under different water pricing scenarios (%).

4. Discussion

4.1. Drivers of WYE, WCE, and Compensation Funds

The spatiotemporal variations in WYE and WCE reflect the compound impacts of natural water availability, socioeconomic water demand, and environmental pollution pressures, rather than the influence of any single factor. In regions with intensive socioeconomic activities, elevated industrial and domestic water use directly escalates physical water withdrawals and wastewater discharge, thereby intensifying localized water stress. Importantly, even among counties with comparable levels of physical water use, marked disparities in industrial structures and pollution control efficiencies result in significant heterogeneity in pollutant loads. These underlying mechanisms demonstrate that shifts in eco-compensation responsibilities should be conceptualized through the systemic balance between WYE and WCE, rather than being simplified into regional differences in natural water yields. Generally, counties characterized by high WYE and low WCE serve as net ecological service providers and should act as primary compensation recipients; conversely, counties with high WCE represent major consumers of water resources and environmental capacity, thereby bearing greater financial compensation obligations.

Further comparison of compensation amounts with local fiscal revenue indicates that the absolute amount of compensation alone does not fully reflect the actual economic incentive intensity for local governments; its policy effect also depends on the size of compensation funds relative to local fiscal revenue. For example, although Yanqing County did not receive the highest compensation amount, its compensation-to-fiscal-revenue ratio was the highest because of its relatively small fiscal revenue base, reaching 12.76% in 2013 under the baseline scenario. This indicates that the compensation amount reflects the scale of financial transfers, whereas its share of local fiscal revenue better captures the relative fiscal impact and potential incentive strength of the eco-compensation scheme. Therefore, even when counties receive or pay similar amounts of compensation, their policy responses may differ because of differences in fiscal capacity. For recipient counties, a higher compensation-to-fiscal-revenue ratio can translate ecological protection into more substantial fiscal benefits, thereby strengthening economic incentives for water source protection and non-point-source pollution control. For paying counties, a higher payment-to-fiscal-revenue ratio may impose a stronger fiscal constraint; even when the absolute payment is relatively modest, it may encourage local governments to place greater emphasis on pollution control, resource conservation, and industrial restructuring. Thus, the policy effectiveness of eco-compensation depends not only on the scale of financial transfers but also on the relative fiscal incentives and constraints generated by these transfers in relation to local fiscal capacity.

Under the 30% ecological water scenario, reserving a fixed proportion of regional water yield to sustain fundamental ecosystem functions imposes a strict boundary on the volume of water available for socioeconomic

allocation, consequently altering net compensation flows across counties relative to the baseline. In contrast, the SNWDP pricing scenario does not directly alter physical water volume or water quality metrics; instead, it revalues local water resources by introducing the cost of transferred water. Fundamentally, this pricing scenario reflects the shadow price and replacement cost of local water conservation services under a hypothetical substitution framework. Thus, it provides a robust economic benchmark for monetizing compensation standards. In practical policy formulation, decision-makers should integrate ecological flow requirements, water scarcity, pollution abatement responsibilities, and alternative supply costs to design differentiated regional compensation and payment schemes.

4.2. Sensitivity Analysis and Policy Implications

The county-level Water Yield Equivalent and Water Consumption Equivalent accounting framework developed in this study demonstrates strong robustness when dealing with complex hydrological fluctuations. A sensitivity analysis was conducted on three parameters—water withdrawal, wastewater discharge and pollutant load—by increasing their values by 10%. Results indicate that a 10% increase in water withdrawal increased the Water Consumption Equivalent by 3.03%, 1.19%, and 0.98% in 2000, 2008, and 2013, respectively. Conversely, a 10% increase in wastewater discharge led to slight decreases of 0.22%, 0.13%, and 0.11% across the same years. In contrast, a 10% increase in pollutant load exerted the largest impact, raising the Water Consumption Equivalent by 7.19%, 8.94%, and 9.13%, respectively. It is shown that changes in water withdrawal and discharge volumes have smaller impacts on Water Consumption Equivalents and changes in pollutant volumes have a more significant effect on Water Consumption Equivalents. Therefore, emphasis should be made on the impact of pollutant discharge volumes from industrial and domestic uses. Technical and institutional measures should be adopted to reduce pollution discharge and therefore maintain the environmental carrying capacity of water.

This sensitivity pattern indicates that water resource management paradigms must transition from singular volumetric control toward the integrated governance of both water quantity and quality. For the industrial and domestic sectors, emphasis should be placed on enhancing water-use efficiency to reduce water withdrawal requirements per unit of economic output. Furthermore, TN emissions must be mitigated through advanced wastewater treatment, reclaimed water utilization, and pollutant source reduction. In regions with heavy pollution loads, emission reduction performance should be integrated into eco-compensation evaluations, thereby transforming pollution control into a direct incentive that alleviates water consumption pressure. For agriculture-dominated areas, priority should be given to controlling non-point source pollution and optimizing nitrogen fertilizer utilization efficiency to curtail the TN load entering aquatic systems. Meanwhile, for upstream regions characterized by strong water yield capacities and critical ecological conservation functions, differentiated eco-compensation mechanisms should be implemented to bolster their financial capacity for water source protection investments.

4.3. Limitations and Future Research

Despite its contributions, this study has several limitations. In terms of indicator selection, although the proposed framework theoretically supports multi-pollutant integrated accounting, the empirical analysis focuses solely on TN. This choice reflects the practical context of watershed management in the Miyun Reservoir basin. Within this region, indicators such as TP have consistently met regulatory standards, and heavy industries have been largely phased out. In contrast, TN has persistently exceeded target levels constituting water environmental pressure. While this single-pollutant focus improves estimation accuracy, it also reveals certain limitations in empirical application. With the increasing refinement of watershed environmental management, the current accounting framework does not yet incorporate the combined effects of multiple pollutants, such as chemical oxygen demand (COD) and emerging contaminants. Furthermore, it overlooks cross-media interactions, particularly atmospheric nitrogen deposition and its hydrological impacts. These omissions may lead to a potential underestimation of the actual water consumption equivalent under complex pollution conditions. Second, the sensitivity analysis evaluates the response of WCE to changes in selected parameters but does not formally quantify the stability of county rankings and payment directions under parameter uncertainty. In addition, constrained by data availability, the dataset used in this study (2000–2013) exhibits a certain degree of temporal lag, and the spatial resolution is limited to the county level. Although these data do not fully reflect the most recent status of watershed management, they provide a critical historical baseline. They successfully validate the applicability of the proposed accounting framework for establishing eco-compensation under existing governance conditions.

To address these limitations, future research should focus on two main directions. First, the framework should be extended from a single-pollutant perspective to a multi-pollutant integrated approach, incorporating TP, COD, and emerging trace contaminants. Concurrently, future models must account for the cross-media impacts of climate change and atmospheric deposition on water environmental carrying capacity. Second, leveraging high-resolution

multi-source remote sensing data and real-time monitoring datasets, future analyses should refine the spatial scale from the county level to finer resolutions. Such improvements would enhance the representation of spatial heterogeneity and provide a more robust scientific basis for developing precise and dynamic long-term ecological compensation mechanisms. While this empirical study focuses on China's unique administrative eco-compensation mechanism, its core methodology possesses broad international applicability. For example, the Murray–Darling Basin (Australia) has established basin-scale water allocation and environmental water management mechanisms to balance ecological protection with regional water use. By translating such basin-scale goals into quantifiable equivalents, this approach can support similar cooperative water governance globally. For transboundary watersheds worldwide where market-based Payments for Ecosystem Services (PES) are impeded by ambiguous property rights or prohibitive transaction costs, the proposed framework offers a robust tool for intergovernmental financial burden-sharing.

5. Conclusions

This study develops a watershed eco-compensation standard accounting framework that simultaneously considers water quantity and quality from both water production and consumption perspectives. By introducing the WYE and WCE indicators, the framework is applied to nine counties in the Miyun Reservoir watershed.

The results show that, first, influenced by natural water yield, socioeconomic water use, and TN pollution loads, WYE and WCE exhibit substantial spatial heterogeneity across counties, resulting in significant differences in compensation responsibilities and receipts. Under the baseline scenario, Miyun and Luanping counties have relatively high WYE values and therefore receive relatively higher compensation, whereas Chicheng County incurs the highest compensation payment due to its high pollution load. Second, comparison of compensation results with local fiscal revenue indicates that the compensation-to-fiscal-revenue ratio better reflects the potential fiscal incentive or constraint imposed on local governments. In 2013, for example, compensation funds accounted for 6.53% and 4.87% of the fiscal revenues of Miyun and Chicheng counties, respectively, under the baseline scenario. Although Yanqing County did not receive the highest absolute compensation amount, its compensation-to-fiscal-revenue ratio was the highest (12.76%) because of its relatively small fiscal revenue base, indicating substantial differences in the relative fiscal importance of eco-compensation across counties. Finally, scenario analysis shows that key parameters, including ecological water requirements and the SNWDP water price, significantly affect the scale of compensation funds. Using the SNWDP water price as the basis for valuation increases the compensation amounts received or paid by counties across the watershed, thereby potentially strengthening incentives for water resource and environmental protection.

Based on the case-study results, simultaneously incorporating water quantity and quality as well as water production and consumption into the compensation standard can provide a quantitative basis for differentiating compensation responsibilities and benefits among counties in the Miyun Reservoir watershed. It may also provide a more comprehensive representation of the contributions and costs of different counties in water resource conservation and utilization.

Author Contributions

Q.C.: Investigation, analysis, or interpretation of data, visualization, writing—original draft preparation, validation, writing—reviewing and editing. D.H.: Investigation, software, analysis, or interpretation of data, writing—original draft preparation. A.S.: Investigation, data curation, software. Y.R.: Investigation, data curation, software. X.C.: Investigation, data curation, software. X.L.: Analysis, or interpretation of data, writing—reviewing and editing, supervision. B.S.: Conceptualization, methodology, writing—reviewing and editing, supervision. All authors have read and agreed to the published version of the manuscript.

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All data used in this study were obtained from publicly available sources.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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