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Measurement and spatio-temporal characteristics of ecosystem service value flow in yangtze river basin during 2010–2023: a network perspective

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Understanding the spatial flows of ecosystem services (ES) is essential for designing effective ecological compensation mechanisms. This study examines the spatial characteristics and evolution of ES flows in the Yangtze River Basin and their implications for transverse ecological compensation. Using the InVEST model to quantify ES supply and demand and a gravity model to simulate flow paths, we combined network analysis to identify critical nodes and bottlenecks. The results reveal a distinct "upstream supply–midstream transfer–downstream demand" gradient pattern. Upstream regions serve as primary suppliers and compensation beneficiaries, midstream regions function as transfer hubs, and downstream regions act as major demand areas and compensation contributors. From 2010 to 2023, the ES network evolved from a sparse structure into a complex polycentric system, with core nodes consolidating and secondary nodes emerging. Spatiotemporal analysis of ecological compensation shows a clear gradient with a general mitigation of supply–demand mismatch, indicating positive policy outcomes. This study recommends optimizing compensation criteria, enhancing the capacity of peripheral nodes, strengthening regional coordination, and balancing ecological and economic benefits to support sustainable ecological civilization development in the Yangtze River Basin.

KEYWORDS

ecosystem service value, supply–demand-flow, InVEST model, complex network analysis, gravity model

1 Introduction

The Yangtze River Basin is one of China's most water-rich, ecologically diverse, and economically dynamic regions, as well as a critical ecological functional zone on a global scale. Its abundant forest, wetland, and lake ecosystems provide a variety of ecosystem services—including water conservation, water purification, flood mitigation, and carbon sequestration—that underpin regional economic activities and social development (Zhai et al., 2025; Nan and Fang, 2025; Zhang et al., 2022). However, rapid urbanization and economic growth have intensified the mismatch between the supply and demand of ecosystem services within the basin. The upstream areas exhibit strong ecosystem service supply capacity but relatively lower economic development, whereas the midstream and downstream regions face growing ecological constraints amid surging demand (Zhang et al., 2024; Qu et al., 2024). Against this backdrop, understanding the flow of ecosystem services from supply to demand areas and revealing the spatial patterns of value transfer have become essential for improving basin-wide ecological compensation mechanisms.

The flow of ecosystem service value results from the cross-regional transfer of natural resources and their interaction with human economic activities, forming the foundation for equitable and rational ecological compensation (Han and Deng, 2024; Xu et al., 2021; Balzan et al., 2018). While numerous studies have examined the static patterns of supply and demand of ecosystem services, fewer have addressed the spatial dynamics of service flows and the characteristics of value transfer (Huang et al., 2024; Wang et al., 2019). Particularly in complex river basin systems, the movement of ecosystem services is influenced not only by natural factors (e.g., hydrological processes, topographic features) but also significantly shaped by human activities such as land use change, economic development, and policy interventions (Ekka et al., 2020; Geneletti and Linda, 2016). Therefore, a systematic approach to quantify the relationships between supply, flow, and demand of ecosystem services—and to uncover their spatiotemporal dynamics—is urgently needed to inform more effective basin management.

This study investigates the flow of ecosystem service value in the Yangtze River Basin and its implications for transregional ecological compensation through a "supply-flow-demand" network framework. Theoretically, it conceptualizes ecosystem services as a dynamic interaction between providers and beneficiaries, employing a gravity model to quantify interregional flow pathways and network analysis to identify critical nodes and bottleneck areas in value transfer (Shi et al., 2025; Alamá-Sabater et al., 2015). Practically, it aims to provide data-driven support for designing targeted ecological compensation policies by identifying the spatial distribution of service providers and beneficiaries, thereby facilitating a fair and efficient compensation mechanism (Lu and Zhao, 2025; Niksaz et al., 2025). Furthermore, this research highlights the importance of multifunctional landscapes (e.g., zones along urban-rural gradients) that serve as both key suppliers of ecosystem services and crucial hubs of value flow (Rodríguez-Loinaz and Josu, 2015).

Methodologically, this study integrates remote sensing and geographic information system (GIS) technologies, ecosystem service assessment models (e.g., InVEST), gravity models, and network analysis tools to construct a "supply-flow-demand" network that quantifies the dynamic transfer of ecosystem service value (Huang et al., 2024; Chen et al., 2024). The research includes: (1) assessing the supply capacity and demand intensity of major ecosystem services across the Yangtze River Basin to reveal their spatial mismatches and value flow patterns; (2) modeling ecosystem service flows using a gravity model to quantify flow intensity and value distribution; (3) identifying critical nodes and bottleneck areas through network analysis; and (4) proposing policy recommendations for optimizing ecological compensation mechanisms based on value flow. This study is expected to provide scientific support for ecological conservation and resource management in the basin and contribute to regional sustainable development and ecological civilization construction.

The principal innovation of this study lies in introducing a complex network perspective to elucidate the spatial flow of ecosystem services. While previous research has predominantly focused on static supply-demand assessments or simulated flow paths in isolation, a network approach enables the simultaneous characterization of the structural topology, interregional interactions, and dynamic evolution of the entire "supply-flow-demand" system. This perspective allows us to identify not only key supply and demand nodes but also critical transmission hubs, bottleneck areas, and the overall robustness and vulnerability of the service flow system. By integrating the gravity model with network analysis, we move beyond descriptive flow mapping to quantitatively analyze the scaling properties, community structure, and functional roles of nodes within the basin. This methodological framework provides a novel lens for understanding how ecosystem services are transferred across regions and offers a scientific basis for designing targeted, efficient, and resilient ecological compensation mechanisms that account for systemic interdependencies.

The remainder of the paper proceeds as follows. Section 2 briefly reviews relevant literature. Section 3 describes the methodology. Section 4 examines results. Discussions are covered in Section 4. Conclusions and policy recommendations are presented in Section 5.

2 Literature review

2.1 Evolution of ecosystem service supply-demand assessment methods

Research on ecosystem service supply-demand relationships has evolved from theoretical framework construction to dynamic mechanism analysis and policy applications, providing a multidimensional scientific basis for understanding complex ecosystems (You et al., 2024). Early studies primarily focused on revealing the spatial matching between ecosystem service supply capacity and demand intensity, as well as the dynamic coupling mechanisms between them (Liu et al., 2019). The field has progressively developed a research framework encompassing "qualitative identification, spatial localization, quantitative assessment, and policy formulation," which emphasizes not only static supply-demand relationships but also their evolution characteristics under multi-scale and dynamic conditions (You et al., 2024).

In practical applications, watershed case studies have demonstrated significant spatial mismatches between service supply and demand areas. For instance, research in the Huangshui River Basin quantified supply-demand relationships for multiple ecosystem services (including water yield, soil conservation, and carbon sequestration), revealing that upstream regions typically provide higher ecosystem service supply while densely populated downstream areas exert greater pressure on ecosystems due to increasing demand (Fan et al., 2024; Liu et al., 2019). This supply-demand imbalance has become a key driver motivating research on ecosystem service flow networks, while also reflecting the inherent trade-off between regional environmental protection and economic development (Yuan et al., 2023).

Further studies in the Yangtze River Basin have enhanced our understanding of the drivers affecting supply-demand relationships. Through quantitative analysis of how landscape pattern changes influence service supply and demand, researchers have revealed the critical driving effects of landscape fragmentation and land use changes on service flows (Tao et al., 2022). These findings have led to practical strategies for optimizing the matching of service supply and demand, providing valuable insights for achieving coordinated development between ecological protection and regional economies (Tao et al., 2022).

2.2 Advancements in spatial flow simulation approaches

With the deepening of ecosystem service research, spatial flow analysis has gradually emerged as a crucial tool for revealing the dynamic relationships of services. Early methodological contributions established foundational approaches for mapping service flows from supply to demand areas, clearly delineating the spatial characteristics of service flow paths (Ala-Hulkko et al., 2019). These studies demonstrated that service flows not only serve as bridges for supply-demand matching but also provide critical foundations for optimizing service allocation in regional ecological management (Ala-Hulkko et al., 2019). Subsequent research proposed new paradigms for conceptualizing service flows, emphasizing the temporal and spatial dynamics of the service flow process, thereby significantly broadening the perspective of traditional static ecosystem service assessments (Bagstad et al., 2013).

To address the complexity of service flows, researchers began incorporating social-ecological perspectives into flow analysis. Pioneering studies from the perspective of social-ecological system interactions analyzed how stakeholder power relationships affect the efficiency of service flows and the equity of resource allocation (Vallet et al., 2019). This integration of sociological theory into service flow research revealed that in watershed governance, supply areas (typically upstream) face the risk of overexploitation of ecological resources due to limited power and voice, further exacerbating inequities in service flows (Vallet et al., 2019). Complementary research integrating spatial flows of urban cultural services through network analysis and value assessment found that land use types significantly influence service flow paths and intensity (Dang and Li, 2023).

Recognizing the limitations of static models in capturing dynamic flow processes, researchers developed more sophisticated dynamic models coupling human and natural systems (Liu et al., 2017). By simulating service flows under different policy and land use scenarios, these studies revealed key nodes, flow paths, and their spatiotemporal dynamic changes, addressing important gaps in traditional flow network research and providing more comprehensive perspectives for understanding ecosystem service dynamics (Liu et al., 2017). Despite these advancements, significant technical and theoretical challenges remain, particularly regarding interactions among multiple service types and their trade-off mechanisms, including how trade-offs between different services change dynamically and how to quantify the comprehensive impacts of different services on regional ecological and economic systems (Liu et al., 2017).

2.3 Network analysis applications in ecosystem service research

Network analysis has emerged as a powerful approach for understanding the complex relationships in ecosystem service flows. The new paradigm of ecosystem service flows emphasizing spatiotemporal dynamics provides theoretical guidance for understanding the process and value transfer patterns of ecosystem services moving from supply to demand areas in large river basins like the Yangtze (Huang et al., 2024). Social-ecological system perspectives further enrich this understanding by revealing how stakeholder power relationships influence service flows and allocation, providing crucial support for designing equitable ecological compensation mechanisms between upstream and downstream regions (Wang et al., 2023). This is particularly relevant in contexts where upstream areas bear ecological protection responsibilities while midstream and downstream regions benefit (Wang et al., 2023).

In model construction, ecosystem service flow mapping methods that quantify flow paths, intensity, and spatial characteristics between supply and demand nodes offer technical references for constructing ecosystem service flow networks in complex watershed systems (Bagstad et al., 2013). More recently, dynamic models integrating policy scenarios and land use changes have advanced our ability to capture nonlinear dynamic characteristics of service flows (Zhong et al., 2024). These models can simulate service flow patterns under different scenarios, identify key nodes and flow bottlenecks, and provide scientific bases for optimizing service flows and resource allocation (Zhong et al., 2024).

Methodological applications continue to evolve, with gravity models that quantify service flow intensity and paths being combined with supply-demand data to reveal core pathways and value distribution (Bagstad et al., 2013). Similarly, integrated approaches combining network analysis and value assessment provide technical support for evaluating synergies and trade-offs among services (Vogdrup-Schmidt et al., 2017; Barton et al., 2020). These network-based approaches enable researchers to move beyond simple flow characterization to understand the systemic properties and functional relationships within ecosystem service transfer systems.

Despite these advancements, current research still exhibits limitations in several areas, including insufficient integration of multiple service type interactions, limited understanding of network dynamic evolution mechanisms, and inadequate interdisciplinary combination of ecological and sociological approaches. These gaps highlight the need for precisely the kind of integrated “supply-flow-demand” network analysis presented in this study, which combines InVEST modeling, gravity model simulation, and complex network analysis to provide a comprehensive understanding of ecosystem service flows in the Yangtze River Basin.

3 Models and data

Currently, a common method for measuring ecosystem service flows involves calculating the demand for and supply of ecosystem services to derive their spatial distribution (Shi et al., 2025; Goldenberg et al., 2017). Scholars suggest that if the supply-demand balance is greater than zero, it indicates a surplus of ecosystem service value available for export from the region, identifying it as a provider of ecosystem services and thus an object of transverse ecological compensation. Conversely, if the supply-demand balance is less than zero, the region is considered a beneficiary of ecosystem services and thus a subject of transverse ecological compensation (Zhang et al., 2025; Wang et al., 2019).

Therefore, for accounting water yield service flows, the fundamental approach is to first calculate the regional water yield and then determine the regional water demand. Regional water yield is mostly estimated using the InVEST model (Yang et al., 2020), while water demand is generally measured based on the sectoral water demand calculation method proposed in the ARIES model (Zhu et al., 2022).

However, we argue that the spatial flow of water yield services is also influenced by the economic and social development between regions. Economic and social development relies on water demand—the higher the level of development, the greater the demand for water resources. As a result, these socioeconomically advanced regions create a "gravitational pull" for water yield services in spatial terms, and the strength of this pull increases with their development level.

To incorporate this perspective, this chapter first employs the InVEST model to estimate water yield across different regions. Then, when calculating water yield service flows, a modified gravity model—incorporating factors such as geographical distance, economic development, and social development—is applied.

3.1 Ecosystem service supply model and demand assessment

The supply of water yield service was assessed using the InVEST model. As one of the most widely used tools in the field of ecosystem service supply assessment, the InVEST model was developed by the Natural Capital Project team at Stanford University. It simulates the supply capacity of ecosystem services by integrating input data on natural resources and offers assessment modules for marine, freshwater, and terrestrial ecosystem services. Among these, the freshwater module is specifically designed for simulating and quantifying water yield service supply.

In this study, the freshwater module of InVEST version 3.10.2 was applied. Using land use data alongside spatially distributed data on precipitation, temperature, evapotranspiration, soil properties, and root depth, the water yield supply capacity of the Yangtze River Basin was simulated for the years 2010, 2015, 2020, and 2023. This provided essential data for assessing the dynamic changes in regional ecosystem services.

The freshwater module of the InVEST model employs a water balance approach to simulate the total water retention and discharge per grid cell. The water yield, denoted as *Y(X)*, is calculated as the difference between total water retention and total water discharge. The formula for calculating water yield *Y(X)* is:

$$Y(X) = \left(1 - \frac{AET(X)}{P(X)}\right) \cdot P(X) \tag{1}$$

In Equation 1, *Y(X)* represents the annual water yield per grid cell, measured in millimeters (mm). *AET(X)* denotes the annual actual evapotranspiration per grid cell, in millimeters (mm). *P(X)* refers to the annual actual precipitation per grid cell, also in millimeters (mm).

The calculation of water yield in the Yangtze River Basin requires the following input data: land use, annual precipitation, actual evapotranspiration, root restricting layer depth, plant available water content, vector boundary of the study area, evapotranspiration coefficient *(K)*, and seasonal constant *(Z)*. The data sources and acquisition methods for the InVEST model inputs are described in Supplementary Appendix.

Ecosystem service demand was quantified using the sectoral water demand calculation method derived from the ARIES model framework. Water demand was estimated across three major sectors: agricultural, industrial, and domestic. Agricultural demand was calculated based on irrigated crop areas and crop-specific water requirements; industrial demand was estimated using industrial water consumption per unit GDP; and domestic demand was derived from population data and *per capita* water use statistics. This multi-sector approach ensures a comprehensive assessment of regional ecosystem service demand that aligns with the economic and demographic characteristics of each basin region.

3.2 Ecosystem service flow model

The gravity model is a method used to determine the relationships between elements, laying a theoretical foundation for the quantitative study of regional spatial interactions (Roy and Thill, 2004). Since the 1990s, the gravity model has been widely applied to measure the strength of economic connectivity between regions and to predict the flow of people, goods, capital, and information across areas (Hussain et al., 2020).

Generally, the gravity model incorporates two fundamental elements: the first is the influence of "mass," which in this chapter refers to the level of socioeconomic development—the higher the development level, the greater the mass, and thus the stronger the attraction to water yield services. The second is the influence of distance, meaning that the attraction to water yield services decays with increasing geographical distance. The traditional gravity model is expressed as Equations 2, 3.

$$y_{ij} = \frac{\sqrt[3]{P_i E_i G_i}\,\sqrt[3]{P_j E_j G_j}}{\left(\frac{D_{ij}}{g_i - g_j}\right)} \cdot k_{ij} \tag{2}$$

$$k_{ij} = \frac{E_i}{E_i + E_j} \tag{3}$$

In the equations, y_{ij} represents the attraction of water yield services between province i and province j. E_i and E_j denote the water yield service quantities of province i and province j,

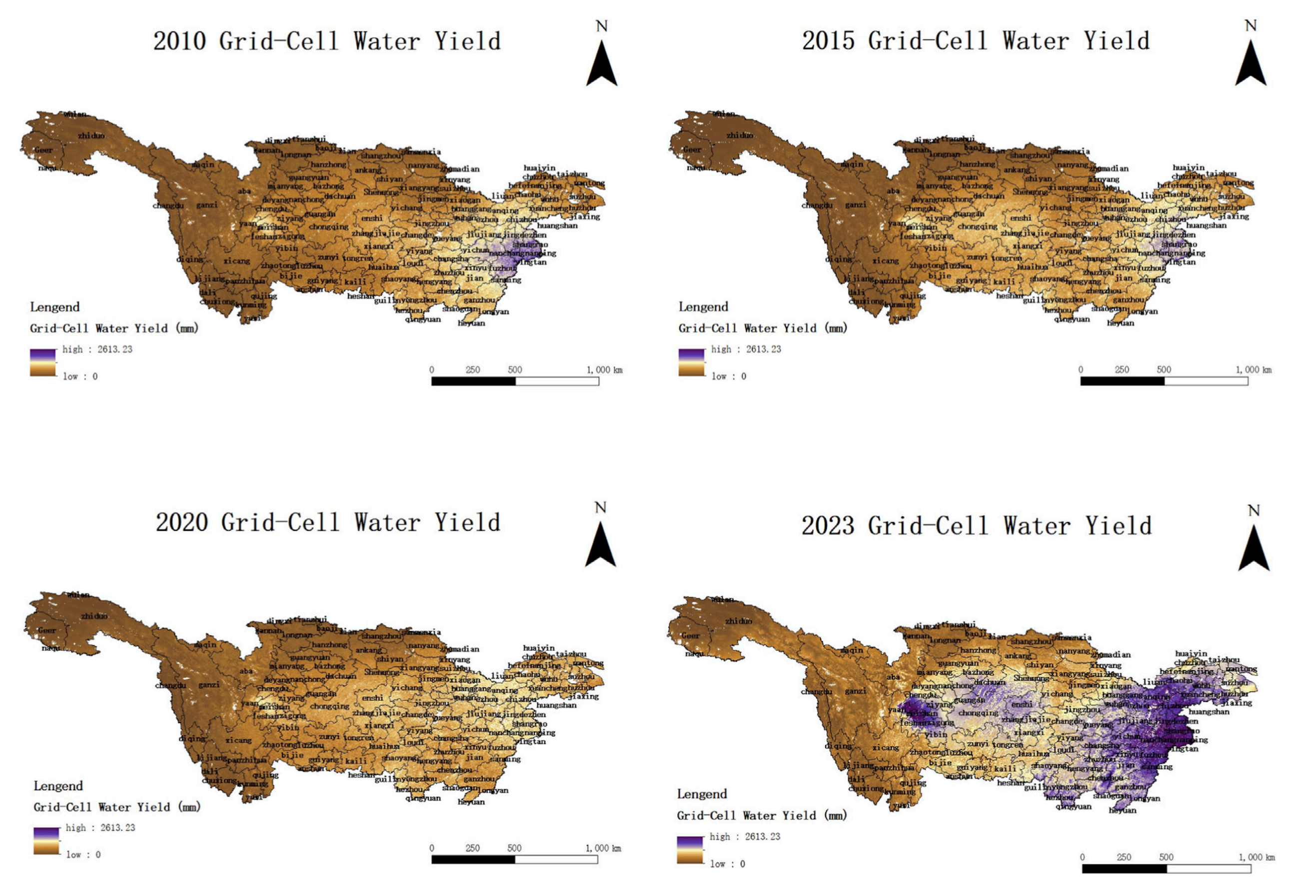

FIGURE 1
Water yield of Yangtze River Basin (2010, 2015, 2020 and 2023).

respectively. P_i and P_j represent the year-end total population of province i and province j, respectively. G_i and G_j indicate the gross regional product of province i and province j, respectively. D_{ij} refers to the geographical distance between province i and province j. g_i and g_j represent the *per capita* gross regional product of province i and province j, respectively. k_{ij} denotes the contribution rate of province i in the water yield service relationship between provinces i and j. By calculating the net inflow and outflow of water yield service attraction across the Yangtze River Basin, the final water yield service flow is determined.

3.3 Transverse ecological compensation model

The theoretical ecological compensation is determined by the water yield service flow and the water rights price (Lv et al., 2021). The conversion of water yield model results to calculable water rights trading prices followed a systematic procedure. First, baseline water rights prices were derived from the China Water Exchange's publicly reported transaction records spanning 2010–2023, focusing on comparable hydrological regions within the Yangtze River Basin. These market prices were calculated as volume-weighted averages of actual transactions within each study year to reflect true economic values. The price data were then adjusted annually according to market fluctuations and regional economic indicators to maintain temporal consistency with our water yield simulations, as shown in Equation 4:

$$\boldsymbol{C_{ij} = Y_{ij} \cdot p} \tag{4}$$

where C_{ij} refers to the theoretical transverse ecological compensation received by province i from province j. Y_{ij} denotes the effective water yield services transferred from province i to province j. p represents the unit water price. The price is substituted with the water rights trading price from the China Water Exchange.

4 Results

4.1 Ecosystem service supply

Based on the water yield module of the InVEST model, a quantitative assessment of water yield services within the ecosystem services of the Yangtze River Basin was conducted. The spatial distribution of water yield for the years 2010, 2015, 2020, and 2023 was obtained, as shown in Figure 1.

From 2010 to 2023, the water yield per grid unit at the prefecture level in the Yangtze River Basin exhibited significant spatiotemporal changes, with particularly pronounced variations in 2023. Overall, between 2010 and 2020, the spatial pattern of water yield remained relatively stable, showing a distinct characteristic of higher values in the east and lower values in the west. The western regions (e.g., Sichuan, Chongqing) generally had lower water yield, while the eastern regions (e.g., Jiangsu, Shanghai) showed higher values. The central regions (e.g., Hubei, Hunan) experienced a gradual increase in water yield, with a more even distribution. In 2010, water yield was primarily concentrated in the eastern parts of the basin, with lower values in the west, overall reflecting a gradual increase from west to east. By 2015 and 2020, although the general pattern did not change significantly, water yield in the central regions increased, especially in areas such as Hubei and Hunan, indicating a growing trend. However, changes in 2023 were particularly notable, with large areas of high-water yield (purple areas) emerging in the central and eastern regions (e.g., Hubei, Anhui, Jiangsu), while changes in the western regions remained minimal. This shift suggests a significant spatial restructuring of water yield in the Yangtze River Basin in 2023.

In terms of temporal changes, water yield in the Yangtze River Basin remained relatively stable from 2010 to 2020, with no drastic alterations in spatial distribution. The main trend was a gradual increase and more uniform distribution of water yield in the central regions. In contrast, changes between 2020 and 2023 were particularly dramatic, with a marked increase in water yield in the eastern and central regions, especially in Hubei, Anhui, and Jiangsu, where extensive high-water-yield areas formed. This sharp change may be closely linked to multiple factors. First, climate change may be a primary driver, as increased precipitation in the Yangtze River Basin in recent years could have influenced the spatial distribution of water yield. Second, land use changes may also play an important role. Activities such as wetland restoration and agricultural irrigation in the central and eastern regions may have enhanced water yield in these areas. Furthermore, ecological protection policies implemented in recent years, such as the "Yangtze River Conservation Initiative," may have profoundly affected the spatiotemporal distribution of water yield, particularly in the central and eastern regions, where policy measures likely promoted rational water resource use and improved ecological conditions.

To quantify this spatial restructuring, we calculated the relative change in mean water yield between 2010 and 2023. The basin-wide average increased by approximately 18%, with the most dramatic increases observed in the central and eastern regions (e.g., Hubei and Jiangsu provinces), where values rose by over 30%, confirming the significant spatial shift observed in Figure 1. Overall, the water yield per grid unit in the Yangtze River Basin showed significant spatiotemporal changes from 2010 to 2023, with a notable increase in the eastern and central regions in 2023 and a clear shift in spatial distribution. These changes reflect the combined effects of multiple factors, including climate, land use, and policy interventions, and highlight the complexity and regional specificity of water resource dynamics in the Yangtze River Basin. This provides a scientific basis for regional water resource management and ecological conservation.

4.2 Spatiotemporal evolution of ecosystem service supply-demand

The supply-demand patterns of ecosystem services in the Yangtze River Basin exhibit significant regional disparities in spatial distribution, as can be seen in Figure 2.

Supply-demand balanced areas (shown in blue) are primarily located in the western part of the basin (e.g., the eastern margin of the Qinghai–Tibet Plateau and the Western Sichuan Plateau). These regions demonstrate a strong capacity for ecosystem service supply coupled with relatively low demand, resulting in a surplus of supply over demand. From 2010 to 2023, the supply-demand balance in these areas remained generally stable with minimal changes in spatial extent, indicating relatively undisturbed ecological conditions and limited impact from human activities.

In contrast, supply-demand imbalanced areas (shown in yellow to red) are mainly concentrated in the Middle-Lower Yangtze Plain and its surrounding regions (e.g., Hubei, Hunan, Anhui, and Jiangsu). These areas are characterized by high population density and frequent economic activities, leading to demand that exceeds supply capacity. In 2010, the degree of imbalance was particularly pronounced in the mid-lower regions, with widespread red areas (gap of supply-demand: 102 to −110) indicating severe shortage. By 2023, the extent of imbalanced areas had reduced, with red zones decreasing and yellow/light green areas increasing, reflecting a certain mitigation of the supply-demand imbalance.

Temporally, the supply-demand patterns of ecosystem services in the Yangtze River Basin underwent significant changes between 2010 and 2023. From 2010 to 2015, changes were relatively minor, with the spatial distribution of balanced and imbalanced areas remaining largely stable. Supply-demand tensions remained prominent in the mid-lower regions, especially around economically developed areas along the Yangtze River (e.g., Wuhan, Nanjing). Between 2015 and 2020, the extent of imbalanced areas began to decrease, with a noticeable reduction in red zones, suggesting an alleviation of supply-demand imbalance in the mid-lower reaches—likely attributable to the implementation of ecological protection policies and restoration projects. From 2020 to 2023, changes became more pronounced: supply-demand tensions in the mid-lower regions further eased, red areas almost disappeared, yellow zones transitioned to light green, and the supply-demand gap narrowed. Meanwhile, the western regions maintained a stable supply-demand balance with consistently strong supply capacity. The mitigation of the supply-demand imbalance can be quantified by the reduction in the spatial extent of the "severe shortage" areas (red regions, with gaps from −102 to −110). Between 2010 and 2023, the areal proportion of these severe imbalance regions decreased by an estimated 40%, while the proportion of "moderate imbalance" (yellow) and "near balance" (light green) areas correspondingly increased.

The spatiotemporal changes in ecosystem service supply-demand patterns across the Yangtze River Basin are influenced by both natural conditions and human activities. The western region's complex topography, high vegetation coverage, and strong ecosystem service supply capacity, combined with low population density and limited demand, contribute to a stable supply-demand balance. The mid-lower regions, with their flat terrain, dense population, and intensive economic activities, exhibit high demand for ecosystem services but limited supply capacity, leading to frequent imbalances. Moreover, recently implemented ecological protection policies—such as the "Yangtze River Conservation" strategy and the "Grain for Green"

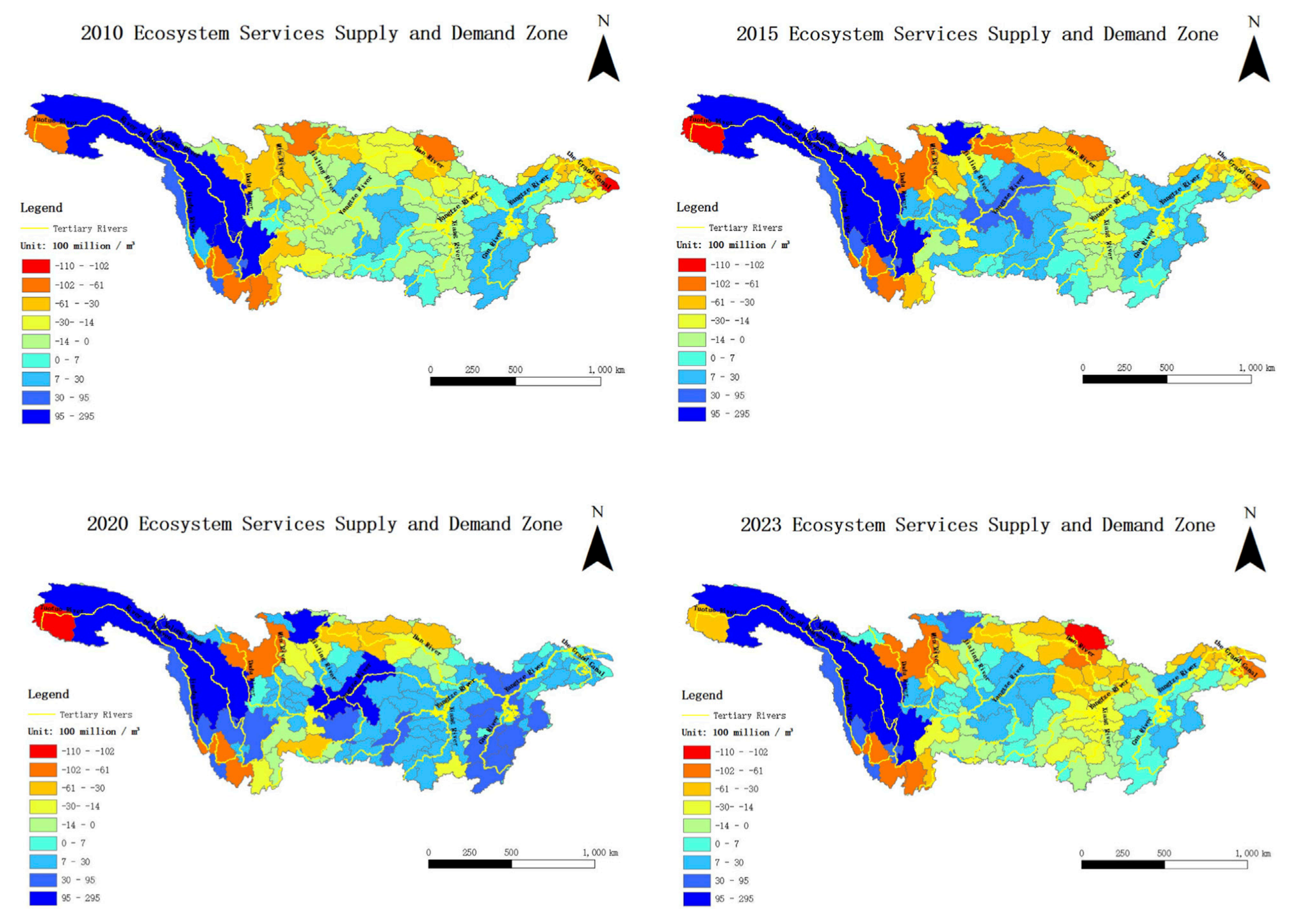

FIGURE 2
Supply-demand patterns of ecosystem services in Yangtze River Basin (2010, 2015, 2020 and 2023).

program—have significantly enhanced the supply capacity of ecosystem services, particularly in the mid-lower regions, effectively mitigating supply-demand tensions. Concurrently, urbanization and economic development have also played important roles in shaping the dynamic changes in supply-demand patterns.

4.3 Ecosystem service supply-flow-demand network

From 2010 to 2023, the ecosystem service network in the Yangtze River Basin underwent a significant evolution from a sparse to a highly complex structure, with a gradual increase in network connectivity and a more pronounced characterization of ecosystem service flows (as shown in Figure 3).

In 2010, the network exhibited a "core-periphery" structure, where ecosystem service flows were mainly concentrated among a few core cities (e.g., Chongqing, Wuhan, Shanghai). Peripheral nodes had low levels of participation, service flows were unidirectional, and followed a primary transfer pattern from upstream to midstream and downstream regions. By 2015, network connectivity had strengthened, secondary core nodes (e.g., Chengdu, Changsha, Nanjing) began to emerge, and the network started to show preliminary signs of polycentricity, with an expanded scope of inter-city ecosystem service flows. In 2020, the network structure became further complexified, forming a multi-tier "core–secondary core–periphery" network. The role of core nodes (e.g., Chongqing, Wuhan, Shanghai) was reinforced, secondary core nodes played significant roles, and cross-regional linkages increased markedly. By 2023, the network reached a high degree of complexity: the number of core and secondary core nodes increased, connectivity density peaked, interregional ecosystem service flows became more multidirectional and frequent, and the participation of peripheral nodes improved significantly—though these remained primarily service exporters. Overall, the network evolved from sparse to complex, with core nodes continuously strengthening their positions, a trend toward polycentricity, and a stable pattern of service flow direction maintaining a gradient transfer from upstream to midstream and downstream regions.

The formation and evolution of communities within the ecosystem service relationship network of the Yangtze River Basin were driven by multiple factors, including geographical proximity, supply-demand relationships of ecosystem services, economic development levels, and policy initiatives. In 2010, communities initially formed primarily based on geographical proximity, divided into three regional groups: upstream, midstream, and downstream. The upstream community, centered

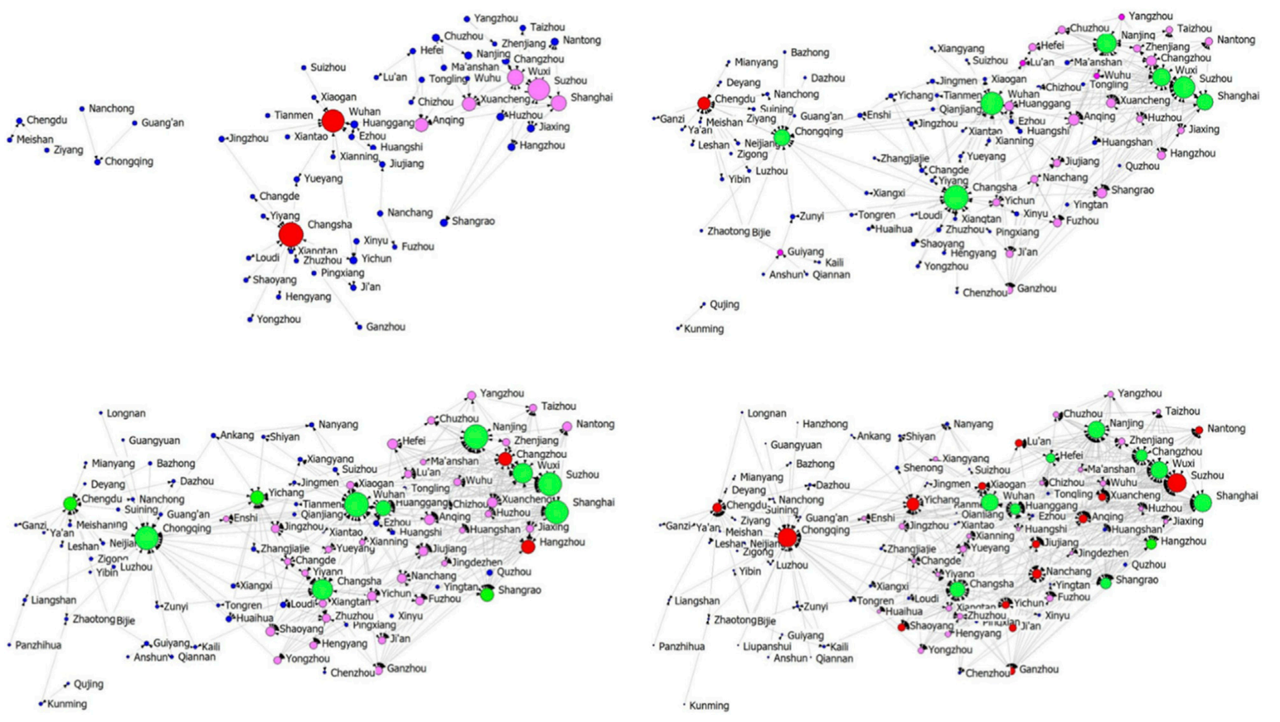

FIGURE 3
Ecosystem service supply-flow-demand network of Yangtze River Basin (2010, 2015, 2020 and 2023).

on Chongqing, mainly supplied ecosystem services; the midstream community, centered on Wuhan, served as a transit hub; and the downstream community, centered on Shanghai, was primarily a demand area for ecosystem services. By 2015, community scales expanded, connectivity strengthened, secondary core nodes (e.g., Chengdu, Changsha) rose in prominence, and cross-community linkages began to increase—though core cities remained the central hubs. In 2020, the community structure showed a trend toward polycentricity: the upstream community was co-led by Chongqing and Chengdu, the midstream community was driven by the dual cores of Wuhan and Changsha, and the downstream community was centered on Shanghai and Nanjing. Ecosystem service flows within and between communities significantly intensified. By 2023, the community network became highly complex: the upstream community expanded to include the entire Sichuan and Chongqing region, the midstream community further strengthened its bridging role, the downstream Yangtze River Delta region exhibited the densest connectivity, and cross-community collaboration reached its highest level. Overall, communities evolved from regionally distributed groups into a highly complex networked structure, with core cities dominating community formation and evolution, and cross-community ties significantly enhancing.

The ecosystem service relationship network in the Yangtze River Basin developed gradually from a sparse structure in 2010 into a complex network by 2023, with significantly increased connectivity density. The increase in network connectivity density was substantial. From 2010 to 2023, the density value increased by 153% (from approximately 0.15–0.38), quantitatively supporting the observed evolution from a sparse to a highly interconnected network. Core nodes and community structures gradually formed and were reinforced. The status of core cities (e.g., Chongqing, Wuhan, Shanghai) was continuously consolidated, secondary core nodes (e.g., Chengdu, Changsha, Nanjing) emerged, and the network exhibited a polycentric pattern, with ecosystem service flows maintaining a stable gradient transfer from upstream to midstream and downstream regions. Communities evolved from initially regional distributions into highly complex networked structures, with markedly enhanced cross-community linkages, and both the number and scale of communities increasing annually along with higher connectivity density. In the future, the network structure is expected to become further complexified, cross-regional collaboration will continue to strengthen, and the role of peripheral nodes is likely to improve. To achieve the sustainable development of ecosystem services in the Yangtze River Basin, it is essential to enhance ecological protection in upstream regions, optimize the bridging function of midstream regions, promote ecological compensation in downstream regions, and establish regional collaborative governance mechanisms to improve overall network efficiency and facilitate interregional ecosystem service flows and cooperation.

4.4 Evolution of network structure

We further analyzed the degree distribution of the network, as shown in Figure 4.

The figure reveals that the degree distributions of the ecological service network in the Yangtze River Basin for the years 2010, 2015, 2020, and 2023 all exhibit certain power-law characteristics (linear

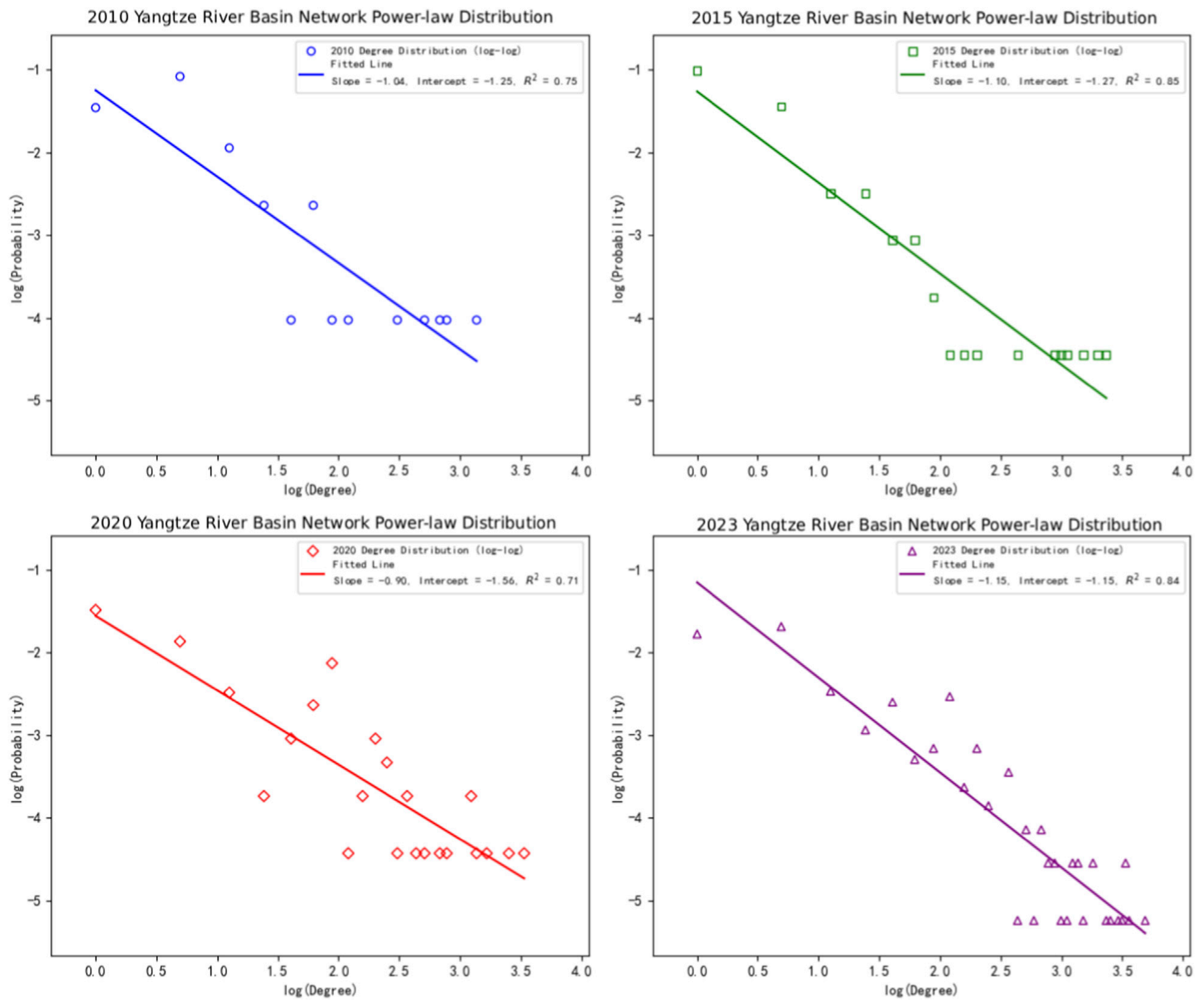

FIGURE 4
Degree distribution of supply-demand network of Yangtze River Basin (2010, 2015, 2020 and 2023).

relationships in log-log coordinates), indicating that the network possesses scale-free properties. This reflects the presence of a small number of highly connected core nodes (hub nodes), while the majority of nodes demonstrate low connectivity. This power-law distribution profoundly influences the flow of ecological services.

In 2010, the fitted slope was −1.04 with R^2 = 0.75, indicating relatively weak power-law characteristics. The influence of core nodes was not yet fully apparent; the network was generally sparse, with ecological service flows mainly concentrated among a few core nodes (e.g., Chongqing, Wuhan, Shanghai). Peripheral nodes exhibited low participation, and the scale-free nature of the network was still in its initial stages, with insufficient differentiation in the connectivity of core nodes. By 2015, the fitted slope was −1.10 with R^2 = 0.85, showing strengthened power-law properties. The connectivity of core nodes further increased, secondary core nodes (e.g., Chengdu, Changsha, Nanjing) began to emerge, and the scale-free characteristics became more pronounced. A small number of core nodes demonstrated significantly higher connectivity than others, ecological service flows became increasingly concentrated around these hubs, and the hierarchical nature of the network began to take shape. In 2020, the fitted slope was −0.90 with R^2 = 0.71, indicating a slight weakening of power-law features. The network structure became more complex, the role of secondary core nodes (e.g., Chengdu, Changsha, Nanjing) was further enhanced, connections among core nodes became denser, and the participation of peripheral nodes improved. A trend toward polycentricity emerged, ecological service flows no longer relied entirely on a few core nodes, and the overall balance of the network improved. By 2023, the fitted slope was −1.15 with R^2 = 0.84, and power-law characteristics strengthened again. The high goodness-of-fit (R^2) values for the power-law distributions (ranging from 0.71 to 0.85 across the study years) provide strong statistical evidence for the scale-free properties of the network. The consistently high R^2 values indicate a stable and robust nonlinear relationship between node rank and connectivity. The disparity in connectivity among core nodes became significant; the network reached a high degree of complexity; the status of core nodes (e.g., Chongqing, Wuhan, Shanghai) was further consolidated; and secondary core nodes (e.g., Chengdu, Changsha, Nanjing) also became important hubs for ecological services. The participation of peripheral nodes improved markedly, though their connectivity remained substantially lower than that of core nodes. The scale-free properties of the network stabilized, and the directionality and hierarchy of ecological service flows became more defined.

The power-law distribution is first reflected in the efficient hub function of core nodes. Owing to their high connectivity, core nodes (e.g., Chongqing, Wuhan, Shanghai) serve as major hubs for ecological service flows, undertaking most supply, demand, and transfer functions. These nodes significantly enhance the flow efficiency of ecological services through strong connections, enabling rapid coverage across the network. For instance, Chongqing, as a core supply node in the upstream region, forms strong connections with Wuhan in the midstream and Shanghai in the downstream, facilitating cross-regional flows of ecological services. Simultaneously, the presence of core nodes reinforces the concentration of service flows, which are predominantly channeled among these hub nodes, forming a gradient flow pattern of "upstream supply → midstream transfer → downstream demand." However, this concentration also leads to the dependency of peripheral nodes. Peripheral nodes (e.g., Panzhihua, Zhaotong) have low connectivity, and their ecological service flows primarily depend on connections to core nodes to interact with other regions, while their direct flow capacity remains limited. Most peripheral nodes are located in upstream areas and function mainly as suppliers of ecological services, with strongly directional flows toward core nodes. Although this dependency improves the overall flow efficiency of the network, it also exacerbates regional imbalances. Furthermore, the power-law distribution significantly influences the network's robustness and vulnerability. Scale-free networks exhibit strong robustness against random node failures; even if some peripheral nodes fail, ecological service flows can still maintain overall network functionality through core nodes. However, the failure of core nodes severely impacts the network. Should a core node (e.g., Wuhan or Shanghai) become compromised, ecological service flows would be significantly obstructed, potentially leading to a breakdown of the entire network. Thus, the stability of core nodes is crucial for the flow dynamics within the ecological service network.

Over time, a trend toward polycentricity has gradually emerged in the network. The rise of secondary core nodes (e.g., Chengdu, Changsha, Nanjing) has dispersed flow pressure and optimized network flow efficiency. This polycentric trend not only reduces reliance on individual core nodes but also enhances interregional collaboration, resulting in a more balanced distribution of ecological service flows. For example, the emergence of Chengdu and Changsha has shared the flow pressure initially borne by Chongqing and Wuhan and promoted ecological service flows throughout upstream and midstream regions. Concurrently, the power-law distribution reinforces the gradient flow pattern of ecological services from upstream (supply areas) to midstream (transfer areas) and then to downstream (demand areas). The high connectivity of core nodes ensures the stability of this flow direction, while strong connections between core nodes enable ecological services to quickly cross regional boundaries, enhancing overall flow efficiency. In summary, from 2010 to 2023, the power-law distribution characteristics of the ecological service network in the Yangtze River Basin became increasingly evident. The connectivity of a small number of core nodes was significantly higher than that of other nodes; the scale-free properties of the network stabilized; the status of core nodes continued to strengthen; and the rise of secondary core nodes encouraged polycentric development. Although the connectivity of peripheral nodes increased annually, their role remained primarily focused on exporting ecological services, with limited influence over the overall network. In the future, as regional collaboration deepens, the complexity of the network will further increase, connections between core and secondary core nodes will become denser, and the participation of peripheral nodes is expected to improve. It is essential to strengthen ecological protection of core nodes while using policy guidance to enhance the ecological service supply capacity of peripheral nodes, thereby promoting balanced network development. By establishing regional collaborative governance mechanisms, the efficiency of ecological service flows can be optimized, further consolidating the scale-free properties and polycentric structure of the network.

4.5 Effectiveness and evolution of the ecological compensation mechanism

Based on the aforementioned analysis, we have structured the network characteristics and evolution of ecological service supply, flow, and demand in the Yangtze River Basin. Furthermore, through simulation analysis of the spatial flow of ecosystem services, we calculated the theoretical transverse ecological compensation amounts between provinces within the basin. The results reveal significant temporal and spatial differences and gradient characteristics in ecological compensation across the Yangtze River Basin (as shown in Figure 5).

The theoretical transverse ecological compensation amounts, derived from our ecosystem service flow network (Figure 5), provide a data-driven basis for re-evaluating the rationality and feasibility of current compensation standards. While the stable gradient pattern—with upstream regions as net recipients and downstream regions as net payers—aligns well with the "beneficiary pays" principle and mirrors actual policy trends [Citation, e.g., Xu et al., 2021], our analysis uncovers a critical nuance often overlooked in existing frameworks.

A key finding is the potential inequity faced by midstream regions (e.g., Hubei, Hunan). These areas function as crucial transfer hubs in the network, enhancing connectivity and flow efficiency, yet our model shows they receive minimal compensation. This misalignment suggests that current policies, which primarily focus on the endpoints of supply and demand, may fail to capture the full value created within the service delivery chain. Compensating these transit hubs could improve the system's overall resilience and incentivize the maintenance of critical flow paths.

The close convergence between our modeled values and real-world compensation trends, such as the decreasing payments to upstream provinces as their ecological conditions improved, validates the use of water rights trading prices as a realistic proxy for ecosystem service value. This demonstrates the feasibility of

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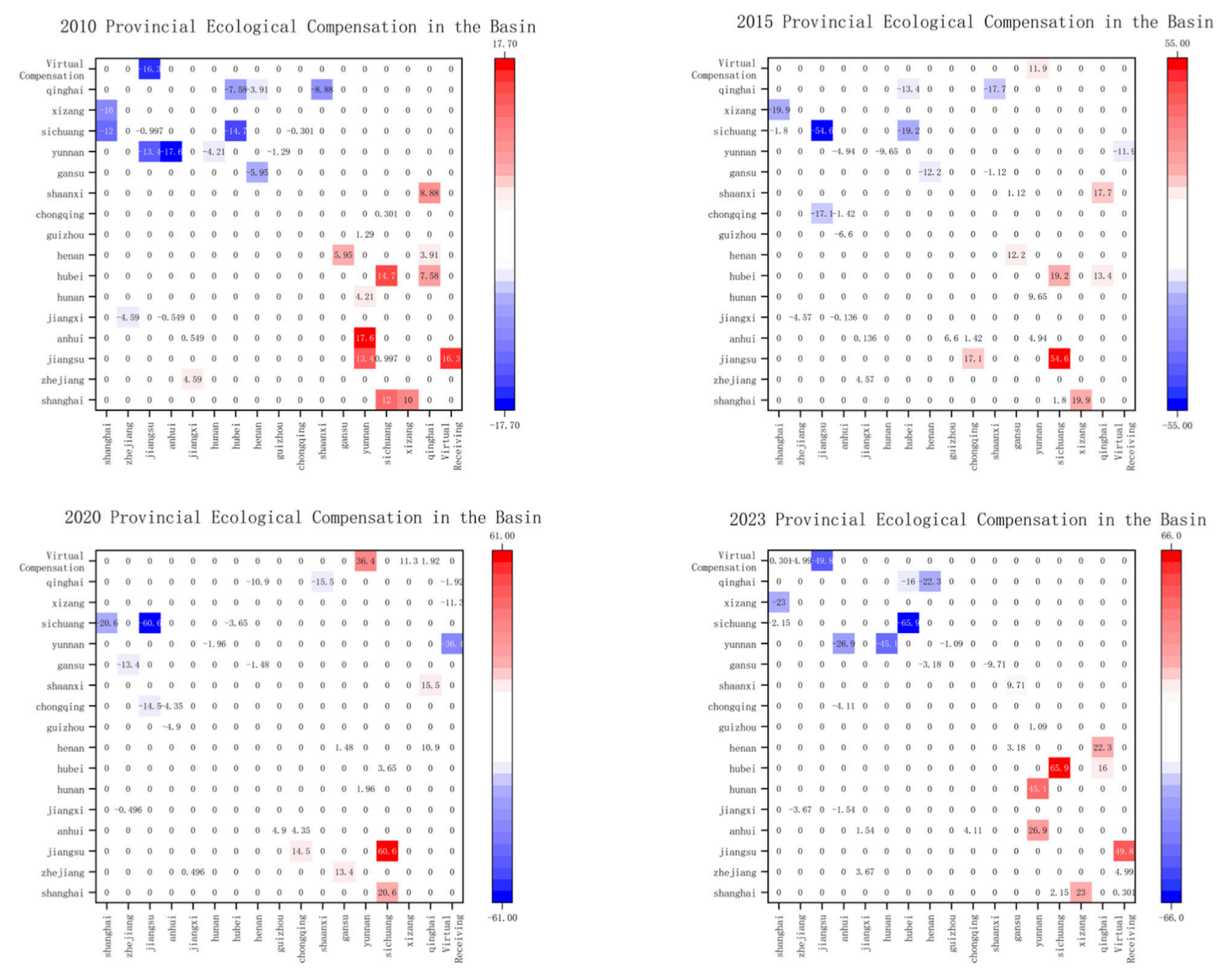

FIGURE 5
Theoretical transverse ecological compensation amounts between provinces within Yangtze River Basin (2010, 2015, 2020 and 2023).

integrating market-based signals into compensation design. Our network-based approach offers a more nuanced and scientifically-grounded framework for designing compensation mechanisms that are not only equitable but also effective in sustaining the entire "supply-flow-demand" system of the basin.

5 Discussions

5.1 Ecological and policy implications of supply-demand dynamics

Our quantification of ecosystem service supply-demand patterns reveals not only significant spatial mismatches but also notable temporal improvements in the Yangtze River Basin. The gradual mitigation of supply-demand imbalances, particularly in the mid-lower reaches, represents a significant finding with important policy implications. The reduction of "severe shortage" areas by approximately 40% between 2010 and 2023 suggests that the implementation of major ecological conservation initiatives, particularly the "Yangtze River Conservation" strategy, has produced measurable benefits (Zhang et al., 2024). This improvement aligns with the national priority of ecological civilization construction and demonstrates that targeted policy interventions can effectively address regional environmental challenges.

The persistent gradient pattern of "upstream supply-midstream transfer-downstream demand" underscores the fundamental interdependence of regions within the basin. This spatial structure necessitates a basin-wide perspective in ecological management, as decisions in one region inevitably affect ecosystem service availability in others (Liu et al., 2019). Our findings provide empirical support for the watershed as an appropriate management unit and highlight the importance of considering the entire "supply-flow-demand" chain rather than focusing solely on either supply or demand in isolation (You et al., 2024). The stability of this pattern despite significant land use changes suggests it represents a fundamental characteristic of large river basins that should inform long-term planning.

5.2 Structural insights from ecosystem service flow networks

The evolution of the ecosystem service flow network from a sparse, core-periphery structure to a complex polycentric system represents a key finding of our study. The emergence of secondary core nodes (Chengdu, Changsha, Nanjing) alongside the consolidation of primary hubs (Chongqing, Wuhan, Shanghai) indicates a maturing network structure that enhances regional resilience. This structural evolution parallels patterns observed in economic and transportation networks, suggesting common principles of network development across different types of flow systems (Wang et al., 2023).

The scale-free properties of the ES flow network, evidenced by high R^2 values (0.71–0.85) for power-law distributions across all study years, carry important implications for ecological risk management. While this topology promotes efficiency through hub-based routing, it also creates vulnerability to targeted disruptions at critical nodes (Zhong et al., 2024). The potential cascade effects of disruptions at major hubs like Wuhan or Shanghai necessitate specific protective measures for these crucial interchange points. Simultaneously, the increasing participation of peripheral nodes, though still primarily as service exporters, suggests a trend toward more distributed responsibility in ecological stewardship.

The community structure evolution within the network reveals how functional regions self-organize around geographical and economic factors. The strengthening of cross-community ties, particularly between the upstream Sichuan-Chongqing community and the midstream Wuhan-Changsha community, indicates growing regional integration in ecological service flows. This emerging connectivity provides a natural foundation for developing sub-basin management partnerships that could operate within the broader watershed governance framework.

5.3 Rethinking ecological compensation standards: rationality and feasibility from a network perspective

The theoretical transverse ecological compensation amounts, derived from our ecosystem service flow network, provide a critical lens through which to evaluate the rationality and feasibility of current compensation standards. Our model reveals a compensation structure that largely aligns with the "beneficiary pays" principle, confirming the logical foundation of existing policies where downstream beneficiaries (e.g., Jiangsu, Shanghai, Zhejiang) compensate upstream suppliers (e.g., Sichuan, Yunnan). This convergence with real-world policy trends, such as the documented decrease in compensation to upstream provinces as their ecological conditions improved, validates the use of water rights trading prices from the China Water Exchange as a credible and market-informed proxy for ecosystem service value (Xu et al., 2021). This alignment underscores the feasibility of integrating our flow-based, data-driven approach into existing policy frameworks.

However, a deeper analysis from the network perspective uncovers a significant potential for refinement in current compensation criteria. Our findings highlight a critical gap: the systematic under-compensation of midstream regions (e.g., Hubei, Hunan), which function as vital transfer hubs. While these areas undertake the crucial role of relaying ecosystem services, our calculated compensation flows show they receive minimal economic recognition. This misalignment suggests that prevailing compensation mechanisms, which predominantly focus on the endpoints of supply and demand, fail to capture the full value created within the service delivery chain. Compensating these transit hubs is not merely an equity issue but a strategic necessity to incentivize the maintenance and optimization of critical flow paths, thereby enhancing the entire network's efficiency and resilience (Lv et al., 2021).

Therefore, we argue for a paradigm shift in compensation standard design—from a static "supply-demand" model to a dynamic "supply-flow-demand" network model. The rationality of our proposed framework lies in its ability to quantify and valorize the function of transfer, not just the fact of supply or consumption. In practice, this could translate to introducing "transfer capacity incentives" for hub regions, funded by a small levy on the downstream compensation flows that these hubs facilitate. Such a mechanism is feasible as it builds upon the existing compensation financial architecture while distributing the economic responsibility for maintaining network connectivity more equitably among all beneficiaries, including the downstream end-users who rely on the efficient flow of services.

5.4 Methodological contributions and research limitations

Our integrated methodology, combining InVEST modeling, gravity-based flow simulation, and network analysis, provides a comprehensive framework for analyzing ecosystem service flows across multiple scales. This approach advances beyond traditional static assessments by capturing the dynamic interactions between supply, demand, and flow processes (Bagstad et al., 2013). The successful application of complex network theory to ecosystem service flows demonstrates its utility for understanding the structural and functional organization of socio-ecological systems.

Several limitations should be acknowledged. First, our focus on water yield services, while providing a clear case study, limits direct generalization to other ecosystem services with different flow characteristics. Future research should expand to multiple service types to identify potential trade-offs and synergies. Second, our use of annual average data necessarily simplifies the seasonal and interannual variability inherent in hydrological processes. Third, while we incorporated economic factors through the gravity model, a more explicit integration of institutional and cultural dimensions would strengthen future analyses.

Despite these limitations, our study provides both theoretical advances and practical tools for ecosystem service management. The explicit mapping of service flows and their network properties offers a scientific basis for designing targeted, efficient ecological compensation mechanisms. As regions worldwide grapple with transboundary environmental challenges, our approach demonstrates how understanding the connectivity and structure of ecological service flows can inform more effective and equitable governance strategies.

6 Conclusion

This study constructed a "supply-flow-demand" network of ecological services in the Yangtze River Basin, revealing distinct spatial flow characteristics and their implications for transverse ecological compensation. By integrating the InVEST model, gravity model, and complex network analysis, we quantified the gradient pattern of "upstream supply-midstream transfer-downstream demand" and tracked its evolution from 2010 to 2023. The consolidation of core nodes (Chongqing, Wuhan, Shanghai) and emergence of secondary cores (Chengdu, Changsha, Nanjing) created a polycentric network structure that enhanced connectivity while maintaining directional flow stability from upstream to downstream. Our analysis of theoretical ecological compensation amounts revealed both temporal trends (initial increase followed by decrease) and spatial differentiation (upstream beneficiaries, downstream payers), demonstrating the close relationship between ecosystem service flows and compensation mechanisms.

Based on the gradient patterns identified, we propose tailored policy recommendations for different basin regions: for upper reaches, establish differentiated compensation standards that reflect not only water yield quantity but also ecological protection costs, with premium compensation for key source areas like the Sichuan and Yunnan headwaters. In middle reaches, develop transfer capacity incentives for hub regions like Hubei and Hunan, recognizing their crucial relay function through infrastructure investments and operational subsidies. For lower reaches implement diversified compensation mechanisms including funds, technology transfer, and industrial cooperation to share ecological protection burdens more equitably across Jiangsu, Shanghai, and Zhejiang.

While our study provides comprehensive insights into ecosystem service flows, several limitations warrant attention. First, the reliance on administrative boundary data may overlook finer-scale ecological processes and cross-boundary interactions that affect service flows. Second, our compensation calculations, while theoretically grounded, would benefit from validation against actual compensation transactions and incorporation of stakeholder willingness-to-pay assessments.

Future research should: (1) expand to multiple ecosystem services to identify trade-offs and synergies in flow patterns; (2) develop dynamic network models that can simulate response to extreme climate events and policy interventions; and (3) incorporate social network analysis to understand how governance structures influence ecological service flows. Such integrated approaches will further advance our ability to design effective, adaptive governance systems for large river basins.

Despite these limitations, our study demonstrates that network-based analysis of ecosystem service flows provides a powerful framework for understanding and managing complex socio-ecological systems. The approaches developed here can guide more targeted, efficient ecological compensation mechanisms that balance regional development with ecological protection, contributing to the sustainable development of the Yangtze River Basin and similar large river systems worldwide.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation. Requests to access these datasets should be directed to luxiangyi@xnu.edu.cn.

Author contributions

MW: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Supervision, Visualization, Writing – original draft, Writing – review and editing. XL: Conceptualization, Formal Analysis, Funding acquisition, Investigation, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing. YX: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review and editing.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2025.1710854/full#supplementary-material

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