Evaluating water provision service at the sub-watershed scale by combining supply, demand, and spatial flow

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ABSTRACT

Water provision service is crucial for human society to survive and develop. It is essential to evaluate the importance of sub-watersheds, based on their different capacities to provide water resources to manage an entire watershed. Previous studies have assessed the importance of the sub-watershed by analyzing its supply and/or demand of water provision service. However, few studies have considered the influence of spatial flow. In this study, we proposed an assessment framework that combined supply, demand, and spatial flow of water provision service. The Qiantang River Basin in China was selected as our study area. The importance of the sub-watershed was evaluated using the importance index, which was calculated using the spatial flow and the accumulative beneficial population of the water provision service. The spatial flow was simulated using a simplified water flow model, and the accumulative beneficial population was based on the direction and path of water provision service spatial flow. The results indicated that 60% of sub-watersheds with "very high" importance were located in the middle and lower reaches of Xin’an River and Lan River. Due to the internal consumption and sink of the water provision service, the upstream area may provide less spatial flow and may have a lower level of importance. When limited by the direction and scope of water provision service delivery, some sub-watersheds with high surpluses and without external beneficiaries were of low importance. Our study emphasizes the quantity and routing of water provision service delivery and enhances the understanding of the capacity of the sub-watershed for providing water provision service.

1. Introduction

Water resources are important natural resources and are inseparable from all aspects of human production and life (Schroter et al., 2005). Water resources are related to a series of ecosystem services (ESs), such as flood regulation, water purification, recreation, and especially water provision (MA, 2005). Water provision service is the provision of water to humans by the ecosystem for multiple purposes, including industrial consumption, irrigation, drinking, and other needs (Brauman et al., 2007). A clean water supply is the most valuable provisioning ecosystem service (Boithias et al., 2014; de Groot et al., 2012; Raymond et al., 2009). Due to the constraints of natural conditions and the influence of human activities, different sub-watersheds have different capacities to provide water provision service. Therefore, to manage water resources effectively, it is essential to evaluate the importance of the sub-watershed for water provisions.

Some researchers have used the supply to assess the importance of region for water provision service. Schroter et al. (2005) applied the variable of surface runoff to represent the supply of water provision service and hypothesized that a higher level of surface runoff was associated with a more important region for water provision service. Brauman et al. (2007) calculated the value of the supply of water provision service and characterized the importance of the region for water provision service by that value. Some researchers have assessed water provision service using supply and demand surpluses for evaluating the importance of the region. Chan et al. (2006) calculated the surplus water available for human use to quantitatively evaluate important regions for water provision service. Burkhard et al. (2012) used an expert evaluation matrix to map supply and demand surpluses for evaluating the importance of the region. Chan et al. (2006) calculated the surplus water available for human use to quantitatively evaluate important regions for water provision service in the Central Coast of California in the United States. Burkhard et al. (2012) used an expert evaluation matrix to map supply and demand surpluses, and qualitatively evaluated the importance based on surpluses in central Germany. Boithias et al. (2014) considered spatial extensions and introduced the supply to demand (S:D) ratio to
evaluate the important regions for water provision service in the Ebro basin. However, previous studies that evaluated water provision service to assess the importance of a region for water provision service focused on static indicators such as supply and/or demand, and most did not consider the influence of spatial flow.

The spatial flow of water provision service is defined as the service delivered from upstream areas to downstream areas along the direction of the water flow after satisfying local demands (Li et al., 2017; Shi et al., 2020). Water provision service is delivered from the providing areas to beneficiaries across remote distances, using the spatial flow along a specific direction and path (Li et al., 2019; Serna-Chavez et al., 2014; Wolff et al., 2015). Bagstad et al. (2014) presented an approach based on elevation and stream network data, using the method of Service Path Attribution Networks (SPANs), to quantify the spatial flow of water provision service and simulate the directions and path of the spatial flow. Li et al. (2017) revised this method into a simplified water flow model with lower data requirements and applied the spatial flow of water provision service to regional water security in the Beijing-Tianjin-Hebei region, China. Moreover, few studies have considered the spatial flow to evaluate the importance of the sub-watershed for water provision service.

The Qiantang River Basin in China is a complete basin, covering all areas from river sources to the estuary, with the clear water system and a significant elevation gradient. The western region has a high terrain, abundant water resources, and relatively few people, and lags the eastern region in economic and urban development. The eastern region has a flat terrain and a dense population, with a high demand for water resources and low available water resources per capita. This requires large amounts of water to be extracted from rivers such as the Qiantang River. The imbalanced distribution of water resources in the Qiantang River Basin could be further aggravated in the future by rapid economic development and continuous population growth. This highlights the importance of evaluating the water provision service at the sub-watershed scale, to prioritize the protection of important sub-watersheds, and to ensure the sustainable development of the watershed. At present, studies about the Qiantang River Basin focused on the assessment of water provision service supply, without considering the demand and spatial flow. Xu et al. (2013) calculated the precipitation, potential evapotranspiration, and river runoff of upper reaches of the Qiantang River Basin through the SWAT (Soil Water Assessment Tool) model, and results implied that fewer water resources would be available in the future due to climate change. Sun et al. (2019) evaluated the effects of land use change on ESSs for sustainable development and found the supply of water provision service decreased in the sources of the Qiantang River Basin from 2000 to 2015. Therefore, it is necessary and urgent to evaluate the water provision service in the Qiantang River Basin, combining supply, demand, and spatial flow, for the sustainable development of water resources.

This study evaluated the importance of the sub-watershed for water provision service using the importance index, which combines supply, demand, and spatial flow. The study addressed the following three areas: (1) Quantifying the supply and demand of water provision service using the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) model; (2) Simulating the spatial flow of water provision service using the simplified water flow model; (3) Evaluating the importance of the sub-watershed for water provision service using the importance index. This paper identified locations having a high impact on the basin, providing theoretical guidance for managing the basin’s water resources.

2. Method

2.1. Study area

The Qiantang River Basin is located at 117° 38′-121° 13′E and 28° 12′-30° 27′N in China. It is located mostly in Zhejiang Province (93.4% of the basin area) and partially in southeastern areas of Anhui Province (6.6% of the basin area) (Fig. 1a). In this study, the areas of the Qiantang River Basin in the Jiangxi and Fujian Provinces were not covered. The Qiantang River Basin is mainly composed of Xin’an River in the upper reaches of the north, Lan River in the upper reaches of the south, Fuchun River in the central mainstream, Qiantang River in the lower mainstream, and tributaries such as Fenshui River, Puyang River and Caо’e River (Fig. 1b). Using the Hydrology Analyst Tools in ArcGIS 10.2, major rivers and river system distribution, the study area was divided into 22 sub-basins and numbered from 0 to 21 (Xu et al., 2004; Zhang et al., 2010).

The Qiantang River Basin includes 30 counties in 7 cities (Fig. 1c) with approximately 21.7 million people; the area covers 5.2 × 10^5 km^2 and the average annual per capita water consumption is 405 m^3. The average annual temperature is 17.1 °C to 19.5 °C and the average annual precipitation range is 1398 to 1848 mm. The basin is surrounded by mountains, with altitudes ranging from 0 to 1826 m (Fig. 1b). The important ecological barriers of the Yangtze River Delta are located in the upstream areas of the Qiantang River Basin (National Development and Reform Commission, People’s Republic of China (NDRC), 2016). And the downstream areas of the Qiantang River Basin are among the fastest growing regions in China (National Bureau of Statistics of China (NBS), 2019a, 2019b, 2019c; Xu et al., 2013). With the development of the society and growth of the water consumption has increased sharply. The areas that are high in water supply do not overlap with the areas that have high water demand.

2.2. Quantification of the supply and demand of water provision service

To quantify water supply and demand, a land use map with 30 m resolution in 2015 was used, which was obtained from the National Earth System Science Data Sharing Infrastructure of China (http://www. geodata.cn) and was derived from Landsat TM images. The projected coordinate system (WGS.1984 UTM Zone.51 N) was used to generate the maps. Table 1 listed the data sources. The study did not consider groundwater, due to the method and data limitation. To finely calculate water yield and water consumption, the land use types were divided into eight categories: cultivated land, forest land, grass land, water body, unutilized land, urban construction land, rural construction land, and other construction land (Fig. 1c and Table 2). In this study, the climate data including average precipitation, temperature, wind speed, and relative humidity were the daily observations from more than 2,000 meteorological stations in China, in units of 0.1 mm, 0.1 °C, 0.1 m/s, and 1%, respectively. After calculation and Kriging interpolation according to the location data of meteorological stations, the climate data were used in the calculation of the annual water yield.

2.3. Water supply

Water supply is defined as the amount of water resources available to humans, and is calculated as the difference between precipitation and evapotranspiration, namely, the annual water yield (m^3) (Boithias et al., 2014). It was estimated using the water yield module of InVEST, a widely used model for evaluating ecosystem services and supporting ecosystem management and decision-making. The model offers the advantages of low data requirements, algorithm optimization, and multiple application scenarios.

The water yield module is based on the Budyko curve and annual precipitation (Zhang et al., 2012). In the InVEST model, the annual water yield Y per pixel is calculated according to:

\[ Y = \left(1 - \frac{AET}{P}\right) \times P \]

(1)

where AET is the actual annual evapotranspiration in the pixel, mm; and P is the annual precipitation on the pixel, mm. AET/P is estimated as follows (Zhang et al., 2001).
where $R$ is the ratio of potential evapotranspiration to precipitation, which is the dimensionless Budyko Dryness index per pixel under the given land use/cover. The variable $\omega$ is the plant-available water coefficient and is a nonphysical parameter.

$$R = k \times ET_0$$
$$\omega = Z \times AWC$$

where $ET_0$ is the reference evapotranspiration per pixel (in mm), which depends on altitude, latitude, humidity, and slope. The variable $k$ is the plant evapotranspiration coefficient for land use/cover on the pixel, which is the dimensionless index; and $Z$ is a seasonality parameter and the dimensionless index, associated with seasonal rainfall distribution and depths (Gu et al., 2018). The variable $AWC$ is the plant-
available water content (in mm) and is determined based on soil texture, effective soil depth, and root depth. The variable ET\textsubscript{0} was estimated by the FAO Penman-Monteith method (Allen et al., 1998).

\[ ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{\text{PRME} T^2}}{\Delta + \gamma (1 + 0.34u_2)} \] (5)

where \( R_n \) is net radiation at the crop surface, MJ\cdot m^{-2}\cdot day^{-1}; G is the soil heat flux density, MJ\cdot m^{-2}\cdot day^{-1}; T is the mean daily air temperature at a height of 2 m, °C; \( u_2 \) is wind speed at a height of 2 m, m/s; \( e_s \) is the saturation vapour pressure, kPa; \( e_a \) is the actual vapour pressure, kPa; \( \Delta \) is the slope vapour pressure curve, kPa/°C; and \( \gamma \) is psychrometric constant, kPa/°C.

### 2.4. Water demand

Water demand is defined as the sum of industrial, agricultural, and domestic water consumption in a year (m\(^3\)), excluding ecological water consumption (Boithias et al., 2014; Lin et al., 2021). The formula is represented as follows:

\[ D_w = D_i + D_a + D_d \] (6)

where \( D_w \) is water demand in a year, m\(^3\); \( D_i \) is industrial water consumption in a year, m\(^3\); \( D_a \) is agricultural water consumption in a year, m\(^3\); and \( D_d \) is domestic water consumption in a year, m\(^3\). Details about the industrial, agricultural, and domestic water consumption were obtained from the statistical yearbooks of relevant cities. The amount of industrial water consumption was allocated equally to urban construction land and other construction land; the amount of agricultural water consumption was allocated equally to cultivated land; and the amount of domestic water consumption was allocated to the grid using population density as the weight. Industrial, agricultural, and domestic water consumption on the grid scale were obtained, respectively (Chen et al.,...
2.5. Simulation of water provision service spatial flow

The spatial flow paths and directions of the water provision service were simulated using the DEM and stream network data (Fig. 2) (Bagstad et al., 2013; Li et al., 2017). The simulated quantity of the spatial flow was based on following four maps: the supply map, the demand map, the direction map, and the boundary map. These reflected the continuous spatial distribution of the parameters, as follows. The supply map simulated the surface runoff, which was the result of water supply (Fig. 2a). The demand map simulated the human consumption of water resources, which was the result of water demand (Fig. 2b). The direction map clarified the direction in which each unit flowed downstream (Fig. 2c) and was processed in ArcGIS 10.2 using Hydrology Analyst Tools. There were eight specific values provided in the direction map (D8) (i.e., 1, 2, 4, 8, 16, 32, 64 and 128), with each value indicating a direction (Fig. 2d). The boundary map defined the scope of the calculation of the spatial flow, which was the boundary of sub-watersheds (Fig. 2g). The inflow was defined as the sum of the spatial flow into the area, and the outflow as the sum of the spatial flow leaving the area. The net spatial flow was the difference between the inflow and the outflow, which was the spatial flow out of the region after meeting local needs, without receiving services from upstream areas of the region. The water provision service inflows, outflows, and net spatial flow among different areas were computed (Fig. 2h). As water provision service was delivered during the simulation, their quantities decreased based on contact with beneficiaries and increased based on contact with the providing areas. These decreases and increases represented the change in the quantity of water provision service during the flow process (Fig. 2f). The surplus of water provision service differed from the quantity of water provision service spatial flow (Fig. 2c). All calculations and simulations were performed in ArcGIS 10.2.

2.6. Evaluation of the importance of the sub-watershed for water provision service

The relationship of the spatial location between the spatial flow and beneficiaries affects the benefits received by human beings (Mandle et al., 2015). Sub-watersheds influence populations differently depending on the benefit provided by the spatial flow of water provision service (Kong et al., 2019). In this study, the DEM and population density data were used as input datasets into the flow length tool in ArcGIS 10.2. This facilitated the calculation of the accumulative benefits for populations along the spatial flow path of each sub-watershed, from downstream to upstream within the Qiantang River Basin (Fig. 3). The areas that benefit are the downstream sub-watersheds that receive water provision service from the upstream sub-watersheds.

The accumulative beneficial population represents the total beneficiaries along the direction and paths of the spatial flow. The net spatial flow represents the amount of water provision service that a sub-watershed provides to downstream sub-watersheds after meeting local needs. In this study, the importance of the sub-watershed for water provision service was calculated as the net spatial flow multiplied by the number of downstream beneficiaries (the accumulative beneficial population). This approach considered the supply, demand, and spatial flow. Thus, the importance index was introduced to evaluate the water provision service, with the following formula (Ouyang et al., 2016):

$$ I_i = F_i \times P_i $$

where $I_i$ indicates the importance of the sub-watershed $i$ for water provision service, which is the dimensionless index; $F_i$ is the net spatial flow of sub-watershed $i$ in a year, $m^3$; and $P_i$ is the total population who received the spatial flow of water provision service provided by sub-watershed $i$, people.

In this study, the importance index was arranged in descending order, assigning the “very high” importance designation to the top 25% of sub-watersheds, the “high” designation to 25–50% of sub-watersheds, the “medium” to 50–75% of sub-watersheds, and the “low” to 75–100% of sub-watersheds.

3. Results

3.1. The supply and demand of water provision service

In 2015, the total water supply was $6.72 \times 10^{10} m^3$ in the Qiantang River Basin, and the average was $1.29 \times 10^9 m^3/km^2$. The western basin was a high-value water provision service supply area and was the source for the Qiantang River Basin (Fig. 4a). The inflow was defined as the sum of the spatial flow into the area, and the outflow as the sum of the spatial flow leaving the area. The net spatial flow was the difference between the inflow and the outflow, which was the spatial flow out of the region after meeting local needs, without receiving services from upstream areas of the region. The water provision service inflows, outflows, and net spatial flow among different areas were computed (Fig. 2h). As water provision service was delivered during the simulation, their quantities decreased based on contact with beneficiaries and increased based on contact with the providing areas. These decreases and increases represented the change in the quantity of water provision service during the flow process (Fig. 2f). The surplus of water provision service differed from the quantity of water provision service spatial flow (Fig. 2c). All calculations and simulations were performed in ArcGIS 10.2.

3.2. The spatial flow of water provision service

Fig. 6 shows the inflow, outflow and net spatial flow of water provision service from the sub-basins numbered 0 to 21. In 2015, the outflow was higher than the inflow and the net spatial flow exceeded zero at the sub-basin scale (Table 3). The sub-basins located in the sources of the river had no inflow. The sub-basins numbered 0–4 and 6 showed high inflow and outflow values, because they represent the main streams of the Qiantang River, Fuchun River, and Lan River. These sub-basins receive cumulative spatial flow from multiple tributaries; sub-basins that are closer to estuaries experienced high inflow and outflow values. The spatial distribution of the net spatial flow of water provision service in the Qiantang River Basin differed from the inflow and the outflow. The high value of the net spatial flow was not distributed neither in the sub-basins with the river sources, nor in the areas with the high inflow and outflow. Rather, high net spatial flows were distributed in the middle of the Qiantang River Basin, in No. 5 and 6 sub-basins with the high surplus. Basins with the low surplus also experienced lower net spatial flows; this included sub-basins No. 0–4, 16–18, and 20–21.

3.3. The importance of the sub-watershed for water provision service

Fig. 7 shows that the closer the sub-watershed to the source of the river, the greater the accumulative beneficial population. There was a
larger accumulative beneficial population that benefitted from the east source of Lan River compared to that from other sub-basins. At the same time, the net spatial flow of the western sub-watersheds was generally higher compared to that of the eastern sub-watersheds; therefore, the importance index and the importance of the sub-watershed for water provision service showed the spatial pattern of being high in the west and low in the east in 2015 (Fig. 8). Sub-basins of “very high” and “high” importance were concentrated around Xin’an River, Lan River, and the source of Fenshui River. The abundant spatial flow of water provision service provided benefits for many people. Sub-basins located in the middle and lower reaches of the Qiantang River Basin were of lower importance. These sub-basins were closer to the estuary, and had a smaller accumulative beneficial population compared to the upper reaches. The local economy was relatively developed, with a large...
demand for water resources, and a relatively limited spatial flow.

The results of this study indicated that the upstream sub-watershed was not always more important compared to other places. The No. 9 sub-basin is the source of the Xin’an River and the upper reaches of No. 7 sub-basin. However, the No. 9 sub-basin is less important than the No. 7 sub-basin. The situation was similar for sub-basins No. 8, 10, 11, and 13. The net spatial flow provided by these sub-basins was smaller than that by the downstream sub-basins, No. 6 and 7.

4. Discussion

4.1. Evaluation of the importance of the sub-watershed for water provision service by combining supply, demand, and spatial flow

Human dependence on ESs stems from not only the capacity of the ecosystem to provide services, but also the societal demand (Chen et al., 2019). The structure and processes of ecosystems cannot form ESs without humanity as the beneficiaries (de Groot et al., 2010; Fisher et al., 2009). However, many efforts in assessment of ESs have been directed toward the provision capacity of the ecosystem (Mensah et al., 2017). Chan et al. (2006), Egoh et al. (2011) and Zhang et al. (2020) valued the area based on the ESs generated locally, without the demand. Fig. 9a shows the spatial distribution of important sub-watersheds for water provision service considering only the supply. This generated different outcomes than the result considering the supply, demand, and spatial flow. The importance of several sub-watersheds exhibited a change, for example, the No. 0 sub-watershed underwent a change from “low” importance to “medium” importance. Although the No. 0 sub-watershed generated medium supply, most of it was consumed locally and provided only $0.05 \times 10^3$ m$^3$ net spatial flow (the minimum in the Qiantang River Basin). Disregarding ES demand results in the identification of the sub-watershed with high importance but possibly low ES provision to beneficiaries (Cimon-Morin et al., 2014; Verhagen et al., 2018). Verhagen et al. (2017) quantified the importance accounting for the demand in evaluating ESs for identifying priority areas and found that it was important to consider the fraction of the supply that fulfilled a demand, and the result was consistent with the findings of our study. When evaluating the regional importance for ESs, it is necessary to consider not only the ability of the ecosystem to provide services, but also the spatial changes in the demand (Wolff et al., 2015).

Some studies that considered both supply and demand of ESs identified the distribution pattern for important areas but did not emphasize the contribution of ES spatial flow (Fan and Shibata, 2014; Verhagen et al., 2018). The method is based on the gray/black box theory and it is suitable for ESs with obvious supply–demand relationship and uncertain flow mechanism, or in-situ ESs such as soil formation. Noteworthy, for ESs with special delivery mechanisms, such as water provision service, the influence of ESs spatial flow should be considered (Xie et al. 2019). Failing to understand and to consider the spatial flow into regional, national and even international ES assessments may lead to incomplete and potentially distorted conclusions, impairing the ability to sustainable management and decisions (Schröter et al., 2018).

The ES is frequently limited by direction and scope (Costanza, 2008; Fisher et al., 2009; Schröter et al., 2018). In other words, the needs can only be met when the beneficiaries are within the flow scope of ESs (Verhagen et al., 2017). Methods that only consider ES supply and demand could fail to address the possibility that some high surplus sub-watersheds actually provide less than expected services or have limited delivery scope. For example, water is the carrier of the water provision service spatial flow and is impacted by gravity. The direction of water provision service spatial flow is the water flow direction (Burkhard et al., 2014; Costanza, 2008; Fisher et al., 2009). This means the spatial flow of water provision service is not available in remote areas due to spatial barriers (such as high mountains) and cannot be naturally transferred inversely or across basins (Verhagen et al., 2018). For example, in this study, the No. 19 sub-basin was “high” importance considering supply and demand (Fig. 9b). Combining the spatial flow, it was found that the No. 19 sub-watershed of “low” importance near the estuary had no external beneficiaries. Our findings were consistent with the study, reporting that accounting for flow scope influenced the
location of priority areas (Verhagen et al., 2017).

4.2. Must the upstream sub-watershed be more important?

Upstream water provision service in a basin usually benefits residents in downstream areas, which could flow downstream along the river driven by terrain and gravity (Qin et al., 2019; Xu et al., 2019). Theoretically, the area that potentially benefits from the upstream sub-watershed is the largest in a basin, with the upstream sub-watershed providing water provision service along the river; this is critical for
spatial flow led to diverse results. Consistent with our results, the spatial service and the importance were not necessarily higher. The assessment stream sub-basin necessarily higher than the downstream sub-basin (Lin et al., 2021; Wang et al., 2020).

Watershed in China were more important than downstream sub-watersheds, by quantifying the balance of supply and demand of water provision service function and the beneficiary population. Our study concluded that, although the accuracy of water provision service spatial flow in ecological compensation. On this basis, combining with the importance ranking, the ecological compensation mechanism in the Qiantang River Basin was established. Areas of “low” importance should pay for ecological compensation, and areas of “high” and “very high” importance should obtain funds from ecological compensation. According to the delivery route of water provision service, the Puyang River Basin and the Cao’er River Basin cannot obtain external benefits and the importance of sub-basins were “low” and “medium”, Shaoxing City shouldn’t pay for ecological compensation or get financial support. The areas of “low” importance were located in Xiaoshan County and Hangzhou County, which should pay for ecological compensation based on the water resource value of the inflow. The areas of “high” and “very high” importance (the counties located at the Xin’an River Basin, the Lan River Basin, and the Fenshui River Basin) should obtain funds from ecological compensation allocated by the ecological compensation coefficient. The ecological compensation coefficient would be calculated by the importance index divided by the sum of the importance index of the “high” and “very high” importance areas.

In China, top-down strategies dominate, however, strengthening of the trans-regional coordination efforts, such as the ecological compensation, is an important component of sustainable water management (Liu and Yang, 2012). The ecological compensation not only contributes to the sustainable water supply, but also changes people’s values, attitudes, and behaviors toward water resources, and improve the efficiency of water consumption (Zheng et al., 2013). The ecological compensation program in the Xin’an River Basin was successful in achieving improvements in water quantity and water quality (Wang et al., 2016). More than 80% of residents in the Xin’an River Basin were supportive of the ecological compensation practices, and over 45% were satisfied with the effects of ecological compensation (Ren et al., 2020). Besides, investment in ecological conservation would promote the development of the related industry and drive employment and economic development.

The results of this study can also provide information that supports the ecological compensation of water provision service in the basin. Ecological compensation can serve as an effective method to provide economic incentives for ES providers, which is conducive to the sustainable development of the regional economy and ecology (Engel et al., 2008). Gao et al. (2020) determined ecological compensation funds and allocation based on the balance of ES supply and demand, realizing the spatial connection between the service-providing area and the beneficiary area. Pei et al. (2019) emphasized the influence of water provision service spatial flow in ecological compensation. On this basis, combining with the importance ranking, the ecological compensation mechanism in the Qiantang River Basin was established. Areas of “low” importance should pay for ecological compensation, and areas of “high” and “very high” importance should obtain funds from ecological compensation. According to the delivery route of water provision service, the Puyang River Basin and the Cao’er River Basin cannot obtain external benefits and the importance of sub-basins were “low” and “medium”, Shaoxing City shouldn’t pay for ecological compensation or get financial support. The areas of “low” importance were located in Xiaoshan County and Hangzhou County, which should pay for ecological compensation based on the water resource value of the inflow. The areas of “high” and “very high” importance (the counties located at the Xin’an River Basin, the Lan River Basin, and the Fenshui River Basin) should obtain funds from ecological compensation allocated by the ecological compensation coefficient. The ecological compensation coefficient would be calculated by the importance index divided by the sum of the importance index of the “high” and “very high” importance areas.

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### Table 3

<table>
<thead>
<tr>
<th>Sub-watershed code</th>
<th>Area (km²)</th>
<th>The inflow (10^3 m³)</th>
<th>The outflow (10^3 m³)</th>
<th>The net spatial flow (10^3 m³)</th>
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<td>47.72</td>
<td>47.77</td>
<td>0.05</td>
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<td>40.98</td>
<td>41.81</td>
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Fig. 7. The accumulative beneficial population along the spatial flow paths of sub-watersheds in the Qiantang River Basin in 2015.
through the industrial chain.

4.4. The limitations

Similar to many studies, this study also suffered from specific limitations to be addressed in future research. First, the supply of water provision service is affected by precipitation and actual evapotranspiration, and demand is influenced by human activities. Supply and demand both change with time. Multiple time dimensions should be added to reflect the changes in the spatial flow of water provision service. Next, the spatial flow of water provision service has been hypothesized under natural conditions, without considering the impact of human factors, such as water conservancy projects. Calculations need to be optimized by taking into account the actual water flow. Finally, further simulation is needed to establish future scenarios, adjust the water resource management models, and respond to climate change and land use changes.

5. Conclusions

This study quantified the spatial flow of water provision service, simulated the directions and paths of the spatial flow, determined the accumulative beneficial population, and evaluated the importance of the sub-watershed for water provision service in the Qiantang River Basin in China. This study showed that while the upstream sub-watersheds had a large accumulative beneficial population, the spatial flow provided was not necessarily high. As such, the importance was not consistently more important compared to other places. The study clearly elucidated the importance of the spatial flow in assessing the water provision service, improving our understanding of water provision service spatial flows. This study could be further generalized to other basins to provide a reference for improved water resource management and utilization. Future research should consider the factors and mechanisms affecting the sink and the loss in the spatial flow process.

CRediT authorship contribution statement


Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

Fig. 8. The importance of the sub-watershed for water provision service in the Qiantang River Basin in 2015; (a) the importance index; (b) importance level.
the work reported in this paper.

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References


Fig. 9. The importance of the sub-watershed for water provision service, without considering the spatial flow: (a) the water provision service supply of sub-watersheds; (b) the water provision service surplus of sub-watersheds.


