Is the ‘water tower’ reassuring? Viewing water security of Qinghai-Tibet Plateau from the perspective of ecosystem services ‘supply-flow-demand’

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Abstract

Ecosystem service flow plays a vital role in the formation, transportation, transformation, and maintenance of ecosystem services. For ecosystem services with spatiotemporal mismatch of supply and demand, ecosystem service flow explains the integrated process of ‘supply-flow-demand’ of ecosystem services. The present study evaluates the supply and demand of ecosystem water provision services in the Qinghai-Tibet Plateau and simulates the spatial flow pattern and transmission mechanism of water provision services. Additionally, the study establishes dynamic and static water security indices and identify water security level to quantify the water resources security of Qinghai-Tibet Plateau under the changing ecological environment. The research shows: (a) the annual total water surplus were 6.71 × 10^{11} m^3, 8.43 × 10^{11} m^3, 7.86 × 10^{11} m^3 and 2.91 × 10^{11} m^3. The supply–demand relationship of water provisioning service in the Qinghai-Tibet Plateau shows an obvious oversupply condition; (b) The water security level of the plateau is high (level V and level IV), indicating that the water security status of the Qinghai-Tibet Plateau is under good condition, however, the area with low-security levels (Level I and Level II) is increasing. (c) From the perspective of ‘supply-demand-flow’ of ecosystem services, although the function of the water tower on the Qinghai Tibet Plateau has declined, it remained safe condition on the whole study area. The method of establishing spatial correlation between mismatched supply and demand of ecosystem services and evaluating regional water security based on ecosystem service flow constructed in this study presents the water security status and spatial distribution of Qinghai-Tibet Plateau more scientifically, providing a reference for water resource management in other regions.

1. Introductions

Water security refers to the level/ability of an area to ensure reasonable production and domestic water use for human society, as well as the maintenance of the ecological water-use capacity of a natural ecosystem with a particular structure, function, and process (Vörösmarty et al 2010). With the rapid development of social economy in recent decades, the intervention of human activities in the natural ecosystem has gradually increased, which resulted in the supply of water resources decreased, while people’s demand for water resources is increasing, and the imbalance and mismatch between supply and demand of water resources have become increasingly prominent (Purohit and Devotta 2005, Bastian et al 2012, Green
et al 2015). Therefore, the assessment of regional water security based on the matching of supply and demand and flow characteristics of water resources has practical significance for ensuring regional ecological security and improving human well-being (Grizzetti 2012, Liu et al 2016).

Ecosystem services refer to the benefits that human beings obtain from the ecosystem (Daily 1997, Board 2005, Brauman et al 2007). The ecosystem service flow refers to the dynamic process of a certain ecosystem service with mobility and transmissibility in different spatial regions within a certain time scale (Kroll et al 2012, Bagstad et al 2013). This flow can dynamically couple ecosystem service supply with human demand (Qin et al 2019). It is an indispensable link between the natural ecosystem and the human socio-economic system (Serna-Chavez et al 2014, Li et al 2017). Moreover, it provides a new perspective and direction for the research of watershed ecological security and ecological compensation policy (Costanza et al 1997, Anton et al 2010, Burkhard et al 2012). Water provisioning service is a kind of service with obvious flow nature. Presently, the water supply and demand assessment models and tools comprise different temporal and spatial scales; however, only a few studies have investigated the spatial flow of water provision services (Liu et al 2021a). Previous reports evaluating regional water security have mainly considered the water security under static state (Bothias et al 2014, Liu et al 2016). Since water resources are mobile resources (Jansson et al 1999), their supply and demand regions usually have spatial differences. Compared with the static water security assessment, the dynamic water security assessment considering mobility can provide a more accurate regional water security assessment structure (Villa et al 2014, Palomo et al 2018).

Qinghai-Tibet Plateau is the birthplace of many rivers (Yu et al 2022). It has always been known as the ‘natural water tower’ (Immerzeel et al 2020, Wang et al 2022). Water provision services, typical mobile services in the ecosystem, is one of the most important ecosystem services in Qinghai-Tibet Plateau (Wu et al 2022), which provide water resources for China and surrounding countries. Although researchers have researched the ecological service function of the Qinghai-Tibet Plateau, research on the ecosystem service flow of the Qinghai-Tibet Plateau has not been quantified. The present study contributes to providing a clear understanding of the water provision service capacity and water security of the Qinghai-Tibet Plateau. Findings of this study may be useful in promoting environmental protection and sustainable development on Qinghai-Tibet Plateau.

In view of the problem that it is hard to build a spatial correlation between mismatched supply and demand of water provisioning services, this study, from the perspective of ecosystem service flow, uses land cover, remote sensing data, meteorology, hydrology and other data, simulates the supply of water provisioning services based on integrated valuation of ecosystem services and trade-offs (InVEST) model, and simulates the demand of water supply services based on ArcGIS software to clarify the spatial-temporal distribution pattern of water provisioning services. Combined with digital elevation model (DEM) and the distribution of river system, the spatial flow model of water provisioning service is constructed to determine the spatial flow process of water provisioning service from supply to demand unit; Using the concept of water security index, a water security level based on water security index is established to obtain the spatial and temporal pattern of water security in the Qinghai-Tibet Plateau, and to explore whether the ‘water tower’ is reassuring. By solving the problem of expressing the spatial flow process of ecosystem services, this study can enrich the research methods of ecosystem services flow, and promote the ecological environment protection and sustainable development of the Qinghai Tibet Plateau.

2. Methods

2.1. Study areas

The Qinghai-Tibet Plateau is located at a high altitude, and its water resource distribution is affected by several meteorological factors such as precipitation, evaporation, and glacier distribution (Liu et al 2021b). The distribution of water resources thus presents a spatial pattern, being more in the southeast and less in the northwest. The water system formed by the Qinghai-Tibet Plateau can be categorised into the external water system and the internal water system. Among these systems, the external water system is mainly located in the southeast of the Qinghai-Tibet Plateau, particularly in the Yangtze River, Yellow River, and Lancang River. These rivers in the northwest are mostly a part of the internal water systems. Compared with rivers in the external water system, those in the internal water system are usually the seasonal rivers, which are greatly affected by climate change and their water volume is also unstable. Grassland is the main land cover type in the Qinghai-Tibet Plateau (Li et al 2022); its area ranges from $149.16 \times 10^4$ km$^2$ to $149.41 \times 10^4$ km$^2$ in 2000, 2005, 2010, and 2015, accounting for 59.25%–59.35% of the total area of the entire region. The total area of grassland and desert accounts for >80%, indicating that the regional structure characteristics are dominated by the ‘grassland—desert’. Based on the ecological environment and the geographical characteristics, the Qinghai-Tibet Plateau can be categorised into ten ecological areas, and the geographical environment of the same ecological area shows relatively consistent characteristics (figure 1, supplementary figure A.1).
2.2. Research structure

The core objective of the ecosystem service ‘supply-flow-demand’ research is to connect the supply and demand through the simulated flow path for solving the problem of incorrect evaluation outcomes caused by the imbalance of supply and demand (Silvestri and Kershaw 2010, Owuor et al. 2017). The present study comprises three main parts. (a) Based on the remote sensing images, land use and land cover, climate, DEM data, and field survey data, the soil and water assessment tool (SWAT) and InVEST models were used to simulate the water supply of water provision service in the Qinghai-Tibet Plateau, with ArcGIS being used to simulate the water demand of the water provision service in the Qinghai-Tibet Plateau for obtaining the temporal and spatial patterns of water supply and demand of the Qinghai-Tibet Plateau. (b) Based on the calculation of the temporal and
spatial patterns of water supply and demand, the flow of water supply services was simulated according to the terrain, and a flow-based water provision service pattern was established. (c) The water security level standard based on the water security index was established to evaluate the static water provision service and the dynamic water provision service, respectively, and the final results of the temporal and spatial patterns of water security in the Qinghai-Tibet Plateau were finally obtained.

2.3. Simulation of the water provision service flow

The flow simulation of the water provision service space only considers the flow process under the natural confluence state and does not consider the human intake and other influencing factors temporarily. The flow simulation is based on three matrices with the same number of rows and columns in the study area, representing the spatial distribution of three variables, namely flow direction (figure 2(b)), water supply (figure 2(c)), and water demand (figure 2(d)). The water supply matrix was mainly obtained based on the InVEST models (supplementary A.2). The water demand matrix was obtained by establishing a spatial correspondence between different types of water consumption and the land cover types (supplementary A.3). The direction matrix was extracted from DEM based on ArcGIS, according to the D8 flow rules, comprising 1, 2, 4, 8, 16, 42, 64, and 128, respectively, representing a specific direction (figure 2(e)) (Li et al 2017).

Based on the water supply and water demand matrix of the water provision services, the static water surplus (figure 2(f)) was obtained subtract water demand matrix from water supply matrix. A negative value indicates that the local water supply could not meet water demand and that there was a static...
water demand gap. It is, therefore, necessary to rely on the flowing water resource in other regions to compensate for the static water demand gap, which is the actual benefit area of the water provision services. In the process of flow simulation, the static water surplus flows preferentially according to the relationship between upstream and downstream regions, which was defined in figure 2(e). When water flows through a grid unit with static water demand gaps, the remaining flowing water decreases. Conversely, the remaining flowing water continues to accumulate and flow downstream, eventually resulting in a dynamic water surplus (figure 2(g)). The dynamic water surplus, however, remains negative, indicating a dynamic water demand gap after the natural confluence process, which cannot be met through the natural confluence process and require supplementation via manual water intake. To avoid interrupting the flow process, the flow simulation required to be calculated separately for each divided watershed, and the water provision service flow simulation was realised based on interactive data language (IDL) programming of the environment for visualizing images (ENVI) platform.

2.4. Water security level
The water safety index (WSI) is the basis of the water safety level, as indicated by the following formula (Li et al 2017):

\[ WSI_{\text{static}} = \log \left( \frac{P}{D} \right) \]  \hspace{1cm} (1)  
\[ WSI_{\text{flow}} = \log \left( \frac{\text{Flow} + P}{D} \right) \]  \hspace{1cm} (2)

where \( P \) represents the water supply of the grid unit, \( D \) represents the water demand of the grid unit, and Flow represents water flowing into the grid unit from upstream. Owing to the huge value of upstream water, the logarithm was taken in the calculation to offset the impact caused by the excessive supply and demand ratio.

In this equation, a WSI value of >0 indicates a surplus of water in the area, whereas a WSI value of <0 indicates a shortage of water in the area.

For the accurate management of water resources, water supply, water demand, and water flow surplus all should be considered. The WSI can further provide information for regional water resource management. To determine the potential of local water resources, considering the regional water resources related to upstream and downstream is necessary. We suggest the following three-state variables to determine the water security level of the Qinghai-Tibet Plateau:

(a) Water shortage—unaffected by upstream water resources—water shortage;
(b) Water shortage—affected by upstream water resources—water shortage;
(c) Water shortage—affected by upstream water resources—safe supply;
(d) Safe supply—unaffected by upstream water resources—safe supply;
(e) Safe supply—affected by upstream water resources—safe supply.

Level I indicates the intensive use of freshwater without upstream water to reduce the pressure. Level II indicates the water demand cannot be met by the limited upstream fresh water in water-deficient areas. Level III indicates the areas where upstream water resources filled the local water demand gaps. Levels IV and V indicate that the local water resources were rich, although level V could be affected by upstream freshwater.

2.5. Data sources
To assess the supply, demand, and flow of water provision services, meteorological data, social-economic statistical data, land cover data, and DEM data were acquired in this study (table 1).

3. Results and analyses
3.1. The supply–demand pattern of water provision services
In 2000, 2005, 2010, and 2015, the annual water yield of the Qinghai-Tibet Plateau ranged from 0 to
2075.5 mm, with the annual average water yield being 265.36 mm, 332.98 mm, 310.82 mm, and 116.23 mm, respectively. The corresponding total annual water yield were $6.75 \times 10^{11}$ m$^3$, $8.47 \times 10^{11}$ m$^3$, $7.90 \times 10^{11}$ m$^3$, and $2.95 \times 10^{11}$ m$^3$. The general water yield in the four years displayed a decreasing trend. In 2015, the water yield was extremely low, and it was only 37.34% of that in 2010. The excessive decrease in water production in 2015 can be ascribed to the El Niño effect. The precipitation in the plateau decreased sharply, which seriously affected the total water yield in 2015 (figure 3).

In 2000, 2005, 2010, and 2015, the annual water demand of the Qinghai-Tibet Plateau ranged from 0 to $2.80 \times 10^6$ m$^3$ km$^{-2}$, with annual average water demand per unit area being $1255.01$ m$^3$ km$^{-2}$, $1310.54$ m$^3$ km$^{-2}$, $1375.29$ m$^3$ km$^{-2}$, and $1508.14$ m$^3$ km$^{-2}$, respectively. The corresponding total annual water demand were $3.19 \times 10^9$ m$^3$, $3.33 \times 10^9$ m$^3$, $3.50 \times 10^9$ m$^3$, and $3.83 \times 10^9$ m$^3$. Overall, the annual water demand in the Qinghai-Tibet Plateau showed a gradually increasing trend from 2000 to 2015. The annual water demand in 2000 was lowest, whereas that in 2015 was the highest. Compared with the annual water demand in 2010, the in 2015 increased by 20.17%.

The balance between supply and demand of water provision services in the plateau depends on the water yield and water demand. In 2000, 2005, 2010, and 2015, the annual average water surplus being $2.64 \times 10^9$ m$^3$ km$^{-2}$, $3.32 \times 10^9$ m$^3$ km$^{-2}$, $3.09 \times 10^9$ m$^3$ km$^{-2}$ and $1.15 \times 10^9$ m$^3$ km$^{-2}$. The corresponding total annual water surplus were $6.71 \times 10^{11}$ m$^3$, $8.43 \times 10^{11}$ m$^3$, $7.86 \times 10^{11}$ m$^3$ and $2.91 \times 10^{11}$ m$^3$. The supply–demand relationship of water provisioning service in the Qinghai-Tibet Plateau shows an obvious oversupply condition. The annual water surplus of the plateau was initially high and then decreased, and compared with the annual water surplus in 2010, that in 2015 decreased by 62.93%.

3.2. Water provision service flow

The dynamic water surplus for water provision services in the Qinghai-Tibet Plateau depends on the water yield, water demand, and the direction of water flow owing to the land elevation. Because of these factors, the flowing/dynamic water surplus varies greatly across different regions. In terms of time scale, the average annual dynamic water surplus in 2000, 2005, 2010, and 2015 showed an initial increasing trend and then a gradually decreasing trend. The average dynamic water surplus in 2005 was the highest, whereas that in 2015 was the lowest. Compared with the annual dynamic water surplus in 2010, the average dynamic water surplus in 2015 decreased by 65.28%. With respect to the spatial scale, the dynamic water surplus of water provision services in the Qinghai-Tibet Plateau was significantly higher than the static water surplus, and the area with water shortage was significantly reduced after flow simulation. High-value areas are generally distributed in the north and south of the Qinghai-Tibet Plateau. These areas are generally low in terrain and hence receive water from the upstream region. In 2015, the precipitation of the Qinghai-Tibet Plateau was low due to
the El Niño effect, and the supply of water provision services decreased. Some areas in the southwest of the Qinghai-Tibet Plateau exhibit a negative dynamic water surplus (figure 4).

Based on the grid-scale flow model simulation results, the regional-scale flow model was used to calculate the inflow and outflow of water provision services among ten ecological areas of the Qinghai-Tibet Plateau. In 2000, 2005, and 2010, the net outflow of water provision service in the temperate semi-humid hard broad-leaf forest—dark coniferous forest of the eastern mountain and steep gorge ecological area—was the lowest ($-9.21 \times 10^{10} m^3$, $-1.36 \times 10^{11} m^3$, and $-1.12 \times 10^{11} m^3$, respectively). In 2015, the net outflow of water provision service in the arid desert grassland of the cold zone of the Kunlun plateau ecological area was the lowest ($-2.12 \times 10^{10} m^3$). In 2005, 2010, and 2015, the net outflow of water provision service in the alpine meadow and alpine desert of the Qinghai-Tibet Plateau ecological areas was the highest ($1.27 \times 10^{11} m^3$, $1.10 \times 10^{11} m^3$, and $3.80 \times 10^{10} m^3$, respectively). In 2000, the net outflow of water provision service in the semi-arid grassland of the Qiangtang plateau of the sub-cold zone ecological area was the highest ($7.59 \times 10^{10} m^3$) (figure 5).

3.3. Water security level

Water security of the Qinghai-Tibet Plateau is mainly at level V and level IV. In 2000, 2005, 2010, and 2015, the area with water security levels V and IV accounted for 89.40% of the total area (figure 6). In 2015, the area with water security levels IV and V accounted for more than 98% of the total area in 2000, 2005, and 2010, whereas in 2000, the area with levels IV and V accounted for 99.90% of the total area, indicating that the proportion this area increased in 2000 and 2005. In 2010 and 2015, the safety level of water resources was high, and water resources were abundant. On the other hand, during 2000, 2005, 2010, and 2015, the areas with water resources security levels IV and V showed a gradually decreasing trend, whereas the areas with poor water security levels I and II gradually increased (figure 7). Even after excluding the impact of extreme weather conditions in 2015, the trend of reduction of areas with high-security levels continued, and an increase in areas with a low-security level was observed in 2000, 2005, and 2010. However, the overall water security scenario of the Qinghai-Tibet Plateau is good, and the area with water security levels IV and V is large; however, with rapid development, the water resource security cannot be relaxed (supplementary B.2).

4. Discussion

4.1. Whether the water safety level is reasonable from NDVI

The flow simulation of water supply services changes the state of the water resource security level. Water resources are a key factor for plant growth; hence, the vegetation status can be used as a reference/indicator for the water resource status. Normalised difference vegetation index (NDVI) is an indicator of plant growth (figure 8).

Among the five water security levels, the area corresponding to level III was affected by water flow, which changed the original state of water resources (from insecurity to security). In 2000, 2005, and 2010, the corresponding regions with the water resource security levels IV and V accounted for 98%, and the regions with levels I, II, and III accounted for less than 2% of the total area. Therefore, level III cannot be considered as the representative for evaluating the change in the water resource security level, its resources, and environmental effects under the flow state. Affected by extreme weather in 2015, the precipitation decreased greatly, and the proportion of areas with levels I, II, and III reached 10%. Therefore, the grade of water resources and NDVI in 2015 were analysed. In 2015, the average values of NDVI corresponding to water safety grade areas from level I to grade 5 were 0.18, 0.19, 0.22, 0.37, and 0.33 respectively. In 2015, the average value of NDVI in the regions corresponding to level 3 was higher than that in the regions corresponding to level I and level II. To some extent, this finding suggests that the water security assessment method proposed according to the simulation of ecosystem service flow is reasonable.
Figure 5. The inflow and outflow of water provision services among ten ecological areas.

Figure 6. Distribution of water resource security levels in the Qinghai-Tibet Plateau.

4.2. The importance of ecosystem services flow
Ecosystem service flow can effectively connect supply and demand with spatial heterogeneity. It is an indispensable link between the natural ecosystem (Provision) and human socio-economic system (Demand). Although some scholars have studied the flow of ecosystem services, it is difficult to determine the flow effect of ecosystem services, that is, the scope and flow of ecosystem services. The determination of scope and flow is an important basis for regional resource
security assessment, landscape planning, and ecological compensation.

The flow simulation of water provision services can not only accurately evaluate the regional water security situation but also effectively combine with the water resources ecological compensation policy by identifying the supply and benefit areas. In the area located upstream of the basin or sub-basin, after deduction of the local water consumption from the water yield, the remaining water resources will flow according to the principle of terrain from high to low and from upstream to downstream regions. The area that can receive the remaining water resources upstream can be regarded as the beneficiary area of the spatial flow effect of water provision services in the Qinghai-Tibet Plateau. The areas where no water resources are left after deducting the water resources required (water consumption) from the water resources produced (water yield) or the remaining water resources in the upstream have been consumed by water-deficient areas on the flow path before they arrive cannot receive the remaining water resources in the upstream, which are called the non-beneficiary area of water provision service space flow (figure 9).

Because the supply area and the beneficiary area often do not coincide in time and space, the time required for the accumulation and transfer of ecosystem services from the supply area to the beneficiary area may be long. Therefore, simply transferring the trend chart to connect the supply area and beneficiary area in space cannot fully reflect the relationship...
between these areas. This study provides insights into the process of ecosystem service flow in every aspect and effectively evaluates the socio-economic value of ecosystem services, which has important theoretical significance. The spatial flow model of ecosystem water provision services established in this study simulates the spatial flow of water supply services from the perspectives of ecosystem service supply, demand, flow path, and flow volume. This model effectively enriches the quantitative method of ecosystem service flow and provides a reference for understanding the regional water resource security scenario and formulating interregional ecological compensation policies.

5. Conclusions

The study simulates the spatial flow of water provision service from supply to demand in the Qinghai Tibet Plateau, and realizes the assessment of dynamic water security in the Qinghai Tibet Plateau. This study provides a new method of water security assessment, and the assessment results are more scientific than the static water security assessment in previous studies. Simulation of water provision service flow and the evaluation of water security in the Qinghai-Tibet Plateau in 2000, 2005, 2010, and 2015 indicated that the water security levels of the plateau are mainly at level V and level IV, indicating that the water resources of the plateau are well-protected. The characteristics of the ‘water tower’ function of the Qinghai-Tibet Plateau did not change, even under the impact of the extreme climate phenomenon El Niño in 2015. However, this study did not simulate the future scenario, and the future water security situation of the plateau must be evaluated in further studies. The evaluation method proposed in this study can also be used to formulate and solve the problems related to the management of other resources under the framework of sustainable development goals, thereby providing a reference for similar research.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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