

Article

Spatiotemporal Dynamics of Ecosystem Service Values in the Water Source Regions of the Western Route of the South-to-North Water Diversion Project in China (2002–2022): An Emergy-Based Assessment

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Abstract

The Western Route of the South-to-North Water Diversion Project is a significant water conservancy project that has undergone years of discussion. This study employed the emergy method to evaluate the ecosystem service value (ESV) of its water source areas from 2002 to 2022, analyzing spatial heterogeneity, and evaluating trade-offs and synergies among ecosystem services. The high-emergy areas for water supply are concentrated in the lower reaches of the basin, Liangshan Prefecture had the highest emergy, increasing from 1.14×10^{21} sej to 1.65×10^{21} sej over the 20 years. The climate regulation emergy values of Ganzi Prefecture, Aba Prefecture, and Liangshan Prefecture were relatively stable. The biodiversity remained relatively stable with small fluctuations, but exhibited significant spatial heterogeneity. Liangshan Prefecture and Lijiang City had the highest biodiversity emergy values, at 1.21×10^{21} sej and 2.05×10^{21} sej respectively, corresponding to as many as 7661 and 13,000 species, respectively. Among the service types, provisioning services and supporting services account for a relatively high proportion. The water supply increased by 6.13%, while the biodiversity decreased by 5.42%. The relationship showed particularly intense conflict of -0.965 . Analyzing the spatiotemporal evolution of ESV in water source areas is of great significance for rationally guiding the phased and seasonal allocation of water transfer volumes, implementing ecological compensation, and assessing the impacts of water conservancy projects on the ecological environment.

Keywords: Western Route of the South-to-North Water Diversion Project; ecosystem service value; water source areas; water supply; biodiversity



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1. Introduction

The South-to-North Water Diversion Project (SNWDP) represents a significant hydraulic engineering initiative aimed at mitigating the spatial imbalance of water availability in northern China [1–3]. The SNWDP has played a significant role in raising the groundwater table in water-scarce regions, increasing groundwater reserves [4], and even mitigating flood disasters during the rainy season [5]. The SNWDP comprises three routes [6], the East, Middle, and West Routes, which channel water from the water-rich south to the arid north [7]. Since commencing operation in 2013, the eastern route of the South-to-North

Water Diversion Project (ER-SNWDP) has channeled seven billion cubic meters of Yangtze River water, effectively covering water consumption for household, farming, industrial, and ecological needs [8]. For the middle route of the South-to-North Water Diversion Project (MR-SNWDP), this large-scale project is designed to deliver over 44 billion cubic meters of fresh water per year from the Yangtze River basin to the Yellow, Huai, and Hai River basins, a feat that will ultimately improve the lives of over 300 million people [9].

Currently in the feasibility study phase, the western route project is planned for the northwestern region, an area characterized by high altitudes and a fragile ecosystem. The changes in ecological and environmental benefits resulting from water diversion in the western route project are a key concern for policymakers and researchers. In particular, the impact on the water source area and the associated ecological compensation following water transfer are practical issues that require urgent resolution. In response to the ecological and environmental problems, interest adjustments, and value flows caused by the redistribution of water resources in the western route project, it is imperative to establish a technical system for assessing the ecological service value. It can describe the ecological gains and losses in the water source area of the western route of the South-to-North Water Diversion Project.

Ecosystem service value refers to the services or products that contribute directly or indirectly through interactions with humans [10,11]. Methods for evaluating ecosystem service value include the emergy method [12–14] and the value quantification method [15,16], among others. The value-equivalent method is often used for eco-economic value calculating [17], highlighted by its low data dependency, ease of use, and efficiency in synthesizing and comparing the values of various services. The method, however, is a broad-brush tool designed for large-scale use, which can result in diminished accuracy at finer spatial scales [18]. The use of the value equivalent method for quantitative analysis fails to thoroughly investigate the energy flows and value flows within the ecological-economic system [18]. While offering a convenient way to calculate the monetary value derived from an ecosystem, this method is limited by its dependence on the prevailing regional economic level [19,20], and produces significantly higher valuations [21]. The parameters of the emergy method are relatively complex, compared to the more biophysically grounded emergy analysis, because it is obtained by calculating the flows of matter and energy within an ecosystem [22]. Emergy represents the available solar energy (expressed in solar joules, sej) used up, directly or indirectly, to generate a service or product [22]. This common denominator allows for the measurement of various resources on a single scale, overcoming the challenge of comparing heterogeneous ecosystem services [23]. This paper is suitable for employing the emergy method to evaluate the ecosystem service value in the water source areas. By thoroughly investigating the energy flows within the ecological–economic system, key influencing factors can be identified, thereby providing a research basis for assessing the impacts of the Western Route Project following its implementation. The research objectives of this paper cover the following three main aspects: (i) quantifying changes in ecosystem service values, (ii) analyzing spatial heterogeneity, and (iii) evaluating trade-offs and synergies among ecosystem services.

Water diversion projects are important measures for the redistribution of water resources. The Western Route of the South-to-North Water Diversion Project has been under discussion for many years. This study focused on the ecosystem energy flow in the water source areas of the Western Route, employing the emergy method to uniformly quantify the ecosystem service value and evaluate both the ecological and economic values of water resources. It does so by selecting key indicators, including water supply, gas regulation, climate regulation, nutrient cycling maintenance, biodiversity maintenance, and aesthetic landscape, and discussed the trade-offs among various indicators of ecosystem services.

The findings might potentially provide a research foundation for scientifically assessing the ecological impacts of water conservancy projects and optimizing water resource allocation.

2. Materials and Methods

2.1. Study Area

The water source area of the West Route Project is located at the eastern foot of the Qinghai–Tibet Plateau. The ecosystem in this region exhibits distinct vertical zonality. In the plateau areas, the terrain is hilly, with an average altitude ranging from 4200 to 4700 m. The relative height difference between the mountains and the surrounding environment is approximately 300 to 500 m. The climate is relatively cold, the ecological environment is fragile, and the vegetation is primarily grassland and meadow. The water source area is shown in Figure 1. The study area mainly includes nine cities and prefectures in Figure 1a: Ganzi Prefecture, Aba Prefecture, Liangshan Prefecture, Golog Prefecture, Yushu Prefecture, Panzhihua City, Ya'an City, Leshan City, and Lijiang City.

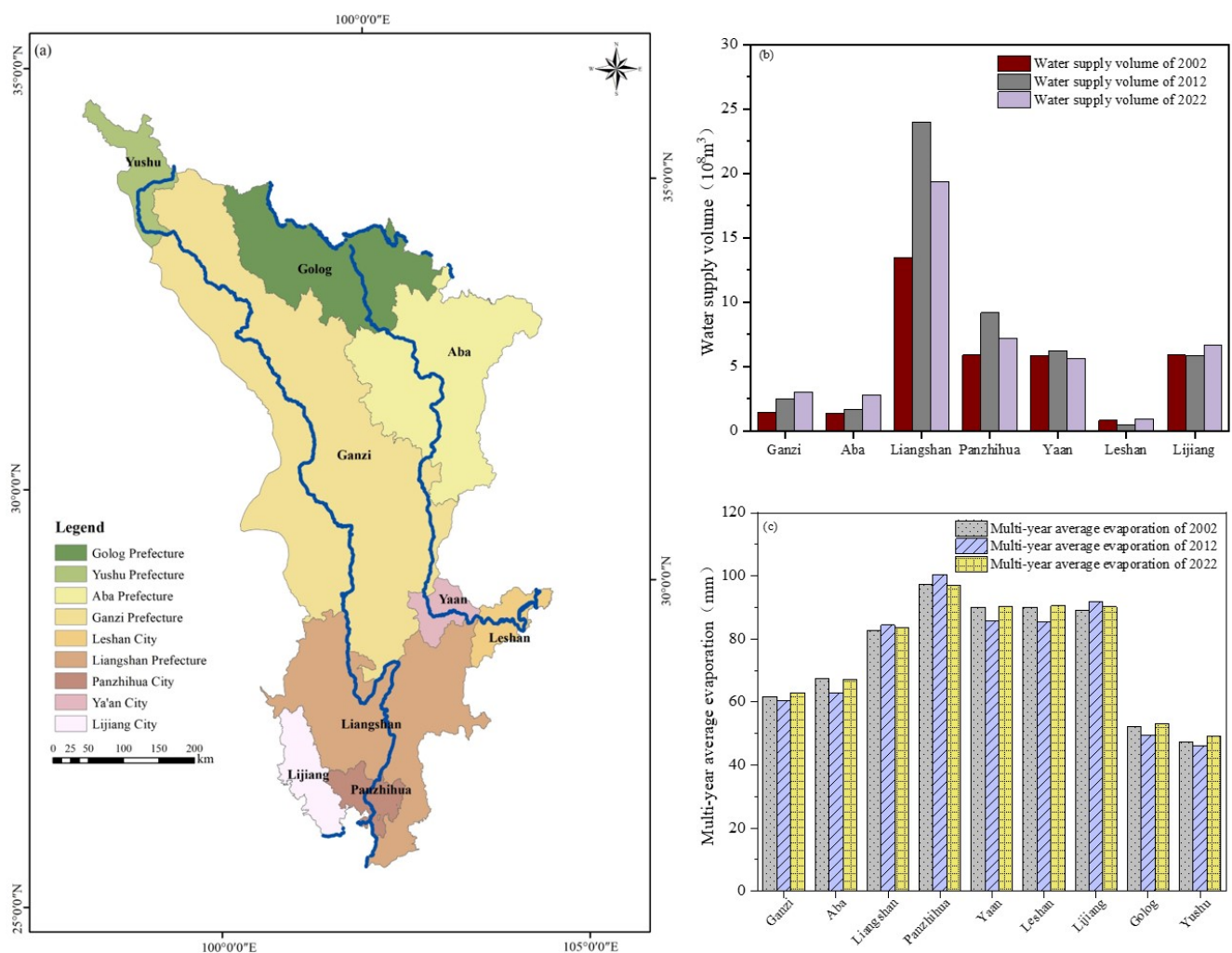


Figure 1. Basic situation of the water source area. (a) The study area of the water source area; (b) the water supply volume between 2002 and 2022; (c) the multi-year average evaporation between 2002 and 2022.

Water supply [12] in the water source area is an important provisioning function. The water supply volume from 2002 to 2022 is shown in Figure 1b. Liangshan, Panzhihua, Ya'an, and Lijiang had the largest water supply volumes, accounting for 42.49%, 15.75%, 12.37%, and 14.63% of the total water supply in 2022, respectively. The water supply volumes in

Ganzi Prefecture and Aba Prefecture showed an increasing trend. Over the 20-year period, the water supply in Ganzi Prefecture increased from 146 million m³ to 303 million m³, an increase of 2.08 times; the water supply in Aba Prefecture increased from 136 million m³ to 276 million m³, an increase of 2.03 times. Liangshan, Panzhihua, and Ya'an showed a trend of first increasing and then decreasing, while Leshan and Lijiang showed a trend of first decreasing and then increasing.

The mean annual evaporation [12] from 2002 to 2022 is shown in the Figure 1c. The areas with higher mean annual evaporation were Liangshan, Panzhihua, Ya'an, Leshan, and Lijiang. In 2002, the mean annual evaporation varied between 47.46 mm and 97.22 mm; in 2012, it varied between 45.99 mm and 100.40 mm; and in 2022, it varied between 49.15 mm and 97.04 mm. Interannually, the mean annual evaporation in the cities and prefectures of the water source area was relatively stable between 2002 and 2022. However, in 2012, there were significant differences among them. Specifically, Liangshan Prefecture, Panzhihua, and Lijiang had values significantly higher than in other years, while Aba Prefecture, Ya'an, Leshan, and Golog Prefecture had values significantly lower than in other years. Ganzi Prefecture and Yushu Prefecture remained relatively stable.

2.2. Data Sources

According to data from the statistical yearbooks of the cities and prefectures in the water source area, the emergy usage in the water source region included contributions from both renewable and non-renewable resources [24]. The study area mainly covers two major river basins, the Yalong River and the Dadu River, which are also important components of China's water network construction. Data sources for land use, temperature, evaporation, mean annual precipitation, and water supply are detailed in Table 1.

Table 1. Data sources of resources (2002, 2012, 2022).

Data Type	Source	References
Land cover	Zenodo	[15]
Annual runoff	Water Resources Bureau	[12]
Water supply	Water Resources Bureau	[12]
Temperature	China Meteorological Administration	[12]
Precipitation	China Meteorological Administration	[12]
Solar radiation	China Meteorological Administration	[12]
Evaporation	China Meteorological Administration	[12]
Wind speed	China Meteorological Administration	[12]
GDP	The Statistical Yearbook for each province and city.	[24]
Population	The Statistical Yearbook for each province and city	[24]

The water-system characteristics and land-use structure of the study area constitute the basic data for system energy input. The land-use status in the water source area agrees with the study results [25]. The solar, wind, rainwater potential, and chemical energy serve as renewable energy sources, shown in Figure 2. In contrast, coal energy in the study area was a non-renewable resource. The water source area is located on the eastern side of the Qinghai–Tibet Plateau. Its primary function is to provide water resources, and the economy is relatively underdeveloped. Therefore, contributions such as commodity sales are not considered in the energy value.

2.3. Evaluation Indicators for Emergy-Based Ecological Service Value

The emergy method uses solar energy as a benchmark for measuring energy by converting and quantifying the specific value of evaluation indicators [23]. The ecological and environmental value of water transfer projects primarily includes ecological value

and environmental value. In this study, the ecological value indicators mainly consisted of water supply, biodiversity, net primary productivity and biomass, while the environmental value indicators mainly included climate regulation, carbon fixation and oxygen release, and recreational value.

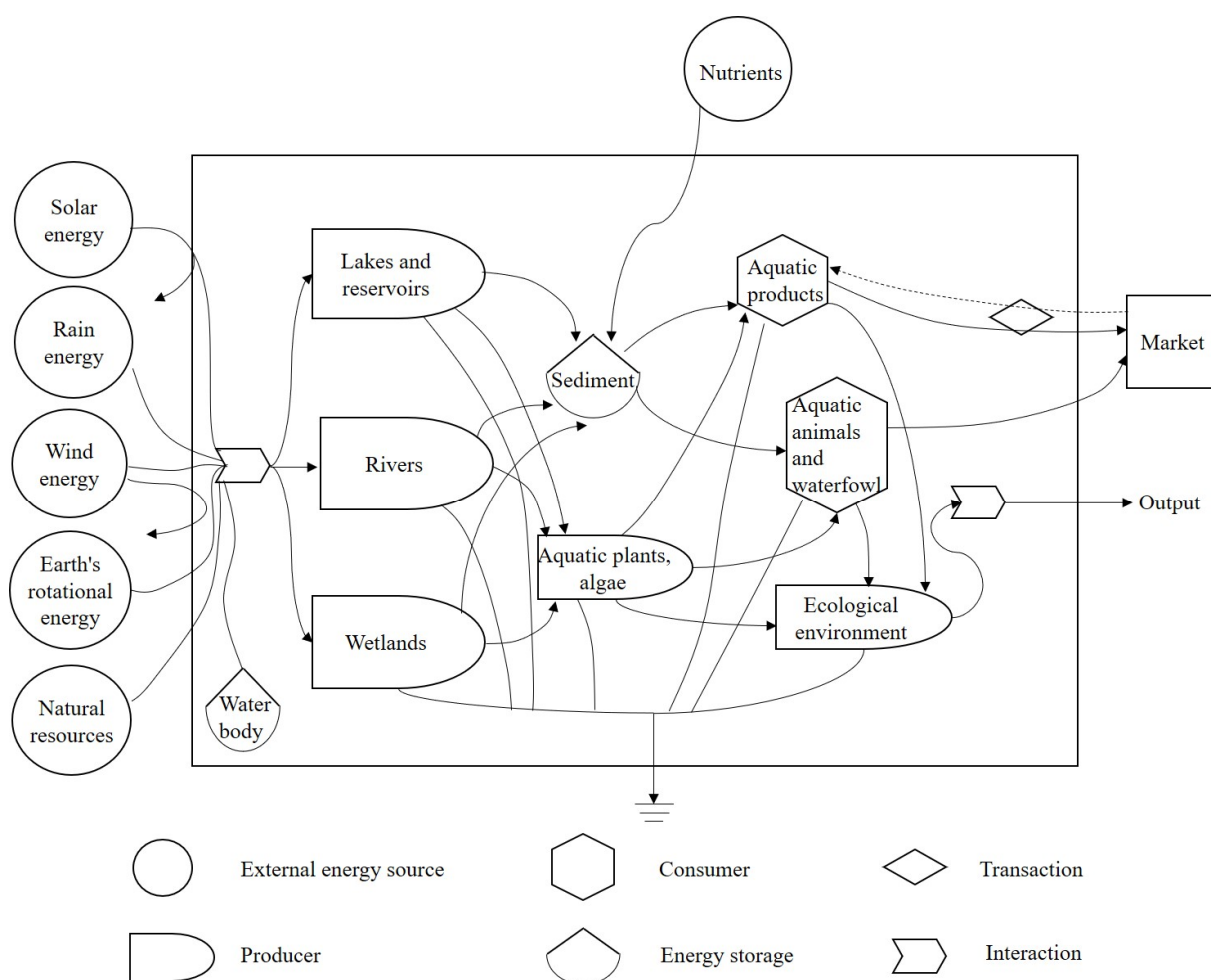


Figure 2. Energy network diagram for the water subsystem.

The calculation formula of ecological service value was as follows:

$$N_i = \sum M_i \quad (1)$$

$$W = \frac{N_i}{T_{GDP}} \quad (2)$$

$$ESV_i = \frac{\sum V_i \times \varphi_i}{W} \quad (3)$$

where N_i was the energy of the main resource material, sej; M_i was the energy of the i -th resource material, sej; W was the energy-to-money ratio, sej/CNY 100 million; T_{GDP} was the regional gross domestic product, CNY 100 million. ESV_i was the ecological service value, CNY 100 million; V_i was the quantity of the i -th material, m^3 ; φ_i was the solar energy transformity of the i -th material, sej/ m^3 .

The calculation of ecological–economic value involves renewable and non-renewable natural resources, as well as socio-economic resources, within various subsystems. These resources exist in different forms and dimensions. Emergy analysis technology can uniformly convert the various types of energy and matter mentioned above into comparable standard emergy [18]. The emergy conversion rate serves as the conversion relationship

between different types of energy [23]. Because all energy is ultimately solar-derived, the solar energy conversion rate enables the transformation of diverse, incomparable energy types within the system into a single standard of solar energy.

Water resource supply ensures local domestic and industrial water use. The water supply formula for this calculation was:

$$E_W = Q_W T_W \quad (4)$$

E_W was the emergy of water resource supply, sej; Q_W was the total water supply, m^3 ; and T_W was the transformity of surface water using 8.50×10^{11} sej/ m^3 [26].

Aquatic plants absorb CO_2 and release O_2 through photosynthesis, storing the resulting organic matter within their tissues, thereby playing a role in carbon fixation and oxygen release.

$$E_{\text{CO}_2} = Q_{\text{CO}_2} T_{\text{CO}_2} \quad (5)$$

$$E_{\text{O}_2} = Q_{\text{O}_2} T_{\text{O}_2} \quad (6)$$

E_{CO_2} and E_{O_2} were the emergy of CO_2 fixed and O_2 released, sej; Q_{CO_2} and Q_{O_2} were the amount of CO_2 fixed and O_2 released, kg; T_{CO_2} and T_{O_2} were the emergy transformity of CO_2 and O_2 , the transformity of CO_2 is 3.78×10^{10} sej/kg, and that of O_2 is 5.11×10^{10} sej/kg.

The influence of water surface evaporation on atmospheric humidity and temperature constitutes the climate regulation function. The emergy value of water evaporation was calculated as follows:

$$E_T = Q_T T_S \quad (7)$$

E_T is the emergy of climate regulation value, sej; Q_T was the heat absorbed by surface water evaporation, J; and T_S was the steam emergy transformity, which was related to altitude, 21.4–115.0 sej/J.

The calculation parameters for the net primary productivity of marshes and wetlands is $2500 \text{ g}/\text{m}^2/\text{a}$, and the biomass is $15 \times 10^3 \text{ g}/\text{m}^3$. The calculation method for the emergy of net primary productivity and biomass was as follows:

$$E_P = Q_P T_P \quad (8)$$

E_P represented the emergy of net primary productivity and biomass, sej; Q_P represented the mass of net primary productivity and biomass, g; and T_P represented the emergy transformity of net primary productivity and biomass, using 5.11×10^6 sej/g [27].

Maintaining the stability of its own species composition and quantity and providing a life carrier to sustain the material cycle and energy flow within the system, constituted the value of biodiversity.

$$E_B = Q_B T_B \quad (9)$$

E_B was the emergy for maintaining biodiversity, sej; Q_B was the number of biological species, and T_B was the emergy transformity of the biological species, using 1.26×10^{25} sej/species [28].

The calculation primarily considered aesthetic and recreational value, which can be derived from tourism revenue, with water bodies accounting for approximately 12.3% of tourism income.

$$E_Y = I \times \varphi \times 12.3\% \quad (10)$$

E_Y represented the emergy of aesthetic value, sej; I represented tourism revenue, CNY 100 million; and φ represents the emergy-to-money ratio, sej/CNY 100 million.

3. Results and Discussion

3.1. Provisioning Services

The emergy of water supply from 2002 to 2022 is shown in the Figure 3a–c. Over the past 20 years, Liangshan and Golog Prefecture did not supply water. Aba Prefecture and Ganzi Prefecture showed an increasing trend. In Aba Prefecture, it increased from 1.16×10^{20} sej to 2.35×10^{20} sej, and in Ganzi Prefecture, it increased from 1.24×10^{20} sej to 2.58×10^{20} sej, an increase of 1.03 times and 1.07 times respectively over the 20-year period. Liangshan Prefecture had the highest emergy, increasing from 1.14×10^{21} sej to 1.65×10^{21} sej over the 20 years. Panzhihua, Ya'an, and Lijiang had relatively high emergy values for water supply. The emergy in Panzhihua fluctuated between 5.00×10^{20} sej and 7.79×10^{20} sej, reaching its maximum in 2012. The emergy in Ya'an fluctuated between 4.79×10^{20} sej and 5.30×10^{20} sej, reaching its maximum in 2012 and its minimum in 2022. The emergy in Lijiang fluctuated between 4.94×10^{20} sej and 5.67×10^{20} sej, reaching its minimum in 2012 and its maximum in 2022. The high-emergy areas for water supply are concentrated in the lower reaches of the basin, which is related to the larger water volume and wider water surface in the lower reaches.

3.2. Regulating Services

3.2.1. Climate Regulation

The changes in climate regulation emergy values for each region from 2002 to 2022 are shown in the Figure 3d–f. The climate regulation emergy values of Ganzi Prefecture, Aba Prefecture, and Liangshan Prefecture fluctuated very little during the study period, maintaining a high degree of stability. Over the 20 years, Ganzi Prefecture's climate regulation emergy value ranged from 4.55×10^{17} sej to 4.64×10^{17} sej; Aba Prefecture's value ranged from 2.88×10^{16} sej to 3.08×10^{16} sej; and in Liangshan Prefecture, it varied between 1.30×10^{17} sej and 1.33×10^{17} sej. The remaining regions all showed varying degrees of increase, with the growth rates for Leshan, Panzhihua, Ya'an, Lijiang, Golog, and Yushu being 6%, 3%, 5%, 3%, 7%, and 7%, respectively.

The climate regulation function was related to evaporation. The interannual variation trends of regional climate regulation emergy values are generally consistent with evaporation, but may also be comprehensively influenced by factors such as underlying surface properties. Based on the emergy data, Ganzi Prefecture and Liangshan Prefecture have the strongest climate regulation capacity. The regulation capacity of Golog Prefecture is greater than that of Aba Prefecture, while Yushu Prefecture and Ya'an have the weakest regulation capacity.

3.2.2. Carbon Fixation and Oxygen Release

The emergy of carbon fixation and oxygen release from 2002 to 2022 is shown in the Figure 3g–i. From the perspective of temporal changes, over the 20-year period, the emergy of carbon fixation and oxygen release in Ganzi Prefecture decreased from 3.54×10^{19} sej to 2.69×10^{18} sej; in Aba Prefecture, it decreased from 4.20×10^{18} sej to 2.03×10^{17} sej; in Liangshan Prefecture, it fluctuated between 2.83×10^{17} sej and 3.01×10^{18} sej, with the lowest value of 2.83×10^{17} sej occurring in 2012; the emergy in Panzhihua decreased from 3.48×10^{18} sej to 2.10×10^{16} sej; the emergy in Ya'an decreased from 1.19×10^{18} sej to 6.88×10^{16} sej; the emergy in Leshan decreased from 4.87×10^{18} sej to 2.63×10^{17} sej; the emergy in Golog Prefecture decreased from 2.68×10^{18} sej to 3.87×10^{17} sej; the emergy in Yushu Prefecture decreased from 1.92×10^{18} sej to 1.35×10^{17} sej; the emergy in Lijiang decreased from 1.30×10^{15} sej to 8.98×10^{14} sej. Land use change can cause variations in carbon storage [19]. The results indicated that the decline in carbon sequestration and

oxygen release capacity coincide with the decreasing trend of cultivated land and water body areas.

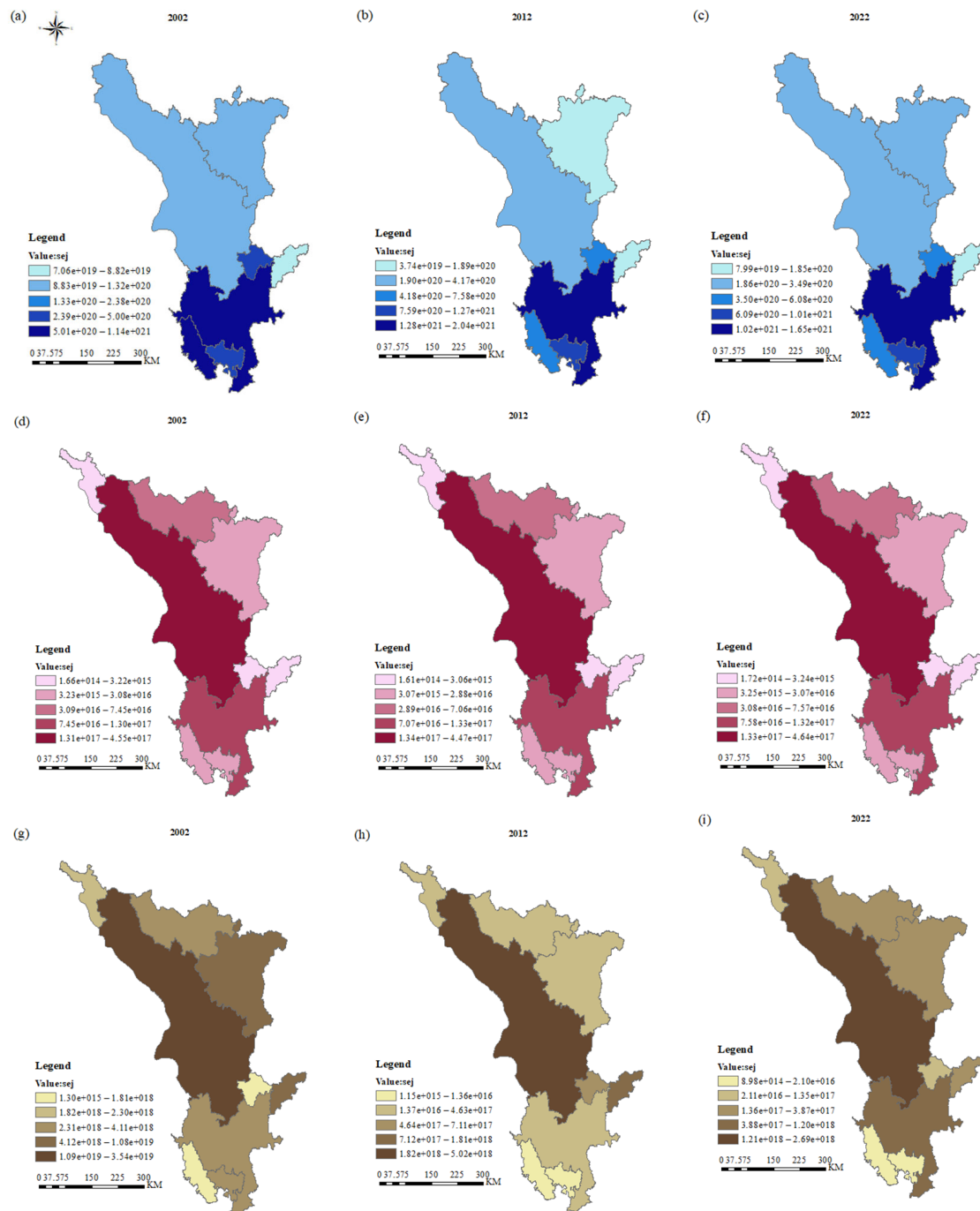


Figure 3. The provisioning services and regulating services of the water source area: (a) the emergy of water supply in 2002; (b) the emergy of water supply in 2012; (c) the emergy of water supply in 2022; (d) the emergy of climate regulation in 2002; (e) the emergy of climate regulation in 2012; (f) the emergy of climate regulation in 2022; (g) the emergy of carbon fixation and oxygen release in 2002; (h) the emergy of carbon fixation and oxygen release in 2012; (i) the emergy of carbon fixation and oxygen release in 2022.

From the perspective of regional differences, the carbon fixation and oxygen release capacity in the water source area generally showed a gradual decreasing trend. Ganzi Prefecture had the strongest capacity and is also the main distribution area in the upper

and middle reaches of the Yalong River. The weakest capacity was in Lijiang, which is located in the lower reaches of the basin.

3.3. Supporting Services

3.3.1. Net Primary Productivity and Biomass

Referring to the emergy transformity, the transformity for net primary productivity (NPP) is taken as 5.78×10^7 sej/g, and for biomass as 5.11×10^6 sej/g. Based on this, the changes in NPP and biomass that were primarily focused on water body areas such as wetlands, lakes, and rivers for each region from 2002 to 2022 were calculated, as shown in Figure 4a–c. Although Ganzi Prefecture ranks highest in emergy value, fluctuating between 1.06×10^{18} sej and 1.40×10^{19} sej, it shows a decreasing trend. The emergy values of Liangshan Prefecture varied between 1.12×10^{17} sej and 1.19×10^{18} sej. In Golog Prefecture, it varied between 1.53×10^{17} sej and 1.06×10^{18} sej. In Aba Prefecture, the emergy varied between 8.03×10^{16} sej and 1.66×10^{18} sej, were all at a moderate level. The Lijiang City has the lowest emergy value and also showed a declining trend, with its variation range between 3.55×10^{14} sej and 5.15×10^{14} sej. The decline in net primary productivity may be related to the decrease in crop yield and water body areas.

3.3.2. Biodiversity

The biodiversity assessment covers the major animal and plant species within the region. This study, based on the species emergy transformity of 1.26×10^{25} sej/species proposed by [23], combined with the proportion of biologically active areas in each region, conducted emergy calculations to derive the temporal changes in biodiversity emergy from 2002 to 2022 (as shown in the Figure 4d–f). Overall, the biodiversity function in the study area remained relatively stable over the 20-year period with small fluctuations, but exhibited significant spatial heterogeneity.

In the high-value areas, Liangshan Prefecture and Lijiang City had the highest biodiversity emergy values, at 1.21×10^{21} sej and 2.05×10^{21} sej respectively, corresponding to as many as 7661 and 13,000 species, respectively. Ganzi Prefecture and Aba Prefecture followed, with emergy values of 9.27×10^{20} sej and 7.17×10^{20} sej respectively, corresponding to 5881 and 4557 species. The lowest emergy values were found in Golog Prefecture and Yushu Prefecture, at 2.78×10^{20} sej and 2.40×10^{20} sej, corresponding to 1761 and 1525 species, respectively. This indicates that the biodiversity function in the water source area is maintained at a relatively stable level, with Liangshan and Lijiang being the core areas for regional biodiversity conservation.

3.4. Cultural Services

The cultural services of the water source area primarily focused on leisure and entertainment functions. This study used tourism value as the characterization index for its emergy evaluation in Figure 4g–i. Time series analysis showed that from 2002 to 2022, the emergy value of cultural services in the study area generally increased, but exhibited significant spatial heterogeneity, with Aba Prefecture and Ganzi Prefecture being the high-value agglomeration areas for this service. In Ganzi Prefecture, the cultural service emergy value fluctuated and grew between 4.12×10^{12} sej and 1.35×10^{13} sej, reaching its maximum in 2022. In Aba Prefecture, the emergy value ranged from 8.34×10^{12} sej to 2.85×10^{13} sej, peaking in 2012. The emergy in Liangshan Prefecture varied between 3.69×10^{11} sej and 1.64×10^{12} sej, with the maximum also occurring in 2012. Lijiang showed a steady and sustained growth trend, with emergy varying between 3.51×10^{12} sej and 6.08×10^{12} sej. Yushu Prefecture and Golog Prefecture also exhibited an increasing trend; the emergy in Yushu Prefecture varied between 2.35×10^{11} sej and 1.50×10^{12} sej, while the Golog emergy value grew from 8.49×10^{10} sej to 1.96×10^{12} sej.

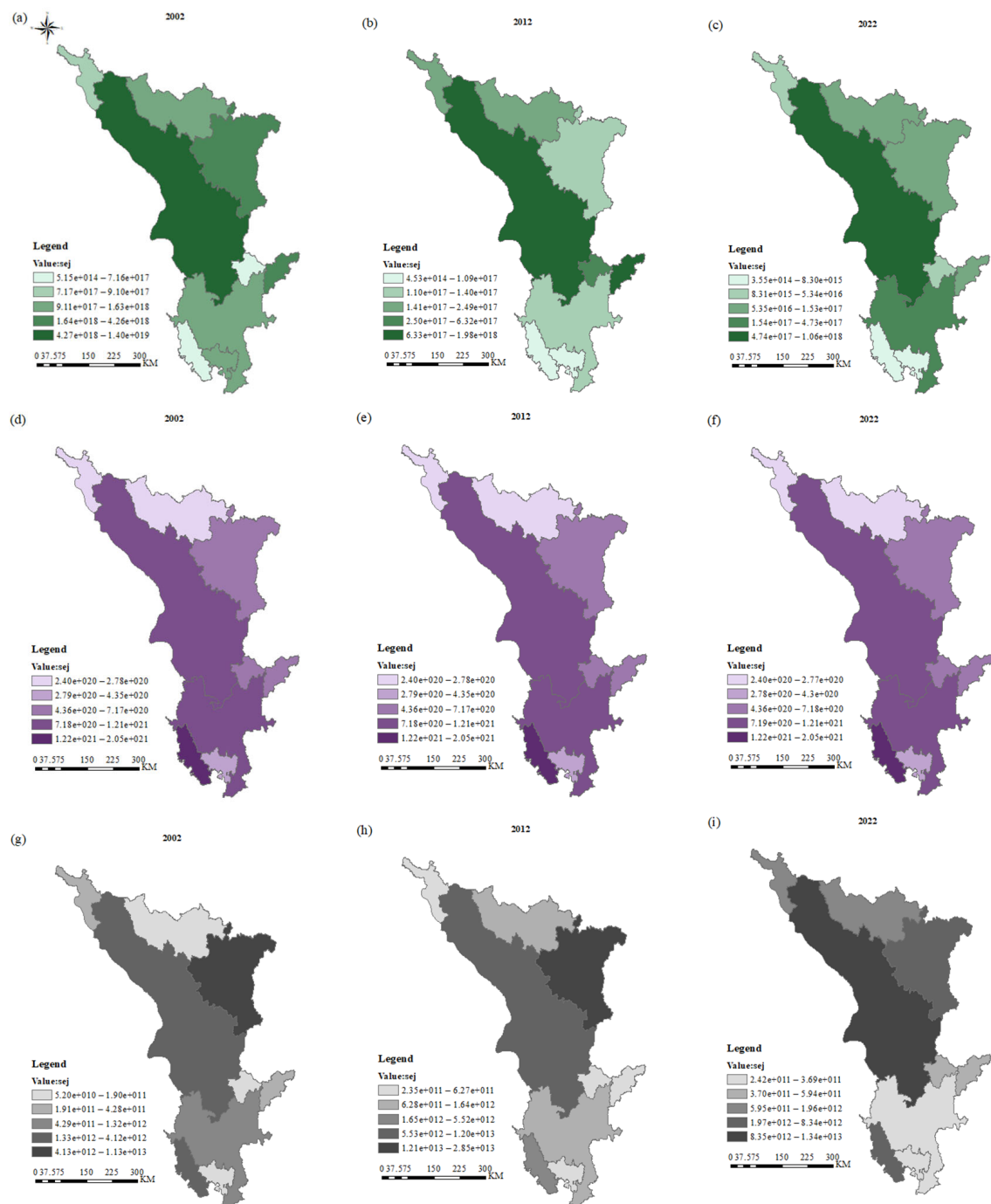


Figure 4. The supporting services and cultural services of the water source area: (a) the energy of net primary productivity and biomass in 2002; (b) the energy of net primary productivity and biomass in 2012; (c) the energy of net primary productivity and biomass in 2022; (d) the energy of biodiversity in 2002; (e) the energy of biodiversity in 2012; (f) the energy of biodiversity in 2022; (g) the energy of culture in 2002; (h) the energy of culture in 2012; (i) the energy of culture in 2022.

3.5. Relationship Between Service Values

The proportion of energy for water supply, carbon fixation and oxygen release, climate regulation, net primary productivity and biomass, biodiversity, and leisure and entertainment in the water source area from 2002 to 2022 are shown in the Figure 5. Water supply and biodiversity were the two ecological service values with the highest energy proportions, followed by carbon fixation and oxygen release, net primary productivity, and biomass. Similarly, water supply accounts for a relatively high proportion in other

studies [12]. Over the 20-year period, the proportion of energy for water supply increased from 29.12% to 35.25%, while the proportion for biodiversity decreased from 70.10% to 64.68%. The proportion of energy for carbon fixation and oxygen release decreased from 0.56% to 0.05%, and the proportion for net primary productivity and biomass decreased from 0.22% to 0.02%. The proportion of energy for climate regulation remained essentially unchanged at 0.01%, while the proportion for leisure and entertainment was relatively low and negligible. The decrease in the number of biological species was the main reason for the reduction in the proportion of biodiversity energy, while the reduction in water bodies, wetlands, and marshes was the main reason for the decline in the proportions of energy for carbon fixation and oxygen release, as well as net primary productivity and biomass.

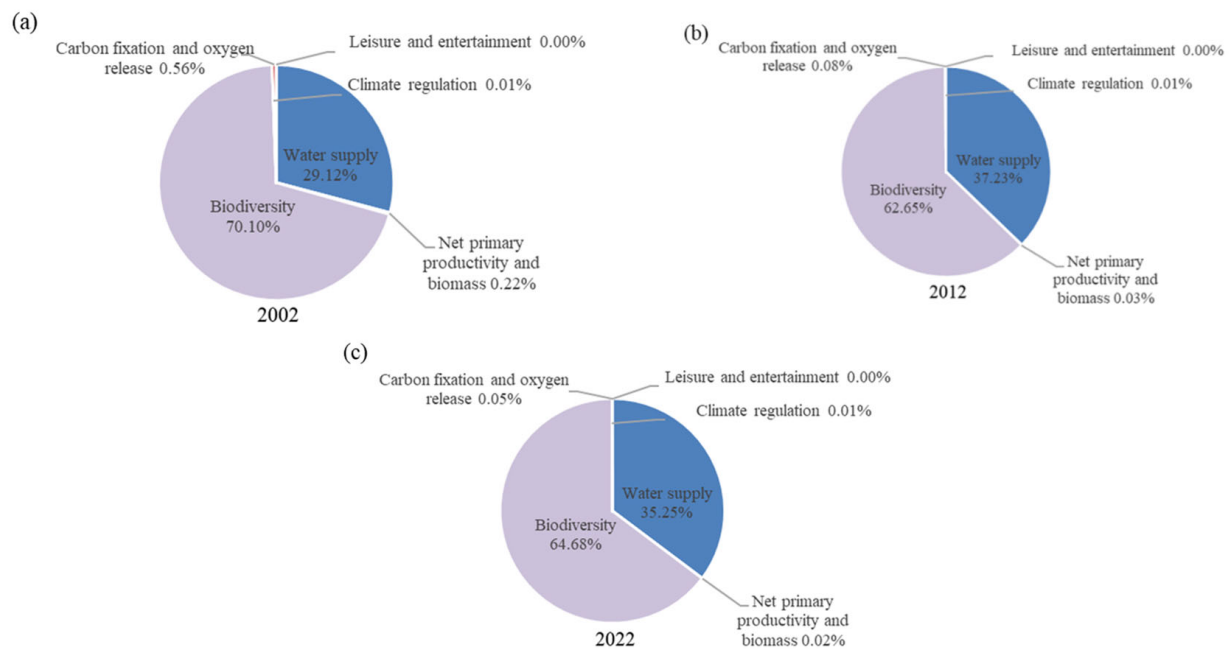


Figure 5. The relationship between service values: (a) the proportion of service values in 2002; (b) the proportion of service values in 2012; (c) the proportion of service values in 2022.

The correlation matrix of ecosystem services revealed significant trade-offs or synergies among different services (Figure 6). A strong trade-off exists between provisioning services and regulating/supporting services. A strong synergy ($r = 0.997$) was observed between biodiversity and productivity. The correlation coefficient between biodiversity and net primary productivity and carbon fixation was close to 1, indicating that higher biodiversity leads to greater ecosystem productivity and stronger carbon sequestration capacity. The climate regulation showed no correlation with biodiversity with -0.026 . Simply enhancing biodiversity or afforestation may have little effect on improving regional climate. The cultural service functions of water source areas depended on water surfaces. However, there was a conflict between water supply and biodiversity, biomass, and carbon sink functions. The conflict between water supply and biodiversity was particularly intense with -0.965 , the greater the water supply volume, the lower the biodiversity. When considering water source areas holistically, it is crucial to adopt a coordinated approach. Water supply should be guaranteed in core water source areas, while ecological core areas should focus on protecting biodiversity and carbon sinks with strict controls on water diversion. Therefore, scientifically determining water diversion volumes in phases and by season is particularly important.

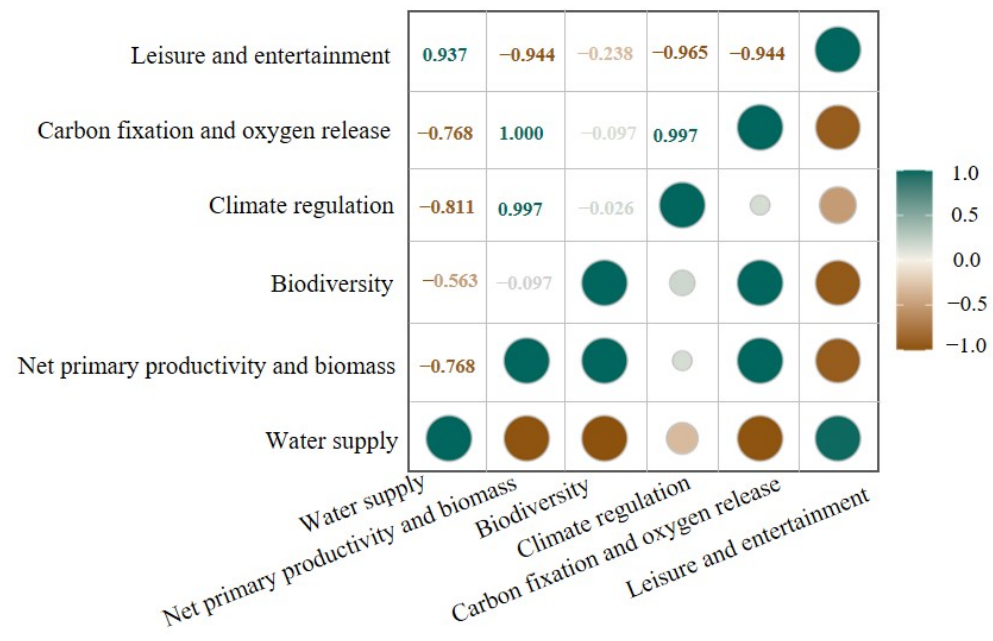


Figure 6. The correlation matrix of ecosystem services.

3.6. Ecosystem Service Value

The ecosystem service value of Ganzi Prefecture, Aba Prefecture, Liangshan Prefecture, Panzhihua City, Ya'an City, Leshan City, Lijiang City, Golog Prefecture, and Yushu Prefecture in the water source area from 2002 to 2022 is shown in the Figure 7. The total ecological service value of the water source area was CNY 24.252 billion in 2002, CNY 138.795 billion in 2012, and CNY 278.838 billion in 2022, increasing by 10.5 times over the 20-year period. The ecological service value of all cities and prefectures showed an increasing trend. Ganzi Prefecture increased from CNY 71 million to CNY 1.176 billion, an increase of 15.2 times. Aba Prefecture increased from CNY 145 million to CNY 1.692 billion, an increase of 10.6 times. Liangshan Prefecture increased from CNY 2.644 billion to CNY 37.468 billion, an increase of 13.2 times. Panzhihua, Ya'an, Leshan, and Lijiang increased by 7.5 times, 9.0 times, 11.9 times, and 16.2 times, respectively. Yushu and Golog increased by 7.8 times and 7.0 times, respectively.

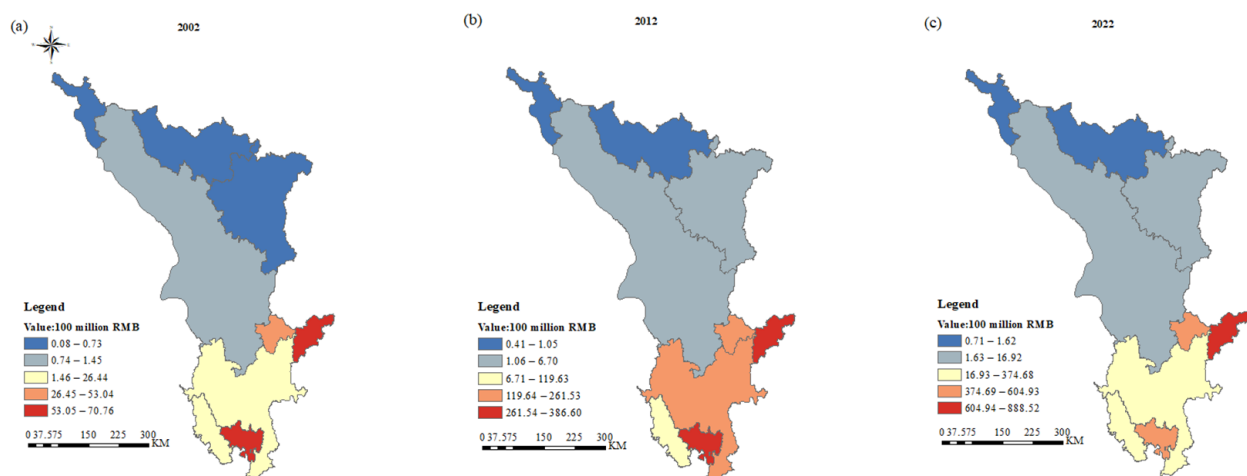


Figure 7. The ecosystem service value in the water source area between 2002 and 2022: (a) the ecosystem service value of 2002; (b) the ecosystem service value of 2012; (c) the ecosystem service value of 2022.

The changes in ecosystem service value for the nine cities and prefectures in the water source area from 2002 to 2022 are shown in the Table 2. Among the service types, provisioning services and supporting services account for a relatively high proportion. In Ganzi Prefecture, located in the upper and middle reaches of the basin, the service types with higher values were water resource supply and biodiversity functions. Water resource supply increased from CNY eight million to 255 million yuan, an increase of about 30 times, while biodiversity increased from 61 million yuan to 917 million yuan, an increase of about 14 times. In Aba Prefecture, located in the upper reaches of the basin, the service types with higher values were also water resource supply and biodiversity functions. Water resource supply increased from CNY 20 million to CNY 417 million, an increase of about 20 times, while biodiversity increased from CNY 124 million to CNY 1.275 billion, an increase of about nine times. In Liangshan Prefecture, located in the lower reaches of the basin, water resource supply increased from CNY 1.285 billion to CNY 21.609 billion, an increase of about 16 times, while biodiversity increased from CNY 1.354 billion to CNY 8.542 billion, an increase of about five times. The water resource supply and biodiversity services in the mid-to-lower reaches of the water source area, including Liangshan Prefecture, Panzhihua, Ya'an, Leshan, and Lijiang, are higher than those in the cities in the upper and middle reaches of the basin. This is because the mid-to-lower reaches collect the highest amount of water resources and have the largest number of biological species.

Table 2. Changes in ecosystem service value of nine prefectures and cities in the water source area from 2002 to 2022 (Unit: 100 million yuan).

Year	Service Type	Indicator	Ganzi	Aba	Liangshan	Panzhihua	Ya'an	Leshan	Lijiang	Golog	Yushu
2002	Provisioning services	Water supply	0.082	0.200	12.848	37.622	24.382	6.448	4.103	0.000	0.000
	Supporting services	Net primary productivity and biomass	0.009	0.003	0.013	0.103	0.023	0.176	0.000	0.000	0.001
		Biodiversity	0.612	1.242	13.540	32.769	28.572	61.901	16.750	0.080	0.200
	Regulating services	Climate regulation	0.000	0.000	0.001	0.001	0.000	0.000	0.000	0.000	0.000
		Carbon fixation and oxygen release	0.023	0.007	0.034	0.262	0.058	0.446	0.000	0.001	0.002
	Cultural services	Leisure and entertainment	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Total		0.726	1.453	26.437	70.757	53.036	68.972	20.852	0.082	0.202
2012	Provisioning services	Water supply	0.773	1.090	144.179	247.949	124.399	19.721	23.248	0.000	0.000
	Supporting services	Net primary productivity and biomass	0.007	0.001	0.008	0.002	0.066	0.378	0.000	0.000	0.001
		Biodiversity	3.413	5.610	85.421	138.633	136.899	357.112	96.386	0.407	1.055
	Regulating services	Climate regulation	0.002	0.000	0.009	0.006	0.000	0.002	0.001	0.000	0.000
		Carbon fixation and oxygen release	0.018	0.003	0.020	0.004	0.167	0.956	0.000	0.001	0.002
	Cultural services	Leisure and entertainment	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Total		4.213	6.704	229.638	386.594	261.531	378.168	119.634	0.407	1.058

Table 2. Cont.

Year	Service Type	Indicator	Ganzi	Aba	Liangshan	Panzhihua	Ya'an	Leshan	Lijiang	Golog	Yushu
2022	Provisioning services	Water supply	2.550	4.167	216.086	353.064	239.394	93.737	77.802	0.000	0.000
	Supporting services	Net primary productivity and biomass	0.011	0.001	0.062	0.005	0.014	0.122	0.000	0.000	0.000
		Biodiversity	9.171	12.747	158.360	251.842	291.002	794.353	280.976	0.713	1.615
	Regulating services	Climate regulation	0.005	0.001	0.017	0.010	0.001	0.004	0.002	0.000	0.000
		Carbon fixation and oxygen release	0.027	0.004	0.157	0.012	0.034	0.309	0.000	0.001	0.001
	Cultural services	Leisure and entertainment	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Total		11.762	16.920	374.682	604.933	530.445	888.525	358.780	0.714	1.617

The emergy-based assessment of ecosystem service values in the water source area is of significance beyond merely quantifying the ecological gains and losses of the specific region. Its methodological framework, indicator system, and analytical rationale can serve as a transferable technical approach for other analogous projects or regions. The results derived from this study are expected to support informed decision making in reconciling economic development with ecological conservation and in optimizing water resource allocation. Moreover, the spatiotemporal evolution patterns identified herein have practical implications for regional ecosystem management.

The emergy method uses solar emergy as a unified measurement unit, placing different forms of energy and materials under the same objective standard for comparison. It measures the solar emergy consumed by the ecosystem in the process of forming products or services. However, minerals, information, and other elements are difficult to accurately measure using solar emergy. It reflects natural supply but cannot represent the scarcity of ecosystem services. This method primarily emphasizes the impact of water surfaces, neglecting other effects of the underlying surface. When evaluating ecosystem service value, other methods can be integrated to comprehensively consider various elements of the ecological environment, thereby providing better guidance for the scientific assessment of the Western Route of the SNWD Project.

4. Conclusions

The emergy method was used to analyze the spatiotemporal variation patterns of ecosystem service value in the water source areas of the Western Route of the South-to-North Water Diversion Project. Among the service types, provisioning services and supporting services account for a relatively high proportion.

Water supply and biodiversity were the two ecosystem service values with the highest emergy proportions especially in Ganzi Prefecture and Aba Prefecture, followed by carbon fixation and oxygen release, net primary productivity, and biomass. The high-emergy areas for water supply are concentrated in the lower reaches of the basin, which is related to the larger water volume and wider water surface in the lower reaches. Overall, the biodiversity function remained relatively stable over the 20-year period with small fluctuations, but exhibited significant spatial heterogeneity, with Liangshan and Lijiang being the core areas for regional biodiversity conservation. The carbon fixation and oxygen release capacity generally showed a gradual decreasing trend. Ganzi Prefecture had the strongest capacity

and is also the main distribution area in the upper and middle reaches of the Yalong River. Ganzi Prefecture and Liangshan Prefecture have the strongest climate regulation capacity.

A strong trade-off exists between provisioning services and regulating/supporting services. It is a high degree of synergy between biodiversity and productivity. Higher biodiversity leads to greater ecosystem productivity and stronger carbon sequestration capacity. Simply enhancing biodiversity or afforestation may have little effect on improving regional climate. The conflict between water supply and biodiversity was particularly intense, -0.965 , which means the greater the water supply volume, the lower the biodiversity. This method primarily emphasizes the impact of water surfaces, which is needed to integrate other effects of the underlying surface. When considering water source areas holistically, it is crucial to adopt a coordinated approach. Water supply should be guaranteed in core water source areas, while ecological core areas should focus on protecting biodiversity and carbon sinks with strict controls on water diversion. Therefore, scientifically determining water diversion volumes in phases and by season is particularly important.

This study represented the first systematic application of the emergy method to assess the spatiotemporal evolution of ecosystem service values in the water source area of the Western Route of the South-to-North Water Diversion Project over the period 2002–2022. It revealed spatial heterogeneity, identified key driving factors, and established a unified evaluation framework based on solar emergy joules that overcome the dimensional incomparability inherent in conventional approaches. The findings uncover 20-year spatiotemporal trends and their linkages with land-use dynamics, marking a methodological advancement from static estimation to dynamic analysis. Future research could extend this framework through cross-regional comparisons to test its generalizability, and integrate climate and land-use scenarios for predictive modeling.

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