Postprint: Sustainable Utilization of Water Resources in Yulin City Based on the Emergy Ecological Footprint Model

Authors: Li Xiaoge

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Abstract

To investigate the development and utilization of water resources in semi-arid climate zones, taking Yulin City as a case study, this paper employs the emergy ecological footprint model to conduct a comprehensive evaluation of Yulin' s water ecological footprint, water ecological carrying capacity, and related indicators from 2000 to 2019 based on water resource statistical data, thereby revealing the changing characteristics of water resource development and utilization in Yulin City and comparing them with the traditional water ecological footprint model. The results show that: (1) From 2000 to 2019, the annual average value of Yulin' s water resource emergy ecological footprint was 1.17 hm2·人-1, the annual average value of water resource emergy ecological carrying capacity was 0.49 hm·2 人-1, with a significant ecological deficit showing an increasing trend; (2) The annual average value of Yulin' s water resource ecological pressure index was 2.43, which is in a sub-safe state; (3) The annual average value of the water resource eco-economic coordination index was 1.31, which is relatively stable; in the traditional water resource ecological footprint, the annual average value of water footprint per 10,000 yuan GDP decreased from 0.97 hm2 ·(104 元) -1 to 0.04 hm2 ·(104 元) -1, indicating that water resource utilization efficiency is gradually improving. Overall, the water resource ecological security situation in Yulin City remains severe; increasing water conservation efforts in agriculture and industry, innovating wastewater treatment technologies, advocating for domestic water saving, and improving the comprehensive efficiency of water resource utilization are the main pathways to promote the sustainable development of water resources in Yulin City.

Full Text

Abstract

To investigate the development and utilization of water resources in semi-arid climate zones, this study takes Yulin City as a case study. Based on water resource statistics, the emergy ecological footprint model was employed to comprehensively evaluate Yulin' s water ecological footprint and water ecological carrying capacity from 2000 to 2019, revealing the changing characteristics of water resource development and utilization. The results were compared with those from the traditional water ecological footprint model. The findings indicate that: (1) The annual average water resource emergy ecological footprint in Yulin City was 1.17 $hm^2 \cdot person^{-1}$, while the annual average water resource emergy ecological carrying capacity was 0.49 $hm^2 \cdot person^{-1}$. The ecological deficit is evident and increasing. (2) The annual average water resource ecological pressure index was 2.43, indicating a semi-safe state. (3) The annual average water resource eco-economic coordination index was 1.31, reflecting relatively stable coordination between the water resource ecosystem and socio-economic system. In the traditional water ecological footprint analysis, the water footprint per 10,000 yuan GDP decreased from 0.97 hm^2 per 10,000 yuan to 0.04 hm^2 per 10,000 yuan, demonstrating gradually improving water resource utilization efficiency. Overall, the ecological security situation of water resources in Yulin City remains severe. Strengthening water conservation in agriculture and industry, innovating wastewater treatment technologies, promoting domestic water saving, and comprehensively improving water resource utilization efficiency are essential pathways to promote sustainable water resource development in Yulin City.

Keywords: emergy analysis; water resources ecological footprint; water resources ecological carrying capacity; sustainable utilization; Yulin City

1. Introduction

Sustainable utilization of water resources is a critical component of ecological civilization construction and a primary focus of resource and environmental research. Existing literature encompasses numerous studies on water resource sustainability, ranging from national to county-level scales, addressing water resource ecological security, sustainable utilization, optimal allocation, and management policies. Common methodologies include the water footprint approach and ecological footprint method. The water ecological footprint extends traditional ecological footprint theory by incorporating water resource functions and applications, making it the most widely used method in China. Scholars have applied this approach to assess water resource development across various regions, including southern China (Jiangsu, Zhejiang, Guangxi), northeastern China (Liaoning, Jilin), and central-western regions (Shanxi, northern Shaanxi), offering targeted recommendations. Model improvements have been introduced to better reflect regional realities, such as incorporating regional water resource equivalence factors and yield factors, proposing concepts of water ecological footprint breadth and depth, and constructing three-dimensional ecological footprint models. Some researchers have integrated water ecological footprint with decoupling theory to analyze the coordination between water resource environment and economic development.

However, the water ecological footprint model traditionally employs global equivalence factors and yield factors, neglecting regional and temporal differences, which may introduce errors. To address this limitation, emergy theory was integrated into the ecological footprint model, evolving into a systematic emergy ecological footprint model through continuous application. For instance, Huang Xianfeng et al. analyzed the benefits of ecological water supply using emergy theory, Lü Cuimei et al. quantified water resources' contribution to agricultural production, Huang Xiaorong et al. compiled a water resource balance sheet using emergy models, and Wang Huiliang et al. evaluated the water resource ecosystem of the Yellow River Basin based on emergy theory. Emergy theory converts different energy types into unified solar emergy through solar transformity, enabling quantitative analysis of various energy forms and accurately reflecting the relationship between ecological environment and socio-economic development. Compared with traditional models, the water resource emergy ecological footprint model uses solar transformity as a parameter to unify all emergy flows in the system, more accurately simulating dynamic changes in regional water resource development and utilization. Therefore, applying this method to analyze water resource sustainability in Yulin City holds significant value.

1.1 Study Area Overview

Yulin City is located in northern Shaanxi Province, characterized primarily by sandy grassland and loess hilly-gully landforms, with a semi-arid climate and fragile ecological environment. According to the Shaanxi Provincial Water Resources Bulletin, Yulin has a total freshwater area of 1,386.67 hm^2. The multi-year average (2000–2019) self-produced water resources total 22.14×10^{8} m^3, comprising 15.50×10^{8} m^3 surface water, 9.28×10^{8} m^3 groundwater, and 2.64×10^{8} m^3 overlap. In 2019, Yulin' s per capita water resources and water resources per unit cultivated land were 548 m^3 · person^{-1} and 2,670 m^3 · hm^{-2}, respectively—26.43% and 12.43% of national averages, both below the internationally recognized water scarcity threshold of 1,000 m^3 · person^{-1}, classifying it as a resource-based water-scarce region.

In recent years, Yulin has accelerated socio-economic development and ecological civilization construction, intensifying urbanization and industrialization and exacerbating water supply-demand contradictions. Accurately assessing water resource development status is fundamental for local ecological environment construction and scientific decision-making, and crucial for promoting sustainable development of the ecological economy in semi-arid desert regions.

1.2 Data Sources

Based on statistical data from Yulin' s 12 counties and districts, this study selected 2000–2019 as the research period, using overall city averages. Water resource data for the emergy ecological footprint model were obtained from the Shaanxi Provincial Department of Water Resources' *Shaanxi Water Resources Bulletin*, including annual average total water resources and water consumption. Pollution-related water use primarily refers to wastewater discharge volumes of chemical oxygen demand (COD) or ammonia nitrogen, sourced from the *Shaanxi Statistical Yearbook*. Additional data including GDP, registered population, regional area, and rainfall were obtained from the *Yulin Statistical Yearbook*. Emergy conversion rates were primarily derived from relevant literature.

1.3.1 Water Resource Emergy Ecological Footprint Model

The water resource emergy ecological footprint model integrates emergy theory with the ecological footprint model, comprising two components: water consumption ecological footprint and water quality ecological footprint. Water consumption is categorized into agricultural, industrial, urban public service, residential, and ecological water use. Water quality ecological footprint represents water resource consumption for diluting pollutants to certain standards, also called pollution footprint.

The calculation method is as follows:

$$EEF_w = EEF_k + EEF_q$$

$$EEF_k = \sum_{i=1}^{n} \frac{C_{ki}}{P_w}$$

$$C_{ki} = \frac{E_{ki}}{M_{ki}} = \frac{\tau_{ki} \times M_{ki}}{N}$$

$$EEF_q = \max\left(\frac{E_{\text{COD/NH3-N}}}{P_w}\right)$$

Where: - EEF_w = per capita water resource emergy ecological footprint ($\text{hm}^2 \cdot \text{person}^{-1}$) - EEF_k = per capita water consumption ecological footprint ($\text{hm}^2 \cdot \text{person}^{-1}$) - EEF_q = per capita water pollution footprint ($\text{hm}^2 \cdot \text{person}^{-1}$) - C_{ki} = per capita emergy of water use type i ($\text{sej} \cdot \text{person}^{-1}$), $i = 1, 2, 3, 4, 5$ - M_{ki} = water consumption of type i (m^3) - τ_{ki} = solar transformity of water use type i ($\text{sej} \cdot \text{m}^{-3}$) - N = population of Yulin City - P_w = global average emergy density (3.104\$×10^{14}\$ $\text{sej} \cdot \text{hm}^{-2}$) - $E_{\text{COD/NH3-N}}$ = emergy of COD or ammonia nitrogen (sej) - ρ_w = water density (1\$×10^{6}\$ $\text{g} \cdot \text{m}^{-3}$) - H_w = calorific value conversion coefficient (2.56$×10^{4}$ J · kg^{-1}) - U_w = unit emergy of water (8.54$×10^{4}$ sej · J^{-1}), calculated as the multi-year average of total rainwater chemical emergy divided by surface water (groundwater) chemical energy

The calculation formula is:

$$EE_{rc} = \tau_{rc} \times M_u \times G \times \text{Rain}$$

Where: - EE_{rc} = rainwater chemical emergy (sej) - M_u = water resource volume (m^3) - G = Gibbs free energy (4.94 J · g^{-1} for rainwater, 4.90 J · g^{-1} for surface/groundwater) - Rain = average rainfall (mm) - θ = evapotranspiration coefficient - S = regional area (hm^2) - τ_{rc} = solar transformity of rainwater chemical energy (1.80$×10^{4}$ sej · J^{-1})

1.3.2 Water Resource Sustainable Utilization Evaluation Indicators

1) Water Resource Ecological Deficit/Surplus (ED/ES)

This indicator evaluates regional water resource sustainability and supply-demand balance, calculated as the difference between ecological carrying capacity and ecological footprint. If $EEC_w < EEF_w$, ecological deficit occurs, indicating water resource consumption exceeds ecological capacity and threatens local water security. Conversely, if supply meets demand, it favors sustainable development. When $EEC_w = EEF_w$, ecological balance is achieved.

$$ED/ES = EEC_w - EEF_w$$

2) Water Resource Ecological Pressure Index (EPI)

EPI is the ratio of water resource ecological footprint to carrying capacity, evaluating ecological security. When EPI < 1, water resource consumption is within carrying capacity (safe state). When EPI > 1, consumption exceeds supply capacity (unsafe state). EPI = 1 indicates balance.

$$EPI = \frac{EEF_w}{EEC_w}$$

3) Water Resource Eco-economic Coordination Index (ECI)

Coordination between water resource ecosystems and socio-economic development reflects the relationship between economic development level and water resource utilization. ECI measures this coordination, with a range of (1, 1.414). Values closer to 1 indicate poorer coordination; values closer to 1.414 indicate better coordination. ECI = 1.414 represents optimal coordination.

$$ECI = \frac{EEF_w + EEF_w^2}{EEC_w^2 + EEC_w^2}$$

1.3.3 Traditional Water Resource Ecological Footprint Evaluation

To further analyze water resource development, a traditional water resource ecological footprint model was constructed for comparative analysis with the emergy approach. Following Zhu Guanglei et al., the calculation formula is:

$$EF_w = \frac{\Phi_w \times \gamma}{P_w}$$

Where: - EF_w = traditional water resource ecological footprint (hm^2) - Φ_w = global water resource equivalence factor (value = 2) - γ = global average water production capacity (3,140 $\text{m}^3 \cdot \text{hm}^{-2}$)

Water resource utilization efficiency can be expressed as water ecological footprint per 10,000 yuan GDP. A smaller ratio indicates higher efficiency:

$$WFG = \frac{EF_w}{\text{GDP}}$$

Where WFG = water ecological footprint per 10,000 yuan GDP.

2. Results

2.1 Trends in Water Resource Emergy Ecological Footprint

From 2000 to 2019, Yulin' s water resource emergy ecological footprint (EEF_w) increased from 0.97 $\text{hm}^2 \cdot \text{person}^{-1}$ to 1.48 $\text{hm}^2 \cdot \text{person}^{-1}$, showing a fluctuating upward trend with a 52.29% increase. Agricultural, industrial, urban public service, residential, ecological, and pollution water use accounted for 49.69%-72.84%, 11.21%-36.47%, 0.16%-1.27%, 3.74%-6.10%, 5.13%-13.80%, and 0%-1.46% of the total emergy ecological footprint, respectively. Agricultural water use is the primary contributor, followed by industrial and pollution water use, with ecological water use contributing the least.

Analyzing trends by water use category reveals that industrial, residential, and urban public service water footprints increased annually, while agricultural and pollution water footprints decreased. The industrial water account trend closely mirrors the total per capita emergy trend, suggesting it is the main driver of total emergy ecological footprint changes. The analysis shows that while agricultural water demand is substantial, its economic contribution is relatively low, with agricultural water consumption gradually decreasing in recent years. Conversely, industrial water demand has increased, driving industrial output growth and economic development. This indicates that Yulin' s water resource allocation structure has been gradually adjusting over the past 20 years, promoting optimization and upgrading of industrial and agricultural structures.

2.2 Trends in Water Resource Emergy Ecological Carrying Capacity

Yulin' s water resources primarily come from rainwater, surface water, and groundwater. From 2000 to 2019, total emergy fluctuated between 7.04\$×10^{20}\$ and 1.41\$×10^{21}\$ sej, with emergy ecological carrying capacity showing a fluctuating upward trend. The highest value occurred in 2019 at 2.35\$×10^{6}\$ hm^2. The multi-year average EEC_w was 0.49 $hm^2 \cdot person^{-1}$, fluctuating between 0.35-0.62 $hm^2 \cdot person^{-1}$. Rainwater potential energy contributed most to carrying capacity, while surface water and groundwater contributions were relatively smaller.

EEC_w is significantly affected by rainfall, with a correlation coefficient of 0.85 between water resource ecological carrying capacity and annual rainfall, indicating that rainfall plays a decisive role in Yulin' s water resource ecological carrying capacity.

2.3 Analysis of Water Resource Sustainable Utilization

1) Ecological Deficit and Pressure

From 2000 to 2019, Yulin consistently experienced water resource ecological deficit (ED), which increased annually from -0.62 $hm^2 \cdot person^{-1}$ to -0.98 $hm^2 \cdot person^{-1}$, a 57.29% increase. The per capita water resource ecological pressure index (EPI) showed slow fluctuations with relatively small inter-annual variation, averaging 2.43 and indicating a semi-safe state. The minimum EPI of 1.88 occurred in 2003.

Although the Yellow River water diversion project has alleviated Yulin' s water deficit to some extent, recent climate change and human activities have significantly reduced actual water inflow in the Yellow River Basin. Meanwhile, Yulin's rapid industrialization has increased water demand, highlighting supply-demand contradictions and threatening sustainable ecological development. Long-term ecological deficit will constrain socio-economic development and hinder regional economic growth.

2) Eco-economic Coordination Index (ECI)

Yulin's water resource eco-economic coordination showed fluctuations, with ECI ranging from 1.27 to 1.35 and averaging 1.31. This indicates relatively stable coordination between the water resource ecosystem and socio-economic system. Recent adjustments to industrial and agricultural structures have improved water use efficiency, though coordination still needs further enhancement.

3) Water Use Efficiency

Using the traditional water ecological footprint approach, water use efficiency measured as water footprint per 10,000 yuan GDP decreased from 0.97 hm^2 per 10,000 yuan to 0.04 hm^2 per 10,000 yuan, a 96.16% reduction with an annual decrease rate of 15.76%. This decreasing trend indicates continuously improving water use efficiency, consistent with ECI findings, resulting from structural adjustments in water resource development and economic industries, as well as transformation of economic growth patterns.

[Figure 3: see original paper] [Figure 4: see original paper] [Figure 5: see original paper]

3. Discussion

3.1 Comparison Between Traditional and Emergy Water Resource Ecological Footprints

Both traditional and emergy water resource ecological footprints show increasing trends, but emergy values are larger. Traditional calculations use global water resource equivalence factors and average production capacity, assuming equal biologically productive land area per unit of freshwater consumed across all water use types. The emergy model accounts for varying contributions and regional differences through different transformity coefficients, better reflecting actual conditions in Yulin.

Comparison of ecological carrying capacities also shows emergy values exceeding traditional values, with greater fluctuation. Emergy-based carrying capacity incorporates energy flows and converts various land types' contributions through solar transformity, while traditional calculations may overlook certain land types.

[Figure 6: see original paper] [Figure 7: see original paper]

3.2 Water Resource Utilization in Yulin City

From 2000 to 2019, Yulin's per capita water resource emergy ecological footprint fluctuated upward, primarily influenced by industrial water use, which correlates significantly with per capita GDP ($r = 0.99$, $p < 0.01$). Agricultural water use is the main contributor to the footprint but shows a decreasing trend due to improved irrigation technology and planting structure adjustments. Pollution water footprint increased before 2017 but decreased afterward, likely related to Yulin' s 2016 Water Pollution Prevention and Control Work Plan, which strengthened emission control and water pollution treatment.

EEC_w fluctuates mainly with rainfall, with notable impacts in wet and dry years. The Yellow River water diversion project, initiated in 2016, uses Yellow River surface water, but the allocated volume is fixed at 3.17$\times10^{8}$ m^3 (about 14% of Yulin' s total water resources). With decreasing actual inflow in the Yellow River Basin, relying on diversion to increase carrying capacity is unsustainable. Future improvements may require artificial technological interventions to enhance water resource ecological carrying capacity.

4. Conclusions and Recommendations

1) Yulin' s annual average ED and EPI were -0.68 $hm^2 \cdot person^{-1}$ and 2.43, respectively, indicating persistent water resource ecological deficit and semi-safe status. However, ECI (1.31) and water footprint per 10,000 yuan GDP (0.04 hm^2 per 10,000 yuan) show relatively stable ecosystem-socioeconomic coordination and continuously improving water use efficiency.

2) Yulin' s water resource ecological security remains concerning. High agricultural and industrial water consumption leads to low efficiency. Recommendations include:

    - **Agriculture**: Adjust planting structure, adopt advanced irrigation technologies, and improve agricultural water use efficiency
    - **Industry**: Guide coal and chemical industries toward low-pollution, low-water-consumption production processes, enhance technological levels, and reduce industrial pressure on water environment
    - **Domestic use**: Establish water-saving incentive systems, promote public awareness, and improve water use efficiency
    - **Pollution**: Apply advanced technologies for wastewater recycling and reuse treated wastewater in urban ecological construction to improve water environmental safety

This study analyzed Yulin's water resource development using the emergy ecological footprint model, incorporating pollution accounts and considering regional rainfall and water storage differences, with comparative analysis against traditional methods, yielding relatively accurate results. However, limited data may have introduced some parameter errors requiring further research. The discussion of methodological differences and suggestions for artificial intervention technologies provide references for future water resource management in Yulin.

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Note: Figure translations are in progress. See original paper for figures.