

# Multi-Dimensional Spatiotemporal Differentiation of the Supply-Demand Relationship for Ecosystem Water Yield Services in the Liupan Mountains Postprint

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## Abstract

Against the backdrop of ecological protection and high-quality development in the Yellow River Basin, the ecosystem water yield services of the Liupan Mountain area, acclaimed as a “wet island”, are becoming increasingly prominent in their significance for the arid Loess Plateau. By establishing assessment methodologies for ecosystem water yield service supply and demand tailored to mountainous regions, and integrating approaches such as the InVEST model and supply-demand matching index, this study systematically evaluates the multi-dimensional differentiation characteristics of the ecosystem water yield service supply-demand relationship across temporal and spatial dimensions. The results indicate that over the past 30 years, both the supply and demand of ecosystem water yield services in the Liupan Mountain area have exhibited a trend of initial decrease followed by increase, with the southeastern mountainous region showing the maximum variation amplitude in supply (13.1%) and the northern mountainous region showing the maximum variation amplitude in demand (-37.1%). In the study area, regions above 2000 m elevation function as supply zones for ecosystem water yield services and high supply-demand matching zones, while areas below 2000 m constitute demand zones. After 2000, high-demand areas shifted from the northern region to the southeastern and southwestern mountainous areas, consequently forming a spatiotemporal distribution pattern of supply-demand matching characterized by relatively high levels in the north, moderate levels in the southwest, and lower levels in the southeast. Overall, the supply-demand relationship of ecosystem water yield services in the Liupan Mountain area demonstrates multi-dimensional and non-equilibrium distribution patterns across spatiotemporal and vertical dimensions. With temporal progression and increasing altitude, the supply-demand matching degree in the northern mountainous area increased before 2000 while decreasing in the

southwestern and southeastern mountainous areas; conversely, after 2000, the matching degree in the northern mountainous area decreased while increasing in the southwestern and southeastern areas. The research findings reveal the spatial differentiation patterns of water resource supply-demand relationships in the Liupan Mountain area, providing a scientific basis for optimal water resource allocation in arid mountainous regions.

## Full Text

# Multidimensional Spatiotemporal Differentiation of the Supply-Demand Relationship of Ecosystem Water-Yielding Services in the Liupan Mountain Area

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## Abstract

Against the backdrop of ecological protection and high-quality development in the Yellow River Basin, the water-yielding service of the Liupan Mountain area—renowned as a “wet island”—has become increasingly critical for the arid Loess Plateau. This study establishes an assessment methodology for ecosystem water-yielding service supply and demand tailored to mountainous regions. By integrating the InVEST model, supply-demand matching indices, and other analytical tools, we systematically evaluate the multidimensional differentiation characteristics of the supply-demand relationship for ecosystem water-yielding services across temporal and spatial dimensions. The results demonstrate that both supply and demand of ecosystem water-yielding services in the Liupan Mountain area exhibited a trend of initial decrease followed by increase. The southeastern mountainous area experienced the most significant supply variation (13.1%), while the northern mountainous area showed the largest demand variation (−37.1%). Regions above 2000 m elevation serve as supply zones with high supply-demand matching, whereas areas below 2000 m are predominantly demand zones. After 2000, high-demand areas shifted from the northern region to the southeastern and southwestern mountainous areas, forming a spatiotemporal distribution pattern characterized by relatively high matching in the north, moderate in the southwest, and low in the southeast. Overall, the supply-demand relationship of ecosystem water-yielding services in the Liupan Mountain area displays a multidimensional, uneven distribution pattern across spatiotemporal dimensions and vertical zones. With increasing time and altitude, the matching degree in the northern mountainous area increased before 2000 but decreased in the southwestern and southeastern areas; after 2000, the matching degree in the northern area declined while it increased in the southwestern and southeastern regions. These findings reveal the spatial differentiation patterns of water resource supply-demand relationships in the Liupan

Mountain area, providing a scientific basis for optimal water resource allocation in arid mountainous regions.

**Keywords:** InVEST model; ecosystem services; supply-demand matching; spatiotemporal differentiation; Liupan Mountain area

Water ecosystem services represent a comprehensive manifestation of natural environmental conditions and ecological benefits, playing crucial roles in water yield, water purification, and soil conservation. However, due to spatial heterogeneity in ecosystems, water-yielding services exhibit significant variations across different regions and environmental conditions. Rapid socioeconomic development and growing water demands have further intensified the spatiotemporal imbalance of ecosystem water-yielding services and their supply-demand relationships. Therefore, quantitative simulation and evolutionary analysis of supply-demand matching patterns across multiple spatiotemporal scales are both necessary and urgent. The Liupan Mountain area, acclaimed as the “wet island of the Loess Plateau,” serves as a vital ecological barrier for the region, playing an irreplaceable role in water conservation, soil retention, and regional ecological security. Situated in a transitional zone between arid and semi-arid climates, the area experiences uneven spatiotemporal distribution of precipitation and surface runoff, resulting in significant seasonal fluctuations and spatial heterogeneity in water resource supply. Furthermore, the well-developed forest and grassland ecosystems, characterized by high vegetation coverage and ecological functions, make forest and grassland water consumption a major component of water-yielding service demand in mountainous areas. Based on this context, our study employs forest and grassland water consumption as an indicator of water-yielding service demand, constructing an assessment methodology suitable for mountainous regions to reveal the multidimensional, uneven distribution patterns of supply-demand relationships across spatiotemporal dimensions and vertical zones. The findings provide theoretical support for optimal water resource allocation in the Liupan Mountain area and for ecological protection and high-quality development of the Loess Plateau.

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### 1.1 Study Area Overview

The Liupan Mountain area encompasses seven counties (districts) with a total area of 3,962.9 km<sup>2</sup>. The multi-year average annual precipitation ranges from 212–661 mm. Based on our data, we utilized hydrological analysis in ArcGIS software to identify watershed and sub-watershed boundaries in the Liupan Mountain area (Fig. 1). According to topographic differentiation and drainage development characteristics, the region was further divided into three sub-regions: the northern mountainous area, southwestern mountainous area,

and southeastern mountainous area. The northern mountainous area primarily comprises the Qingshui River basin above the Quanyanshan hydrological station, featuring a typical dendritic drainage pattern that converges gradually from south to north along the terrain. The southwestern mountainous area mainly consists of the Huli River basin above the Qin' an hydrological station, also exhibiting a dendritic pattern that converges from northeast to southwest. The southeastern mountainous area is dominated by the Jing River basin above the Yangjiaping hydrological station, with its drainage development controlled by the eastern foothills of the Liupan Mountains, showing a dendritic pattern converging from northwest to southeast.

Data sources included: DEM data from the Geospatial Data Cloud; precipitation and potential evapotranspiration data from the China Daily Precipitation Dataset and the High-Resolution Mountain Environment Mapping Program; land use data from the CLCD dataset at Wuhan University and the China Multi-Period Land Use Remote Sensing Monitoring Dataset; measured runoff data from water resources bulletins and river sediment bulletins. InVEST model parameters such as plant-available water content were calculated based on the Harmonized World Soil Database and the Zhou Wenzuo empirical estimation model; root restriction layer depth data were derived from the China Soil Depth Map. All raster data were resampled to  $30\text{ m} \times 30\text{ m}$  resolution via bilinear interpolation, with the study period unified to 2000–2020. Detailed data sources and preprocessing are listed in Table 1.

[Figure 1: see original paper]

### 1.3.1 Supply of Ecosystem Water-Yielding Services

We employed the water yield module of the InVEST model to assess ecosystem water-yielding service supply in the Liupan Mountain area. Specific calculation procedures follow those described in the literature. Based on our data and the InVEST model user manual, combined with the FAO' s “Crop Evapotranspiration and Crop Water Requirements” guidelines and references, we determined evapotranspiration coefficients and root depth parameters for each land use type (Table 2). The Zhang coefficient was calculated using the formula  $N = 0.2 \times N$ , where  $N$  represents the number of annual rainfall events ( $\geq 1\text{ mm}$ ) based on daily precipitation statistics.

### 1.3.2 Demand for Ecosystem Water-Yielding Services

Ecosystem water-yielding service demand was calculated using the land surface evaporation quota method:

$$Deco = 1000 \times ETeco \times Aeco$$

where  $Deco$  represents ecosystem water-yielding service demand ( $\text{m}^3$ ),  $Aeco$  is the area of moderately-high coverage grassland, forestland, and shrubland

( $\text{km}^2$ ), and  $ET_{\text{eco}}$  is land surface evaporation (mm), calculated using the Fu Baopu formula.

### 1.3.3 Supply-Demand Matching Degree of Ecosystem Water-Yielding Services

Following established literature, we calculated the supply-demand matching index ( $M$ ) for ecosystem water-yielding services. A smaller  $M$  value indicates poorer matching, while a larger value indicates better matching. Grid data were processed using formula (1), and the matching degree was classified according to formula (2):

- $M < M - 0.5\delta M$ : extremely low matching
- $M - 0.5\delta M \leq M < M - 0.25\delta M$ : low matching
- $M - 0.25\delta M \leq M < M + 0.25\delta M$ : moderate matching
- $M + 0.25\delta M \leq M < M + 0.5\delta M$ : high matching
- $M \geq M + 0.5\delta M$ : extremely high matching

where  $M$  and  $\delta M$  represent the mean and standard deviation of grid data values, respectively.

#### 2.1.1 Spatiotemporal Distribution Characteristics of Water-Yielding Service Supply

Over the past two decades, the average water-yielding service supply in the Liupan Mountain area was  $18.8 \times 10^6 \text{ m}^3$ , showing a fluctuating trend of decrease-increase-decrease-increase with variations of 47.4%, 96.7%, -66.5%, and -31.5%, respectively. The southeastern mountainous area exhibited the largest amplitude of change (-69.8% to 98.7%). The northern mountainous area had an average supply of  $7.9 \times 10^6 \text{ m}^3$  with variations of 96.6% and -74.8%. The southwestern mountainous area showed an average supply of  $8.2 \times 10^6 \text{ m}^3$  with variations of 38.3% and -77.5%.

The overall spatial pattern of supply in the Liupan Mountain area presented high values in the southwest and low values in the north (Fig. 2). Low-value areas remained stable in the northern mountainous region, while high-value areas showed phased changes: distributed in the central-southern part of the southwestern mountainous area and high-altitude regions of the Liupan Mountains during 2000-2005; in the southern part of the northern mountainous area and southwestern mountainous area during 2005-2010; in the southern part of the southwestern mountainous area and high-altitude regions during 2010-2015; and stabilizing after 2015, with persistent high-value areas in the southern part of the southwestern mountainous area and high-altitude regions. Overall, the supply displayed a decreasing-then-increasing trend, with the southeastern mountainous area showing the largest decrease and the largest increase after 2015. High-value supply areas remained stable in high-altitude regions, while low-value areas concentrated in the northern mountainous region.

[Figure 2: see original paper]

### 2.1.2 Spatiotemporal Distribution Characteristics of Water-Yielding Service Demand

Over the past two decades, the average water-yielding service demand in the Liupan Mountain area was  $39.6 \times 10^6 \text{ m}^3$ , following a decreasing-then-increasing trend with variations of  $-30.4\%$  and  $22.8\%$ . The southwestern mountainous area had an average demand of  $7.1 \times 10^6 \text{ m}^3$  with relatively small fluctuations. The southeastern mountainous area showed an average demand of  $22.0 \times 10^6 \text{ m}^3$ , decreasing then increasing with variations of  $-25.4\%$  and  $25.9\%$  after 2015. The northern mountainous area exhibited an average demand of  $10.5 \times 10^6 \text{ m}^3$ , decreasing then increasing with variations of  $-51.3\%$  and  $29.2\%$ .

The overall spatial pattern of demand in the Liupan Mountain area showed high values in the east and low values in the north (Fig. 3). High-value demand areas were primarily located in the northern mountainous area before 2000 and in the southeastern and southwestern mountainous areas after 2000. Low-value areas were mainly distributed in high-altitude regions of the Liupan Mountains before 2000 and in the northern mountainous area after 2000. In summary, all three sub-regions showed decreasing-then-increasing demand trends, with the northern mountainous area displaying the largest variation amplitude.

[Figure 3: see original paper]

### 2.1.3 Spatiotemporal Distribution Characteristics of Supply-Demand Matching

The ecosystem water-yielding service supply-demand matching degree in the Liupan Mountain area predominantly fell into the moderate category, followed by extremely low and low matching areas, with high and extremely high matching areas being the least common. Over the past two decades, low and extremely low matching areas showed a decreasing trend (with the southwestern mountainous area experiencing the largest decline), while high and extremely high matching areas exhibited an increasing trend (with the southeastern mountainous area showing the largest increase) (Fig. 4).

The northern mountainous area, as a stable high-value region, saw its high matching area expand continuously before 2010 and then contract. The southwestern mountainous area, as a secondary high-value region, was dominated by low-value areas before 2010 but transformed into a persistent high-value area afterward. The southeastern mountainous area, initially dominated by high-value areas before 2010, transformed into a persistent low-value area afterward. Overall, the high matching areas in all three sub-regions showed increasing trends, while low matching areas decreased.

[Figure 4: see original paper]

## 2.2 Multidimensional Differentiation Characteristics of Supply-Demand Relationships

To examine multidimensional differentiation characteristics, we analyzed supply-demand matching across time and elevation intervals in sub-watersheds (Fig. 5). The study area was divided into sub-watersheds based on terrain and hydrological characteristics, and spatiotemporal patterns of supply-demand matching were examined at this scale. The findings indicate that with increasing time and altitude, supply in all three sub-regions decreased before 2000, with the southeastern mountainous area showing the largest decrease (average variation of  $-34.6\%$  per 500 m interval). After 2000, supply increased in all sub-regions, with the southeastern mountainous area showing the largest increase (average variation of  $20.7\%$ ).

Supply above 2000 m was primarily distributed in the northern mountainous area, while supply below 2000 m was mainly distributed in mid-upstream areas of the southeastern mountainous area. The southwestern mountainous area consistently showed the highest supply, while the northern mountainous area showed the lowest (Fig. 6). The supply-demand matching degree in the northern mountainous area increased significantly, shifting from low to high matching, while the southwestern mountainous area decreased from high to moderate matching, and the southeastern mountainous area decreased substantially from moderate to low matching.

With increasing time and altitude, demand in the southeastern and southwestern mountainous areas increased before 2000 (average variations of  $22.7\%$  and  $23.3\%$ , respectively), while demand in the northern mountainous area decreased (average variation of  $-24.8\%$ ). After 2000, demand in the southeastern and southwestern areas decreased with time and altitude (average variations of  $-31.0\%$  and  $-3.4\%$ , respectively), while demand in the northern area increased with time and altitude (average variation of  $10.1\%$ ). Demand below 2000 m exceeded that above 2000 m, with the northern mountainous area showing the highest demand below 2000 m.

The supply-demand matching index ( $M$ ) in the southeastern and southwestern mountainous areas decreased with time and altitude before 2000 (average variations of  $-51.4\%$  and  $-69.8\%$ , respectively), while  $M$  in the northern mountainous area increased (average variation of  $22.2\%$ ). After 2000,  $M$  in the southeastern and southwestern areas increased with time and altitude (average variations of  $10.1\%$  and  $10.84\%$ , respectively), while  $M$  in the northern area increased with time but decreased with altitude (average variation of  $-5.8\%$ ). The  $M$  values above 2000 m exceeded those below 2000 m, with the southwestern mountainous area showing the highest values.

Overall, the three sub-regions exhibited similar multidimensional spatiotemporal patterns in supply with increasing time and altitude. However, demand and  $M$  in the northern mountainous area showed opposite patterns compared to the southeastern and southwestern areas.

[Figure 5: see original paper]

[Figure 6: see original paper]

### 3.1 Assessment Model and Regional Comparison

We validated the InVEST model predictions using measured surface runoff data. According to the *Gansu River Sediment Bulletin (2023)*, the multi-year average runoff at Yangjiaping Station was  $6.55 \times 10^6 \text{ m}^3$ , while the predicted supply value for the southeastern Liupan Mountain area was  $7.26 \times 10^6 \text{ m}^3$  (a difference of 10.84%). The *Ningxia Water Resources Bulletin (2023)* reported total surface water resources of  $1.40 \times 10^6 \text{ m}^3$  at Quanyanshan Station, while the predicted value for the northern mountainous area was  $1.68 \times 10^6 \text{ m}^3$  (a difference of 15.66%). These comparisons demonstrate that our approach, which objectively determines the Zhang coefficient using the method proposed by Donohue et al., yields supply estimates that closely match actual conditions. The estimation errors remain within reasonable ranges, accurately reflecting regional surface water resources and providing a scientific basis for ecosystem water-yielding service assessment.

For demand estimation, previous studies commonly used quota methods based on population or GDP grid data combined with land use information to estimate demands in river basins such as the Yellow River and Weihe River. While suitable for flat, densely populated plains, these methods produce large deviations when applied to mountainous regions due to complex terrain, climate, and vegetation conditions. In mountainous areas, forest and grassland water consumption constitutes a significant portion of demand. Therefore, this study uses forest and grassland water consumption as the demand indicator, establishing a mountainous-region-appropriate assessment method.

### 3.2 Differentiation Characteristics Under Natural and Human Factors

Under the combined influence of natural and human factors, the ecosystem water-yielding services and their supply-demand relationships in the study area exhibit multidimensional spatiotemporal differentiation. Supply is primarily affected by precipitation, increasing with higher rainfall and showing good spatial consistency. Specifically, the southwestern mountainous area's high precipitation and low evaporation correspond to high supply; the southeastern area's high precipitation and evaporation correspond to moderate supply; and the northern area's low precipitation and evaporation correspond to low supply.

The southeastern mountainous area, located on the windward slope, receives abundant precipitation corresponding to high supply, but its extensive shrubland results in high demand and extremely low matching, highlighting prominent supply-demand conflicts. The southwestern area also has high precipitation and supply, but relatively high demand leads to low matching. The northern area, dominated by grassland with lower water consumption, shows lower demand and higher matching despite low precipitation and supply. Additionally, the

Grain for Green Program has altered land cover types, increasing vegetation water consumption and thus demand after reforestation.

Vertical gradient effects are also evident. Studies show that on the Loess Plateau, supply positively correlates with vegetation coverage, but decreases when coverage exceeds certain thresholds. In our study area, high-altitude regions are mainly forested (Fig. 7), where intense transpiration leads to high water consumption, yet supply remains relatively low. Grassland water consumption and evaporation are significantly lower than forest values, resulting in lower demand in the northern mountainous area dominated by grassland. Overall, elevation gradients influence water cycling not only through temperature and precipitation but also indirectly through vegetation community structures, creating vertical zonation characteristics in supply-demand relationships.

[Figure 7: see original paper]

### 3.3 Policy Recommendations

To effectively alleviate regional water resource conflicts and protect water conservation functions in the Liupan Mountain area, differentiated strategies should be implemented according to altitude-specific supply characteristics. High-altitude supply zones should be designated as protected areas with strict development prohibitions to ensure water conservation and stable output. Low-altitude supply zones should optimize water use, increase forest cover to enhance water retention, and promote resource replenishment.

Zoning management based on supply-demand matching degrees is essential: The southeastern low-matching area should improve water resource capacity through forest management and reservoir construction, implement water quota management to enhance efficiency, and establish ecological compensation mechanisms. The southwestern moderate-matching area should strengthen upstream ecological protection, increase afforestation above 2000 m, prioritize water conservation strategies, and moderately develop water-saving irrigation agriculture while maintaining self-sufficiency balance. The northern high-matching area requires more refined management, ensuring ecological water demand in valley regions, enforcing efficient water use policies, and encouraging water-saving irrigation practices.

## 4 Conclusions

This study constructs a mountainous-region-appropriate assessment methodology for ecosystem water-yielding service supply and demand, revealing multidimensional, uneven distribution patterns across spatiotemporal dimensions and vertical zones. The main conclusions are:

1. Both supply and demand of ecosystem water-yielding services showed decreasing-then-increasing trends, with the southeastern mountainous

area exhibiting the largest supply variation and the northern mountainous area showing the largest demand variation.

2. Areas above 2000 m elevation function as supply zones, while areas below 2000 m serve as demand zones. High-demand areas shifted from the northern region to the southeastern and southwestern mountainous areas after 2000.
3. With increasing time and altitude, supply and demand in the northern mountainous area decreased before 2000 while matching degree increased; after 2000, supply and demand increased while matching degree decreased. Conversely, the southeastern and southwestern mountainous areas showed opposite patterns.
4. The study area exhibits a spatiotemporal distribution pattern of relatively high matching in the north, moderate in the southwest, and low in the southeast. These results provide a scientific foundation for optimizing water resource allocation in arid mountainous regions.

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