Identification of Development Types of Rural Settlements in the Loess Hilly and Gully Region: A Case Study of Wuqi County (Postprint)

Authors: Li Jiahui, Wu Jinhua, Wang Zhen, Bai Yuxia, Wu Jinhua

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Abstract

Utilizing the Minimal cumulative resistance (MCR) model, this study determines the suitability of residential settlement layout from both ecological and construction perspectives, supplemented by social network analysis to examine the spatial network relationships of settlements. Based on the overall suitability and individual importance of settlements, the development types of settlements in Wuqi County, Yan'an City, Shaanxi Province are identified. The results indicate: (1) Terrain and transportation conditions constitute the key constraints determining the spatial layout of settlements in the loess hilly and gully region. The overall degree of settlement agglomeration is relatively low, characterized by a predominant ribbon distribution pattern with dispersion within aggregation. (2) The suitability zoning results demonstrate a characteristic of "overall agglomeration with partial dispersion". Rural settlements located within suitable construction areas account for 62.83%, while the distribution of certain settlements impacts regional ecological stability. (3) The existing settlement network structure is non-uniform, necessitating the cultivation of village nodes with greater development potential to promote balanced development in rural-town areas. (4) Based on the suitability and network analysis results, four types are classified: "Direct Urbanization", "Priority Development", "Conditional Development", and "Restricted Expansion", with corresponding development priorities proposed. The research findings can provide references for the rational planning and development of rural settlements in the loess hilly and gully region.

Full Text

Preamble

Identification of Rural Residential Development Types in Loess Hilly and Gully Regions: A Case Study of Wuqi County

LI Jiahui, WU Jinhua, WANG Zhen, BAI Yuxia
(School of Land Engineering, Chang'an University, Xi'an 710065, Shaanxi, China)

Abstract: This study employs the Minimal Cumulative Resistance (MCR) model to determine the suitability of rural residential layout from ecological and construction perspectives, supplemented by social network analysis to examine spatial network relationships among settlements. Based on overall suitability and individual importance of settlements, we identify development types for rural residential areas in Wuqi County, Yan'an City, Shaanxi Province. The results indicate: (1) Terrain and traffic conditions are the key constraints determining the spatial layout of settlements in loess hilly and gully regions. The overall clustering degree of settlements is low, with a predominant zonal distribution pattern characterized by clustering within dispersion. (2) Suitability zoning results demonstrate characteristics of "overall agglomeration and partial dispersion," with 62.83% of rural settlements located within suitable construction zones. (3) The existing settlement network structure is uneven, with some settlement distributions affecting regional ecological stability, necessitating the cultivation of village nodes with greater development potential to promote balanced development across townships. (4) Based on suitability and network analysis results, four development types are identified: "direct urbanization," "priority development," "conditional development," and "restricted expansion," with corresponding development priorities proposed for each. These findings provide a reference for rational planning and development of rural settlements in loess hilly and gully regions.

Keywords: rural residential area; loess hilly and gully region; suitability zoning; social network analysis; residential development types

Rural settlements constitute an important component of urban-rural construction land, carrying comprehensive functions such as rural production and living [1]. Their spatial structure and development trends are critical to rational rural spatial layout. However, China's rural areas face enormous variations in village scale, morphology, and spatial structure due to factors including economic development paths, urbanization, and land systems [2], with widespread problems such as abandoned homesteads, scattered layout, lack of infrastructure, and environmental pollution [3], which affect the stability and sustainability of rural development. There is an urgent need to grasp rural heterogeneity, explore development potential, and promote efficient rural land use. Against the backdrop of rural revitalization, identifying different settlement development types from a micro perspective [4] and exploring rural development pathways guided by this approach constitute an inevitable choice for promoting healthy and long-term rural development.

International research on this topic started earlier, focusing primarily on rural settlement site selection and layout theories [5] as well as settlement optimization for special circumstances [6]. Domestic scholars have proposed theories such as new rural construction, hollow villages, and rural spatial reconstruction

[7] based on China's characteristics. Empirical research has concentrated on spatial distribution patterns and influencing factors [8], evolution and driving mechanisms [9], layout optimization, spatial reconstruction, and type identification [10], introducing GIS spatial analysis [11], the MCR model, and weighted Voronoi diagrams [12] to explore settlement optimization pathways from perspectives such as farmer willingness [13] and farming radius [14]. Overall, existing research features rich theories and diverse methods, but studies on settlements in special landform types are relatively lagging, mostly concentrated in vulnerable areas [15] and traditional agricultural regions [16]. This paper takes Wuqi County as an example, uses the MCR model to determine settlement layout suitability, supplements it with social network analysis to analyze settlement network characteristics and screen important nodes, and finally identifies different rural settlement development types based on suitability and node importance, proposing corresponding development pathways to provide theoretical and practical references for village development.

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Funding: National Natural Science Foundation of China ( )
Author introduction: LI Jiahui ( ), female, master's student, mainly engaged in land use and rural geography research.
Corresponding author: WU Jinhua ( ), female, Ph.D., professor, mainly engaged in land information systems and land use planning research.
Email: 2574594645@qq.com; jinghuaw@chd.edu.cn

1 Study Area Overview

Wuqi County (107°38 57 ~108°32 49 E, 36°33 33 ~37°24 27 N) is located in northwestern Yan'an City, Shaanxi Province, bordering Hua Chi County of Gansu Province. It governs 1 street and 8 towns, with a total area of 3.79$×10^{3}$ km^2. The terrain is highly undulating with complex slope variations, belonging to a typical loess hilly and gully region (Fig. 1). The county's per capita settlement area is 162.74 m^2. As one of the counties with the most severe soil erosion, Wuqi pioneered the implementation of the Grain for Green Program, becoming China's first county to do so. Under the influence of grazing prohibition and rural revitalization strategies, the ecological environment has significantly improved and infrastructure has gradually been perfected, but settlements exhibit loose patches and obvious regional differences. There is an urgent need to improve rural settlement development conditions from an ecological perspective and promote healthy rural development.

Fig. 1 [Figure 1: see original paper] Schematic diagram of the study area

2.1 Data Sources and Preprocessing

The basic data include: (1) Digital Elevation Model (DEM) data, obtained from the Geospatial Data Cloud (https://www.gscloud.cn/), from which slope and aspect data were derived through surface analysis; (2) Landsat-8 imagery data; (3) Land use data from the Third National Land Survey, extracting rivers, roads, and rural settlements (merging settlement patches divided by roads or public boundaries); (4) Nighttime light data from LuoJia-1, processed through radiometric calibration, mutual correction, and mask extraction to obtain nighttime light imagery for the study area; (5) Socioeconomic data from statistical yearbooks. All data use the 2000 National Geodetic Coordinate System with a spatial resolution of 30 m.

2.2 Analysis Methods for Residential Spatial Characteristics

Spatial analysis and distribution indices are used to examine the main influencing factors and distribution characteristics of settlement spatial layout [17]. Kernel density analysis is introduced to analyze settlement spatial agglomeration effects. The distribution index formula is:

$$P = \frac{S_{ie}/S_e}{S_i/S}$$

where P is the distribution index; S_{ie} is the area of settlement i in region e (m^2); S_e is the total area of region e (m^2); S_i is the total area of rural settlements (m^2); and S is the total land area (m^2).

2.3 Suitability Zoning Method

The MCR model essentially analyzes and seeks the minimum cumulative resistance path that humans or other organisms overcome when moving from a source to a destination [18]. Its calculation formula is:

$$MCR = \sum_{j=1}^{n} (D_{ij} \times R_i)$$

where MCR is the minimum cumulative resistance value; D_{ij} is the distance from source i to unit j; and R_i is the resistance coefficient for source i expansion.

The model simulates the expansion process of residential "sources" and ecological "sources." By calculating the difference between the two ($MCR_{difference}$), the suitability of settlement layout is determined:

$$MCR_{difference} = MCR_{residential} - MCR_{ecological}$$

where $MCR_{residential}$ and $MCR_{ecological}$ represent the expansion resistance for settlements and ecology, respectively. When $MCR_{difference} < 0$, settlement expansion is suitable; conversely, ecological expansion is suitable. As

$MCR_{difference}$ approaches 0, the resistance difference between the two diminishes.

2.3.1 Selection of Expansion "Sources"

(1) Residential "Sources." From the perspectives of rationality, agglomeration, expandability, and representativeness, residential expansion sources are selected. Additionally, nighttime light data has a significant positive correlation with the economy [19]. The correlation between Gross Domestic Product (GDP), permanent population, and total nighttime light values (time light) of each township was analyzed. The determination coefficients of the linear models for GDP and permanent population with nighttime light were 0.84 and 0.79, respectively, with relative errors between simulated and actual values of 2.84% and 8.01%. Total night light can thus reflect the economic and population conditions of the study area.

(2) Ecological "Sources." The study area is environmentally sensitive. Through sensitivity evaluation, areas prone to ecological problems are identified as important patches for maintaining ecological stability. However, sensitivity evaluation alone may overlook core patches that maintain ecological stability. Therefore, Morphological Spatial Pattern Analysis (MSPA) is combined to identify ecological "sources."

Ecological Sensitivity Evaluation Index Construction and Classification. Landform, vegetation cover, land use, and rainfall are the main factors affecting regional ecological stability. However, as rainfall differences are minimal overall, elevation, slope, and other factors are selected, with higher values indicating greater sensitivity (Table 1).

Index Weight Determination. The entropy weight method is used to determine weights based on data dispersion degree—greater dispersion means more information and higher weight.

Ecological Sensitivity Evaluation. Various factor indicators are weighted and superimposed to obtain ecological sensitivity values.

MSPA Analysis. MSPA divides target pixels into seven non-overlapping types including core areas and bridge zones, enabling rapid acquisition of core patches [20]. Forest land, grassland, cultivated land, and water bodies are extracted as primary ecological patches, with a core patch area threshold set at 2.00$×10^{4}$ m^2 and edge width at 1.

Table 1 Evaluation index system of ecological sensitivity

Factor	High Sensitivity	Medium-High Sensitivity	Medium Sensitivity	Medium-Low Sensitivity	Low Sensitivity	Weight
Elevation (m)	1550-1795	1473-1550	1400-1473	1321-1400	1226-1321	0.15
Slope (°)	>27	20-27	15-20	6-15	0-6	0.25
Land Use	Construction land	Unused land	Grassland	Cultivated land, orchard	Forest land, water	0.35
Distance to water (m)	0-300	300-500	500-800	800-1200	>1200	0.10
NDVI	0.5-0.7	0.3-0.5	0.0-0.3	-	-	0.15

2.3.2 Resistance System Construction and Weight Determination

Residential and ecological expansion exhibit competitive relationships to some extent [21]. Under the same system, comparing resistance magnitudes strengthens the connection between them. Terrain, location, land use, and economic factors are interrelated, determining settlement quantity and spatial layout [22]. In the study area, settlements are more likely to cluster in gentle slopes, low elevations, sunny aspects, moderate distances from water, proximity to roads and towns, and economically better areas. Therefore, 10 resistance factors are selected from terrain, location, land use, and economic perspectives. Referencing relevant literature, the analytic hierarchy process (AHP) is used to construct a judgment matrix and determine factor weights (Table 2).

Table 2 Indicators of resistance system for residential expansion and ecological expansion

Factor	Residential "Source"	Ecological "Source"	Weight
Elevation (m)	1226-1321:1 1321-1400:20 1400-1473:40 1473-1550:60 1550-1756:80	1550-1795:100 1473-1550:80 1400-1473:60 1321-1400:40 1226-1321:20	0.15
Slope (°)	0-6:1 6-15:20 15-20:40 20-25:60 >25:80	>27:100 20-27:80 15-20:60 6-15:40 0-6:20	0.20

Factor	Residential "Source"	Ecological "Source"	Weight
Land Use	Construction land:1	Forest land, water:1	0.25
	Forest land, orchard, grassland:20	Grassland:60	
	Cultivated land:40	Cultivated land:80	
	Unused land:60	Unused land:90	
	Water, special use land:80	Construction land:100	
Distance to water (m)	0-300:1	0-300:1	0.10
	300-500:20	300-500:40	
	500-800:40	500-800:60	
	800-1000:60	800-1000:80	
	>1000:80	>1000:100	
Distance to road (m)	0-300:1	0-300:1	0.15
	300-600:20	300-600:40	
	600-900:40	600-900:60	
	900-1200:60	900-1200:80	
	1200-4013:80	1200-4013:100	
Night light value	0-1200:1	0-1200:1	0.15
	1200-4013:20	1200-4013:40	
	4013-10200:40	4013-10200:60	
	10200-17178:60	10200-17178:80	
	>17178:80	>17178:100	

2.3.3 Difference Zoning Method

The MCR model simulates the outward movement of "sources," represented spatially as different intervals [23]. Therefore, statistical methods are used to analyze categorical and quantitative differences, seeking mutation points to determine zoning boundaries.

2.4 Residential Network Analysis Method

Close spatial connections exist among settlements [24]. Each administrative village center is simplified as a node, with connections between nodes represented by lines. A gravity model is introduced to establish the settlement network (Equation 5), with the average connection strength between a node and other nodes set as a threshold to delete invalid connections.

$$Q_{ij} = K_{ij} \times \frac{A_i A_j}{d_{ij}^b}$$

where Q_{ij} is the connection strength between villages i and j; A_i and A_j are the settlement areas of villages i and j (m^2); d_{ij} is the road distance between villages i and j; b is the distance friction coefficient (taken as 2), reflecting the attraction between different settlement scales; and $K_{ij} = \frac{A_i}{A_i + A_j}$.

Network degree centrality, out-degree, and in-degree are used to reflect node importance in the settlement network [25].

(1) Degree Centrality. Represents total node connection strength, reflecting control and influence. Using the natural breaks method, nodes are classified as central, sub-central, or general nodes.

(2) Out-degree and In-degree. Out-degree indicates a node's influence on others, while in-degree indicates the degree of influence received from others. When out-degree exceeds in-degree, the node holds a "radiating position" in resource flow, with driving capacity over other nodes, representing output characteristics; conversely, it represents input characteristics.

2.5 Village Type Identification Method

A two-dimensional matrix is used to display spatial mismatch between suitability and network analysis results [26]. With suitability as the X-axis and network analysis results as the Y-axis, suitable construction zones and central nodes are assigned "high," buffer zones and sub-central nodes "medium," and ecological protection zones and general nodes "low." Combinations of high-high, high-medium, and medium-high indicate greater development prospects as "priority development"; high-low combinations show obvious shortcomings as "conditional development"; low-high combinations represent leading settlements as "direct urbanization"; and low-low combinations with smaller development potential are "restricted expansion."

3.1 Residential Spatial Characteristics Analysis

Spatial Distribution Characteristics. Rural settlement distribution in Wuqi County shows clear association with terrain and roads. In elevation zones above 1550 m, distribution indices are all less than 1, while in the 1226-1550 m range, indices exceed 1, indicating this as the advantageous zone for settlement distribution. In terms of slope, distribution indices are 1.25 in the 6°-15° range and 1.08 in the 15°-20° range, making 0°-20° the advantageous slope for settlement distribution. Additionally, within 0-300 m of roads, the distribution index reaches a maximum of 1.56, indicating that transportation is a priority consideration for settlement layout in the study area. As distance from roads increases, settlement area decreases, with 0-200 m being the sharp decline interval; beyond 500 m, settlement area stabilizes at 3.00$\times10^{\{4\}-3.25\times10}\{4\}$ m^2. Therefore, the spatial service range of roads for settlements in the study area is within 500 m.

Settlement Agglomeration Characteristics. Wuqi County exhibits balanced settlement distribution with similar variation trends, primarily zonal with clustering within dispersion (Fig. 2). Settlements with kernel density values below 0.5 account for the largest proportion, with the highest value being 1.23 in Changcheng Town at the northernmost tip. The radiation effect of towns is not obvious, with rural settlements mainly distributed along major traffic arteries.

Fig. 2 [Figure 2: see original paper] Kernel density distribution of Wuqi County

3.2.1 Expansion "Source" Selection Results

Residential Expansion "Source" Selection. Elevation 1226-1550 m, slope 0°-20°, and road distance 0-300 m constitute the advantageous zone for settlement layout. From production and living perspectives, settlements within road service radius maintain close contact and economic exchange with surrounding areas. Areas above 1550 m have relatively backward economic and population conditions with incomplete infrastructure. Therefore, rural settlements below 1550 m elevation, with slopes under 20° and within 500 m of roads are selected as expansion "sources" (Fig. 3). Areas below 1550 m belong to valley plains with favorable conditions for agricultural production, planting, and transportation, where production factors agglomerate; above 1550 m, living costs increase and land fragmentation intensifies, hindering intensification and industrial development.

Ecological Expansion "Source" Selection Results. Using the natural breaks method, ecological sensitivity evaluation results are divided into high, medium, and low categories. The "high" category is extracted, comprising 74.09% of ecological patch area, which can maintain regional ecological stability (Fig. 3). The MSPA method identifies 65.04% of patches smaller than 2.00$×10^{4}$ m^{2} with obvious fragmentation characteristics. Following the approach of Liang et al. [27], ecological expansion "sources" are extracted, with 7 patches selected.

Fig. 3 [Figure 3: see original paper] Ecological patches and expansion source selection results

3.2.3 Suitability Zoning

The suitable construction area covers 1.46$×10^{4}$ m^{2}, accounting for 38.83%, concentrated in Tiebiancheng, Wucangbao, Wuqi, and Zhouwan towns where terrain is relatively flat, development costs and difficulty are low, and location conditions are superior, making them suitable for various development and construction activities. The ecological protection area covers 1.43$×10^{4}$ m^{2}, accounting for 37.64%, distributed in the northeast and southwest as large ecological important patches and core patches requiring protection and restricting settlement construction and expansion. The buffer zone, with an area of 8.89$×10^{3}$ m^{2}, is uniformly distributed across townships where neither construction nor ecological advantages are obvious, serving as a transitional buffer between settlement construction and ecological expansion (Fig. 4). Overlaying settlements with zoning results shows that in 2020, 1.08$×10^{4}$ m^{2} of settlements (62.83% of total patch area) were located in suitable construction zones, concentrated in flat areas with good road access and development conditions; 3.86$\times10^{3}$ m^2 (22.96%) were in buffer zones; and 2.41$\times10^{3}$ m^2 (14.75%) were in ecological protection zones with poor basic conditions and scattered distribution, affecting regional ecological stability.

Table 3 Area proportion of suitability subareas

Zone Type	MCR Difference	Area (m^2)	Proportion (%)
Suitable Construction Zone	[-31054, -1264)	1.46$\times10^{4}$	38.83
Buffer Zone	[-1264, 2879)	8.89$\times10^{3}$	23.53
Ecological Protection Zone	[2879, 6815]	1.43$\times10^{4}$	37.64

Note: MCR difference is the difference between residential expansion resistance and ecological expansion resistance.

Fig. 4 [Figure 4: see original paper] Suitability subareas of Wuqi County
Fig. 5 [Figure 5: see original paper] Rural residence network in Wuqi County

3.3 Residential Network Analysis Results

The analysis reveals that central nodes have the most spatial connections with other nodes and occupy important positions in local networks, capable of driving development of surrounding nodes. Sub-central nodes can effectively obtain resources from other villages and exert certain "radiation" effects, though development conditions are slightly inferior to central nodes. General nodes have the fewest spatial connections and are disadvantaged in network structure with weaker resource acquisition capacity. Additionally, output-type villages have more spatial connections than other types, with stronger influence and control. Therefore, output-type villages mostly play important roles in local network systems and often have potential to become central nodes. Village importance can be judged based on settlement type and number of spatial connections. However, some nodes become central nodes not through output characteristics but through favorable location conditions with strong capacity to receive and absorb resources from other villages. Overall, each township includes at least one central node, with nodes around towns and main urban areas having the most spatial connections and most superior development conditions. Villages far from towns are mostly general nodes, indicating limited town radiation range. The existing network structure cannot drive development of surrounding nodes, suggesting the need to cultivate nodes with greater development potential to promote balanced development of villages and towns.

3.4 Village Type Identification

Direct Urbanization Type (Quality-focused): These settlements have relatively superior conditions, relatively flat terrain, high settlement agglomeration, low ecological sensitivity, and strong attractiveness, favorable for living, production, and transportation, with potential to drive regional development, involving

8 administrative villages. Future development should fully leverage central node agglomeration effects, improve residents' quality of life while consolidating existing advantages, improve town-level infrastructure from the perspective of daily production, living, and travel needs, create a "basic living service circle" for rural residents, enhance living convenience, maintain and expand central node competitiveness and driving force, and achieve urbanization locally to drive surrounding villages, ultimately realizing point-to-area direct promotion of regional urbanization.

Priority Development Type (Addressing Weaknesses): Priority development villages are either central nodes in buffer zones or located in suitable construction zones where node influence has not been fully exerted, involving 28 administrative villages. These villages bear the important task of town integration in the overall settlement network system and need to share the pressure of continuous expansion of central node construction land, thus deserving priority development status. Future development should identify village development weaknesses and advantages, enhance sustainable development potential, and strengthen intensive and efficient resource utilization. In buffer zones, policy incentive mechanisms should be established to encourage development appropriate to local conditions—forestry where suitable, agriculture where suitable, and animal husbandry where suitable—promoting harmonious development among forestry, agriculture, and people. In suitable construction zones, breakthroughs should be sought by integrating agriculture with loess farming culture, exploring suitable local agricultural industrial structures, improving development weaknesses, emphasizing internal development vitality, and maintaining connections with surrounding central nodes to ensure rural development continuity and sustainability.

Conditional Development Type (Following Nature): These settlements only hold advantages in either suitability or spatial connections, constrained by ecological environment or internal factors, placing them in weak competitive positions against other central or sub-central nodes, involving 68 administrative villages. Development should respect and follow natural conditions. In suitable construction zones where conditions are slightly inferior to priority development types, the focus should be on improving internal and external connectivity supplemented by internal potential development. Externally, more accessible road networks connecting towns and villages should be pursued to provide more convenient travel and production environments; internally, potential should be tapped by reorganizing settlements that damage village appearance to achieve more rational layout and improve living environments. For non-construction zone suitable areas, implementation of coordinated "fields, forests, roads, and canals" and comprehensive management of "beams, hilltops, slopes, and gullies" should be breakthrough points to restrict rural construction land scale, consolidate ecological advantages, improve production conditions, develop intensive modern agriculture, and strive to upgrade to higher-level settlements.

Restricted Expansion Type (Ecology-focused): These settlements are located in ecological protection or buffer zones, involving 35 administrative villages. The land surface is fragmented, belonging to areas with many ecologically sensitive patches, far from central towns with insufficient self-radiation and attraction capacity, making it difficult to attract quality resources, with multiple restrictions on agricultural production and living. Future development should emphasize regional ecological functions and strictly restrict random settlement expansion. For forest areas, protection priority should be maintained according to local conditions with combined closure and cultivation. For residents' living circles, ecological governance should be combined with development of characteristic industries. Planting ecologically and economically valuable crops such as apples, peonies, and roses can provide ecological service value while leveraging ecological advantages to enhance environmental service functions, develop rural tourism, and explore a coordinated development pattern of "production-village-people" and integrated progress of "residence-industry-tourism."

4 Discussion

The combination of the MCR model and social network analysis to identify different settlement development types from the perspective of overall suitability and individual importance can compensate for the shortcomings of single evaluation methods. In settlement suitability evaluation, researchers often use villages as study units to construct corresponding indicator systems for evaluating village suitability to classify settlement types [28]. This study selects locally characteristic expansion "sources" and measures settlement layout suitability from both ecological and construction perspectives. This approach considers not only the suitability of land as rural settlements under ecological constraints but also reflects the competitive relationship between residential and ecological expansion, aligning with the consensus of ecology-first green development. When using the gravity model to reflect spatial connections between villages, relevant studies directly apply the gravity model to reflect inter-village attraction [29]. This study considers resident travel and contributions from different settlement scales to modify the gravity model, thereby screening important nodes. However, actual settlement type identification involves numerous factors. This study overlooks factors such as local customs and surrounding urban radiation, which require further investigation in future research.

5 Conclusion

(1) From the perspective of settlement spatial characteristics, rural settlements in Wuqi County exhibit a zonal distribution pattern with clustering within dispersion. Compared with town radiation effects, terrain and traffic conditions are the key constraints determining settlement spatial layout in loess hilly and gully regions. The overall clustering degree is low, with a generally small average scale of 1500 m^2.

(2) Suitability zoning using the MCR model considers land suitability for rural

settlements under ecological constraints. Zoning results show that suitable construction zones, buffer zones, and ecological protection zones exhibit "overall agglomeration and partial dispersion" characteristics. A total of 62.83% of rural settlements are located in suitable construction zones with a reasonable overall layout, though some settlement layouts affect regional ecological stability.

(3) Network analysis results indicate that each township in Wuqi County includes at least one central node, but the existing network structure of some towns is uneven and cannot drive development of surrounding nodes. Village nodes with greater development potential should be cultivated to promote balanced development across townships.

(4) Based on overall suitability and individual importance of rural settlements, four types are identified: direct urbanization, priority development, conditional development, and restricted expansion. Direct urbanization type should focus on quality improvement; priority development type should address weaknesses; conditional development type should follow natural conditions to upgrade settlement levels; and restricted expansion type should emphasize ecological protection and services.

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