Geographic Information Application Practice for the Protection and Enhancement of the "Four Mountains" in Downtown Chongqing

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Key words: Survey and Monitoring, UAV, Ecology, Data Fusion, Analysis and Evaluation

1. SUMMARY

The "Four Mountains" of Chongqing's central urban area—Jinyun, Zhongliang, Tongluo, and Mingyue—constitute a critical ecological barrier in the upper reaches of the Yangtze River. These areas have historically faced significant challenges, including unauthorized construction, encroachment on forest lands, and inefficient supervision. The complex topography further complicates manual inspections, while insufficient inter-departmental collaboration and a need for enhanced risk warning and intelligent management have hindered conservation efforts.

This paper is based on the sequential monitoring practices of the "Four Mountains" from 2021 to 2024. It details the construction of a "4+10+52" comprehensive monitoring and evaluation index system for natural resources. By integrating "UAV + 3D Real-scene + AI" technologies, this study successfully achieved centimeter-level, 3D Real-scene modeling and high-frequency, precise monitoring across the entire 1,509-square-kilometer area.

The results indicate a significant enhancement of the "Four Mountains'" ecological functions. In 2024, the indices for water conservation, soil retention, and windbreak/sand-fixation reached 0.67, 0.64, and 0.73, respectively. In terms of governance, industrial and mining land was reduced by 621.07 hectares, and 1,902.83 hectares of historical illegal buildings were addressed. All monitoring achievements have been integrated into the "Cloud-based Four Mountains" comprehensive management service platform, providing scientific support for decision-making in the protection and high-quality development of the region's natural resources.

This practice demonstrates that a chain-based work mechanism, a multi-dimensional index system, and stereo-perceptual methods founded on geographic information technology can effectively elevate the systematicness and efficacy of natural resource monitoring in large-scale mountainous cities. This work not only offers precise decision support for Chongqing's "Four Mountains" conservation, robustly serving ecological protection, law enforcement, and the

"Digital Chongqing" initiative, but its "UAV + 3D Real-scene + AI" technology suite and comprehensive evaluation system also provide a replicable reference solution for ecological monitoring and governance in similar urban environments. It is a vivid embodiment of the philosophy that "lucid waters and lush mountains are invaluable assets," holding significant demonstrative value for promoting the green development of the Yangtze River Economic Belt and fostering harmony between humanity and nature.

SUMMARY (optional summary in one other language in addition to English, e.g. your own language)

重庆市中心城区缙云山、中梁山、铜锣山、明月山（“四山”）是长江上游重要生态屏障，此前存在乱搭乱建、林地蚕食、监管低效等问题，且地形复杂导致人工巡查难度大，跨部门协同治理不足、风险预警与智能化水平有待提升。本文以2021年至2024年“四山”时序化监测实践为研究基础，构建了“4+10+52”自然资源综合监测评价体系，融合“无人机+实景三维+AI”技术，实现了1509平方公里全域的厘米级实景三维建模与高频次精准监测。结果表明，“四山”生态功能显著提升，2024年水源涵养、土壤保持、防风固沙指数分别达0.67、0.64、0.73，治理成效方面，工矿用地减少621.07公顷，历史形成建筑处置面积达1902.83公顷，监测成果已集成于“云上四山”综合监测管理服务平台，为“四山”自然生态资源保护与高质量发展提供科学决策支持。实践表明，基于地理信息技术的链条化工作机制、多维度指标体系与立体化感知手段，能有效提升超大山地城市自然资源监测的系统性与实效性。本工作不仅为重庆市“四山”保护提升提供了精准决策支撑，有力服务了生态保护、执法监督及“数字重庆”建设，其形成的“无人机+实景三维+AI”技术组合与综合评价体系，更为同类山地城市的生态监测与治理提供了可复用的参考方案。该实践是“绿水青山就是金山银山”理念在超大山地城市的生动体现，对推动长江经济带绿色发展、促进人与自然和谐共生具有重要的示范意义和推广价值。

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1 Introduction

1.1 Research Background

With the development of urbanization, the boundaries of production and living areas have expanded rapidly, resulting in the frequent occurrence of various " urban social diseases " and restricting the sustainable development of urban ecosystems. Coordinating the coupling relationship between urbanization with " cities in mountains and mountains in cities " and urban ecological space with " cities of mountains and rivers and ecological cities " requires a three-dimensional spatiotemporal perspective, normalized three-dimensional monitoring, and comprehensive composite evaluation.

1.2 Study area

Municipal Government Work Report explicitly requires the promotion of the protection and enhancement of the "Four Mountains" in the central urban area of Chongqing. To implement the municipal government 's requirements , since 2021, the Survey and Monitoring Division of the Chongqing Municipal Planning and Natural Resources Bureau has been conducting routine monitoring of natural resources such as cultivated land, orchards, forests, grasslands, wetlands, and water areas in the "Four Mountains" region of the central urban area , and has also carried out targeted thematic monitoring and analysis. This work, as one of the key special monitoring projects, is an important supplement to improving the basic survey and routine monitoring of the "Four Mountains," and plays a decision-making support role in promoting the protection and utilization of natural resources in the " Four Mountains " and serving natural resource management. The area covers 1,509 square kilometers and consists of Jinyun Mountain, Zhongliang Mountain, Tongluo Mountain, and Mingyue Mountain from west to east, forming an important ecological barrier for the central urban area.

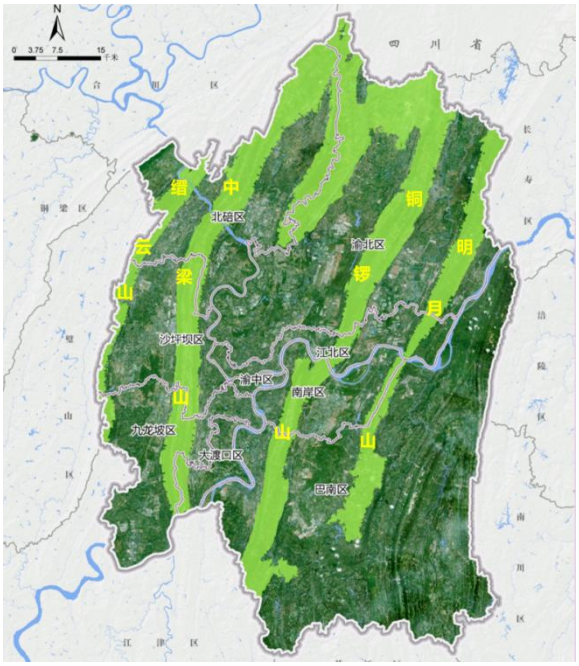


Figure 1Schematic diagram of the "Four Mountains" area in the central urban area of Chongqing.

1.3 Current Status of Natural Resources

2.1.1 Quantity of natural resource elements

According to the survey of land types, in 2024, the "four mountains" included 98,070.19 hectares of forest land, accounting for 65%; 27,520.99 hectares of cultivated land, accounting for 18%; 8,744.25 hectares of orchard land, accounting for 5.79%; 957.41 hectares of grassland, accounting for 0.63%; 2,756.63 hectares of water area and water conservancy facilities land, accounting for 1.83%; and 68.54 hectares of wetland, accounting for 0.05%.

In terms of urban development, in 2024, the total construction land area of the "Four Mountains" was 10,058.51 hectares, accounting for only 6.67%. Among them, commercial and service land was 471.85 hectares, accounting for 0.31%; industrial and mining land was 1,776.33 hectares, accounting for 1.18%; residential land was 4,715.83 hectares, accounting for 3.12%; public management and public service land was 578.76 hectares, accounting for 0.38%; special-purpose land was 533.90 hectares, accounting for 0.35%; and transportation land was 4,399.61 hectares, accounting for 2.92%.

Overall, the "Four Mountains" are dominated by ecological resources, with a superior ecological foundation, balanced element types, and abundant resource endowment. They exhibit natural resource characteristics with forests as the main body and agroforestry as a composite, and human activities occupying the natural ecology at a relatively low level.

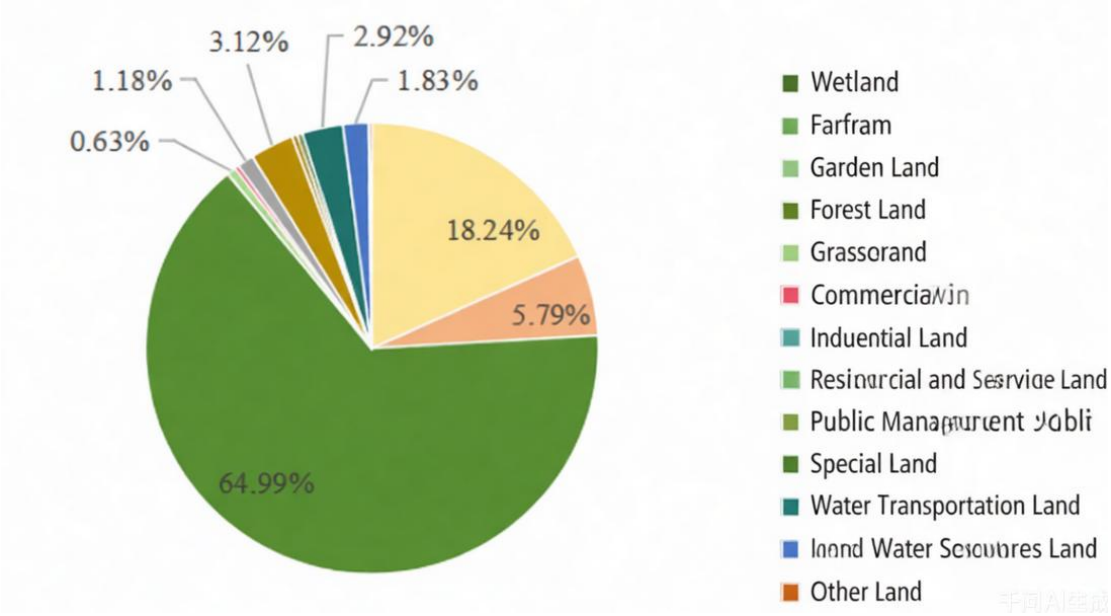


Figure 2Structure Diagram of the "Four Mountains"

2.1.2 Spatial distribution of natural resources

In terms of the overall distribution of natural resources in the "Four Mountains," forest land is more densely distributed in Jinyun Mountain and Mingyue Mountain, with the largest distribution in Beibei District and Yubei District, accounting for 38.41% and 24.23% respectively. Cultivated land is more densely distributed in Zhongliang Mountain, with the largest distribution in Yubei District, accounting for 50.05%, followed by Beibei District and Banan District, accounting for 20.89% and 16.45% respectively. Construction land is more densely distributed in Tongluo Mountain and Zhongliang Mountain, with the largest distribution in Yubei District, accounting for 26.73%, followed by Beibei District and Shapingba District, accounting for 18.48% and 16.99% respectively.

From the perspective of land spatial planning and land use control, the ecological protection red line area of the "Four Mountains" is 619.93 square kilometers, accounting for 41.18%, of which forest land accounts for 92.74%, followed by orchards and cultivated land, accounting for 2.26% and 2.23% respectively. The permanent basic farmland area is 171.16 square kilometers, accounting for 11.45%, of which cultivated land accounts for 98.81%. The urban development boundary area is 47.73 square kilometers, accounting for 3.19%, mainly residential land and industrial and mining land, accounting for 23.07% and 22.71% respectively.

In terms of the distribution of natural resources within the nature reserves, the "Four Mountains" nature reserves cover an area of 429.35 square kilometers, accounting for 28.45%, of which forest land accounts for 89.50%, followed by cultivated land and orchards, accounting for 4.05% and 2.62% respectively.

2.1.3 Natural resource quality status

In 2024, the forest area of the "Four Mountains" was approximately 835 square kilometers, with a forest coverage rate of 55.33% and a forest stock volume of 7.4318 million cubic meters. The Normalized Difference Vegetation Index (NDVI) is a quantitative indicator of surface vegetation cover and growth status. The average NDVI during the growing season (April-October) was calculated using Landsat 8 satellite imagery. The average NDVI for the "Four Mountains" in 2024 was 0.82, an increase of 0.13 compared to 2021, reflecting high vegetation coverage, healthy vegetation growth, and excellent ecosystem function. The national average utilization grade of arable land in the "Four Mountains" was 9.90, placing it at a medium level. The average slope was 3.5, indicating undulating terrain that affects cultivation convenience. The average soil pH was 6.0, indicating a slightly acidic environment suitable for most crops, but there is still room for improvement in the overall utilization value of the arable land.

1.4 Facing challenges

Traditional protection methods, such as setting up boundary markers and manual patrols, have inherent defects in super-large mountainous cities with complex terrain and vast areas, such as limited coverage, poor response timeliness, and difficulty in law enforcement and evidence collection [1] . Therefore, how to use modern geographic information technology to build an efficient, accurate, and intelligent monitoring and evaluation system has become a research hotspot and urgent need in the field of natural resource management. In recent years, the development of geographic information technology has brought revolutionary changes to the monitoring and evaluation of ecological protection areas. Its technical means have evolved from macro to micro, from two-dimensional to three-dimensional, and from manual interpretation to intelligent analysis.

Applications and limitations of conventional remote sensing technology : Since the 1970s, medium and low resolution satellite remote sensing images represented by Landsat, SPOT, MODIS, etc. have provided long-term data support for dynamic monitoring of land use/land cover change (LUCC) and vegetation index (NDVI) on a macro scale, and have important value for identifying large-scale forest changes and water body fluctuations [2] . In the 21st century, high resolution satellites represented by Gaofen series and Sentinel have provided more detailed surface information and can identify small-scale patch changes. However, for areas like the "Four Mountains" with large topographic relief, frequent cloud and fog weather, and complex surface cover, satellite remote sensing still faces challenges such as insufficient resolution to identify small illegal buildings, fixed revisit cycles making emergency response difficult, optical images being easily blocked by clouds and fog, and inability to accurately perceive the three-dimensional structure and vertical changes of the surface.

In order to overcome the limitations of conventional remote sensing technology, a series of cutting-edge technologies characterized by high precision, high timeliness and high

dimensionality have emerged. UAV Remote Sensing: UAVs have become a powerful supplement to traditional aerial remote sensing and satellite remote sensing due to their advantages of maneuverability, relatively low cost and ability to quickly acquire centimeter-level resolution images. They can fly through the clouds to achieve "instant" data collection, showing great potential for illegal building identification, project progress monitoring and disaster emergency assessment [3] .

LiDAR: Especially airborne or UAV-borne LiDAR technology, by actively emitting laser pulses, can penetrate the vegetation canopy and directly obtain high-precision three-dimensional point cloud data of the ground surface. This gives it irreplaceable advantages in the construction of digital elevation models (DEM/DTM), estimation of forestry carbon sinks and biomass , and early identification of geological disaster hazards [4, 5] . 3D Reality Modeling: Reality 3D models generated based on UAV oblique photogrammetry technology can realistically, three-dimensionally and comprehensively reproduce the original appearance of the site, providing an immersive visual experience and accurate spatial measurement functions. This not only revolutionizes the traditional map expression method, but also provides an intuitive "baseboard" for planning and design, engineering supervision, and law enforcement evidence collection [6] .

Artificial intelligence and deep learning: Applying deep learning algorithms (such as convolutional neural networks CNN, U-Net, etc.) to the interpretation of high-resolution remote sensing images can automatically and efficiently extract and classify ground features, such as buildings, roads, water bodies, and forests. This greatly improves the automation level and accuracy of change detection and target recognition, freeing monitoring personnel from tedious manual interpretation [7] .

Despite the abundance of cutting-edge technologies, the application of single technologies or the simple combination of technologies still faces numerous challenges in the comprehensive management of large-scale and complex mountainous ecological zones like the "Four Mountains":

(1) The problem of fusion and standardization of multi-source heterogeneous data: Satellite remote sensing, UAV imagery, LiDAR point cloud, ground sensor data and other sources are diverse, and their data formats, spatial resolutions, temporal resolutions and coordinate systems are different. How to effectively fuse these "multi-source heterogeneous" data, establish a unified spatiotemporal benchmark, and form a complete and consistent data system is the primary obstacle to achieving comprehensive monitoring and analysis [8] .

(2) The pressure of processing and analyzing massive amounts of data: The centimeter-level UAV images and real-world 3D models often reach TB or even PB levels, and their storage, transmission, processing and rendering place extremely high demands on computing resources. Traditional geographic information system (GIS) software and workstations are unable to handle such a huge data processing task, resulting in the phenomenon of "fast data collection, slow data usage".

(3) Insufficient intelligent analysis and decision support: Most current applications are still at the level of "data display", that is, they provide high-precision images or models, but deep-seated issues such as where the changes are, how big the risks are, and how to deal with them still need to rely on human judgment. The lack of intelligent analysis models that can transform raw data into decision information such as early warning signals, assessment reports, and disposal suggestions leads to a disconnect between technology and management business [9] .
(4) Lack of systematicness and comprehensiveness in the monitoring and evaluation system: The health status of an ecosystem is a complex entity involving multiple elements such as mountains, rivers, forests, fields, lakes, and grasslands. Previous monitoring has mostly focused on single indicators (such as green space ratio and building area), lacking a comprehensive evaluation indicator system that can fully reflect the structure, function, and pressure of the ecosystem. This makes it difficult for managers to grasp the overall evolution trend of the ecosystem from a global and systemic perspective.

2 Methodology and Data

2.1 Technical framework

Guided by the modernization of the national land space governance system and governance capabilities, and with the goal of driving the transformation of basic survey and routine monitoring technologies and improving the normalized monitoring and supervision mechanism of natural resources, this paper provides a full-process technical solution for the comprehensive monitoring and evaluation of natural resources in urban ecological coupled space, including data governance, monitoring, evaluation, and demonstration application, based on the concept of "spatial coupling, element coupling, and process coupling".
First, based on oblique photography and lidar data, a time-series, centimeter-level real-scene 3D model covering the entire area is constructed as the digital twin foundation. Second, high-frequency UAV aerial surveys are used as the primary means of routine, high-precision data acquisition, supplemented by satellite remote sensing for large-scale surveys and historical retrospectives, and combined with ground-based IoT sensors for real-time monitoring of key locations, forming a comprehensive, multi-scale, and three-dimensional data perception capability. Finally, monitoring is expanded from a single element to multiple dimensions such as ecosystem service functions, ecological risks, and governance effectiveness, achieving a leap from "seeing" to "understanding" and then to "predicting." A "Four Mountains" spatial governance platform is developed, integrating all monitoring data, analysis results, and evaluation reports. It serves multiple departments such as planning, land, law enforcement, and forestry through visualization, breaking down information silos and providing a unified entry point and data support for cross-departmental collaborative governance and scientific decision-making.

2.2 Collaborative monitoring and evaluation management chain

Using survey data as a base map and monitoring and evaluation as a means, the aim is to thoroughly understand the resources of the "Four Mountains" (Mountains, Rivers, and Mountains), effectively extending the management chain and establishing a "survey-planning-enforcement" linkage mechanism. This ensures that the "Four Mountains" space is managed in accordance with regulations and that destructive behavior is rectified according to law. First, data is aggregated and content is clarified. Using real-world 3D models as a foundation, more than 10 categories of basic surveys, routine monitoring, and various special surveys and thematic monitoring results from the "Four Mountains" area over the years are collected. Combined with management needs, the survey and monitoring content is refined, key monitoring targets are identified, and the data chain for the "Four Mountains" survey and monitoring is established. Second, benchmarking management and routine analysis are implemented. Focusing on key scenarios such as boundary optimization and "one mountain, one policy," the planning management objectives and monitoring indicators are aligned, and the analysis and evaluation results support planning optimization, deeply serving the protection and improvement of the "Four Mountains." Third, clues are pushed out and rectification is coordinated. For proactively discovered problem clues, they are aggregated to the comprehensive monitoring and supervision platform according to the "real-time monitoring-monthly analysis-quarterly push" method, with an average of more than 10 valid clues pushed out each quarter. For the problematic areas identified through "issuance of supervision and handling," such as the 23.65 million square meters of illegal buildings and 14 non-agricultural audit issues within the "Four Mountains" area, the process follows the path of "information transmission - problem handling - result feedback" to serve the spatial governance and planning optimization of the "Four Mountains," empowering targeted supervision and precise law enforcement.

2.3 Comprehensive monitoring and evaluation system

General Secretary Xi Jinping emphasized that "urban construction should embrace nature's beauty, integrating beautiful mountains, rivers, and scenery into cities to form an ecological network." To this end, focusing on four objectives—safeguarding the bottom line of safety, protecting ecological functions, improving governance, and enhancing the quality of life—a comprehensive monitoring and evaluation system for the natural resources of the "Four Mountains" (Mountains, Rivers, and Mountains) has been constructed, consisting of "4+10+52." First, the monitoring and evaluation indicators are extended according to local conditions. Combining the positioning of the "Four Mountains" with relevant technical regulations (such as the "Evaluation Index System and Technical Guidelines for Natural Resource Survey and Monitoring Data (Draft for Comments)" and the "Urban Physical Examination and Evaluation Procedures for Territorial Spatial Planning" (TD/T1063-2021)), a total of 52 monitoring indicators have been expanded and set. For example, indicators such as land development intensity and non-agricultural/non-grain conversion of arable land are set for production spaces; indicators such as water conservation and soil retention are set for

ecological spaces; and indicators such as per capita public service land area and disposal of historical buildings are set for living spaces, comprehensively analyzing the quantity and quality of resources. Second, comprehensive evaluation and scientific optimization of calculation rules are implemented. The model calculates 10 comprehensive evaluation indicators, including resource endowment index and bottom-line safety index, to comprehensively reflect the quantity and quality of resources, ecological status, and governance level. It quantifies the intensity of spatial conflicts between urban and ecological environments and assesses the level of land space coordination and high-quality development of the "Four Mountains" (mountains, mountains, and forests). Thirdly, it combines management with targeting regional development needs. For example, it strictly implements land use control, optimizes resource guarantees and land use structure, deepens ecological protection and restoration, implements systematic governance tailored to the specific conditions of each mountain, and coordinates urban and ecological spatial relationships, human-land relationships, and arable and forest spatial relationships.

2.4 Low-altitude and ground-based integrated survey methods

The "Four Mountains" region features complex terrain, poor accessibility, low efficiency of manual patrols, and severe tree cover, resulting in highly concealed and fragmented map patches. Therefore, a novel technology combination of "drones + 3D real-scene analysis + AI" was adopted to significantly improve monitoring frequency, interpretation efficiency, and spatial penetration, achieving precise three-dimensional monitoring of the entire terrain of the "Four Mountains." First, drones facilitate efficient inspections. By deploying drone nests for real-time data collection and automatic data processing, key areas are covered more than 12 times annually. For areas difficult for monitoring personnel to reach, drones quickly overcome terrain obstacles, acquiring low-altitude, multi-angle, high-resolution images, effectively reducing shadows and obstructions, significantly improving patrol coverage and efficiency, accurately locating problem patches, and collecting feedback. Second, 3D real-scene analysis. To address the limitations of low image resolution and 2D image data, point cloud reconstruction, texture mapping, and topology optimization were used to model and process the images, constructing a centimeter-level precision 3D real-scene base. Survey, monitoring, and planning management data were uniformly overlaid onto the 3D scene, achieving full coverage of the 1509 square kilometers of the "Four Mountains" area. This provides a comprehensive, multi-element, and three-dimensional representation of terrain undulations, building features, and vegetation cover, significantly improving the accuracy of map patch identification and greatly reducing fieldwork workload. Thirdly, AI-powered intelligent interpretation and extraction were implemented. Nearly 10,000 images of various types, including oblique and infrared images, totaling approximately 70GB, were acquired monthly using a data center. Based on massive sample training models and AI algorithms, the spectral characteristics and texture information of land types were deeply mined, enabling multi-period and multi-source data processing. This supported the accurate interpretation of seven types of natural resource elements: cultivated land, orchards, forests, grasslands, water,

wetlands, and minerals, enabling rapid comparison, automatic labeling, and problem detection of potentially changing map patches. Compared to the traditional satellite remote sensing + fully manual verification model, this technology realizes the transformation from "human wave tactics" to "intelligent mountain patrol", providing a reusable reference solution for monitoring similar areas, and significantly reducing monitoring costs and improving monitoring efficiency.

2.5 Scene-specific analysis and evaluation

Based on the diverse business scenarios required for natural resource management, the monitoring indicator system is dynamically improved, forming an analysis and evaluation mechanism of "dynamic monitoring - monthly summary - quarterly analysis - annual report." Through the dual empowerment of data analysis and business management, diversified support is provided for the protection and enhancement of the "Four Mountains" (mountains, forests, mountains, and rivers), achieving an organic integration of ecological, production, and living spaces, and fully showcasing the verdant landscape of the mountain city. First, in the scenario of major risk prevention and mitigation: Focusing on improving the timeliness of response to major risks, real-time monitoring data is pushed out in the form of rapid reports for risks such as forest fires, red line encroachment, and geological disasters, supporting rapid response and disposal by forestry and emergency departments, and consolidating the bottom line of natural ecological security. Second, in the scenario of natural resource supervision and enforcement: Addressing the needs of illegal construction control and ecological protection red line supervision, more than 100 monitoring patches are updated monthly, and more than 10 clue patches are pushed out quarterly. The evaluation results directly support the construction of the law enforcement evidence chain, accurately serving supervision and enforcement actions, and improving the timeliness and targeting of enforcement. Third, in the scenario of multi-plan integration and spatial governance. Integrating in-depth research based on identified issues, this supports the optimization and adjustment of plans related to the "Four Mountains" control boundaries, the "Three Zones and Three Lines" scope, and the nature reserve system. It also promotes the organic integration of various plans within the "Four Mountains" area, resulting in four quarterly analysis reports. Fourth, to empower high-quality development scenarios and address the issue of siloed and static data, the "Four Mountains" module database within the national land space "one map" is updated annually. This generates mid-term and semi-annual monitoring and evaluation reports, empowering ecological protection and restoration, improving the quality of the living environment, and upgrading the vitality of characteristic industries, thereby promoting high-quality development of the "Four Mountains."

3 Results & Discussion

3.1 The bottom line of resource security continues to be consolidated.

From 2021 to 2024, the cultivated land area in the "Four Mountains" region generally increased, adding a total of 1068.77 hectares. The decline in forest area narrowed year by year,

grassland continued to increase, adding a total of 339.78 hectares, with a change rate of 55.01%. Water area also increased to some extent, adding a total of 36.50 hectares. The integrity and stability of the ecosystem were enhanced, and the regional ecological function was gradually optimized. Construction land in the "Four Mountains" region showed a contraction trend, with industrial and mining land decreasing particularly significantly, decreasing by 621.07 hectares, with a change rate of -25.91%, indicating the initial effectiveness of industrial spatial layout adjustment. In addition, the construction land area within the ecological protection red line decreased slightly, reducing by a total of 13.39 hectares, indicating that the implementation of land use control requirements has achieved certain results.

By overlaying various resource areas, arable land quality, and other indicators, the model calculates that the natural resource endowment index of the "Four Mountains" is 1.43, which is 0.43 higher than the guideline reference value. It has an advantage in the richness of natural resources such as mountains, rivers, forests, fields, lakes and grasslands. The resources coexist in a balanced manner and together constitute a stable and resilient complex ecosystem of the "Four Mountains".

By overlaying indicators such as the "Three Zones and Three Lines" and farmland protection targets, and through model calculations, the three pressure indices for ecology, farmland, and urban areas were classified into five levels—very safe, safe, relatively safe, low pressure, and high pressure—at equal intervals of 1 to 5. The resource pressure values for the ecological protection red line and farmland protection red line of the "Four Mountains" were 3.63 and 3.16 respectively, both at a safe level. The resource pressure value for the urban development boundary was 1.37, at a low pressure level. Overall, the bottom-line safety level for the "Four Mountains" was 2.76, at a relatively safe level, and the overall risk to resource security was stable and controllable.

Table 1Changes in the Quantity of Natural Resources in the "Four Mountains" (hectares)

Resource types	2021	2022	2023	2024	Total change	Total rate of change
wetlands	68.57	68.54	68.54	68.54	-0.03	-0.04%
arable land	26452.23	27018.23	27378.52	27520.99	1068.76	4.04%
Garden	9209.38	9016.54	8816.00	8744.25	-465.13	-5.05%
woodland	99054.07	98654.24	98276.09	98070.19	-983.88	-0.99%
grassland	617.63	701.42	837.83	957.41	339.78	55.01%
Commercial service land	437.56	441.03	450.87	471.85	34.29	7.84%
Industrial and mining land	2397.4	2201.8	2054.65	1776.33	-621.07	-25.91%
Residential land	4684.18	4690.73	4704.36	4715.83	31.65	0.68%
Land for public administration and public services	552.2	556.38	565.98	578.76	26.56	4.81%

Special land	515.28	520.75	523.32	533.9	18.62	3.61%
Transportation land	3946.84	4053.12	4239.81	4399.61	452.77	11.47%
Water area and water conservancy facilities land	2750.72	2761.20	2767.14	2787.7	36.98	1.34%
Other land	223.42	225.49	226.37	284.12	60.7	27.17%

3.2 Significant achievements have been made in the protection of ecological functions.

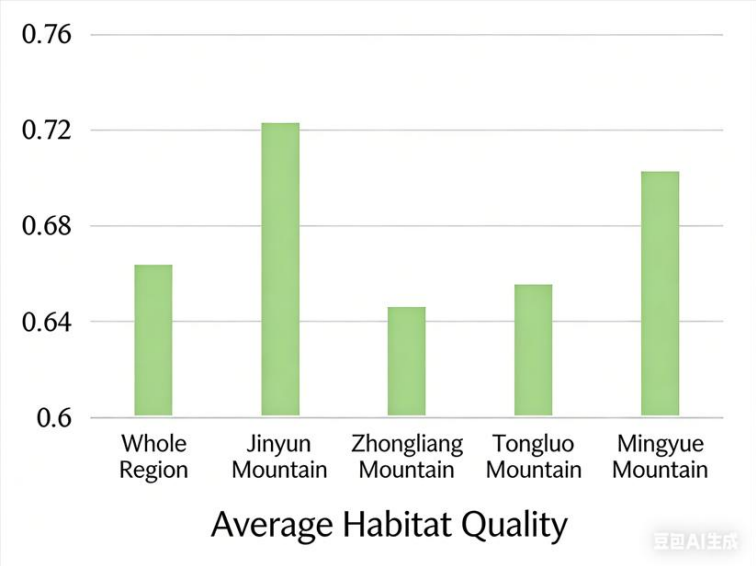
The "Four Mountains" region has always adhered to the concept of prioritizing ecology and green development, and has empowered the integrated protection and restoration of mountains, rivers, forests, fields, lakes, grasslands and deserts through investigation and monitoring, resulting in a continuous enhancement of the stability and service functions of the ecosystem.

Regarding ecosystem regulation functions, the water conservation index was estimated using normalization (in this paper, indices such as water conservation, soil conservation, and windbreak and sand fixation all adopted the Min-Max standardization method, normalizing the results to the [0,1] interval, converting them into dimensionless pure values, facilitating comparison and weighting of indicators of different units or magnitudes). This index measures the region's ability to replenish groundwater, mitigate seasonal river fluctuations, and retain floodwaters during dry seasons. The water conservation index for the "Four Mountains" region was 0.67, an increase of 0.02 compared to 2021. The soil conservation index was estimated using normalization, measuring the region's ability to reduce soil loss and mitigate river and lake siltation. The soil conservation index for the "Four Mountains" region was 0.64, an increase of 0.01 compared to 2021. The windbreak and sand fixation index was estimated using normalization, measuring the region's ability to fix topsoil and intercept wind erosion. The windbreak and sand fixation index for the "Four Mountains" region was 0.73, an increase of 0.01 compared to 2021. Overall, the "Four Mountains" ecosystem is showing a positive trend in effectively regulating water resources, soil, climate, and resisting soil erosion.

Regarding the maintenance of biodiversity, the habitat quality was estimated by normalization to measure the ability of the ecological environment to provide suitable conditions for the survival of organisms. The habitat quality of the "Four Mountains" was 0.66, which is basically the same as in 2021 and has always been at a relatively good level. The living environment of animals and plants is suitable and the degree of human disturbance is low.

Regarding the material cycle of the ecosystem, by estimating carbon storage and carbon density to measure the carbon accumulation capacity of the ecosystem or material, the total carbon storage of the "Four Mountains" is approximately 19.72 million tons, and the carbon density is 131.95 tons/hectare, which is 41.98 tons/hectare higher than the reference value in the guideline. This indicates that the "Four Mountains" play a key role in enhancing regional

carbon sink capacity and regulating ecosystem carbon balance, and is of great significance for promoting carbon cycle and addressing climate change.



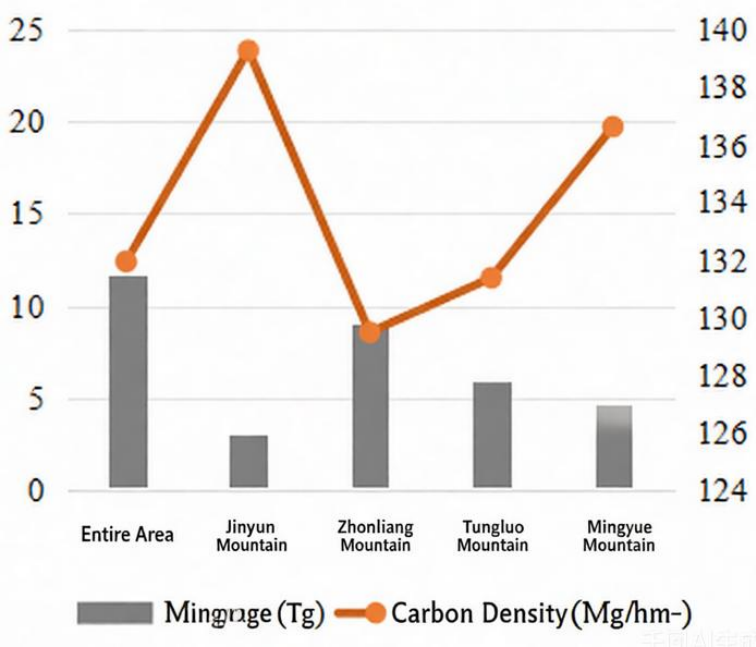


Figure 3Habitat quality, carbon storage, and carbon density of the " Four Mountains "

3.3 People's well-being has been steadily improved.

By coordinating population development and resource allocation, and improving infrastructure and public services, the foundation for people's well-being has been continuously strengthened, and the quality of life for residents has been steadily improved.

Regarding the coordinated development of population and natural resources, we actively promote intensive land use and ecological space restoration. While ensuring the construction

of public service facilities and infrastructure, we consistently emphasize the organic integration with ecological protection. From 2021 to 2024, the land area for public management and public services in the "Four Mountains" area increased by a cumulative 26.57 hectares, and the per capita area of parks and green spaces, science, education, culture and health facilities, and residential land also increased. Through scientific planning of public service land, green space systems, and the proportion of residential land, we have formulated a natural resource utilization strategy based on ecological priority to ensure residents' realistic needs for a beautiful environment and high-quality public services.

In terms of transportation convenience and public service accessibility, from 2021 to 2024, the rural roads in the "Four Mountains" area increased by 289.60 hectares. Through the construction and renovation of "Four Good Rural Roads," including road surface hardening to a width of 4.5 meters and improvements to drainage and protective facilities, the region's transportation convenience and internal and external connectivity efficiency have been significantly enhanced. Overall, public services in the "Four Mountains" area are of higher quality, people's travel is more convenient, and the quality of life continues to improve. From leisure travel and education to medical care and living conditions, the diverse needs of residents for "livable, workable, learnable, and enjoyable" environments are met. While ensuring the construction of public service facilities and transportation infrastructure, ecological protection is always emphasized, building a sustainable development pattern of harmonious coexistence between humans and nature.

3.4 Resource governance efficiency is gradually improving

In the process of natural resource management of the "Four Mountains", a joint working mechanism of "investigation-planning-law enforcement" has been formed, and a monitoring and evaluation mechanism of "dynamic monitoring-monthly summary-quarterly analysis-annual report" has been established. Taking "one policy for each mountain" as the starting point, and focusing on the disposal of historical buildings and the supervision of the non-agricultural and non-grain use of arable land, the effectiveness of comprehensive resource management of the "Four Mountains" has been improved.

The total area of historical buildings in the "Four Mountains" region is 2365.84 hectares. A "one case, one policy" approach was adopted for categorized disposal, employing methods such as illegal construction rectification, preservation and upgrading, and gradual renovation. For those that could be rectified, the necessary procedures were urged to be completed according to law; for those with serious violations, they were resolutely demolished according to law. By the end of 2024, 1627 hectares had been disposed of, and by July 2025, 1902.83 hectares had been disposed of. With the innovation of daily inspection methods and the strengthening of supervision, the disposal of existing illegal structures was accelerated, effectively curbing new ones. From 2021 to 2024, the area of cultivated land converted to non-agricultural uses was 129.84 hectares, and the area converted to non-grain uses was 683.92 hectares. The use of "drones + real-scene 3D + AI" improved monitoring frequency and interpretation efficiency, achieving three-dimensional and precise monitoring of

cultivated land in the "Four Mountains" region. The cumulative decrease in the area of cultivated land converted to non-agricultural and non-grain uses over three years reached 87.24%, effectively curbing the trend of non-agricultural and non-grain conversion of cultivated land in the "Four Mountains" region.

Focusing on the core issues and decision-making needs in the protection and development of the "Four Mountains," this study conducts thematic analysis based on regional characteristics. Through a "one mountain, one policy" approach, it highlights the overall functional positioning of Jinyun Mountain ("gentle breeze and hot springs"), Zhongliang Mountain (" resilient red rocks"), Tongluo Mountain ("cultural vitality"), and Mingyue Mountain ("natural countryside"). Addressing key aspects such as integrated management of the mountain and its surrounding areas, transportation organization, trail connectivity, functional layout, and infrastructure improvement, this study provides a scientific basis for differentiated governance and coordinated regional development by implementing tailored policies for each mountain.

3.5 Excellent overall level of natural resources

Two comprehensive indicators, coupling coordination and comprehensive weighting, are analyzed and evaluated. The coupling coordination degree is used to comprehensively evaluate the coordinated development of natural resource protection and utilization with the endowment system, while the comprehensive weighting index is used to characterize the contribution degree and overall level of each objective dimension.

(1) The coupling coordination degree of the natural resource endowment utilization of the "Four Mountains" is at a medium-to-high level. The coupling coordination degree is used to evaluate the level of scientific and sustainable utilization of natural resources and guide its development from disorder to order. By superimposing comprehensive indicators such as natural resource endowment, and through model calculation, the coupling coordination degree is divided into 10 levels in the interval of 0 to 1 with equal intervals of 0.1. Among them, the coupling coordination degree of levels 1-5 is extremely unbalanced, severely unbalanced, slightly unbalanced, and on the verge of unbalanced, respectively, and levels 6-10 are barely coordinated, primary coordinated, intermediate coordinated, good coordinated, and excellent coordinated, respectively. In 2024, the coupling coordination degree between the two systems of natural resource protection and utilization and natural resource endowment of the "Four Mountains" was 0.701, with a coordination level of 8, which is at a medium level. It is necessary to promote the sustainable utilization of natural resources of the "Four Mountains" with the goal of good coordination and excellent coordination.

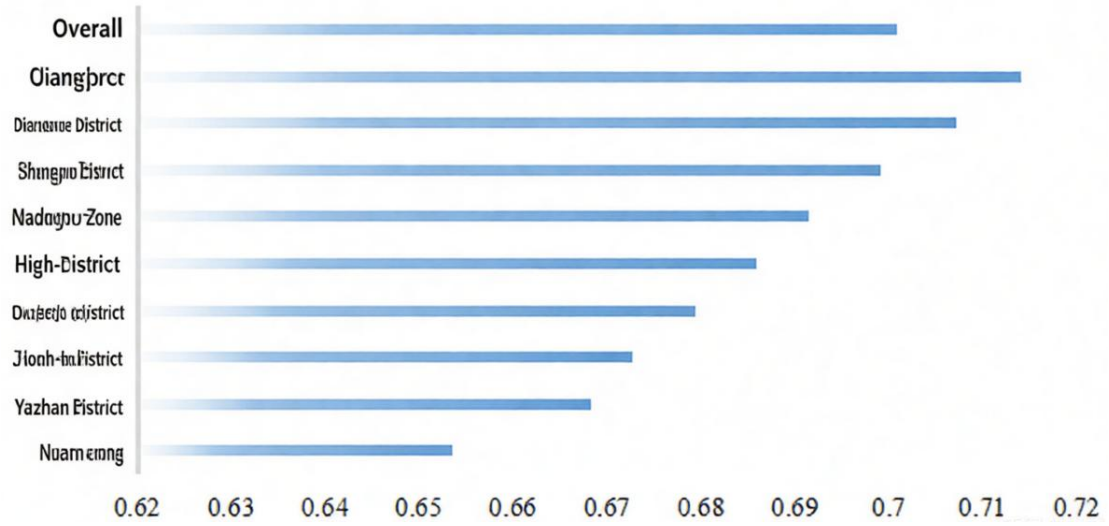


Figure 4 Coordination and Degree of Coupling of Natural Resource Endowment and Utilization in the Four Mountains

(2) The overall level of natural resources in the "Four Mountains" is excellent, but there is still room for improvement. The Normalized Comprehensive Weighted Index of Natural Resources (CEWI) is a comprehensive measure of natural resource endowment, utilization, protection, livelihood, impact, and governance. For different target dimensions, the analytic hierarchy process and the Delphi method are used, and the weights of the indicators are set according to the actual situation of the "Four Mountains". The sum of the products of the normalized values of the evaluation results of each target dimension and the corresponding weights is used as the comprehensive weighted index. The CEWI is divided into five levels from low to high: poor, average, good, excellent, and best, with equal intervals of 0.2 between 0 and 1. The comprehensive calculation shows that the CEWI value of the "Four Mountains" in 2024 is 0.622, and the overall level of natural resources is excellent. In terms of spatial distribution, the comprehensive level of natural resources in areas such as Jinyun Mountain Nature Reserve, Hufeng Mountain Scenic Area, the area along the "Two Rivers" (Yangtze and Jialing Rivers), and Tongluo Mountain and Yufeng Mountain Forest Park is relatively good, while the comprehensive level of natural resources in Zhongliang Mountain, northern Tongluo Mountain, and southern Mingyue Mountain is relatively low. Overall, the "Four Mountains" have achieved a level of coordinated development in many fields, including the exploration, development and utilization of natural resources, ecological protection, improvement of people's livelihoods and governance effectiveness, and have formed a good comprehensive development trend, but there is still room for improvement overall.

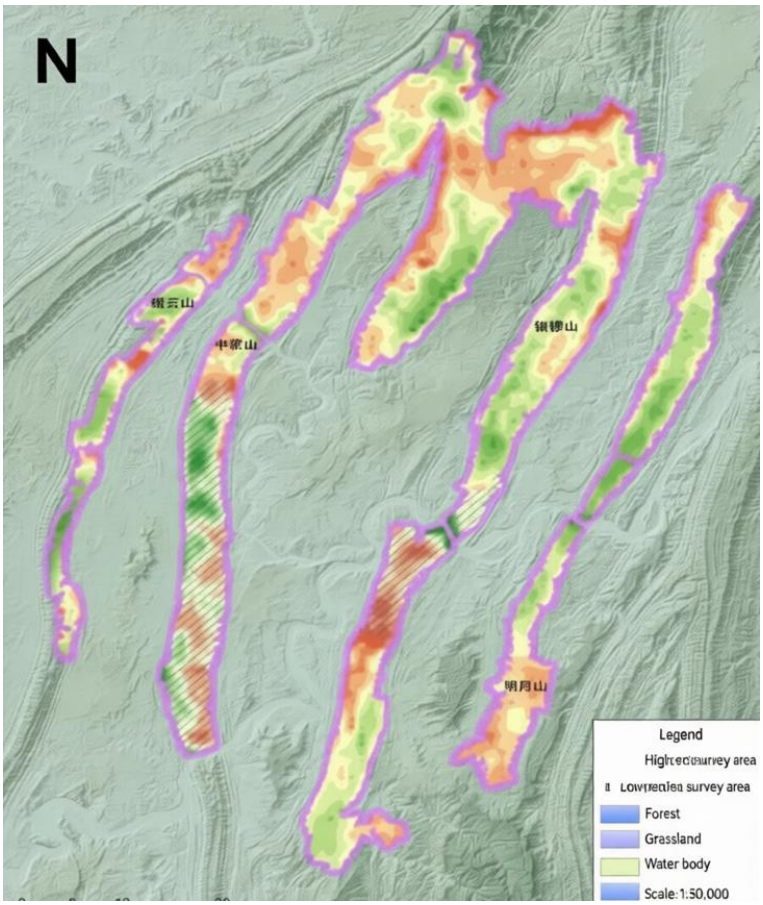


Figure 5 Spatial distribution map of the comprehensive weighted index of natural resources in the "Four Mountains"

4 Conclusions

Overall, with the normalized monitoring and evaluation of the natural resources of the "Four Mountains" as the main focus to empower ecological protection and high-quality development, and based on a thorough understanding of the "Four Mountains" and a clear definition of their functional positioning, a set of indicators that are both systematic and targeted has been constructed. This has achieved significant results in terms of resource security, ecological function protection, people's well-being, and resource governance effectiveness. However, some problems and shortcomings still exist.

(1) Forest resources protection and utilization face pressure, and the relationship between humans and land still needs to be coordinated. From 2021 to 2024, the forest land in the "Four Mountains" area decreased by 983.89 hectares, mainly due to natural factors such as high temperatures and rainstorms leading to forest fires, geological disasters, and biological disasters such as pine wilt disease. 915.89 hectares of forest land were converted into arable land. Some scenic spots and homestays illegally expanded trails and viewing platforms to attract tourists, encroaching on forest space. It is necessary to deepen the implementation of

the "Four Mountains" forest chief system, strengthen forest fire risk early warning, geological disaster prevention and control, and pest and disease control. It is also necessary to plan and provide alternative income-generating pathways for the original inhabitants, such as ecological planting and understory economy, to reduce the conversion of forest land into arable land, balance resource protection and tourism development, and coordinate the relationship between humans and land in the urban green lung space of the "Four Mountains".

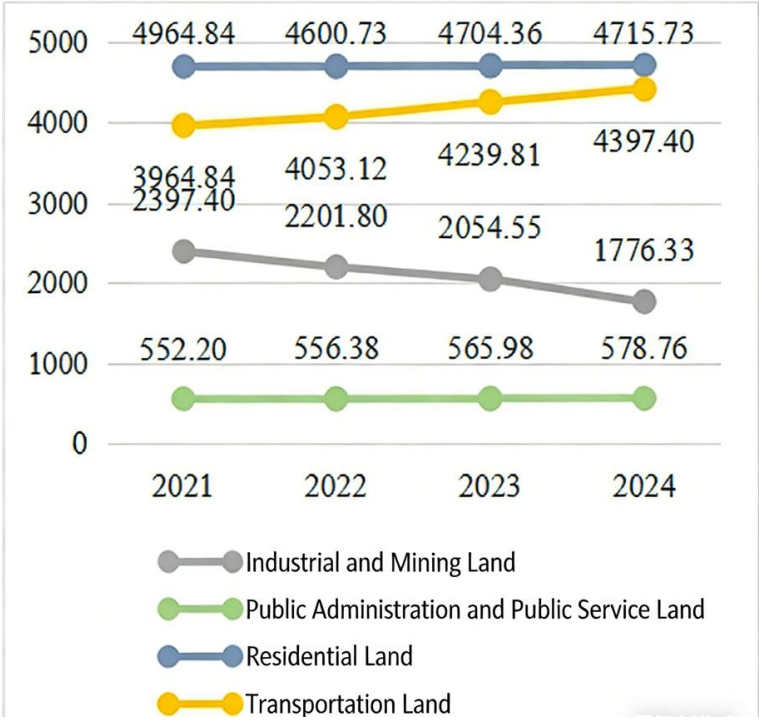


Figure 6Historical variation curves of major natural resources in the " Four Mountains "

(2) Balancing infrastructure development with ecological protection is challenging, and the ecological protection line still needs consolidation. Forest resources within the ecological protection red line of the "Four Mountains" continue to flow out, decreasing by 171.96 hectares from 2021 to 2024, with approximately 70% flowing to rural roads and other transportation land. Conversely, ecological protection also restricts transportation convenience. Besides infrastructure encroaching on forest land, existing industrial, mining, and commercial land within the ecological protection red line also adds to the practical difficulty of coordinating ecological protection and development. There are still 23.90 hectares of industrial and mining land and 16.50 hectares of commercial land within the ecological protection red line, some of which can be phased out in an orderly manner through a "one case, one policy" approach. Promoting the transformation of ecological restoration value through carbon trading and the realization of ecological product value will facilitate high-level protection of the "Four Mountains" ecological barrier and drive high-quality development of the "Four Mountains."

(3) The per capita land area for science, education, culture and health is insufficient, and the guarantee of public service facilities still needs to be strengthened. The per capita land area for science, education, culture and health in the "Four Mountains" is 8.30 m2/person, which is lower than the reference value of 17 m2/person in the guidelines. Specifically, the distribution of primary medical facilities, educational facilities such as schools, and social welfare facilities in the "Four Mountains" is uneven, making it difficult to meet the needs of relatively

remote residents for nearby medical treatment and education. It is necessary to strengthen the guarantee of land for public service facilities such as science, education, culture and health, parks and green spaces, and squares in some areas of Zhongliang Mountain and Mingyue Mountain, further optimize the allocation of medical and educational resources and social welfare institutions in the "Four Mountains", especially the planning and layout of primary hospitals and primary and secondary schools, so as to promote the all-round improvement of the quality of life in the "Four Mountains" by radiating the urban space to the ecological space, and pay attention to guaranteeing and improving the people's livelihood in the "Four Mountains" in the development process, and make new progress in ensuring that everyone has access to education, employment, medical care, old-age care, and housing.

(4) The historical problem of illegal construction has not been eradicated, and the long-term resource supervision mechanism still needs improvement. While the difficulty in discovering historical buildings in the "Four Mountains" area has been effectively addressed, the difficulties in stopping and investigating them remain prominent. Long-term mechanisms are lacking in some areas, and historical problems have not been completely resolved. For historical buildings in areas lacking planning and on vacant rural development land, a smart disposal database with a "one case, one policy" approach will be established according to the principle of "categorized disposal and combined guidance and control." These buildings will be categorized into demolition and greening, completion of procedures, and preservation and upgrading. The land use adjustment model based on the balance of land occupation and compensation will be promoted, and the assessment mechanism and long-term supervision mechanism for illegal construction governance will be improved. A "zero-tolerance" policy will be adopted for newly added illegal construction; each case will be investigated and rectified.

5 Acknowledgments

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