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Settlement evolution and its drivers across contrasting topographic units: Evidence from Tajikistan's socio-economic transition, 1990–2022

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Abstract

Topography is a key factor in mountain settlement evolution, but its effects can vary with socio-economic conditions. This can create different trajectories in river valleys, hilly regions, and high mountains. Understanding how settlement evolution and associated factors differ across terrain zones is important for explaining spatial differentiation under socio-economic transition and informing terrain-sensitive planning. A case in point is Tajikistan. Its mountains, hills, and valley plains support distinctive settlement systems, while socio-economic transition since 1991 has accentuated their differences. Using land-cover, demographic, economic, topographic, hydrological, and transport-network data, this study traces settlement change in Tajikistan during 1990–2022. Terrain zoning, landscape-pattern metrics, and geographically weighted regression (GWR) identify national trends, terrain differences, and temporal changes in factors associated with settlement expansion.

Two main findings emerge. First, the total area occupied by settlements increased over three decades, patch forms became more regular, and overall spatial aggregation declined. The form of expansion nevertheless varied sharply by terrain. Valley plains experienced predominantly contiguous outward growth; settlements in mountain-hill areas extended mainly in belts along piedmont zones; and high-mountain plateaus developed through scattered patches. Settlement size, shape complexity, and spatial aggregation declined in sequence from valley plains to mountain-hill areas and then to high-mountain plateaus. Second, population growth, economic development, conflict disturbance, and elevation were especially influential in the early transition period. In later years, road accessibility and the availability of flat land became the principal associated factors. Dominant influences shifted from population and economic growth to improved transport in valley plains; from elevation and population to flat land and transport in mountain-hill areas; and from the combined constraints of elevation and limited flat land to the joint influence of transport improvement and flat terrain on high-mountain plateaus. These findings provide evidence for understanding mountain settlement differentiation under complex terrain conditions.

Keywords: Mountain settlements; Spatial evolution; Terrain differentiation; Socio-economic transition; Tajikistan

1. Introduction

Settlements arise from the concentration of people and activities needed for production and everyday life. They bring natural, social, material, and cultural elements together within a single spatial system and continually adjust as human–land relationships change (Smith et al., 2021). Urbanisation and industrialisation are now interacting with technological and institutional change to accelerate the movement and reorganisation of population, land, and industry. Settlements consequently expand, change shape, and undergo spatial restructuring (Wang et al., 2023). These changes also register broader shifts in urban–rural relations, land-use practices, and regional spatial organisation (Ma et al., 2026).

Mountains occupy more than 24% of the world's land surface and sustain the livelihoods of approximately 14% of its population (Ehrlich et al., 2021; Kapos et al., 2000). Within mountain systems, valley basins, gently sloping alluvial–diluvial plains, low hills, and high mountains provide markedly different natural conditions and development opportunities. Population movements, divisions of labour, and functional connections nevertheless bind these units into an interdependent whole (Bertram & Chilla, 2023). Human–land tensions are therefore particularly acute in mountain regions. Mountains have restricted and disjointed space for habitation, whereas in plains the land is relatively flat and offers space for habitation in a more or less continuous habitat. Settlement formation and development are in turn more selective and physical environment-dependent (Liu et al., 2025; Ma et al., 2024). Settlements in valley plains, hills and high mountains can experience different dynamics and various response intensities during periods of socio-economic transition – and even react in opposing ways to demographic, economic and transport dynamics. To compare these processes on different terrain units can give insight into how physical constraints and human forces work in various settings. It can also provide further insights into processes of regional differentiation of mountain settlement space and provide evidence from the mountains to the broader field of settlement geography.

A great deal of work has been done on the location of mountain settlements and spatial distribution patterns. In the old farming and herding communities, low productivity dictated a strong dependence on nature. Settlements were concentrated on river valleys and intermontane basins that were lower in elevation, with lower slopes, and more available water. By 2000 BCE, nomadic settlements in the mountainous southeast of Central Asia were topographically adapted, with location depending very closely on elevation and access to water (Frachetti & Maksudov, 2014). Armenian and Greek traditional settlements, much like those in other parts of the world, were also clustered in valleys and places where the conditions for living and producing were best, and big settlements rarely occurred on steep slopes or at high elevations (Asimakopoulos et al., 2016; Ghambaryan et al., 2024). The spatial logic has been found to be lasting. To this day, modern mountain settlements can still be found clustering and extending along gentle slopes, rivers and corridors of transport in valley bottoms and low-relief hills (Addi et al., 2025; Ji et al., 2022; Zhou et al., 2026). Some settlements are decreasing in size, especially at higher elevations, where on average settlements are smaller and more fragmented (Chen et al., 2024; Kong et al., 2026; Zhang et al., 2023). Elevation, slope and hydrological system collectively gives the physical foundation and environment for mountain settlement establishment and development (Shi et al., 2022; Zhao & Li, 2025). These have in turn altered the structure, function and pattern of settlements as a result of urbanisation, shifts in modes of production and intensifying regional connections. The resulting trajectories feature expansion, contraction and abandonment (Ji et al., 2022; Xie et al., 2026), as well as overall trends towards more regular patch shapes and higher aggregation (Yang et al., 2026). These processes are spatially uneven: size, morphology, distribution, and function vary substantially along elevation and slope gradients (Ren et al., 2025; Wang et al., 2024). Yet many studies still treat mountain regions as internally homogeneous, and direct comparisons among terrain units remain uncommon (Bertram et al., 2024). This limits the extent to which regional differences can be identified. Research has also established that terrain, population, economic activity, and transport affect settlement evolution (Bertram & Chilla, 2023; Rao et al., 2025; Śleszyński et al., 2025; Szymanowski & Latocha, 2021; Xie et al., 2026), but most analyses rely on a static pattern observed at one point in time. We consequently know less about how the magnitude and direction of these relationships

change across terrain units during socio-economic transition, or about the mechanisms that produce such variation.

Previous studies have therefore established close links between terrain and mountain-settlement patterns, as well as the importance of several human influences. What remains insufficiently understood is how changing socio-economic forces interact with physical constraints to produce divergent settlement trajectories over time. This study addresses that problem through one central question: how do terrain conditions and evolving socio-economic forces combine to shape mountain settlements during socio-economic transition? The analysis proceeds through two related questions. First, how do changes in settlement size, morphology, and spatial distribution differ among terrain units? Second, how do the strength and direction of natural, demographic, economic, and transport influences vary among those units, and what spatial patterns result?

Tajikistan provides an appropriate setting in which to examine these questions. About 93% of the country is covered by mountains and ranges, river valleys and basins alternate over its territory. Topographic constraints are strong on the development of settlement and human–land relationships are sensitive and fragile. Tajikistan has experienced civil unrest, institutional changes, economic recovery and renewed economic growth since gaining independence in 1991. As a result, the distribution of people and resources over the region has undergone significant shifts (Hofman & Visser, 2021). Complex terrain has also shaped population growth, settlement expansion, and the development of modern transport infrastructure (Sadozaï & Blondin, 2023), adding uncertainty to the course of settlement change. Marked contrasts are now visible among valley plains, hills, and high mountains. This study follows settlement change in these three terrain units from 1990 to 2022, examining size, morphology, and aggregation before comparing the factors associated with their evolution. The analysis supplies evidence for terrain-based comparisons and contributes to a broader understanding of settlement differentiation in mountainous countries undergoing transition.

2. Research Framework

2.1. Measures of Settlement Evolution and Terrain Differentiation

Settlement evolution has been studied from several perspectives: spatiotemporal morphology, historical lineage and hierarchical change, evolutionary type and spatial orientation, and the internal restructuring of social space. This work documents changes in settlement size and spatial pattern, shifts in regional settlement hierarchies (Karácsonyi & Taylor, 2024), the differing incorporation of settlement types into urbanisation (Thinh et al., 2024), and changes in property rights and kinship relations within settlements (Adityo & Shibata, 2026). For long-term analysis based on extensive remote-sensing records, a spatiotemporal morphological approach is particularly suitable (Li & Song, 2020). It quantifies changes in the area, form, and distribution of settlement patches and thereby captures both temporal phases and spatial configurations. Because landscape patterns are the spatial expression of interacting natural and human processes, landscape metrics can measure these structural properties and help infer the human–land processes behind them (Forman & Godron, 1986). Settlement area indicates expansion or contraction. Patch-shape complexity reflects the manner of development and the extent to which boundaries have been disturbed, while spatial aggregation describes how the settlement system is organised. Together, these three dimensions provide the analytical basis for representing settlement evolution.

Before settlement trajectories can be compared across terrain types, the units of comparison must be defined. The classification used here rests on elevation and surface slope. Most global mountain typologies combine elevation with slope or relief. Kapos et al. (2000), for example, classified mountain types using elevation, slope, and local relief, whereas Meybeck et al. (2001) combined mean elevation with terrain ruggedness. In both approaches, elevation represents the vertical hierarchy of landforms and slope or ruggedness captures surface flatness. They therefore offer a useful methodological starting point. Their original purposes, however, were global mountain delineation, forest-resource assessment, or hydrological research, and their scales and objectives differ from those of a study centred on constraints to settlement development. We retain the principle of combining elevation with surface relief but set thresholds suited to Tajikistan's terrain and to the requirements of settlement analysis.

Low-elevation valleys and basins dominate western and southwestern Tajikistan, mountain-hill terrain occupies much of the centre, and the high Pamir Plateau lies to the

east. Conditions for settlement development differ sharply among these areas. Our classification is not intended as a universal geomorphological scheme; it distinguishes three environments that impose different constraints on construction. The zoning rules therefore vary by elevation band. At lower elevations, slope and elevation separate flat valley floors from adjacent slopes. At higher elevations, elevation becomes the main criterion so that locally level surfaces on the Pamir Plateau remain within a zone constrained by high altitude. Table 1 gives the thresholds. Under this classification, valley plains cover 13.97% of Tajikistan, mountain-hill areas 17.37%, and high-mountain plateaus 68.66%.

Table 1. Classification criteria for settlement zoning across terrain units

Terrain Zone	Classification Criteria	Classification Meaning
Valley plain	Elevation < 1,000 m and slope < 5°	Major low-elevation river valleys, basins, and plains where flat terrain provides relatively continuous buildable land
Mountain-hill area	Elevation < 1,000 m and slope ≥ 5°; 1,000 m ≤ elevation < 2,000 m	Side slopes of low-elevation valleys together with mid-elevation mountains and hills, forming the principal transition between valley plains and high mountains
High-mountain plateau	Elevation ≥ 2,000 m	Continuous high-elevation mountains and plateaus, including locally flat valleys and plateau surfaces that remain subject to high-altitude conditions

2.2. Influencing Factors of Settlement Evolution

Changes in spatial pattern are the visible outcome of settlement development; explaining them requires attention to the processes beneath the pattern. Empirical studies consistently associate settlement evolution with both natural endowments and socio-economic forces. Elevation and slope are key constraints on how much buildable land is available, and hence on the cost of construction, and as such, are key controls on the vertical differentiation of mountain settlements (Niyogakiza & Liu, 2026). Historically, rivers provided access and provide water for production and domestic purposes. Demographic change is closely related to socio-economic influences, in particular to the change of the settlement area. High elevation settlements can contract or even disappear due to sustained out-migration, while population growth puts more pressure on settlement land. In general, rapidly growing areas have a higher density of buildings and more diverse land-use patterns, as economic development and industrial transition can expand the size of settlements and diversify land-use patterns (Alamá-Sabater et al., 2025; Jiang et al., 2024). Changing transport systems changes the locational advantage, too. More accessible places tend to have stronger external connections and a greater propensity to expand (Holl, 2025). Terrain, population,

economic activity, and transport thus form the principal groups of factors used to select explanatory variables in this study.

Social conflict is added to these factors because of Tajikistan's recent history. Civil war and subsequent local conflicts have damaged built environments and affected residents' willingness or ability to remain, changing the conditions under which settlements survive (Śleszyński et al., 2025). Conflict disturbance must therefore be represented in the analytical framework. Land institutions, population policies, and cultural practices may also shape settlement evolution. They are not included in the core quantitative analysis for two reasons. National institutions and policies vary little spatially and are consequently ill suited to explaining differences among terrain units, while long-term data with sufficient spatial resolution are unavailable for the remaining factors.

Drawing on this evidence, the aims of the study, and the available data, we organise the explanatory variables into natural and socio-economic dimensions. Elevation, slope, and hydrological accessibility describe the natural setting. Population change, economic development, transport conditions, and social conflict represent the socio-economic setting. Table 2 lists the resulting variables and their calculation.

Table 2. Variables and calculation methods for the influencing factors of settlement evolution

Type	Name	Symbol	Calculation Method
Dependent variable	End-period settlement coverage ratio	*SET_t1*	Settlement area as a proportion of each grid cell in the final year of the period
Baseline control variable	Initial-period settlement coverage ratio	*SET_t0*	Settlement area as a proportion of each grid cell in the first year of the period
Socio-economic factors	Population growth rate	*ΔPOP*	Mean annual logarithmic rate of population change within the grid during the period
	GDP per capita growth rate	*ΔGDP*	Mean annual logarithmic rate of change in GDP per capita within the grid during the period
	Road density change	*ΔROAD*	Change in kernel-estimated road density within the grid between 2014 and 2022
	Conflict exposure intensity	*CONFLICT*	Intensity of conflict exposure within the grid during the period
Natural condition factors	Mean elevation	*ELEV*	Mean elevation within the grid
	Flat surface proportion	*FLAT*	Proportion of grid area with slope ≤ 5°
	Distance to major rivers	*RIVDIST*	Distance from the centre of the grid cell to the nearest major river

Note: Conflict exposure intensity is calculated as $CONFLICT = ln(1 + \frac{KD_{i,p}}{T_p})$. $KD_{i,p}$ is the fatality-weighted kernel density, and T_p is the duration of the period. In UCDP GED, where_prec records the spatial precision of each event. We retained events located at a specific site (where_prec = 1) and those located within approximately 25 km of a known site (where_prec = 2). The estimated number of fatalities (BEST) was used to weight a kernel-density calculation with a 25

km search radius. Results were aggregated to 1 km grid cells, annualised for the duration of each period, and logarithmically transformed.

These elements are brought together in the process–mechanism framework shown in Figure 1. The first stage traces settlement evolution across Tajikistan from 1990 to 2022 and compares trajectories among terrain units. The second estimates, for successive periods, the national relationships between settlement change and the selected natural and socio-economic factors. This identifies changes in the associations between settlement change and the selected factors as socio-economic transition proceeds. The third stage compares the same relationships among terrain units, revealing how physical constraints and socio-economic change jointly produce differentiated settlement outcomes.

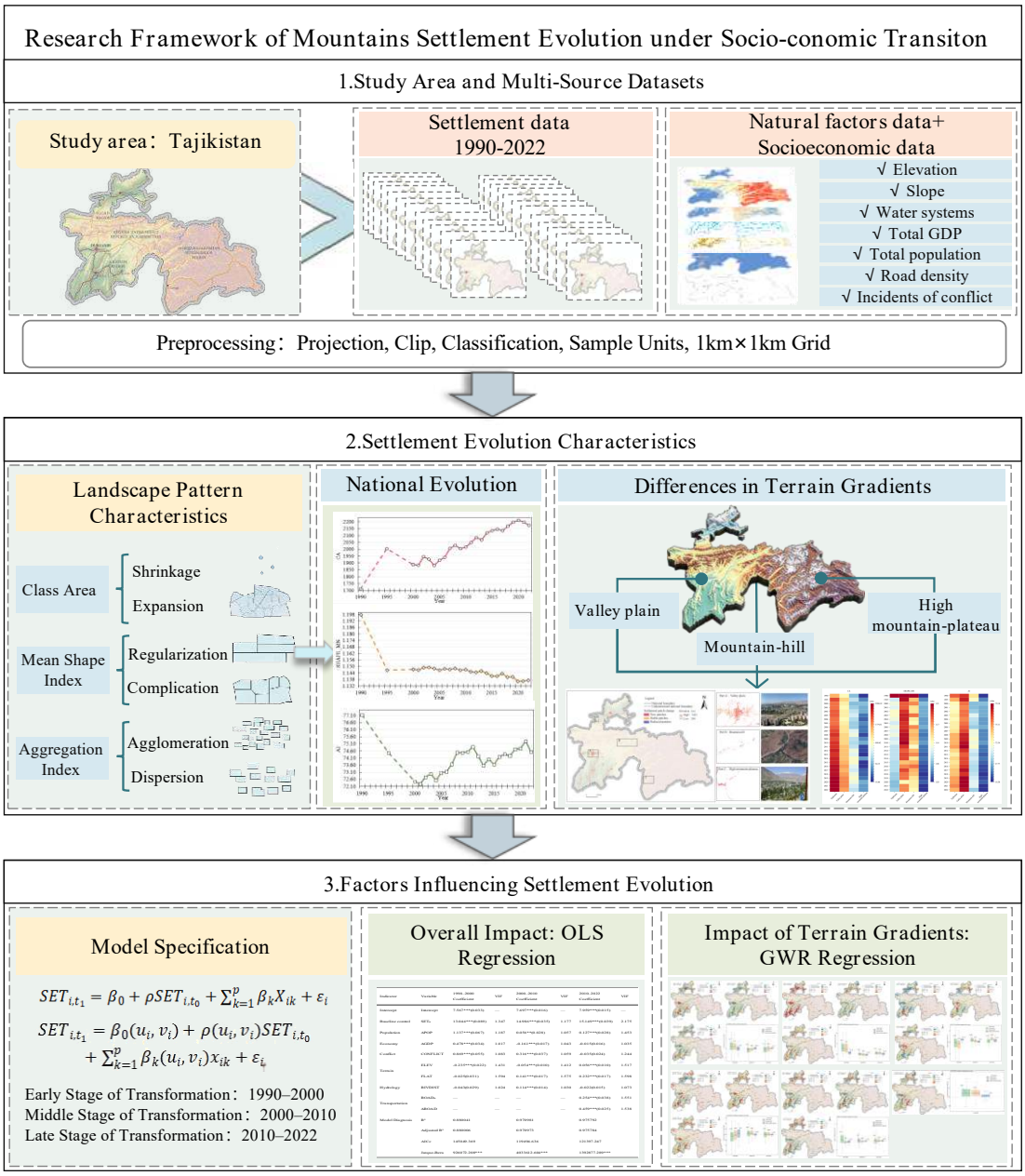


Figure 1. Research framework

3. Data and Methodology

3.1. Study Area

Tajikistan lies in southeastern Central Asia, bordering Kyrgyzstan to the north, Uzbekistan to the west, Afghanistan to the south, and China's Xinjiang region to the east (Figure 2). The country covers 143,100 km²; mountains and plateaus account for 93% of this area.

Elevation ranges from 300 to 7,495 m, and roughly half of the national territory lies above 3,000 m. The land surface generally descends from the eastern Pamir Plateau, whose mean elevation exceeds 4,500 m, towards the west, south, and north. Central Tajikistan belongs to the Gissar–Alay system and includes the Vakhsh, Kafirnigan, and Gissar valleys. The north is part of the Tien Shan system (Kurama, Mogoltau ranges), and the Fergana Basin was always an important transport node of the Silk Road. Tajikistan is a continental climate country. The mean temperature in January is between -2℃and 2℃, and in July between 23℃ and 30℃; the annual precipitation varies between 150 and 250 mm depending on elevation and the aspect of the slope. The Amu Darya, Syr Darya, Vakhsh and other big rivers are fed by extensive glaciers. Low elevation valleys and piedmont oases are the main sites of agriculture and settlement due to the favourable water and temperature regimes. The country's administrative divisions comprise the capital city of Dushanbe, the Districts under Republican Subordination, Sughd Region, Khatlon Region, and the Gorno-Badakhshan Autonomous Region. In 2023, the number of residents was 10.2883 million, which is 86.87% more than the 5.5056 million who were residing in the country on the eve of independence in 1991, with an annual mean growth rate of 1.97%. The urbanisation rate has been slow, with approximately 28.9% of the population residing in urban areas in 2023, while the majority of people still live in rural areas. GDP grew from US$2.537 billion to US$12.244 billion over the same 30 years and over the last five years, the rate of growth has been more than 8% per year. Agriculture, industry, and services accounted for 48%, 35.0%, and 17% of GDP, respectively, in 2023. At the present moment there is an additional process of strengthening investments into infrastructure. Projects that have been finished or are still in the construction phase include the Hisor – Yovon railway and the expansion of the China-Tajikistan highway, while north – south connectivity has been established.

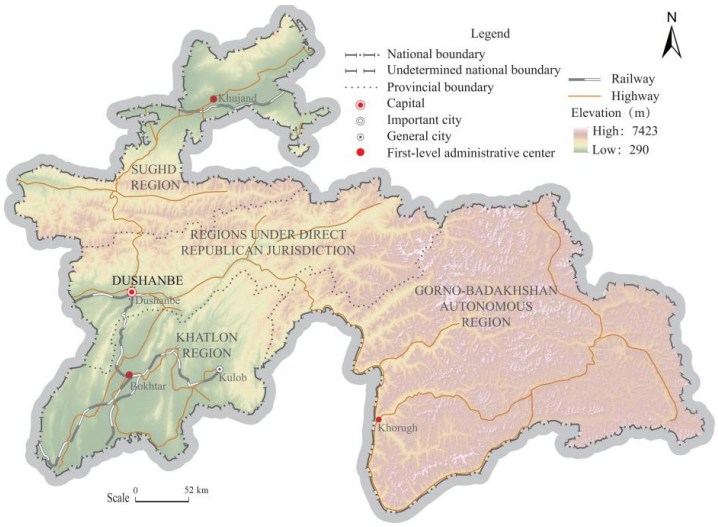


Figure 2. Study area

3.2. Data Sources

Settlement land, population, economic activity, conflict, terrain, rivers and roads data used in the analysis. The sources and the uses are summarised in table 3. Each dataset was reprojected to WGS 1984 UTM Zone 42N and re-sampled to a regular 1 km grid.

Table 3. Research datasets and sources

Type	Source	Period	Application
Land cover	GLC_FCS30D (https://doi.org/10.5281/zenodo.8239305); 30 m resolution	1990–2022	Extraction of impervious surfaces to represent settlement land use
Population	GlobPOP (https://doi.org/10.5281/zenodo.7813301); 1 km resolution	1990–2022	Calculation of population change
GDP	Global gridded GDP dataset (https://doi.org/10.5281/zenodo.10976733); 1 km resolution	1990–2022	Calculation of change in GDP per capita
Digital elevation	GEDTM30 (https://doi.org/10.5281/zenodo.14900180); 30 m resolution	Static	Calculation of mean elevation and the proportion of flat land
Rivers	HydroRIVERS (https://www.hydrosheds.org/)	Static	Calculation of distance from each grid cell to the nearest river
Roads	OSM (https://www.openstreetmap.org/)	2014 and 2022	Calculation of change in kernel-estimated road density
Incidents of conflict	UCDP GED (https://ucdp.uu.se/)	1990–2022	Calculation of conflict-exposure intensity

Note: GLC_FCS30D provides observations at five-year intervals and annual observations after 2000. For Tajikistan, comparable OpenStreetMap road-network data were available only from 2014 onwards. To maintain a consistent three-period framework for analysing settlement evolution, the final study period was retained as 2010–2022, with 2014 serving as the baseline year for calculating road-density change.

3.3. Methodology

3.3.1. Landscape Pattern Metrics

Three landscape metrics were used to quantify settlement evolution: class area (CA), mean shape index (SHAPE_MN), and aggregation index (AI). They represent changes in settlement size, patch morphology, and spatial distribution, respectively. All metrics were calculated in Fragstats 4.2; Table 4 gives their definitions and calculation methods.

Table 4. Settlement evolution metrics and their meanings

Metric	Interpretation	Measurement
Settlement class area (CA)	Measures settlement size; higher values denote a larger built-up area	$\sum_{j=1}^{n} a_{ij} \times \frac{1}{10000}$
Mean shape index (SHAPE_MN)	Measures the shape complexity of settlement patches; higher values denote more complex boundaries	$\frac{\sum_{i=1}^{m}\sum_{j=1}^{n}\left(\frac{0.25c_{ij}}{\sqrt{a_{ij}}}\right)}{N}$
Aggregation index (AI)	Measures settlement aggregation; higher values denote greater adjacency among pixels of the same class	$\left(\frac{g_{ii}}{g_{ii}(max)}\right) \times 100$

Note: a_{ij} denotes the area (m²) of patch j of class i. c_{ij} denotes the perimeter (m) of patch j of class i. N denotes the total number of patches in the landscape. g_{ii} denotes the number of similar adjacencies between pixels of patch type i using the single-count method. $g_{ii}(max)$ denotes the maximum number of similar adjacencies between pixels of patch type i calculated using the single-count method.

3.3.2. Geographically Weighted Regression

We estimated settlement models for 1990–2000, 2000–2010, and 2010–2022 using the 1 km grid as the unit of analysis. This periodisation allows the relationships between physical geography, socio-economic development, and settlement change to be compared across successive stages. Settlement coverage at the end of each period served as the dependent variable. Coverage at the start of the period was entered as a control to account for path dependence in settlement development. Section 2.2 and Table 2 explain the selection and calculation of the explanatory variables. Because the road-density series begins in 2014, change in road density was included only in the 2010–2022 model.

Ordinary least squares (OLS) regression was first used to estimate the global relationship between each explanatory variable and settlement expansion:

$$SET_{i,t_1} = \beta_0 + \rho SET_{i,t_0} + \sum_{k=1}^{p} \beta_k X_{ik} + \varepsilon_i \quad (1)$$

where SET_{i,t_1} and SET_{i,t_0} represent the settlement coverage ratio of grid i at the end and beginning of the period, respectively. X_{ik} denotes the k-th explanatory variable. ρ and β_k are regression coefficients. β_0 denotes the constant term. ε_i is the random error term.

We then applied geographically weighted regression (GWR) to examine spatial non-stationarity in these relationships:

$$SET_{i,t_1} = \beta_0(u_i, v_i) + \rho(u_i, v_i)SET_{i,t_0} + \sum_{k=1}^{p} \beta_k(u_i, v_i)x_{ik} + \varepsilon_i \quad (2)$$

where (u_i, v_i) denotes the spatial coordinates of grid i, and $\beta_k(u_i, v_i)$ denotes the local regression coefficient of variable k at location i.

Spatial weights are central to GWR. We used the Gaussian function, expressed as follows:

$$\omega_{ij} = \exp(-(d_{ij}/b)^2) \quad (3)$$

where ω_{ij} is the observation weight at location i. d_{ij} is the distance between regression point i and data point j. b is the bandwidth, which is a non-negative parameter that defines the functional relationship between weight and distance.

GWR estimates are more sensitive to bandwidth than to the choice of kernel function. A bandwidth that is either too large or too small can reduce model fit. We therefore used the Akaike information criterion (AIC) procedure in ArcGIS Pro to select the bandwidth. The preferred bandwidth, and hence the final GWR specification, was the one that minimised AICc.

4. Results

4.1. Overall Trends of Settlement Evolution

Figure 3 plots class area (CA), mean shape index (SHAPE_MN), and aggregation index (AI) for Tajikistan between 1990 and 2022.

Overall, across Tajikistan, there was an increase in settlement area, an increase in regularity of patch forms and a decrease in spatial aggregation. CA rose by 27.05%, from 1,709.80 km² in 1990 to 2,172.30 km² in 2022 (Figure 3a). This increase was not steady in the initial decade: the area grew from 2,002.48 km² in 1995 to 1,882.27 km2 in 2000. It then went through a period of steady expansion. SHAPE_MN decreased from 1.1975 to 1.1371 (Figure 3b), with the bulk of the change taking place during the 1990s when it became 1.146. After 2000, the rate of decline was reduced and the rate of decline varied slightly, showing that patch boundaries were becoming less complex. AI moved from 77.12 to 74.53

(Figure 3c). Its sharpest fall, from 77.12 to 72.25, occurred between 1990 and 2000. A variable recovery ensued, implying that there was some extent of early dispersal followed by re-concentration, despite the fact that patches were no longer spatially continuous at the same level.

When combined, the three indicators serve to delineate three phases. The settlement area increased during 1990-2000 and decreased thereafter, the patch outline also changed considerably in the direction of being more regular, and the distribution pattern shifted from relative concentration to dispersal. This was the first decade after independence when institutions were changing and there was a civil war. The sudden shifts in population, economic activity, and land use halted building of settlements. There was an unstable and dispersed pattern of settlement with some shrinkage and new locations appearing in isolated places. Settlement area increased steadily and quickly between circa 2000 and 2012. The distribution of patch forms continued to concentrate, although the trend towards dispersal seen previously had been reversed. More continuous development due to greater domestic stability, economic recovery and infrastructure building. Over the past ten years, growth moderated and the general trend was toward equilibrium. Settlement area continued to increase, the patch forms were somewhat more regular and the aggregation increased slightly and then levelled off. Continued demographic and economic growth, combined with transport improvements, meant that there was sustained growth without significant impact on the national distribution.

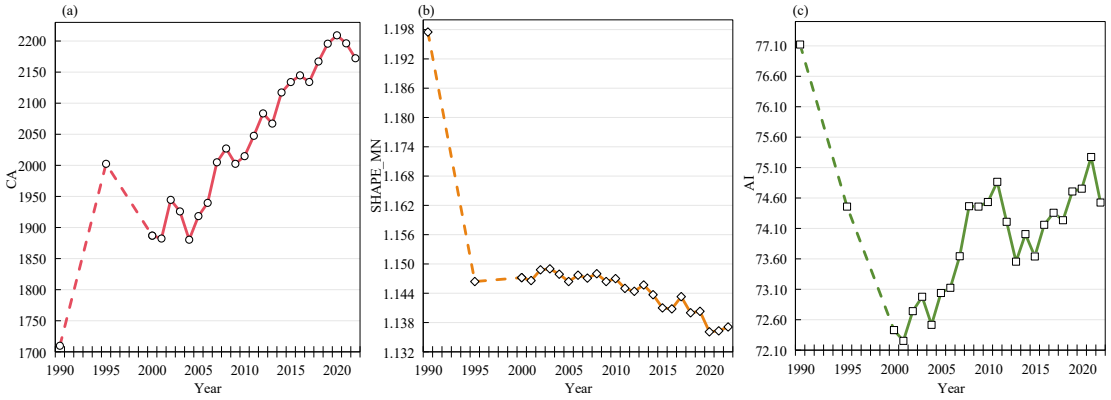


Figure 3. Evolutionary characteristics of settlement landscape patterns in Tajikistan, 1990–2022

Note:(a) Class area (CA); (b) mean shape index (SHAPE_MN); (c) aggregation index (AI).

4.2. Differences in Settlement Evolution Across Terrain Units

Figure 4 and 5 show high topographic difference. Figure 4 is a time-series of CA, SHAPE_MN and AI in valley plains, mountain-hill areas and high mountain plateaus for the period between 1990 and 2022. Patches added, stable or shrinking over the same period are mapped in figure 5. Valley plains had largely continuous expansion. In mountain-hill areas, new development resulted in bead-like sequences or belts along valleys and piedmont areas. A few new patches were found in the high mountain plateaus in a few valleys. Settlement area, patch-shape complexity and aggregation decreased with increasing elevation from valley plains to mountain-hill areas to high-mountain plateaus.

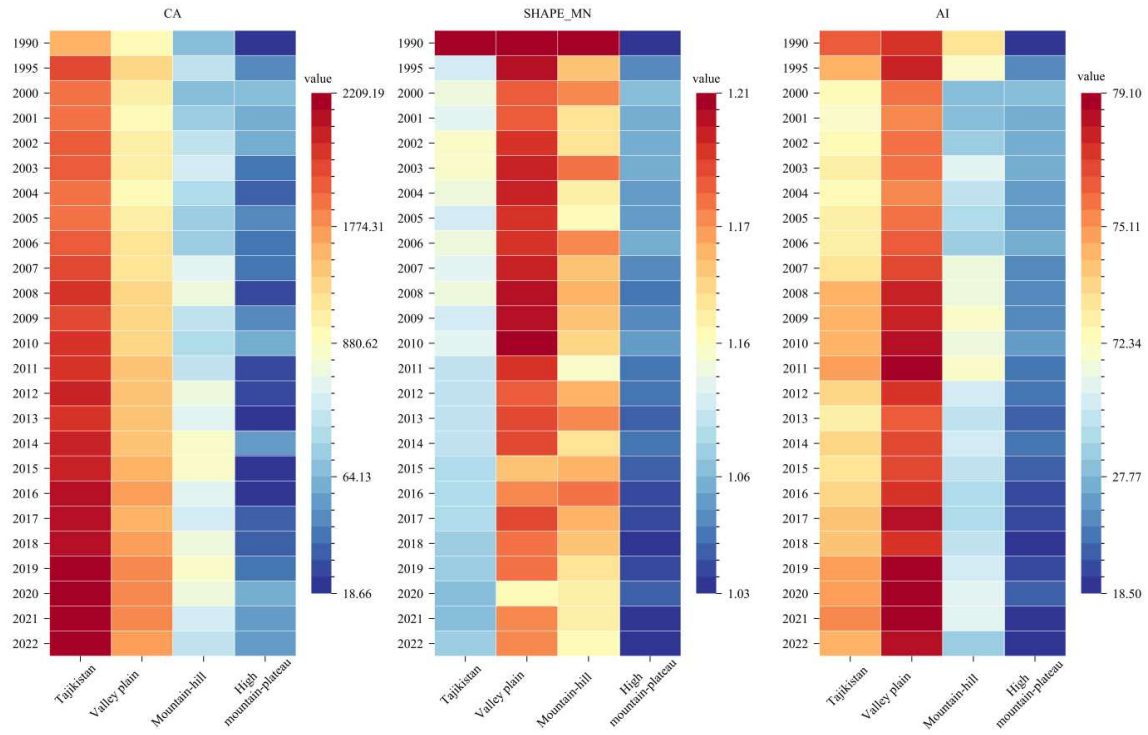
During the study period, Tajikistan's settlement area was more than 80% in valley plains, and the majority of the increase in settlement was in valley plains. CA increased from 1,400.72 km² in 1990 to 1,771.12 km² in 2022; this increment represented 77% of the national increase. The highest of the three terrain types was SHAPE_MN, although this dropped from 1.1969 to 1.1681. The more complex patch forms are commensurate with the higher functional diversity of construction in these areas. It had also the highest aggregation, with AI ranging from 76 to 79 and showing an increasing trend, so reflecting mainly contiguous development. As is seen from figure 5A, new patches have been formed in the Vakhsh River Valley, Gissar Basin and in the western part of the Fergana Basin. Expansion from towns like Dushanbe and Khujand to the slightly sloping peripheral land, many times coalescing old patches. Contraction was scattered, and the expansion pattern retained strong spatial continuity.

Mountain-hill areas form the transition between valley plains and high-mountain plateaus, and their settlements are channelled by the terrain. CA ranked second among the three zones, rising moderately from 290.41 km² in 1990 to 340.55 km² in 2022 and accounting for 15.68% of national settlement area. Patch-shape complexity was intermediate: SHAPE_MN fell from 1.2070 to 1.1632. Because development largely followed individual valleys and piedmont corridors, settlement patches were relatively regular. AI declined from 73.94 in 1990 and stabilised between 64 and 67 after 2000. Mountain barriers fragment buildable land and prevent extensive contiguous settlement, explaining the long-

term decline in aggregation. Figure 5B shows a bead-like pattern of expansion. New patches followed river terraces, gentle piedmont slopes, and transport routes in discontinuous belts, usually among established settlements. The few contracting patches were scattered across steeper slopes. Expansion was therefore strongly confined to topographic corridors.

Settlements on the high-mountain plateaus were the smallest, most dispersed, and least expansive. Their total area nevertheless rose from 18.66 km² in 1990 to 60.63 km² in 2022, with a particularly large increase during 1990–2000. Even by 2022, they accounted for less than 3% of the national total. SHAPE_MN remained close to 1.04, the lowest value among the three zones, because construction is confined to small, level parcels whose boundaries are tightly constrained by surrounding terrain. AI stayed below 30. It rose during the first decade and then gradually declined. As Figure 5C indicates, development occurred through a small number of scattered patches in intermontane basins, upper river valleys, and border ports on the Pamir Plateau. Contracting patches were extremely rare, and the overall intensity of expansion remained low.

Settlement area increased and patch forms became more regular in all three terrain zones, pointing to a shared rise in construction activity and more regular development boundaries during socio-economic transition. Aggregation, however, followed different paths. It increased in valley plains, declined in mountain-hill areas as fragmented terrain constrained continuity, and remained low and variable on high-mountain plateaus. Topography therefore influenced not only how much settlements grew, but also how their spatial organisation changed. As terrain became more complex, contiguous concentration became progressively harder to achieve.

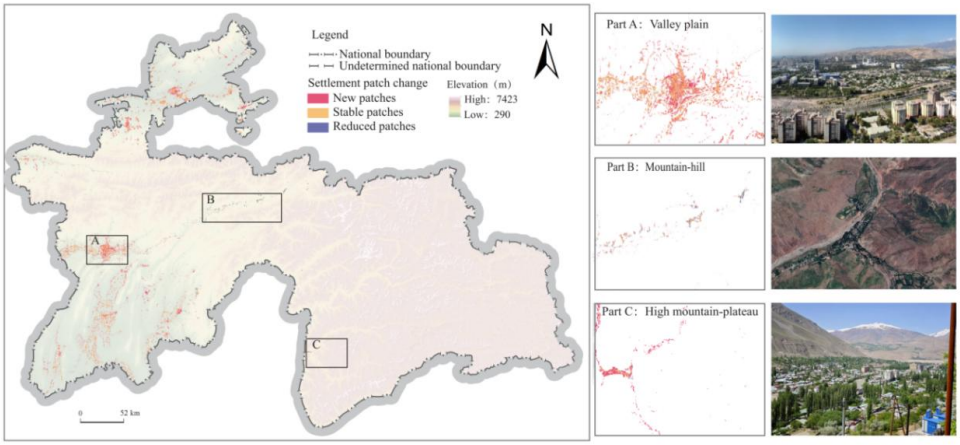


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387 **Figure 4. Temporal changes in settlement landscape pattern metrics across terrain**
388 **zones in Tajikistan, 1990–2022**

389 Note:The three heatmaps show class area (CA), mean shape index (SHAPE_MN), and aggregation index (AI),
390 respectively, for Tajikistan as a whole and the three terrain units.

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393 **Figure 5. Spatial patterns of settlement patch changes across terrain zones in**
394 **Tajikistan, 1990–2022**

Note:The main map shows the spatial distribution of newly added, stable, and reduced settlement patches. Parts A–C present enlarged views and representative photographs of (A) valley plains, (B) mountain-hill areas, and (C) high-mountain plateaus.

4.3. Influencing Factors and Spatial Heterogeneity

4.3.1. Temporal Changes in Factors Associated with Settlement Evolution

The OLS estimates in Table 5 show VIF values below 2.175 for every explanatory variable, providing no evidence of serious multicollinearity. Adjusted R^2 values are 0.880, 0.971, and 0.976 for the three periods, indicating strong model fit. The factors associated with settlement expansion changed as the transition proceeded. Population growth, conflict disturbance, economic growth, and elevation were most important in the first period. Their effects generally weakened during the middle period, when a positive association with flat terrain first appeared. By the final period, flat terrain and change in road density were the leading factors, while the traditional socio-economic variables had lost much of their earlier influence.

Table 5. OLS model global regression results

Indicator	Variable	1990–2000 Coef.	VIF	2000–2010 Coef.	VIF	2010–2022 Coef.	VIF
Intercept	Intercept	7.567*** (0.033)	—	7.697*** (0.016)	—	7.959*** (0.015)	—
Baseline control	SET_t0	13.044*** (0.089)	1.347	14.986*** (0.035)	1.177	15.149*** (0.039)	2.175
Socio-economic factors	ΔPOP	1.137*** (0.067)	1.187	0.056** (0.028)	1.057	0.127*** (0.028)	1.453
	ΔGDP	0.478*** (0.034)	1.017	-0.161*** (0.017)	1.043	-0.015 (0.016)	1.035
	ΔROAD	—	—	—	—	0.459*** (0.025)	1.538
	CONFLICT	0.869*** (0.055)	1.083	0.316*** (0.037)	1.059	-0.035 (0.024)	1.244
Natural conditions	ELEV	-0.235*** (0.022)	1.431	-0.054*** (0.010)	1.412	0.056*** (0.010)	1.517
	FLAT	-0.025 (0.031)	1.594	0.141*** (0.017)	1.575	0.232*** (0.017)	1.598
	RIVDIST	-0.043 (0.029)	1.024	0.114*** (0.014)	1.030	-0.022 (0.015)	1.073
Model diagnostics	R^2	0.8800		0.9710		0.9758	
	Adjusted R^2	0.8800		0.9710		0.9758	
	AICc	145049.369		119494.636		121397.247	
	Jarque–Bera	926072.208***		4033612.604***		1392877.289***	

Note: Parentheses contain heteroskedasticity-robust standard errors. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

The demographic, conflict and economic coefficients diminished with time while the transport improvement was significant in the last period. Population growth had the highest coefficient at the beginning (1.137); conflict incidents had a high and positive relationship with expansion (0.869) as did economic growth (0.478). All the coefficients decreased significantly in the intermediate period. The economic and conflict terms were not found to be important in 2010-2022. Population had a weak positive coefficient (0.127), and change in road density was now the dominant socio-economic coefficient (0.459). The natural controls were also altered. Initially mean elevation was the most important with a significant negative coefficient value of -0.235 while the proportion of flat land was not significant. The elevation coefficient weakened to -0.054 in the middle period as flat land acquired a positive coefficient of 0.141. In the final period, elevation became weakly positive and the coefficient for flat land rose to 0.232, the largest among the natural variables. Distance to a major river was weakly significant only in the middle period and showed no stable relationship with settlement expansion.

4.3.2. Spatial Heterogeneity Across Terrain Units

Strong spatial autocorrelation in the OLS residuals warranted the use of GWR. The local models did not include conflict because it did not demonstrate enough spatial variation and offered unreliable parameter estimates. The adjusted R^2 values of the three GWR models were, respectively, larger than those of the three OLS models, with values of 0.920, 0.978 and 0.981. Residual Moran's I values were 0.297, 0.199 and 0.133, respectively, which showed an improvement in the local fit and less spatial dependence. Figures 6-11 show the mapping of GWR coefficients and distributions of coefficients between terrain zones. The most prevalent associations differed with each setting. The early period showed the highest positive coefficient for population and economic change in the valley plains while road improvement had a higher coefficient later. Elevation exerted the greatest early limitation in mountain-hill areas, while in the later periods flat terrain made the greatest positive contribution and also road improvement was significant. Both the negative effect of elevation and the positive effect of flat places were originally related to high-mountain plateau settlements. In latter periods, most relationships declined there, but flat land and roads were still relatively significant.

(1) Population change

A decreasing positive population coefficient is seen from west to east as shown in figures 6(a) – (c). Initially the highest values were found in the Vakhsh River Valley, the Gissar Basin and the western Fergana Basin. The space of positive coefficients became greatly reduced in the middle period and remained largely within the main valley towns. This resulted in coefficients becoming negative over large areas of mountain-hill and high mountain and in a partial recovery in the last period, which was mainly around the valley basins and important mountain towns. The boxplots in Figure 6(d) reveal a decrease and then an increase in all three zones, but the ordering is valley plains> mountain-hill areas> high mountain plateaus. Median coefficients in the early period were 0.871, 0.633, and 0.189, respectively; by the final period, they had fallen to 0.171, 0.128, and 0.052. The positive association with population was therefore concentrated in valley plains, although the differences among terrain zones narrowed over the course of the transition.

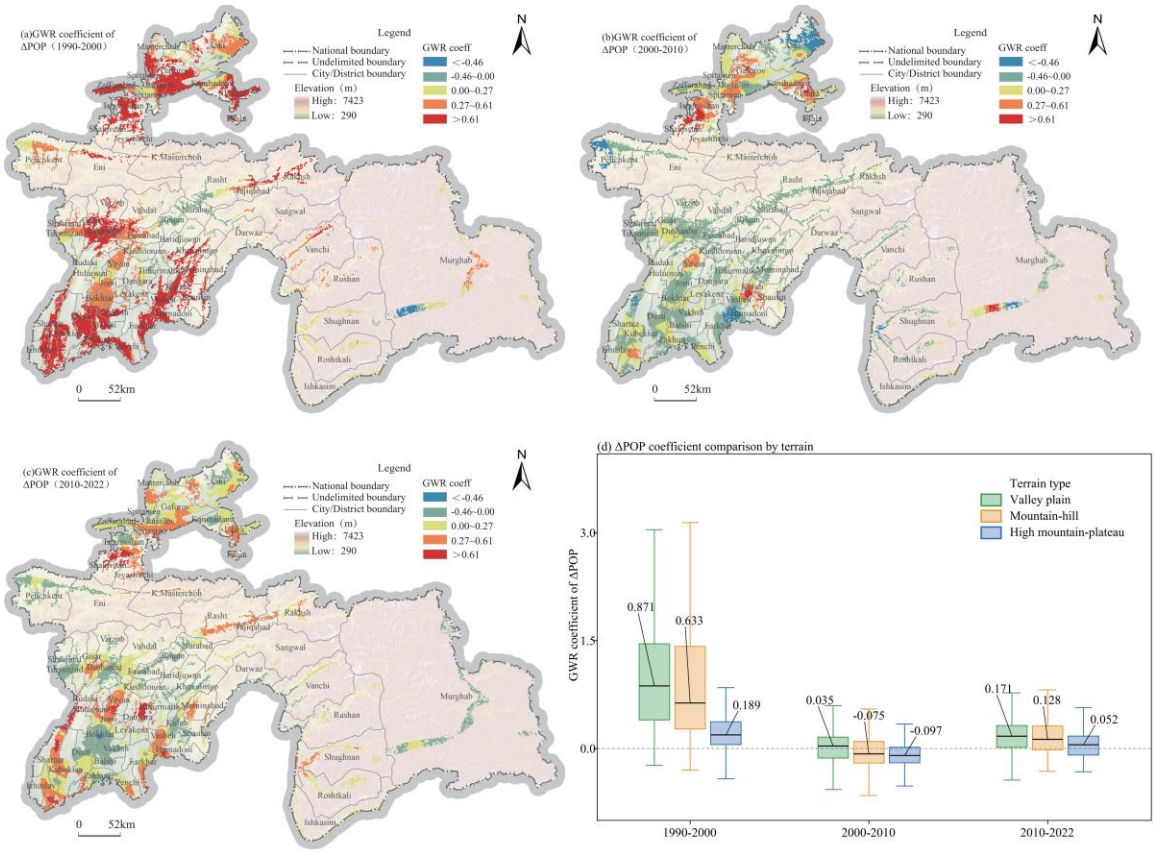


Figure 6. Spatiotemporal and terrain differentiation of ΔPOP effects

Note:(a–c) Spatial distributions of local GWR coefficients for ΔPOP during 1990–2000, 2000–2010, and 2010–2022, respectively. (d) Boxplots of local coefficients across the three terrain units during the three periods.

(2) Economic change

Economic growth had its strongest early positive association in the Dushanbe–Gissar Basin and in agricultural areas along the middle and lower Vakhsh River Valley; coefficients were much smaller on the eastern plateau (Figures 7a–c). During the middle and final periods, the association weakened in the core valleys but extended across a larger share of the mountain-hill and high-mountain zones. Figure 7(d) indicates an overall decline in valley plains and mountain-hill areas, in contrast to a gradual rise on the high-mountain plateaus. In the early period, the median coefficient was highest in valley plains (0.227), followed by mountain-hill areas (0.195), and lowest on high-mountain plateaus. By the final period it had become negative in valley plains, while the corresponding medians were 0.066 in mountain-hill areas and 0.027 on high-mountain plateaus.

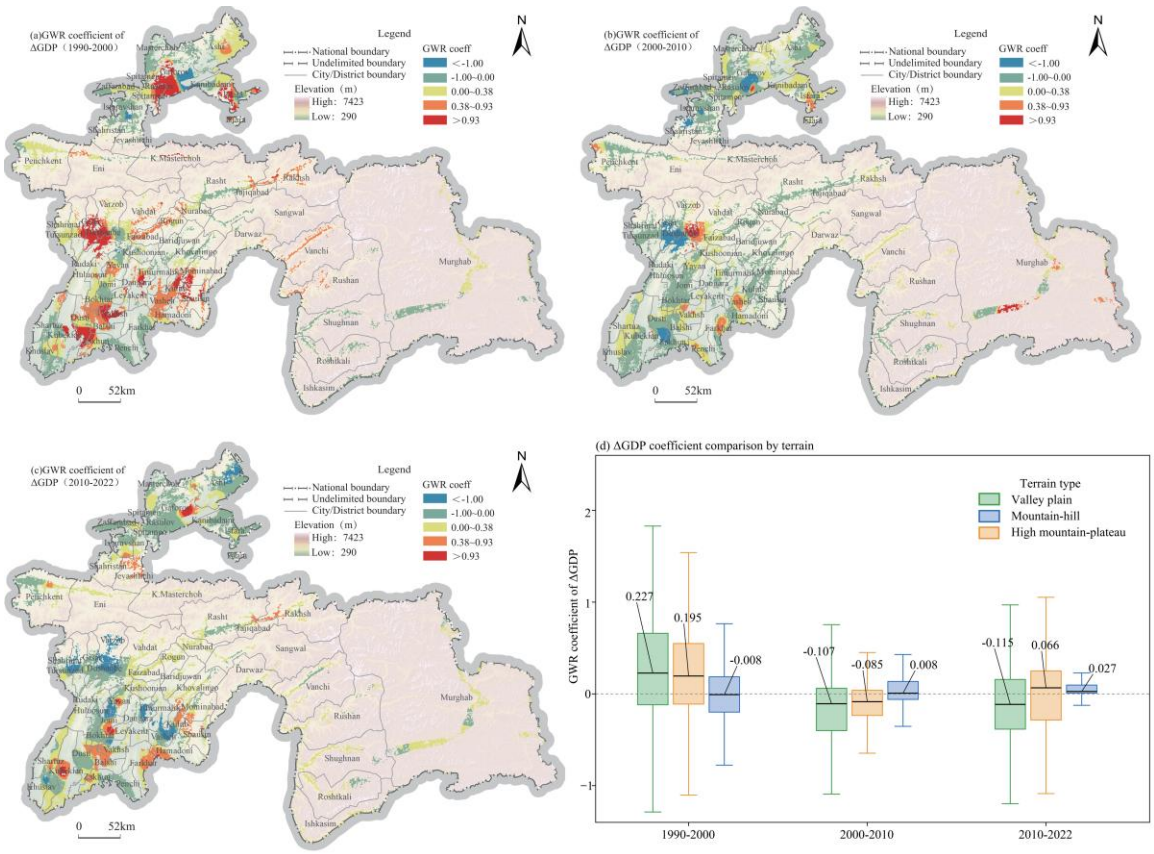


Figure 7. Spatiotemporal and terrain differentiation of ΔGDP effects

Note:(a–c) Spatial distributions of local GWR coefficients for ΔGDP during 1990–2000, 2000–2010, and 2010–2022, respectively. (d) Boxplots of local coefficients across the three terrain units during the three periods.

(3) Road density change

Figures 8(a)–(b) show the road-density coefficient declining concentrically from valley cores towards their margins. High values clustered in the Dushanbe–Gissar Basin and along the urban belt in the middle and lower Vakhsh River Valley. Positive coefficients also formed relatively continuous bands along transport routes on piedmont slopes and basin margins in the mountain-hill zone. On the plateaus, only the principal trunk roads were associated with weak positive values. As summarised in Figure 8(b), the strength of the relationship followed the order valley plains > mountain-hill areas > high-mountain plateaus, with median coefficients of 0.300, 0.292, and 0.106.

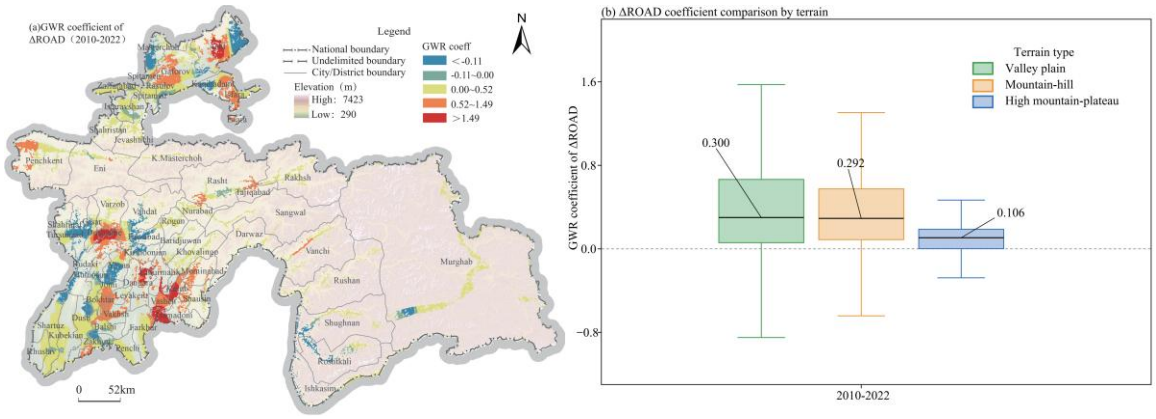


Figure 8. Spatiotemporal and terrain differentiation of ΔROAD effects

Note:(a) Spatial distribution of local GWR coefficients for ΔROAD in the 2010–2022 model. (b) Boxplots of local coefficients across the three terrain units.

(4) Mean elevation

The early-period elevation coefficient was negative across a wide area, with the strongest effects in the central mountains and parts of the high-elevation north and east (Figures 9a–c). In the middle period, negative values became concentrated in the central and western mountains. By the final period, they occupied a much smaller and more fragmented area, mainly in the central and western ranges and a few high-elevation eastern locations. Figure 9(d) shows the general ordering mountain-hill areas > high-mountain plateaus > valley plains in the strength of the negative association. Its magnitude diminished in every zone.

Early-period medians were -0.849 in mountain-hill areas and -0.702 on high-mountain plateaus, while valley plains showed a weak positive value. In the final period, median coefficients were positive in all three zones.

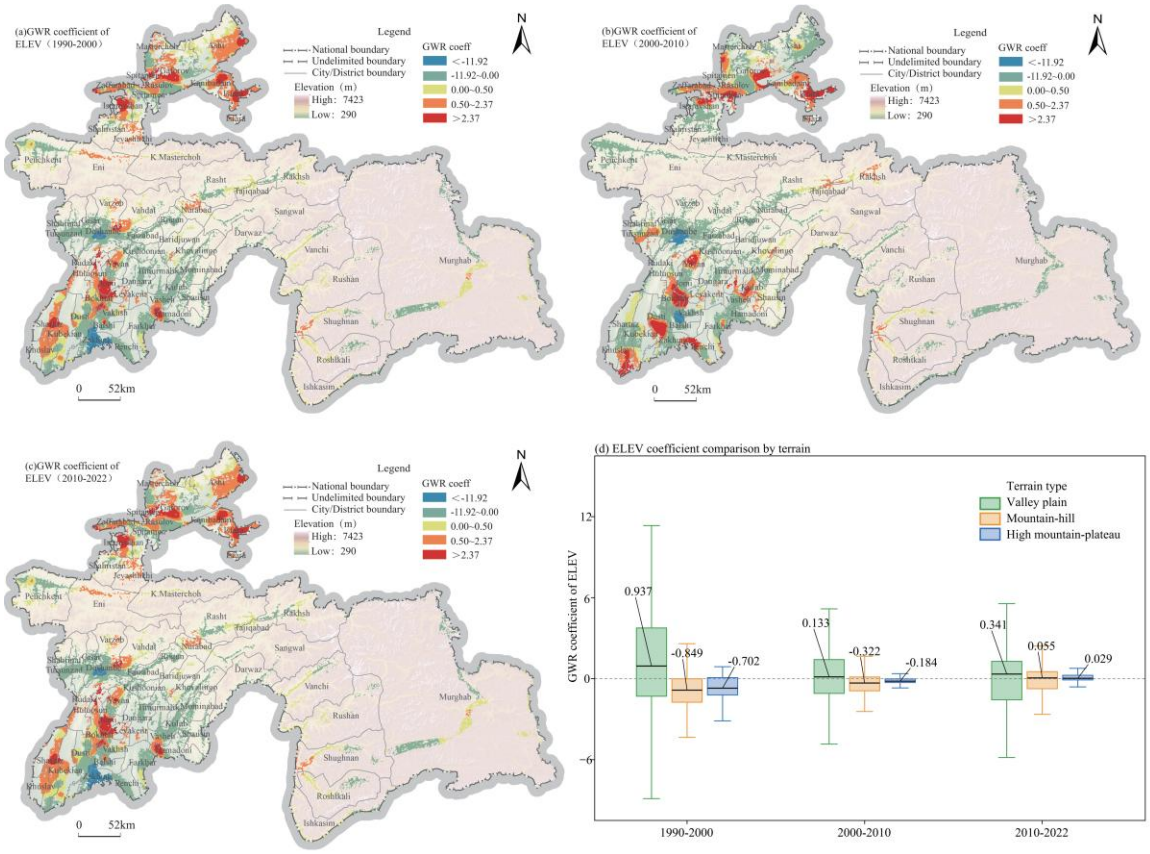


Figure 9. Spatiotemporal and terrain differentiation of ELEV effects

Note:(a–c) Spatial distributions of local GWR coefficients for ELEV during 1990–2000, 2000–2010, and 2010–2022, respectively. (d) Boxplots of local coefficients across the three terrain units during the three periods.

(5) Flat surface proportion

In the early period, the strongest positive coefficients for flat land occurred in local valleys on the high-mountain plateaus (Figures 10a–c). They subsequently shifted towards valley basins and, in the final period, appeared more often around basin margins, piedmont zones, and intermontane valleys. The association weakened markedly in the main valley cores. The boxplots in Figure 10(d) trace a corresponding change among terrain types. High-mountain plateaus had the largest early median (0.318), while valley plains and mountain-

hill areas showed weak negative values. In the middle period, the median was highest in valley plains (0.235), followed by mountain-hill areas, and lowest on high-mountain plateaus. By the final period, mountain-hill areas had the strongest coefficient (0.404); the medians for valley plains and high-mountain plateaus were 0.148 and 0.108.

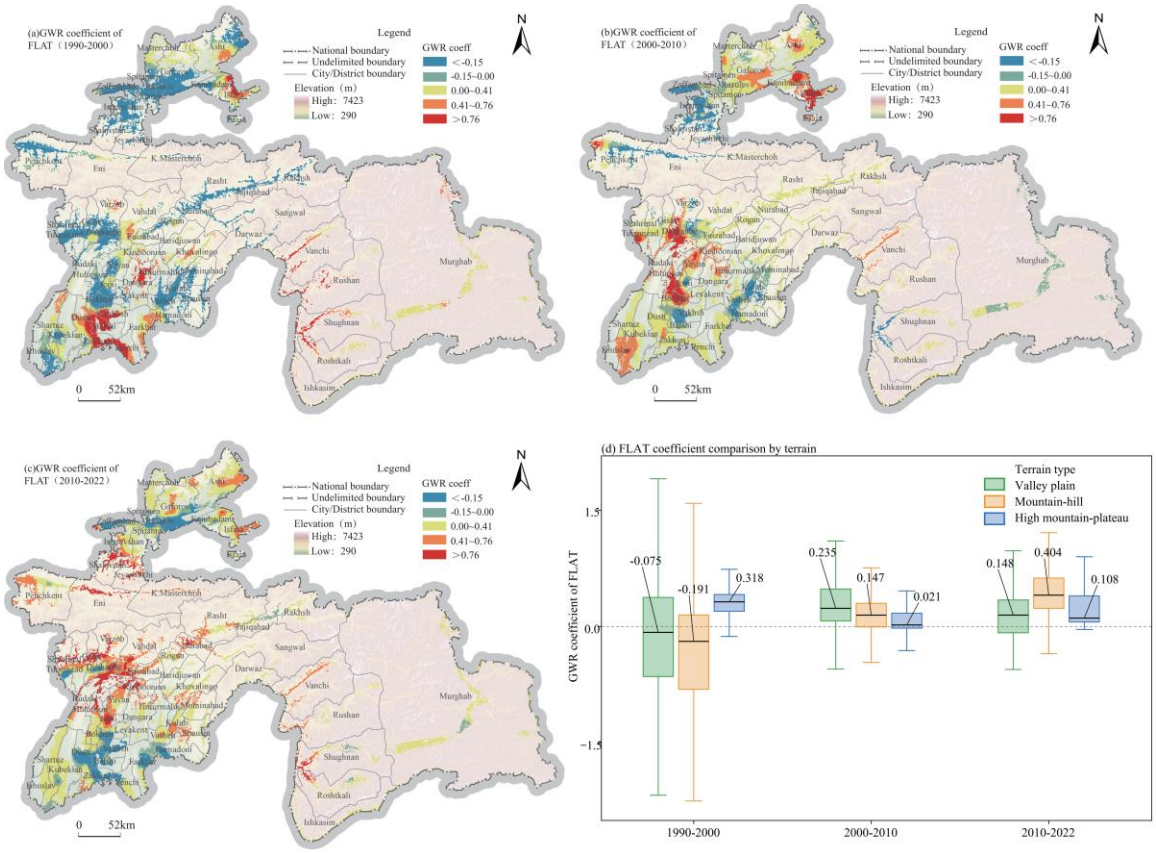


Figure 10. Spatiotemporal and terrain differentiation of FLAT effects

Note:(a–c) Spatial distributions of local GWR coefficients for FLAT during 1990–2000, 2000–2010, and 2010–2022, respectively. (d) Boxplots of local coefficients across the three terrain units during the three periods.

(6) Distance to major rivers

During the early period, distance from major rivers had its strongest negative association in the Vakhsh River Valley, Gissar Basin, and Fergana Basin (Figures 11a–c), indicating more frequent expansion near rivers. The relationship was weak in mountain and plateau areas. Strong negative coefficients became much less extensive in the middle and final periods and remained only in scattered local valleys. Figure 11(d) gives an early median of

-0.140 for valley plains and -0.054 for mountain-hill areas; high-mountain plateaus showed a weak positive value. Negative effects were small in all three zones by the final period, with their strength ordered as valley plains > high-mountain plateaus > mountain-hill areas.

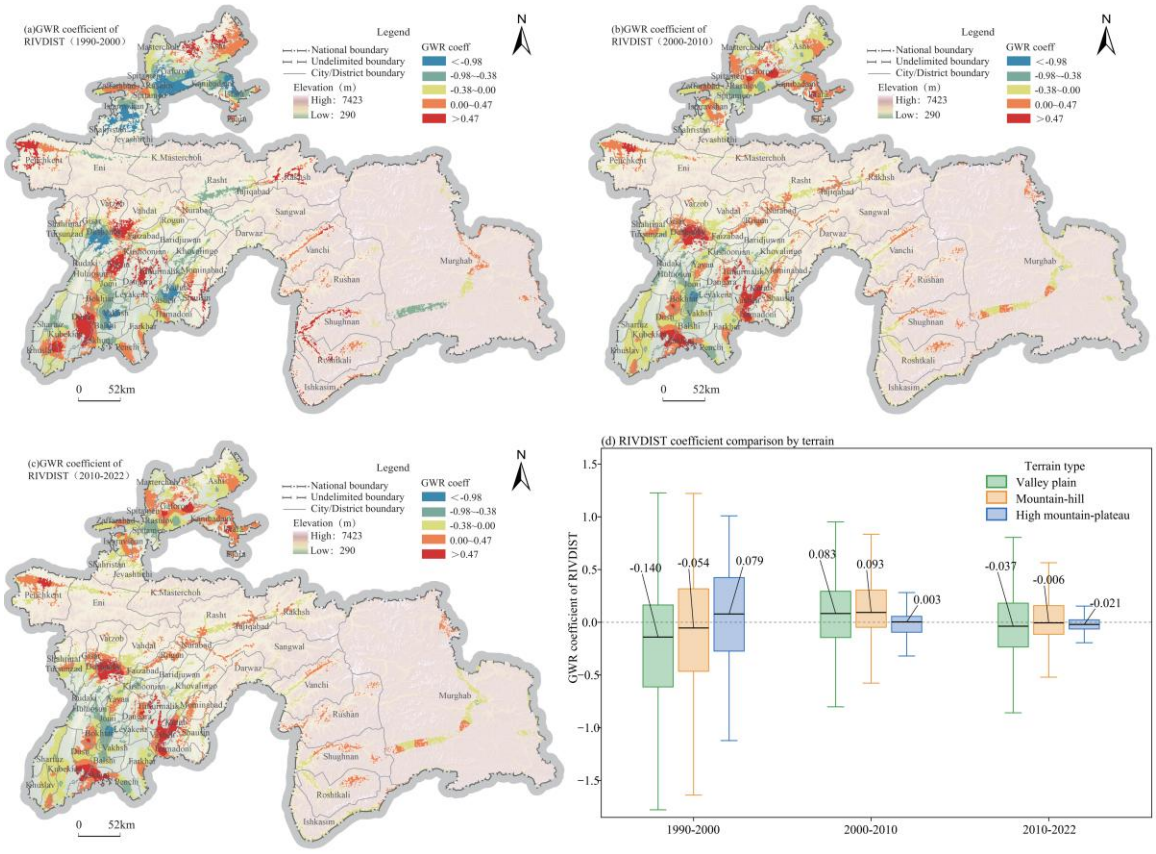


Figure 11. Spatiotemporal and terrain differentiation of RIVDIST effects

Note:(a–c) Spatial distributions of local GWR coefficients for RIVDIST during 1990–2000, 2000–2010, and 2010–2022, respectively. (d) Boxplots of local coefficients across the three terrain units during the three periods.

5. Discussion

5.1. Effects of Social Disturbance on Mountain Settlement Evolution

Research on mountain settlements has usually examined change under relatively stable social and environmental conditions. As urbanisation progresses steadily, land-use policy is supportive, and infrastructure is enhanced, continued expansion, increasingly regular patch forms, and rising spatial aggregation are described by Zhang et al. (2023) and Ji et al. (2022). Trajectories they report are generally straight. Tajikistan went in another

direction. Growth in settlement area fluctuated considerably, while spatial aggregation followed a U-shaped trajectory. This was most pronounced in the first period of socio-economic transition, the period between 1990 and 2000, when institutional change and civil war were associated with fast growth in settlement area and a sharp drop in aggregation.

There are at least two processes which can explain this instability. One relates to the reorganisation of production following the land-system reform. After the breakup of the Soviet Union, Tajikistan transitioned from a command economy to a market economy and gradually dismantled the system of agriculture based on large state and collective farms. Collective farms were transformed into leasehold, shareholding, dehkan and family farms, which meant that production was moved away from centralised organisations towards household and small-scale production (Hierman & Nekbakhtshoev, 2018; Lerman & Sedik, 2008). The household production was hence more closely linked to the individual operational plots. Rural housing would then be able to expand from previous collective-farm housing centers to the actual field being cultivated. The second one is population re-distribution during civil conflict. In 1992 the UNHCR listed approximately 600,000 internally displaced persons in Tajikistan due to the civil war. Substantial population movements occurred among the southern plains, the area surrounding Dushanbe, and the eastern mountainous regions, with some residents seeking refuge in remote areas, including the Gorno-Badakhshan Autonomous Oblast. With the improvement in the situation, part of the displaced population returned (Deng, 1996). These large inflows and outflows altered regional populations and their housing requirements and likely led to the restructuring of settlement construction over the past decade.

The Tajik case study shows that institutional change and social change can redirect settlement evolution as well as the more traditional urbanisation and infrastructure. Mountain systems may be particularly vulnerable to such shocks as they have limited space for people to live, are hard to reach and have limited livelihoods, all of which impact their ability to absorb disruption (Bertram & Chilla, 2023).

5.2. Differences in Settlement Expansion Patterns Across Terrain Types

Terrain is widely recognised as a major source of variation in settlement size, density, and distribution. As topographic complexity increases, settlements generally become smaller,

less dense, and more dispersed, while their morphology changes in systematic ways (Ji et al., 2022; Kong et al., 2026; Shi et al., 2022). Most of this evidence concerns static patterns and regional contrasts. It says less about the spatial form that expansion takes as settlements develop over time.

The long-term record for Tajikistan shows that a common socio-economic transition did not produce a common topographic response. Terrain units differed not only in the rate of area growth but also in the direction of change in aggregation. Valley plains became steadily more aggregated, whereas aggregation declined in mountain-hill and high-mountain plateau areas. Expansion changed accordingly, from continuous areal growth in the plains to linear, belt-like growth in the hills and isolated point growth on the plateaus.

These divergent patterns reflect differences in the continuity of buildable land. Flat land in valley plains is extensive and connected, and the same areas concentrate population, industry, and transport. New development can fill gaps within existing settlements, extend their edges, or join neighbouring small settlements, thereby raising aggregation. In mountain-hill and high-mountain plateau zones, terrain divides suitable land into small, isolated parcels. Tajikistan's population is still predominantly rural and urbanisation remains slow, so valley towns have limited capacity to attract and accommodate most of the additional population. Much of the additional population remains in rural areas, where housing demand is met around existing villages and on scattered level plots. It is therefore hard to achieve contiguous agglomeration. Trunk roads focus activity in the valleys and the more diffuse mountain network fails to challenge the disjointed form of the settlements which reinforces the difference.

5.3. Changing Influences During Socio-economic Transition

As technological and economic development progresses, the physical limitation on the distribution of settlements is generally anticipated to decrease and the economic activity and transportation will grow in importance (Ji et al., 2022; Xie et al., 2026). Our findings indicate a more complex transition process.

Physical constraints were not eliminated but rather their shape altered and the alteration varied for each terrain unit. On the national level, this negative elevation coefficient also declined over time, partly due to the improvement in transport accessibility. Tajikistan has

developed an improved trunk-road network, including tunnels, bridges and mountain roads for access to hard-to-reach areas. The increased access to piedmont areas, high elevation valleys and basin margins resulted in construction outside the traditional low elevation focus. However, when the elevation effect weakened, the positive relationship with flat, low gradient land strengthened, particularly in the mountain-hill areas in the last period. There were no continuous buildable lands, although engineering could alleviate isolation. This basic limitation of the slope and the surface fragmentation was not affected, and local flatness was an increasingly obvious prerequisite for development.

Nor was there an overall increase in the role of socio-economic factors. Overall, their coefficients fell, which would indicate Tajikistan's specific type of growth. The World Bank's assessments are for a growth rate of approximately 7% per year between 2013 and 2023, and an employment elasticity of 0.2. Much of the growth was in capital-intensive, state dominated sectors where there is limited potential for local employment. Remittances, meanwhile, have long exceeded 30% of GDP and constitute the main source of household income. Economic returns are therefore partly detached from local industrial investment and the expansion of construction land. A similar disconnection appears in the demographic relationship. Tajikistan's population has grown rapidly, but a large proportion of the labour force works abroad; demand for domestic residential and production space need not rise at the same rate as the total population. The positive relationship between economic growth and settlement expansion is therefore contingent rather than universal. Industrial composition and the model of growth affect how strongly it is expressed, and externally dependent economies with limited employment absorption convert socio-economic growth into buildable space less efficiently.

Terrain-specific estimates also reveal opposing local relationships that a national model can conceal. Elevation had a much stronger negative coefficient in mountain-hill and high-mountain plateau areas than in valley plains. The positive coefficient for economic growth declined in the plains but rose gradually in the two mountain zones. The influence of flat terrain likewise shifted among terrain types as the transition unfolded. When all observations are pooled, effects that differ in direction or magnitude can offset one another. National averages therefore provide an incomplete account of how individual factors shape settlement evolution.

5.4. Limitations and Future Research

The long time series used here reveals how mountain settlements evolved across terrain units during socio-economic transition, but the analysis has three limitations. First, a regular grid provides a common scale for integrating multiple datasets, representing space continuously, and comparing periods. It is less capable of describing individual settlement boundaries, hierarchical relations, or fine local variation. Village-level analysis can identify differences in expansion and human–land relationships more precisely under complex topographic conditions (Kong et al., 2026). Future work could therefore combine the present grid framework with village or settlement-unit data and link spatial patterns to actors operating at the local level. Second, the study measures settlement area, morphology, and spatial organisation. Divergent topographic trajectories may also correspond to differences in residential, productive, and ecological-protection functions. A functional analysis could examine how these uses change with the external spatial pattern and whether morphological and functional transformations remain coupled across terrain settings. Third, OLS and GWR identify period-specific associations and spatial heterogeneity, but they do not establish causality. Panel models or other causal-identification strategies, supported by longer time series on socio-economic conditions, migration, and infrastructure, could test the pathways linking disturbance, terrain, and settlement change.

6. Conclusions

Using settlement data for 1990–2022, this study examined Tajikistan's socio-economic transition at three levels: national settlement change, differences among terrain units, and shifts in the factors associated with expansion. Three conclusions follow.

Firstly, mountain settlements grew in area, became more regular in patch shape and were less aggregated overall. The trajectory included an initial period of widespread, decentralised growth, a second period of continuous growth with re-concentration, and a final period of decline in rates of growth and a spatial pattern that became more settled.

Second, the expansion was contiguous (in valley plains), bead-like (in mountain-hill areas), and scattered patch (on high mountain plateaus). The three zones showed a systematic decrease in settlement area, patch-shape complexity and aggregation. In each zone area

increased and morphology regularised, whilst aggregation rose steadily in the plains, fell slowly in the mountain-hill zone and was consistently low on the plateaus.

Third, human influences, primarily through population growth, economic development and conflict disturbance, were the primary influences in the early period, a time at which there was also a strong physical constraint due to elevation. The negative effect of the elevation decreased with increasing transition, and the positive effect of flat terrain increased with increasing transition. After the last period, the most important ones were road accessibility and flat land; population lost its importance and the economic and conflict coefficients were no longer significant. The spatial transition was also significant. The focus of the population/economy-led expansion of valley plains was replaced by a higher association with transport improvement. The effect of elevation and population diminished in mountain-hill regions, while the effects of flat topography and road network increased. High mountain plateau settlements were initially linked with locally flat land and were relatively limited in terms of elevation; later, flatness of land and transport conditions were most clearly related to expansion.

Data availability

All datasets supporting the findings of this study are publicly accessible. Detailed descriptions of data sources, time ranges and applications are provided in Table 3 of the manuscript. The data and supporting materials underlying the findings of this study are available from the corresponding author upon reasonable request, subject to applicable third-party data licences and access conditions.

References

Addi YW, Li M, Chen X, Yao L, Zhu L, Liu Y, Liao H (2025) Reconstruction of indigenous settlements in ecologically fragile areas through spatial distribution patterns and suitability in Xiaoliangshan, SW China. Sci Rep 15:37321. https://doi.org/10.1038/s41598-025-21166-4

Adityo A, Shibata Y (2026) The impact of the Javanese rural kinship settlement cluster development on spatial characteristic of traditional garden houses and resident activities. J Asian Archit Build Eng 25(3):2544–2566. https://doi.org/10.1080/13467581.2025.2494083

694 Alamá-Sabater L, Márquez MÁ, Tortosa-Ausina E (2025) Spatio-sectoral heterogeneity and
695 population–employment dynamics: Some implications for territorial development. Reg Stud
696 59(1):2088725. https://doi.org/10.1080/00343404.2022.2088725

697 Asimakopoulos A, Mogios E, Xenikos DG (2016) Geographic location, network patterns and
698 population distribution of rural settlements in Greece. Int J Mod Phys B 30(15):1541009.
699 https://doi.org/10.1142/S021797921541009X

700 Bertram D, Chilla T (2023) Polycentricity and accessibility in mountain areas: The Alpine case.
701 Eur Plan Stud 31(12):2425–2445. https://doi.org/10.1080/09654313.2022.2145874

702 Bertram D, Lambracht M, Chilla T (2024) Settlement systems in mountain regions: A research
703 gap? Mt Res Dev 44(2):A1–A9. https://doi.org/10.1659/mrd.2023.00021

704 Chen S, Wang X, Qiang Y, Lin Q (2024) Spatial–temporal evolution and land use transition of
705 rural settlements in mountainous counties. Environ Sci Eur 36:38.
706 https://doi.org/10.1186/s12302-024-00868-y

707 Deng FM (1996) Report on internally displaced persons: Profiles in displacement—Tajikistan
708 (A/51/483/Add.1). United Nations General Assembly.

709 Ehrlich D, Melchiorri M, Capitani C (2021) Population trends and urbanisation in mountain ranges
710 of the world. Land 10(3):255. https://doi.org/10.3390/land10030255

711 Forman RTT, Godron M (1986) Landscape ecology. Wiley, New York

712 Frachetti MD, Maksudov F (2014) The landscape of ancient mobile pastoralism in the highlands
713 of southeastern Uzbekistan, 2000 BC–AD 1400. J Field Archaeol 39(3):195–212.
714 https://doi.org/10.1179/0093469014Z.00000000085

715 Ghambaryan GG, Potosyan AH, Mkhitaryan VG, Potosyan VA, Ayriyants AA (2024) Settlement
716 pattern features in mountainous countries (on the example of the Republic of Armenia). Popul
717 Econ 8(3):130–155. https://doi.org/10.3897/popecon.8.e118381

718 Hierman B, Nekbakhtshoev N (2018) Land reform by default: Uncovering patterns of agricultural
719 decollectivization in Tajikistan. J Peasant Stud 45(2):409–430.
720 https://doi.org/10.1080/03066150.2016.1249366

721 Hofman I, Visser O (2021) Towards a geography of window dressing and benign neglect: The state,
722 donors and elites in Tajikistan's trajectories of post-Soviet agrarian change. Land Use Policy
723 111:105461. https://doi.org/10.1016/j.landusepol.2021.105461

Holl A (2025) Highways and local development: Insights from two decades of investments. Reg Stud 59(1):2461297. https://doi.org/10.1080/00343404.2025.2461297

Ji Z, Xu Y, Sun M, Liu C, Lu L, Huang A, Duan Y, Liu L (2022) Spatiotemporal characteristics and dynamic mechanism of rural settlements based on typical transects: A case study of Zhangjiakou City, China. Habitat Int 123:102545. https://doi.org/10.1016/j.habitatint.2022.102545

Jiang Y, Long H, Tang Y, Deng W (2024) Deciphering how promoting land consolidation for village revitalisation in rural China: A comparison study. J Rural Stud 110:103349. https://doi.org/10.1016/j.jrurstud.2024.103349

Kapos V, Rhind J, Edwards M, Price MF, Ravilious C (2000) Developing a map of the world's mountain forests. In: Price MF, Butt N (eds) Forests in sustainable mountain development: A state of knowledge report for 2000. CABI Publishing, Wallingford, pp 4–19. https://doi.org/10.1079/9780851994468.0004

Karácsonyi D, Taylor A (2024) Long-term hierarchic changes in settlement systems at geographic 'edges'. Aust Geogr 55(3):345–365. https://doi.org/10.1080/00049182.2024.2377853

Kong X, Lu S, Hu B (2026) Understanding the village-scale expansion of rural settlements in China from a topographic perspective. Environ Impact Assess Rev 119:108344. https://doi.org/10.1016/j.eiar.2026.108344

Lerman Z, Sedik DJ (2008) The economic effects of land reform in Central Asia: The case of Tajikistan (Discussion Paper No. 16.08). Center for Agricultural Economic Research, The Hebrew University of Jerusalem. https://doi.org/10.22004/ag.econ.46249

Li H, Song W (2020) Pattern of spatial evolution of rural settlements in the Jizhou District of China during 1962–2030. Appl Geogr 122:102247. https://doi.org/10.1016/j.apgeog.2020.102247

Liu L, Wu Y, Shi K (2025) Urban ascent with sustainable human development: Extensive cultivated land conservation and urban population capacity growth supported by hillside urban expansion. Appl Geogr 185:103775. https://doi.org/10.1016/j.apgeog.2025.103775

Ma L, Li J, Wang X, Zhang W, Tao T, Zhong Y (2024) Evolution and simulation optimization of rural settlements in urban-rural integration areas from a multi-gradient perspective: A case study of the Lan-Bai urban agglomeration in China. Habitat Int 153:103203. https://doi.org/10.1016/j.habitatint.2024.103203

Ma L, Zhao S, Wang X, Cao C, Zhu Q (2026) Unveiling the dynamics: Tracing rural settlements evolution in urban-rural transition zones. Cities 171:106772. https://doi.org/10.1016/j.cities.2026.106772

Meybeck M, Green P, Vörösmarty C (2001) A new typology for mountains and other relief classes. Mt Res Dev 21(1):34–45. https://doi.org/10.1659/0276-4741(2001)021[0034:ANTFMA]2.0.CO;2

Niyogakiza A, Liu Q (2026) Integrating landscape gene mapping and environmental adaptation for sustainable rural settlements in Rwanda's western highlands. Sustain Dev 34(2):2000–2021. https://doi.org/10.1002/sd.70432

Rao Y, Wu C, He Q (2025) Uneven diffusion: A multi-scale analysis of rural settlement evolution and its driving forces in China from 2000–2020. Humanit Soc Sci Commun 12:319. https://doi.org/10.1057/s41599-025-04660-y

Ren X, Li Y, Luo G, Huang J, Zhang Y, Xu Q, Yang L (2025) The rural human-land relationship transition in southwest karst mountainous areas based on rural population, agricultural production land, and rural settlement coupling. Habitat Int 163:103493. https://doi.org/10.1016/j.habitatint.2025.103493

Sadozaï M, Blondin S (2023) More remote yet more connected? Physical accessibility and new international contacts in Tajikistan’s Pamirs since 1991. Probl Post-Communism 70(3):290–304. https://doi.org/10.1080/10758216.2022.2149557

Shi Z, Ma L, Zhang W, Gong M (2022) Differentiation and correlation of spatial pattern and multifunction in rural settlements considering topographic gradients: Evidence from Loess Hilly Region, China. J Environ Manage 315:115127. https://doi.org/10.1016/j.jenvman.2022.115127

Śleszyński P, Kijowska-Strugała M, Bucała-Hrabia A, Rączkowska Z, Kursa M, Malinowski Z (2025) The relations between settlement and selected environmental features with regard to landslide hazard in the Polish Carpathians. Catena 253:108897. https://doi.org/10.1016/j.catena.2025.108897

Smith ME, Lobo J, Peeples MA, York AM, Stanley BW, Crawford KA, Gauthier N, Huster AC (2021) The persistence of ancient settlements and urban sustainability. Proc Natl Acad Sci USA 118(20):e2018155118. https://doi.org/10.1073/pnas.2018155118

Szymanowski M, Latocha A (2021) Does the environment matter? Depopulation in the Sudetes (case study of the Kłodzko region, SW Poland). Appl Geogr 135:102535. https://doi.org/10.1016/j.apgeog.2021.102535

Thinh NK, Kamalipour H, Peimani N (2024) Morphogenesis of forgotten places: A typology of villages-in-the-city in the Global South. Habitat Int 153:103184. https://doi.org/10.1016/j.habitatint.2024.103184

Wang C, Zhou T, Ren M (2023) Driving spatial network connections in rural settlements: The role of e-commerce. Appl Geogr 159:103067. https://doi.org/10.1016/j.apgeog.2023.103067

Wang Y, Deng Q, Yang H, Liu H, Yang F, Zhao Y (2024) Spatial-temporal differentiation and influencing factors of rural settlements in mountainous areas: An example of Liangshan Yi Autonomous Prefecture, Southwestern China. J Mt Sci 21(1):218–235. https://doi.org/10.1007/s11629-023-8191-6

Xie Y, Yang L, Ma L, Zhang Y, Ren X, Li Y, Zhou L, Wu X (2026) Diversity evolution pattern of rural settlements and its driving mechanism transition: A case study in Southwest China's karst mountains. J Rural Stud 123:104052. https://doi.org/10.1016/j.jrurstud.2026.104052

Yang L, Liu D, Li Y (2026) Coupled dynamics of rural settlements and sloping cropland: Ecological risks and socio-ecological responses in a karst mountainous area. Habitat Int 171:103784. https://doi.org/10.1016/j.habitatint.2026.103784

Zhang H, Chen W, Liu W, Liu Z, Liu H (2023) The evolution of settlement system and the paths of rural revitalization in alpine pastoral areas of the Qinghai-Tibet Plateau: A case study of Nagqu County. Ecol Indic 150:110274. https://doi.org/10.1016/j.ecolind.2023.110274

Zhao X, Li J (2025) Research on the development of rural human settlement environment in the upper reaches of the Lancang River based on ecological carrying capacity constraints. Glob Chall 9(3):2400248. https://doi.org/10.1002/gch2.202400248

Zhou J, Liu Y, Wang W, Cai M, Hou Q (2026) Resilience assessment and optimization of mountainous county settlements based on society-space network: A case study of the Qinba Mountain area. Humanit Soc Sci Commun 13:188. https://doi.org/10.1057/s41599-025-06487-z

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The authors declare no competing interests.

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Informed consent

Informed consent is not required, as the study did not involve human participants.

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