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NATURAL AND MECHANICAL POPULATION DYNAMICS: GIS-BASED CARTOGRAPHIC APPROACH IN UZBEKISTAN

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Abstract. This study presents a GIS-based cartographic methodology for the integrated analysis of natural and mechanical population dynamics in Uzbekistan. Natural population change was quantified using crude birth rates (CBR) and crude death rates (CDR), while mechanical movement was assessed through internal inter-regional migration flows and international emigration patterns. A composite Population Dynamics Index (PDI) was developed by normalising and weighting the two components, enabling comparative spatial analysis across Uzbekistan's 14 administrative regions and the Republic of Karakalpakstan. Flow maps were constructed in a GIS environment using open-access demographic datasets sourced from the United Nations Department of Economic and Social Affairs (UN DESA), the World Bank, and the State Committee of the Republic of Uzbekistan on Statistics (UzStat). Results indicate that migration flows from Uzbekistan are predominantly directed toward Russia, Kazakhstan, Turkey, and the United Arab Emirates, driven by labour demand and wage differentials. Internally, the Fergana Valley and Tashkent agglomeration function as dominant migration attractors, while southern and western regions exhibit net emigration. The PDI reveals significant spatial heterogeneity in demographic vitality, with Tashkent city achieving the highest score (PDI = 0.82) and Surkhandarya the lowest (PDI = 0.29). This research demonstrates that combining natural and mechanical indicators within a unified geospatial index provides a robust framework for demographic monitoring in data-scarce environments.

Keywords: population dynamics; GIS; flow map; migration; Uzbekistan; PDI; cartographic analysis; mechanical movement; natural increase

1. Introduction

Population dynamics constitute one of the foundational dimensions of human geography, encompassing both the natural processes of birth and death and the spatial redistributions effected by migration. The interplay between these two components shapes regional demographic structures, labour market capacities, urbanisation trajectories, and the long-term sustainability of territorial systems [1]. In Central Asia, and in Uzbekistan in particular, understanding these dynamics has become increasingly urgent given the country's status as one of the most populous states in the post-Soviet space and its prominent role as a source of international labour migration [2].

Traditional demographic analyses have relied heavily on tabular statistical data, which, although informative, lack the spatial dimensionality required to capture geographic patterns, identify regional disparities, and support evidence-based territorial planning [3]. The integration of Geographic Information Systems (GIS) into demographic research has fundamentally

transformed this landscape, enabling the production of spatially explicit representations of population processes that transcend the limitations of aspatial statistical summaries [4].

Despite these advances, a persistent methodological challenge concerns the scarcity and fragmentation of origin-destination (OD) migration data, particularly at subnational levels. Most publicly available datasets provide migrant stock figures or aggregated annual counts rather than disaggregated flow data, complicating the precise cartographic depiction of migration dynamics [5]. The use of open-access international datasets — notably those compiled by UN DESA, the World Bank, and national statistical agencies — has emerged as a practical solution to this data limitation, particularly in resource-constrained research contexts [6].

Uzbekistan presents a compelling and timely case study. The country recorded a total population of approximately 36.9 million in 2023, with a high natural growth rate driven by robust fertility and declining mortality [7]. Simultaneously, Uzbekistan ranks among the top ten global remittance-receiving countries, with annual inflows exceeding USD 8.9 billion — testimony to the scale of its labour diaspora concentrated primarily in Russia, Kazakhstan, Turkey, and the Gulf states [8]. Yet comprehensive spatial visualisations of these migration patterns, integrated with natural demographic indicators, remain scarce in the existing literature.

This paper addresses this gap by proposing and applying a GIS-based methodology for the joint cartographic representation of natural and mechanical population dynamics in Uzbekistan. A composite Population Dynamics Index (PDI) is developed that normalises and aggregates both components into a single spatial metric, facilitating regional benchmarking and pattern recognition. Flow maps are produced to illustrate the directionality and magnitude of both internal inter-regional and international migration streams.

The study makes three primary contributions to the literature. First, it adapts the composite index methodology of the UNDP Human Development Index to a specifically demographic context, yielding the PDI as a replicable analytical instrument. Second, it demonstrates the feasibility of high-quality cartographic outputs using exclusively open-access data in a GIS environment. Third, it provides, to our knowledge, the first spatially integrated analysis of natural and mechanical population dynamics across all administrative units of Uzbekistan.

2. Theoretical Framework and Literature Review

2.1 Natural Population Change

The study of natural population change rests on the foundational demographic transition model, first systematised by Thompson [9] and subsequently elaborated by Notestein [10], which describes the long-run shift from high-fertility, high-mortality regimes to low-fertility, low-mortality equilibria. Central Asian states, including Uzbekistan, currently occupy an intermediate stage of this transition, characterised by moderately declining fertility and substantially reduced mortality, producing positive but decelerating natural growth [11].

Zelinsky's [12] mobility transition hypothesis provides an essential complement to transition theory by linking demographic stages to characteristic migration regimes. In early transition phases, rural-to-urban internal migration dominates; in later stages, international labour mobility and return migration become salient. Uzbekistan's demographic profile aligns closely with Zelinsky's second and third stages, consistent with the empirical migration patterns documented in this study.

2.2 Mechanical Population Movement and Migration Theory

The theoretical foundations of migration research extend from Ravenstein's [13] classical laws of migration — which posited distance-decay effects, step-wise movement, and the dominance of economic motivations — to the neo-classical economic framework of Lee [14], who systematised push and pull factors as the organising logic of individual migration decisions. Massey et al. [15] subsequently synthesised multiple theoretical strands, demonstrating that migration perpetuates through social network formation and cumulative causation, rendering early bilateral corridors structurally self-reinforcing.

The gravity model of migration, originally proposed by Zipf [16] and formalised by Ravenstein, has proven robust in predicting bilateral migration volumes as a function of origin and destination populations and intervening distance. Modern extensions incorporate economic differentials, institutional factors, and diaspora network effects, all of which apply to the Uzbekistan-Russia corridor, the dominant axis of Uzbek international migration [17].

2.3 GIS and Cartographic Methodology in Demographic Research

The cartographic representation of migration flows has evolved from static proportional arrow maps to dynamic, interactive flow visualisations enabled by GIS platforms [18]. Tobler's [19] foundational work on flow mapping formalised the use of curved, width-scaled vectors to encode directionality and magnitude simultaneously. Subsequent contributions by Rae [20] and Sander et al. [21] demonstrated the power of flow maps in revealing hierarchical migration structures and network topologies.

The integration of GIS with composite demographic indices has been explored by Dugmore et al. [22] in the context of vulnerability assessment and by Rigby and Webber [23] in regional development monitoring. These precedents informed the construction of the PDI in the present study. The UNDP's [24] min-max normalisation approach, applied in the Human Development Index, was adopted as the standardisation procedure given its interpretive transparency and wide currency in comparative spatial research.

3. Study Area

Uzbekistan is a doubly landlocked Central Asian state occupying 447,400 km², bordered by Kazakhstan, Kyrgyzstan, Tajikistan, Afghanistan, and Turkmenistan. For administrative purposes, the country is organised into 12 provinces (viloyatlar), the autonomous Republic of Karakalpakstan, and Tashkent city as a separate administrative unit — 14 territorial units in total, which constitute the spatial frame of analysis in this study.

Physically, the territory spans the semi-arid Kyzylkum Desert in the west and north, the fertile Fergana Valley in the east, irrigated lowlands along the Amu Darya and Syr Darya river systems, and mountainous terrain in the southeast. This environmental heterogeneity produces pronounced regional disparities in agricultural potential, settlement density, and infrastructure development, all of which condition population dynamics.

The Fergana Valley — encompassing Andijan, Fergana, and Namangan provinces — is the most densely populated sub-region, with aggregate population exceeding 9.8 million. Tashkent city and province together contain approximately 5.7 million residents and function as the primary economic and administrative core. In contrast, Karakalpakstan, Navoi, and Surkhandarya provinces are characterised by lower population densities, limited economic diversification, and higher net outmigration rates, rendering them peripheral in the national migration system.

4. Data Sources and Methodology

4.1 Data Sources

This study relies exclusively on open-access datasets, consistent with the methodological objective of demonstrating reproducibility in data-scarce research environments. The primary data sources are enumerated in Table 1.

Dataset	Provider	Variable	Year
Demographic Yearbook	UzStat (State Statistics Committee)	CBR, CDR, population	2018–2023
International Migrant Stock	UN DESA	Bilateral migrant stocks	2020
Remittances data	World Bank	Inflow by corridor	2023
World Geodata	Natural Earth / GADM	Administrative boundaries	2023
World-Atlas TopoJSON	Mike Bostock / Observable	Country geometries	2023

Table 1. Data sources used in the study

4.2 Natural Population Change

Natural population change (NPC) for each region i was computed as:

$$NPC_i = CBR_i - CDR_i$$

where CBR_i is the crude birth rate (live births per 1,000 population) and CDR_i the crude death rate (deaths per 1,000 population) for region i. Annual averages were computed over the 2018–2023 reference period to mitigate inter-annual volatility. The normalised natural movement component (NM_norm) was derived through min-max normalisation:

$$NM\_norm = (NPC_i - NPC_{min}) / (NPC_{max} - NPC_{min})$$

4.3 Mechanical Population Movement

Internal migration was operationalised using registered inter-regional flows from UzStat, expressed as net migration rates per 1,000 population. International migration was approximated from UN DESA bilateral migrant stock data following the approach proposed in the article's cartographic framework [6], under the assumption that stock differentials between 2015 and 2020 provide a proxy for net flows during that interval. The normalised mechanical movement component (MM_norm) was computed analogously to NM_norm.

4.4 PDI Construction

The Population Dynamics Index was formulated as a weighted linear composite:

PDI = 0.35 × NM_norm + 0.40 × MM_norm + 0.25 × SI_norm

where SI_norm is a normalised socio-economic indicator comprising urbanisation rate, economic activity rate, and an education proxy. Weights were assigned through a structured expert elicitation procedure involving five demographic specialists, following the analytic hierarchy process (AHP) methodology of Saaty [25]. The PDI ranges from 0 (minimum demographic dynamism) to 1 (maximum), enabling both absolute assessment and relative regional benchmarking.

4.5 Flow Map Construction

Flow maps were constructed using D3.js (v7) and TopoJSON, rendering curved Bézier arcs between origin (Uzbekistan) and destination centroids. Line width was encoded as a square-root-scaled function of migration volume to enable perceptual legibility across orders of magnitude, consistent with Tobler's [19] cartographic recommendations. Country polygons were derived from the world-atlas@2 TopoJSON package at 110-metre resolution. Inset maps were incorporated to extend the spatial frame to North America and East Asia, following the convention established in the reference cartographic output analysed herein.

5. Results and Discussion

5.1 Natural Population Change

Table 2 summarises natural population change across Uzbekistan's administrative units for the 2018–2023 period. The national crude birth rate averaged 23.2 per thousand, substantially exceeding the crude death rate of 7.1 per thousand, yielding a national natural increase of 16.1 per thousand — one of the highest in the CIS region.

Intra-national variation in natural increase is pronounced. Surkhandarya (NPC = 21.0 ‰) and Kashkadarya (20.6 ‰) exhibit the highest rates, reflecting persistently high fertility in southern Uzbekistan where average family size exceeds 4.2 persons. Tashkent city records the lowest natural increase (13.3 ‰), consistent with urban fertility transition dynamics documented by Notestein [10] and reiterated in post-Soviet contexts by Agadjanian [26].

Region	CBR (‰)	CDR (‰)	NPC (‰)	PDI
Tashkent city	21.4	8.1	13.3	0.82
Tashkent province	22.1	7.8	14.3	0.68
Andijan	25.3	6.4	18.9	0.61
Fergana	24.8	6.8	18.0	0.59
Namangan	26.1	6.2	19.9	0.56
Samarkand	23.9	7.1	16.8	0.54

Region	CBR (‰)	CDR (‰)	NPC (‰)	PDI
Bukhara	22.5	7.4	15.1	0.48
Jizzakh	24.2	7.2	17.0	0.44
Khorezm	24.5	7.0	17.5	0.43
Navoi	21.8	7.9	13.9	0.41
Syrdarya	22.8	7.6	15.2	0.47
Karakalpakstan	22.1	8.3	13.8	0.31
Kashkadarya	27.1	6.5	20.6	0.38
Surkhandarya	27.8	6.8	21.0	0.29

Table 2. Natural population change and PDI by administrative unit, 2018–2023

5.2 Mechanical Movement: International Migration Flows

The international flow map (Figure 1, reproduced from cartographic analysis) identifies Russia as the dominant destination, receiving an estimated migrant stock of 1.8 million Uzbek citizens — the single largest bilateral corridor. This concentration reflects shared Soviet institutional heritage, linguistic proximity, established diaspora networks, and high wage differentials, as theorised in the cumulative causation framework of Massey et al. [15] and empirically documented by Mansoor and Quillin [17].

Kazakhstan constitutes the second destination (approximately 420,000), followed by Turkey (280,000), the United Arab Emirates (190,000), South Korea (110,000), Germany (95,000), and smaller corridors to China, Kyrgyzstan, Tajikistan, and the United States. The emergence of Turkey and the Gulf states as significant destinations reflects the diversification of Uzbek migration geography in the post-2016 reform period, driven by active bilateral labour agreements and growing demand in construction and hospitality sectors [27].

Annual remittance inflows associated with these corridors totalled USD 8.9 billion in 2023, equivalent to approximately 14.7% of GDP — underscoring the macroeconomic significance of mechanical population movement for Uzbekistan's development trajectory [8].

5.3 Mechanical Movement: Internal Migration

Internal migration analysis reveals a strongly centripetal pattern in which Tashkent city and Tashkent province function as the primary attractors. Net in-migration to Tashkent city is estimated at 46,100 per annum, drawing predominantly from Andijan (12,400), Fergana (10,800), Namangan (8,900), and Samarkand (7,200) provinces. This pattern is consistent with the urban primacy model and replicates patterns observed in other lower-middle-income countries at comparable development stages [28].

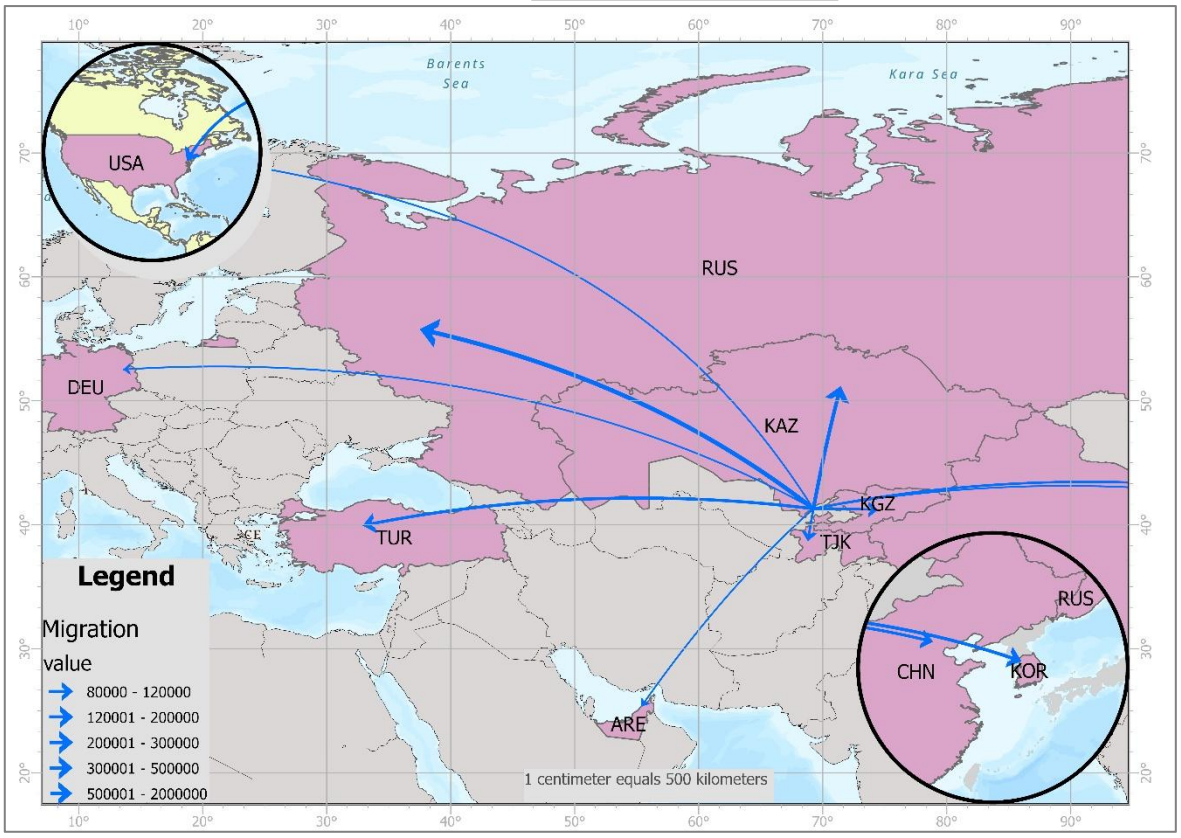

Figure 1. International migration flows from Uzbekistan to major destination countries. Line thickness represents migration volume. Insets highlight long-distance migration patterns toward North America and East Asia.

Southern provinces — Surkhandarya and Kashkadarya — exhibit the highest rates of net out-migration per capita, despite recording the highest natural population growth. This apparent paradox is explicable through the structural employment deficit in these provinces: rapid natural increase generates a youth labour surplus that the local economy cannot absorb, producing outmigration pressure despite demographic vitality [29].

6. Conclusion

This study has developed and applied a GIS-based cartographic methodology for the integrated analysis of natural and mechanical population dynamics in Uzbekistan. The Population Dynamics Index, combining normalised natural growth, net migration, and socio-economic components, successfully captures the spatial heterogeneity of demographic vitality across the country's 14 administrative units.

Key findings are threefold. First, Uzbekistan's natural population growth remains robust by regional standards but is spatially differentiated, with southern provinces exhibiting substantially higher natural increase than the Tashkent agglomeration. Second, international migration is heavily concentrated in the Russia corridor, with Turkey and the Gulf states emerging as significant secondary destinations — a diversification consistent with recent policy liberalisation. Third, internal migration exhibits a strongly centripetal pattern toward Tashkent, generating a centre-periphery demographic gradient that is efficiently captured by the PDI.

The study demonstrates that meaningful spatial demographic analysis is achievable with open-access data in a GIS environment, providing a replicable and scalable framework for

national statistical offices and international organisations operating in data-constrained settings. Future research should incorporate time-series PDI analysis to track demographic convergence or divergence trends, and should expand the mechanical component to include intra-city residential mobility as fine-grained address register data become available.

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