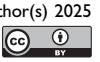
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Revealing urban–rural migration corridors through edge-path bundling of historical census data in Bulgaria

Petrus J. Gerrits[1], Guy Solomon[2], Ana Basiri[1] and M. Erdem Kabadayı[3]

Abstract

This featured graphic visualises internal migration flows in Bulgaria using settlement-level census data from 1934 to 1946, highlighting how topography and local factors shaped migration and urbanisation. By combining spatial interaction models (SIMs) and edge-path bundling techniques, we reveal fine-scale migration corridors and the role of mountainous terrain in influencing mobility. The SIM approach goes beyond aggregate district analysis to provide new insights into rural depopulation and urban growth.

Keywords

internal migration, spatial interaction model, settlement-level analysis, topography, urbanisation, Bulgaria, geospatial visualisation, census, rural depopulation

Main

Internal migration has been a central driver of demographic change in Bulgaria, particularly in the years following 1934, a period marked by political, economic, and social transformation (Mladenov and Ilieva, 2012; Petrov, 2021). Traditional migration analyses in Bulgaria have relied on aggregated district or municipal data, limiting insight into local migration drivers and environmental effects (Mladenov et al., 2008; Peykovska, 2019). In this study, we employ digitised, geocoded settlement-level census data to analyse migration patterns across 5302 settlements for the 1934–1946 intercensal period.

[1]University of Glasgow, Glasgow, UK
[2]The University of Sheffield, Sheffield, UK
[3]Koç University, Istanbul, Turkey

Corresponding author:
Petrus J. Gerrits, University of Glasgow, East Quad, Glasgow G12 8QQ, UK.
Email: p.gerrits.1@research.gla.ac.uk

Data Availability Statement included at the end of the article

The data, sourced from the Bulgarian National Statistical Institute (NSI), comprise population counts for each settlement at the 1934 and 1946 censuses. This fine-grained spatial resolution enables us to model estimates for inter-settlement migration flows, moving beyond prior work focused mainly on higher administrative levels. Migration flows were estimated using a spatial interaction modelling framework, with flows between settlements modelled as a function of population size, accessibility (road network distance), and topography (terrain ruggedness derived from SRTM data) (Dennett, 2018; Ramos, 2016; Wilson, 1971). This allowed us to investigate both demographic and environmental determinants of migration during this formative long-term period in Bulgarian urban–rural development (Kabadayi et al., 2024).

Figure 1 illustrates internal migration flows in Bulgaria. Traditional flow visualisation techniques often generate visually overwhelming results due to line overlap and clutter, obscuring underlying spatial patterns (Vrotsou et al., 2017). To address this, we applied a novel edge-path bundling algorithm (Peterka, 2025; Väisänen et al., 2025a, 2025b; Wallinger et al., 2022) to aggregate parallel flows and reveal coherent migration corridors and regional structures. Urban centres emerge as major attractors, while mountainous regions – covering nearly half the country – display distinctive out-migration and lower connectivity.

Additionally, the background shading in Figure 1 represents a ruggedness index, classified into quantiles, derived from geographic terrain data. This adds environmental context to migration patterns, suggesting an interplay between geography and migration behaviours. Settlements are marked according to their population sizes, further emphasising urbanisation and rural depopulation trends occurring within this period.

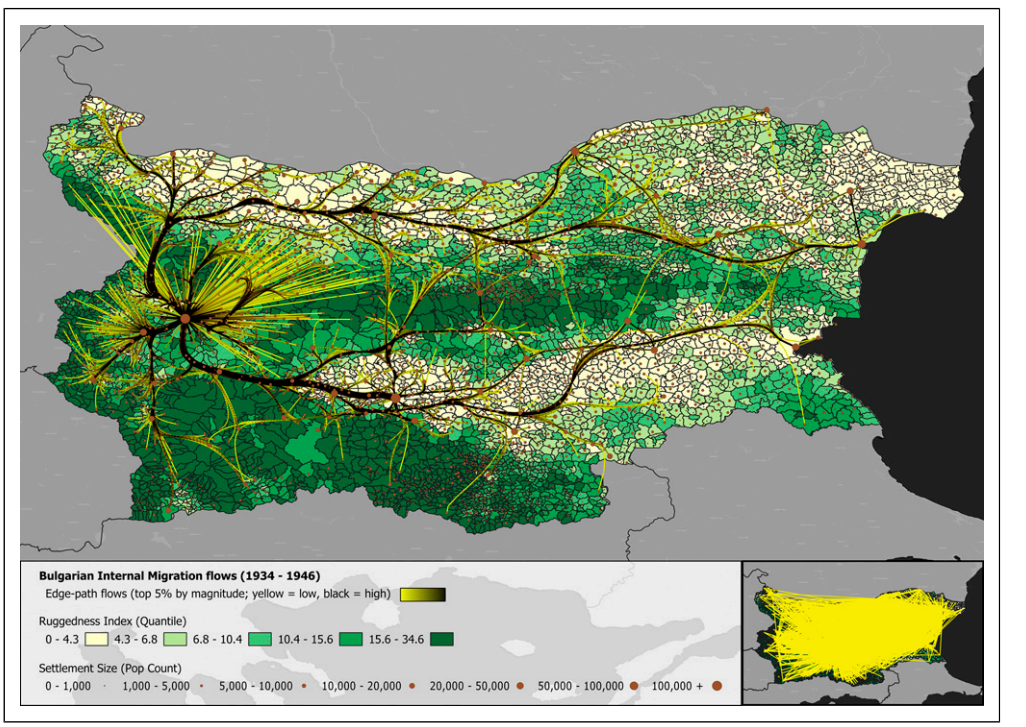


Figure 1. Edge-path bundled (Väisänen et al., 2025a; Wallinger et al., 2022) internal migration flows in Bulgaria (1934–1946) reveal major movement corridors. The line colour and thickness reflect flow magnitude; and settlement marker size shows population count. Only flows above the 95th percentile are shown. The inset on the bottom-rigth corner compares a conventional (unbundled) flow map with the same filters.

In contrast, the inset on the lower right displays the same dataset, without bundling, clearly demonstrating the complexity and visual clutter that traditional methods produce. This direct comparison highlights the efficacy of bundling in clarifying migration routes and allowing researchers to readily interpret spatial relationships and migration trends. The selected colour palette adheres to principles of inclusive design, specifically optimised for colour-blind accessibility, utilising the scientifically validated 'ColorBrewer' scheme (Brewer, 1994; Brewer et al., 2003). In addition, we tested the image using the online image tool of Stevens et al. (Stevens et al., 2024). This ensures that the visual insights presented are accessible to all, making the research more inclusive.

By combining fine-scale census data, spatial interaction modelling, and advanced flow visualisation, our study provides a robust framework for understanding the interplay between migration, landscape, and demographic change. This integrative approach reveals patterns and drivers of mobility that are often lost in aggregate analyses and offers methodological guidance for migration studies in other contexts marked by environmental diversity and rapid urbanisation.

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ORCID iDs

Petrus J. Gerrits https://orcid.org/0000-0001-5808-0144
Guy Solomon https://orcid.org/0000-0002-4394-1498
Ana Basiri https://orcid.org/0000-0002-2399-1797
M. Erdem Kabadayı https://orcid.org/0000-0003-3206-0190

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Declaration of conflicting interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Data Availability Statement

Population data is available on the Bulgarian National Statistics Institute (NSI) website.

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Author biographies

Piet Gerrits is a doctoral researcher in Geospatial Data Science at the *University of Glasgow*. He earned his MA in Archaeology from *Koç University*, where he specialised in landscape archaeology, GIS, and remote sensing, and was a geospatial researcher with the *UrbanOccupationsOETR ERC-project*. His PhD, Back-casting Historical Population, Migration, and Infrastructure, develops spatial models to reconstruct demographic and land-use change in Turkey and Bulgaria. His broader research interests include human–environment interactions, spatial modelling, remote sensing, and data science.

Guy Solomon is a Lecturer in AI and Digital Humanities at the School of History, Philosophy, and Digital Humanities at the *University of Sheffield*. He earned his doctorate from the *University of Exeter* in 2020. His research focuses on the dynamics of cities and urban systems in both historical and contemporary contexts, with a particular emphasis on the application of computational methods in humanities research.

Ana Basiri is a Professor in Geospatial Data Science at the *University of Glasgow*, a UK *Research and Innovation Future Leaders Fellow*, the Director of the *Centre for Data Science and AI*. She also

serves as the Royal Academy of Engineering's Engineering X Champion at the *University of Glasgow*. She is the University of Glasgow's academic lead for the *Alan Turing Institute University Network* and she co-chairs the Scottish Government's *ScotStat Board and Location Data Scotland*.

M. Erdem Kabadayı is an economic historian based at *Koç University*, Istanbul. He obtained his Ph.D. in History and Culture of the Middle East and Turkology at the *University of Munich* after studying economics in Ankara and Vienna. Kabadayı was the principal investigator of the first *ERC Starting Grant (UrbanOccupationsOETR)* on the economic history of the Ottoman Empire and Turkey (2016-2022). He recently completed an *ERC Proof of Concept Grant (GeoAI_LULC_Seg)* in the joint fields of data science, population geography, remote sensing, and history (2022-2024). Kabadayı has published individually and collaboratively in disciplines such as history, digital humanities, data sciences, geographical and earth sciences, and ecology.