

Article

Vulnerable Cores, Expanding Peripheries: Intra-Urban Population Redistribution and Seismic-Risk Exposure Across Istanbul's 847 Mahalle, 2007–2035

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Abstract

This paper develops a scenario-based population modelling framework for the 847 mahalle (smallest administrative unit) of Istanbul, Türkiye, extending an empirical baseline for 2007–2025 into prospective scenarios to 2035. The baseline combines rank-size (Zipf) analysis, density quintile trajectories, trajectory classification, and phase-diagram analysis of early versus late-period growth. It reveals a persistent U-shaped deviation from the Zipf benchmark: both the most and least populous mahalle grew strongly through suburban mega-development and peri-urban expansion, respectively, while the established inner-city middle tier remained essentially unchanged. Density followed an inverted gradient, rising sharply on the low-density suburban fringe and contracting in the hyper-dense core. Building on this baseline, the paper defines a baseline continuation (S0) and four alternative scenarios: moderate economic stress (S1), a major North Anatolian Fault earthquake (S2), a combined shock (S3), and policy-led urban renewal (S4). The baseline trajectory amplifies existing inequalities; seismic and economic shocks compress upper-tail growth while generating displacement demand in outer-ring mahalle; and only S4 partially reverses the density-gradient inversion, by stimulating inner-city regeneration under Türkiye's risky-area programme. The findings link intra-urban population redistribution to seismic-risk exposure and inform spatially targeted planning.

Keywords: Istanbul; Zipf's law; rank-size rule; scenario modelling; seismic risk; population density; urban growth; spatial redistribution; demographic forecasting



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1. Introduction

Istanbul is among the most demographically dynamic metropolitan systems in the world. Since Türkiye's urban transformation accelerated in the early 2000s, the city has increased its population by nearly 50% across its 847 formally enumerated mahalle, yet this aggregate growth conceals profound spatial heterogeneity. Some districts have tripled or quadrupled in population within two decades; others have shed more than three-quarters of their residents to administrative boundary redraws and outmigration.

The conventional instrument for analysing the distributional structure of urban populations is Zipf's Law, or the rank-size rule, which posits a log-linear relationship between a settlement's rank and its population [1,2]. Applied to intra-urban sub-districts, the rank-size framework offers a powerful lens for detecting structural change. However, classical

rank-size analysis of Istanbul's mahalle data yields a somewhat misleading verdict: the Zipf slope changed only modestly between 2007 ($\alpha = -1.338$) and 2025 ($\alpha = -1.294$), implying approximate aggregate stability. The nearly parallel shift in the rank-size curves conceals the U-shaped redistribution documented in this paper.

This paper makes two principal contributions. First, it provides a comprehensive multi-method characterisation of Istanbul's intra-urban demographic dynamics for 2007–2025 using four complementary analytical frameworks: rank-size deviation analysis, density quintile trajectory modelling, trajectory classification by absolute change, and phase-diagram analysis of early versus late growth regimes. Second, it extends this empirical baseline into a scenario-modelling framework that projects the distributional implications of four plausible demographic futures to 2035, including a major seismic event scenario of acute policy relevance, given Istanbul's exposure to catastrophic earthquake risk on the North Anatolian Fault [3,4].

The paper is organised as follows. Section 2 reviews the relevant literature. Section 3 describes the data and methods. Section 4 presents the 2007–2025 empirical baseline. Section 5 introduces the scenario framework. Section 6 presents the scenario results. Section 7 discusses implications, and Section 8 concludes.

2. Literature Review

2.1. Zipf's Law and Rank-Size Dynamics in Urban Systems

Zipf's Law has been one of the most empirically robust regularities in urban economics for more than seven decades [1]. The canonical formulation holds that the population of the r -th largest city is inversely proportional to its rank, implying a power-law exponent of $\alpha \approx -1.0$. Gabaix [2] provided an influential stochastic explanation grounded in Gibrat's Law: if cities grow at random rates with a common mean and variance, their population distribution converges to a Pareto distribution with $\alpha = -1.0$. Eeckhout [5] extended this to show that Gibrat's Law applies across the entire city-size distribution when all settlements are included.

Empirical applications have identified substantial variation in Zipf exponents across countries and scales [6,7]. More pertinent here is the growing literature on intra-urban rank-size applications [8,9], where the relationship captures residential hierarchy rather than inter-city competition. The deviation-from-baseline approach adopted in this paper, plotting $\Delta \log_{10}(P) = \log_{10}(P^t) - \log_{10}(P_{2007})$ at each rank position, builds directly on residual analysis in the urban scaling literature [10–14], exposing where in the size hierarchy actual population change occurred.

While rank-size analysis provides the distributional backbone of the present study, the wider methodological landscape for scenario-based population modelling has advanced considerably. Wilson et al. [15] review the state of the art in small-area population forecasting and identify the treatment of major demographic shocks COVID-19 being their example as an outstanding research need that existing models address poorly, directly motivating the compound-shock scenarios developed here; their review also documents the now-standard practice of allocating projected population change across small areas using gravity-type or suitability-weighted rules. In parallel, spatial simulation research has matured: integrated agent-based and cellular automata models are increasingly used to represent heterogeneous urban residential dynamics [16], and recent reviews chart the rapid uptake of machine-learning-enhanced cellular automata for land-use and population-change prediction [17]. More broadly, the field of computational urban science situates such work within data-driven, network- and simulation-based urban analytics [14,18]. The present scenario framework is complementary to these approaches, trading the fine

spatial granularity of simulation models for transparent, literature-calibrated trajectory assumptions suited to a data-constrained, shock-oriented setting.

2.2. Intra-Urban Population Redistribution and the Dual-Ended Growth Model

The simultaneous growth of elite suburbs and peripheral settlements at both ends of the urban size distribution, with stagnation of the established middle, has been documented in American metropolitan areas [19,20] and rapidly urbanising Asian cities [21,22]. In the Turkish context, Lovering and Türkmen [23] and Kuyucu and Ünsal [24] document the role of gecekondu transformation, urban renewal legislation, and mass housing construction (TOKİ) in reshaping Istanbul's population distribution. The emergence of Başakşehir as a planned new urban pole, the dominant factor in this paper's upper-tail deviation, exemplifies state-directed suburban production [25].

The lower-tail explosion documented here, with the smallest mahalle growing over 207% above 2007 baselines, reflects both administrative redraws and genuine peri-urban growth in Silivri, Arnavutköy, Tuzla, and the outer Başakşehir fringe. This pattern is consistent with the concept of extended urbanisation [26], in which metropolitan growth extends into previously rural hinterlands, generating new residential nodes at low initial densities that grow rapidly as infrastructure catches up.

2.3. Scenario-Based Demographic Modelling and Urban Risk

Scenario-based approaches to population modelling emerged as a response to the limitations of extrapolative forecast methods in contexts of structural uncertainty [27,28]. Istanbul is among the most extensively studied seismically exposed cities given its location on the North Anatolian Fault and the well-documented risk of a major Marmara earthquake [3,4]. Demographic impact assessments of seismic events in Istanbul have primarily focused on mortality estimates and immediate displacement [29], with less attention paid to medium-term redistribution effects on neighbourhood-level population structure. This paper contributes to filling that gap.

The present paper sits within a broader multi-scale research programme on Türkiye's seismic risk and reconstruction policy. At the city-wide level, Kundak et al. [30] develop six scenario-based seismic risk assessments for Istanbul through participatory Impact Chain workshops, integrating temporal and spatial dimensions to identify systemic vulnerabilities in communications, infrastructure, and emergency response that vary materially with the timing and seasonality of the seismic event. At the neighbourhood level, Aşıcı et al. [31] construct damage ratio and Natech Share indices for Istanbul's 939 mahalle from the Istanbul Metropolitan Municipality (IMM) seismic loss estimation database, demonstrating that the 17% of mahalle classified as highest structural-risk concurrently house approximately 31% of the city's population and 24% of businesses engaged in hazardous activities, indicating a pronounced spatial overlap of structural and technological hazard exposure. At the national level, Arslanlı et al. [32] analysed residential energy demand and low-carbon reconstruction policy across all 81 Turkish provinces using two-way fixed-effects panel models, underscoring mandatory building code enforcement under Law No. 6306 as a principal near-term reconstruction lever. The present paper completes this multi-scale picture by introducing the demographic dimension at the mahalle level: which of the structurally vulnerable mahalle identified by [31] are also demographically inert, and conversely, which demographically dynamic mahalle face elevated seismic risk? This dual identification is the empirical foundation for the risk-asymmetry finding developed in Sections 4 and 6.

3. Materials and Methods

3.1. Study Area and Data Sources

Istanbul is Türkiye's largest city and its principal economic and demographic centre, home to more than 15 million residents and organised into 39 districts (ilçe) that straddle the Bosphorus Strait between the European and Asian shores. The European side contains the historic peninsula and the dominant central business districts, while the outer European periphery and the Asian side have absorbed most of the late-period suburban expansion analysed here. The smallest administrative and census unit is the mahalle (neighbourhood), the level at which Turkey's Address-Based Population Registration System (ADNKS) records resident counts; this study analyses the 847 mahalle for which a complete and administratively consistent annual population series is available across the full 2007–2025 observation window, with the treatment of intervening administrative boundary reforms described below. The city's seismic hazard is dominated by the North Anatolian Fault, whose Main Marmara segment runs offshore roughly 15–20 km south of the dense southern shoreline and is widely identified as a late-stage seismic gap capable of producing a major ($M \geq 7$) earthquake within the coming decades a hazard that bears most heavily on the older, higher-density mahalle of the historic core. Figure 1 maps the 847 mahalle and their 2007 baseline populations. For consistency, the historic core denotes the walled historic peninsula (Fatih) and its immediate surroundings; the inner city denotes the contiguous, fully built pre-2000 districts ringing it on both shores (for example, Fatih, Beyoğlu, Şişli, Kadıköy and Üsküdar); and the hyper-dense core denotes the highest 2007 density quintile (Q5).

Istanbul Mahalle — 2007 Baseline Population ($n = 847$)

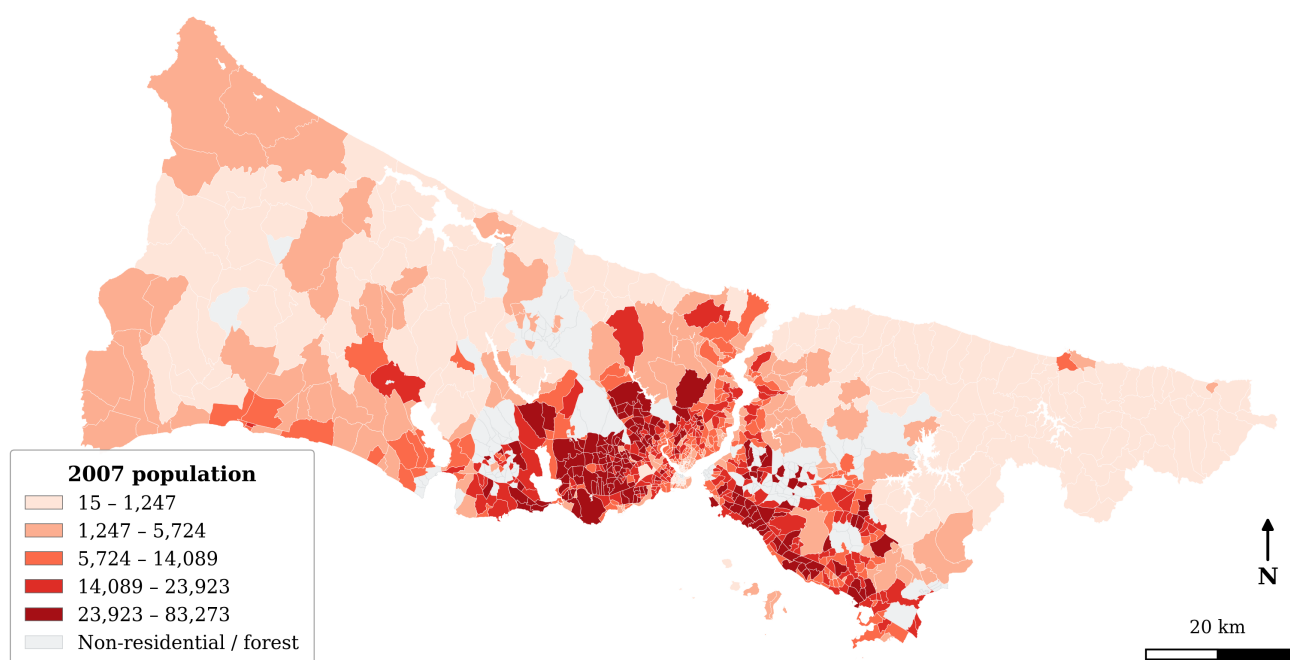


Figure 1. The 847 mahalle of metropolitan Istanbul, shaded by 2007 baseline population in quintile classes; non-residential polygons (forest and water-adjacent land) are shown in grey. Coordinate reference system: ITRF96/UTM Zone 35 N.

The primary data source is the Turkish Statistical Institute (TURKSTAT) Address-Based Population Registration System (ADNKS), providing annual mahalle-level population counts for all formally enumerated sub-district units in Istanbul province for 2007–2025 [33]. The analytical sample is the balanced panel of $n = 847$ mahalle present in every year of

2007–2025, representing the stable administrative core of Istanbul’s sub-district structure; after removing 22 units that exhibit administrative boundary reform discontinuities (detailed below), the genuine demographic-change panel comprises 825 mahalle. Area data for population density calculations derive from the Spatial Address Registry System (MAKS) cadastral boundary shapefile (UTM Zone 35 N). Density is expressed in persons per square kilometre (p/km^2). The 2008 administrative boundary reform, which subdivided several large mahalle in Ümraniye and Ataşehir, is treated as a measurement discontinuity throughout. For comparability with conventional planning practice, the area-weighted city-wide mean density is additionally reported in persons per hectare (p/ha), where $1\text{ person/ha} = 100\text{ persons}/km^2$. These reforms correspond to the 2008 Law No. 5747 and the 2014 Law No. 6360 reassignments; units exhibiting a single-year drop of 40% or more at a reform boundary were identified and separated, yielding the 825 mahalle genuine-change panel referenced above.

All statistical analyses and figure generation were carried out in Python 3.14 (Python Software Foundation, Wilmington, DE, USA) using the NumPy 2.5.0, pandas 3.0.3, SciPy 1.18.0, and Matplotlib 3.11.0 libraries; cadastral boundary processing, density computation, and cartographic output were performed in ArcGIS Pro 3 (Esri, Redlands, CA, USA).

3.2. Analytical Framework: Empirical Baseline

The empirical baseline employs four complementary methods. (i) Classical rank-size (Zipf) analysis: For each year t , mahalle are ranked by population in descending order, and $\log_{10}(P_r) = \beta_0 - \alpha \cdot \log_{10}(r)$ is estimated using OLS. The annual Zipf exponent α and its 95% CI are tracked across all 19 years, along with exponents for the top-50 and top-200 mahalle. (ii) Deviation-from-baseline analysis: For each year t and rank position r , we compute $\Delta \log_{10}(P) = \log_{10}(P_{r,t}) - \log_{10}(P_{r,2007})$, amplifying the signal of distributional change while suppressing the nearly uniform vertical shift in the full rank-size curve. (iii) Trajectory classification: Each mahalle is classified into one of seven groups by absolute population change in the 2007–2025 period: Extreme Rise ($>+50,000$; $n = 5$), Strong Rise ($+25\text{ k to }+50\text{ k}$; $n = 17$), Moderate Rise ($+10\text{ k to }+25\text{ k}$; $n = 64$), Weak Rise ($0\text{ to }+10\text{ k}$; $n = 393$), Weak Decline ($0\text{ to }-10\text{ k}$; $n = 352$), Moderate Decline ($-10\text{ k to }-25\text{ k}$; $n = 10$), and Strong Decline ($<-25\text{ k}$; $n = 6$). (iv) Phase-diagram analysis: Each mahalle is characterised by an early period OLS slope (2007–2013) and a late-period slope (2019–2025) in persons/year, mapping all 847 mahalle into four quadrants: Q1 Continued Growth ($n = 302$, 36%), Q2 Reversed/Rise $\rightarrow$ Decline ($n = 251$, 30%), Q3 Recovered/Decline $\rightarrow$ Rise ($n = 99$, 12%), Q4 Continued Decline ($n = 195$, 23%). These trajectory thresholds are set at round, planning-interpretable magnitudes ($\pm 10,000$, $\pm 25,000$ and $\pm 50,000$ persons; $\pm 10,000$ – $25,000$ corresponds to roughly one large housing estate); the classification is descriptive, and the continuous phase-diagram analysis (Figure 2), which uses no thresholds, corroborates the same dual-ended structure, confirming that the result is not an artefact of the chosen breaks.

Inequality and concentration are tracked using the Gini coefficient on raw mahalle populations, the primacy ratio (rank-1 share of city total), and cumulative top-10 and top-50 concentration shares. Density evolution is analysed by quintile: the 847 mahalle are sorted by 2007 density into five equal-sized quintiles (Q1 = lowest 20%, Q5 = highest 20%), which are held fixed, and median density trajectories are tracked annually through 2025.

3.3. Scenario Construction

Scenarios are constructed at the trajectory-group level. Within each scenario, the OLS slope for each group is modified according to scenario-specific multiplicative factors calibrated against historical analogue events and the academic literature. The growth engine

for all scenarios is the group-level median slope estimated on 2019–2025 data, extrapolated to 2035 with modifications applied from 2025 onward. Uncertainty is represented by propagating the 25th–75th percentile (IQR) spread of slopes within each group. Five scenarios are defined, and Table 1 provides a summary. Projected populations are constrained to be non-negative, and the apparent floor reached by the decline groups reflects this constraint, together with the deceleration of decline as units approach a residual resident population.

Table 1. Scenario framework: parameters, labels, and key assumptions.

Key Assumptions	Label	Scenario
Linear extrapolation of 2019–2025 OLS slopes; no structural shocks.	S0	Baseline Continuation
Currency depreciation; net migration -30% ; fringe growth halved.	S1	Moderate Economic Stress
$M_w \geq 7.0$ on North Anatolian Fault; 200–500 k displacement; corridor absorption.	S2	Major Seismic Event
Simultaneous seismic and economic stress; accelerated suburban consolidation.	S3	Combined Shock
Risky area densification of inner mahalle; growth caps on outer fringe.	S4	Urban Renewal Policy

Note. All scenarios apply group-level median slopes as the growth engine. S1–S3 impose multiplicative dampening factors calibrated from the 2018 currency crisis and seismic displacement literature. S4 applies planning-constrained growth caps to the top 20 outer-fringe mahalle under Law No. 6306.

Because the scenario engine propagates fitted population slopes forward to 2035, the adequacy of a linear specification was examined directly on the 847- mahalle panel. Ordinary least squares fits of population on time over the full 2007–2025 window are only moderately strong at the unit level (median $R^2 = 0.67$; 42% of mahalle exceed $R^2 = 0.75$) and display two systematic departures from the classical linear model: pervasive positive residual autocorrelation (median Durbin–Watson = 0.65, with 94% of units below 1.5) and a statistically significant quadratic term in roughly 69% of mahalle. These diagnostics indicate that a naïve linear extrapolation of each mahalle’s full-period trend would be poorly supported, reflecting the regime change made explicit by the phase analysis of Section 4.5. For this reason, the projection does not extrapolate full-period unit trends; it instead applies group-level median slopes estimated on the most recent sub-period (2019–2025), over which a local linear approximation is far better behaved (median $R^2 = 0.75$; median Durbin–Watson = 1.78, consistent with negligible residual autocorrelation). Departures from this recent-trend baseline are introduced explicitly through the scenario multipliers (Section 5) rather than assumed away, so that nonlinearity enters the projections as a modelled feature rather than an unexamined extrapolation artefact.

4. Empirical Baseline: Istanbul Mahalle Population Dynamics, 2007–2025

4.1. Rank-Size Distribution and Zipf Dynamics

Figure 2 displays the log–log rank-size curves for all 19 years, colour-coded from dark green (2007) to red (2025). Three features are immediately apparent. First, the curves are remarkably parallel: the rank-size slope changes only from $\alpha = -1.338$ (2007) to $\alpha = -1.294$ (2025), a modest flattening within the 95% confidence band. Second, the upper tail ($\log_{10}(\text{rank}) < 0.5$) has visibly lifted across years, confirming disproportionate growth at the top of the size hierarchy. Third, the lower tail ($\log_{10}(\text{rank}) > 2.7$) shows marked upward expansion as newly created peri-urban mahalle grow rapidly.

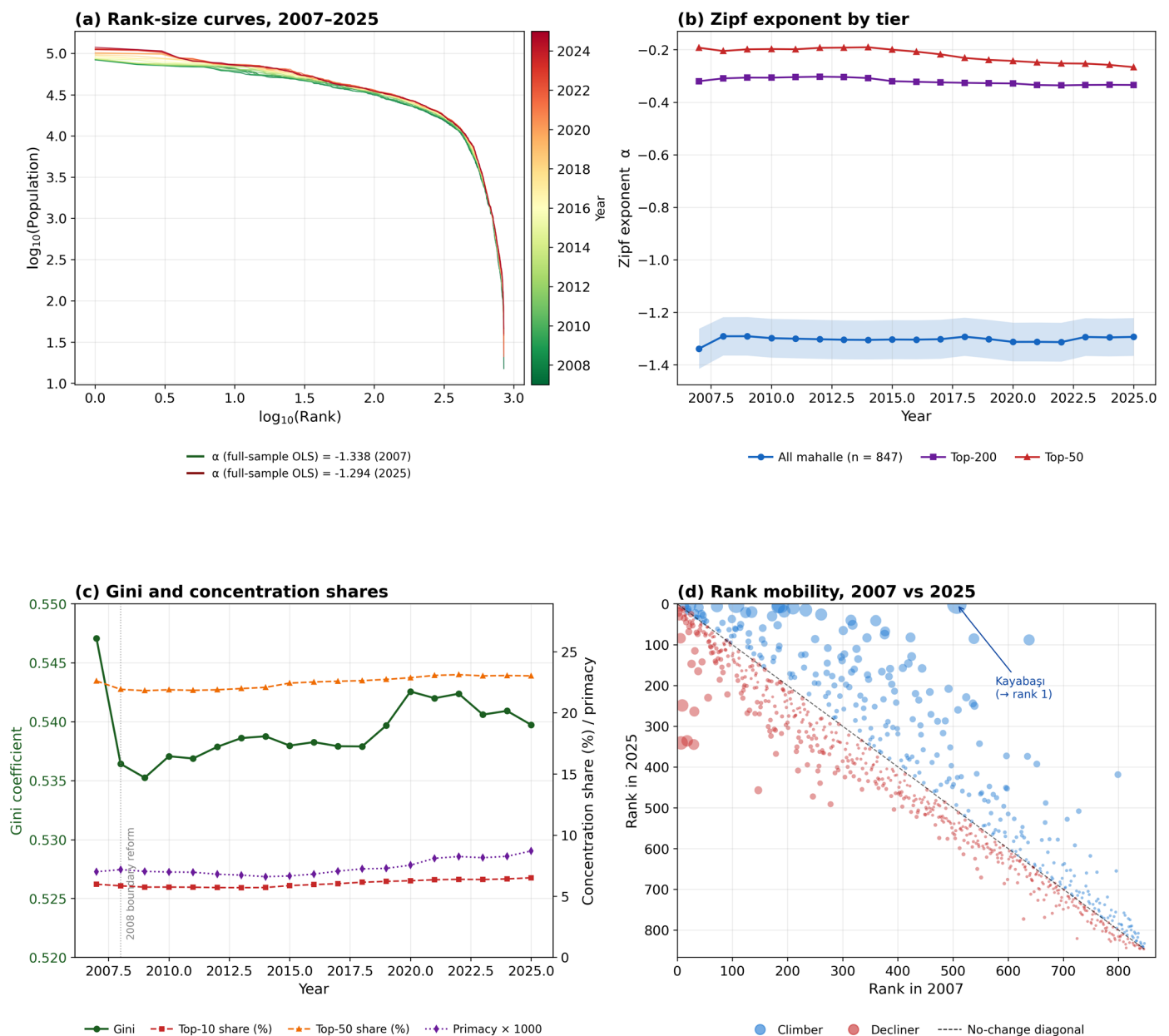


Figure 2. Rank-size (Zipf) distribution and dynamics, Istanbul mahalle 2007–2025. Panels: (a) log–log rank-size curves 2007–2025; (b) annual Zipf exponent by tier; (c) Gini coefficient and concentration shares; (d) rank mobility scatter in 2007 vs. 2025. $n = 847$ mahalle. OLS fit lines for 2007 and 2025 shown in (a). Shaded band in (b) = 95% CI. Bubble size in (d) is proportional to $|\Delta P|$ 2007–2025. Data: TURKSTAT ADNKS 2007–2025.

The tier-specific Zipf analysis (Figure 2b) reveals a structural divergence the full-distribution slope conceals. The top-50 slope steepened from approximately -0.19 (2007) to -0.26 (2025), indicating that the largest mahalle have grown disproportionately and that concentration within the upper tier increased. The Gini coefficient (Figure 2c) declined only marginally on the balanced panel, from 0.547 (2007) to 0.540 (2025), confirming aggregate distributional stability. The primacy ratio rose steadily after 2017 as Kayabaşı/Başakşehir ascended to rank 1; the rank-1 share nonetheless remains very low, rising from 0.70% of the metropolitan total in 2007 to just 0.87% (approximately 118,000 residents) in 2025, confirming the absence of demographic primacy at the mahalle scale. Rank mobility (Figure 2d) reveals that climbers are overwhelmingly peri-urban suburban mahalle in Başakşehir, Bey-

likdüzü, and Tuzla, while fallers are concentrated in formerly large Ümraniye and Ataşehir mahalle split by the 2008 reform.

4.2. The Deviation-from-Baseline Zipf Plot: A U-Shaped Growth Profile

Figure 3 presents the deviation from the 2007 baseline at each rank position for the years 2008–2025, revealing a persistent U-shape invisible in the classical rank-size presentation. Three structurally distinct zones are identifiable. Zone 1 (upper tail, ranks 1–10): Deviation at rank 1 reaches approximately +0.15 by 2025 (+42%), accelerating sharply after 2017 as Kayabaşı overtook all other mahalle through large-scale planned housing development in the Başakşehir corridor. Zone 2 (stable middle, ranks 50–300): There is a near-zero deviation throughout, converging tightly around the 2007 baseline across all 18 years of change, including the 2018 currency crisis, 2020 COVID-19 disruption, and 2023 earthquake sequence. Zone 3 (lower tail, ranks 300–892): Curves fan sharply upward, reaching approximately +0.49 at rank 892 by 2025 (+207%), reflecting both the 2008 boundary reform and genuine peri-urban growth. Zones 1–3 denote rank position bands of the distribution, defined by population rank rather than contiguous geographic areas; the Başakşehir corridor refers to the north-western development axis comprising Başakşehir, Kayabaşı and the adjacent TOKİ mass-housing zones. Zone 2's small year-to-year jitter reflects genuine but minor population fluctuations rather than an artefact of rank ordering, and the band remains tightly centred on the 2007 baseline across all years.

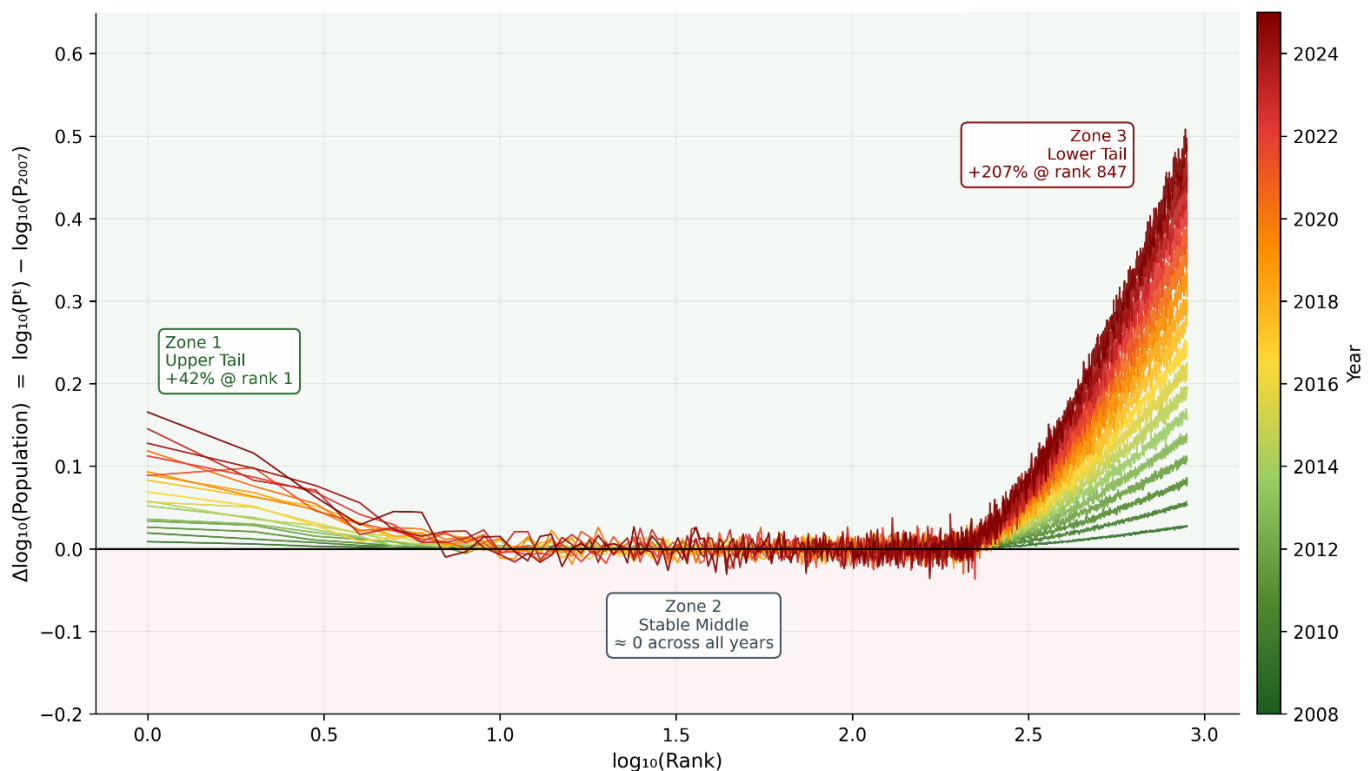


Figure 3. Deviation from 2007 baseline at each rank. Each curve shows $\Delta\log_{10}(P) = \log_{10}(P^t) - \log_{10}(P_{2007})$ at each rank position for 2008–2025. Colour code: dark green = 2008, yellow $\approx$ 2015, deep red = 2025. $n = 847$ mahalle. Zero line = 2007 baseline. Green shading = growth zone; pink shading = decline zone. Data: TURKSTAT ADNKS 2007–2025.

The Ribbon representation (Figure 4) confirms that the upper-tail lift and lower-tail expansion are principally concentrated in the 2019–2025 era, which sits clearly above the earlier periods at both distributional extremes, while the middle register remains near-zero across all four eras.

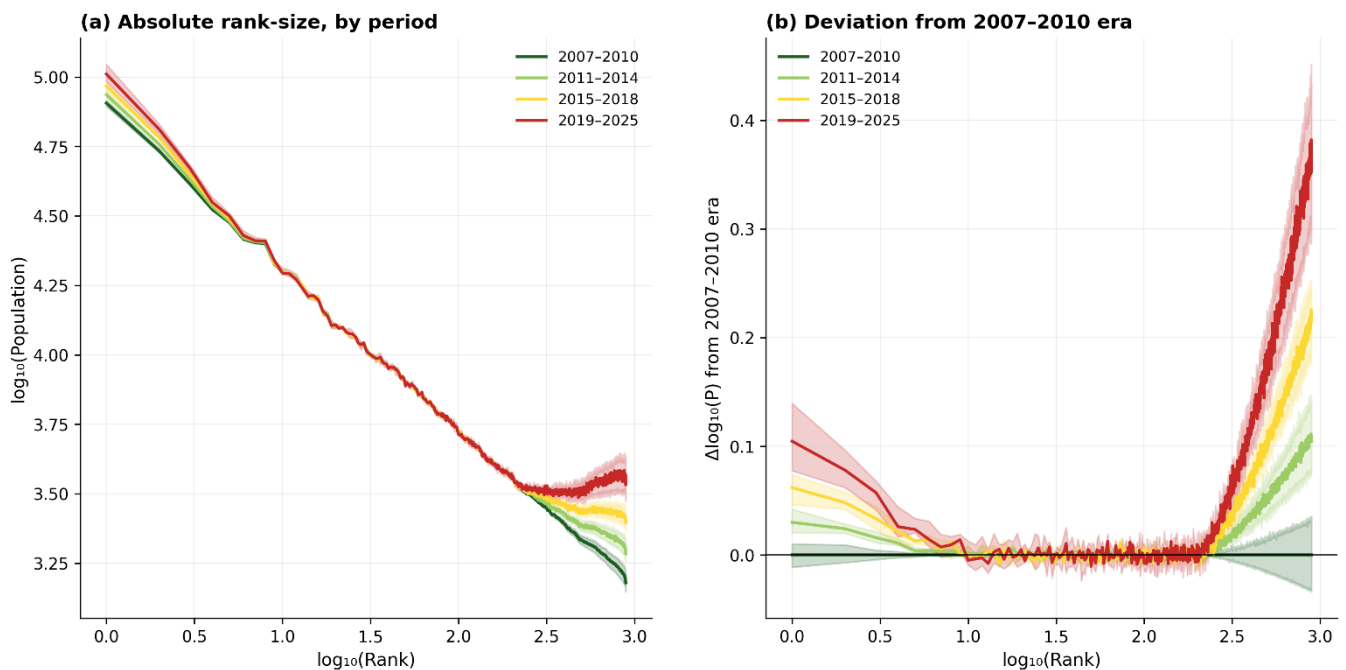


Figure 4. Period Ribbons: rank-size shifts across four eras (2007–2010, 2011–2014, 2015–2018, 2019–2025). (a): absolute $\log_{10}(\text{Population})$ vs. $\log_{10}(\text{Rank})$. (b): deviation from 2007 to 2010 era. Ribbon = 10th–90th percentile range across years in the period; centre line = period median. Data: TURKSTAT ADNKS 2007–2025.

4.3. Population Density Evolution

Table 2 presents selected descriptive statistics of mahalle-level population density for anchor years 2007–2025. The cross-sectional mean density changed only marginally (17,862 to 17,556 p/km²), yet the median density rose from 9976 to 12,077 p/km², reflecting mid-density suburban growth pulling the median upward while the hyper-dense upper tail contracted. Skewness declined from 1.39 (2007) to 1.15 (2025), excess kurtosis from 1.24 to 0.49, and the coefficient of variation from 119.2% to 108.3%; all were computed on density winsorized at the 99th percentile to limit the influence of a few hyper-dense mahalle, indicating progressive normalisation and mild convergence in the cross-sectional density distribution. The near-constant mean alongside a rising median is the statistical signature of this redistribution: the shrinking hyper-dense upper tail (Q5, −12%) holds the mean down, while the expanding mid-density quintiles (Q2, +51%) lift the median.

Table 2. Selected descriptive statistics of Istanbul mahalle population density, anchor years 2007–2025.

CV (%)	Kurt.	Skewness	SD	Mean	Median (p/km ²)	<i>n</i>	Year
121	1.642	1.483	21,135	17,460	9810	847	2007
118.7	1.905	1.499	20,887	17,593	10,488	847	2010
118.5	2.749	1.585	21,629	18,258	10,950	847	2013
113.4	1.097	1.312	20,283	17,880	11,050	847	2016
111.9	0.961	1.271	20,447	18,278	11,845	847	2019
110.6	0.9	1.249	19,984	18,064	12,066	847	2022
108.5	0.631	1.179	18,900	17,411	11,889	847	2025

Note. *n* = 847 mahalle with complete records. All density values in persons per km². Kurt. = excess kurtosis (normal = 0). CV = coefficient of variation (SD/Mean × 100). Data: TURKSTAT ADNKS 2007–2025; areas from MAKΣ cadastral boundary shapefile (UTM Zone 35 N).

The density quintile index (Figure 5) reveals the spatial structure of this convergence. Q2 (suburban fringe) recorded the highest density gain, reaching index 151 (+51%) by

2025, while Q5 (hyper-dense inner city) declined to index 88 (−12%). The city-wide area-weighted mean density rose from 24.25 to 27.76 p/ha (+14.5%), as shown in the waterfall chart (Figure 6). Annual density increments were negative in 2008 (−0.51 p/ha, boundary reform), 2015 (−0.25 p/ha, currency pressure), 2020 (−0.13 p/ha, COVID-19), and 2023 (−0.47 p/ha, earthquake), confirming Istanbul’s repeated exposure to macroeconomic and natural disruptions. The spatial pattern underlying these quintile trajectories is shown in the density quintile map, which colours each mahalle by its 2007 density quintile, allowing the Q1–Q5 trajectories to be located geographically.

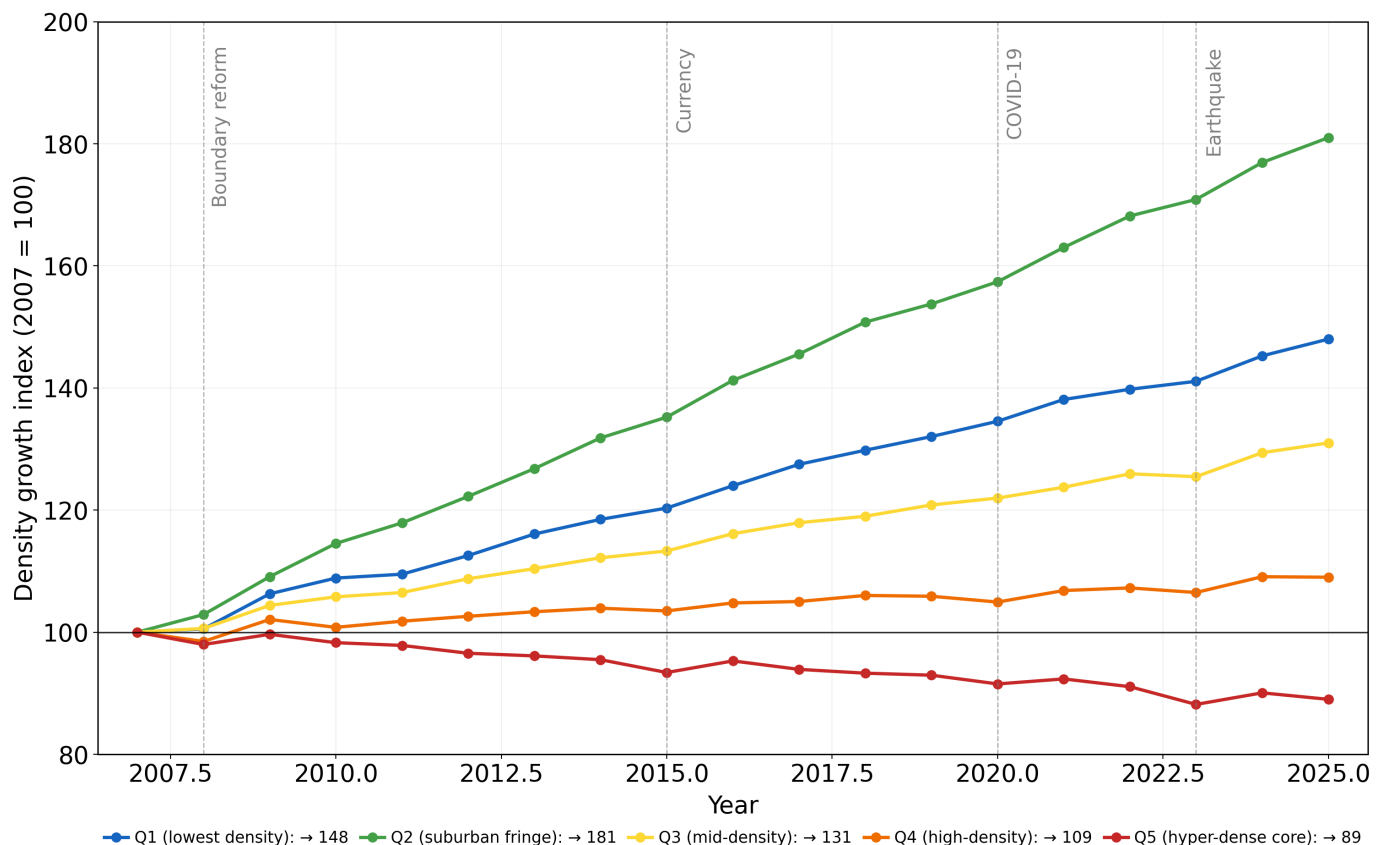


Figure 5. Population density growth index by 2007 density quintile, Istanbul 2007–2025 (2007 = 100). Q2 (suburban fringe) → 151; Q5 (hyper-dense) → 88. Each line = median density index for quintile. Quintiles fixed at 2007 boundaries. Vertical dashed lines = major shocks. Data: TURKSTAT ADNKS 2007–2025; MAKŞ shapefile (UTM 35 N).

4.4. Trajectory Classification and Group Dynamics

Figure 7 presents the trajectory group analysis. The Extreme Rise group ($n = 5$) includes Kayabaşı, Adnan Kahveci, Atakent, Aydınlı, and Başakşehir mahalle, with the group median rising from approximately 22,000 (2007) to over 100,000 (2025) and a 2030 projection slope of +1.5 k/year. Individual gains range from +289% (Başakşehir) to +3940% (Kayabaşı). The three decline categories share a distinctive temporal signature: a sharp drop concentrated in 2008–2010 attributable to the boundary reform, followed by stabilisation at a lower level. The strongest decliners are concentrated in Ümraniye and Ataşehir: Kazım Karabekir (−77%, $\Delta = -53,685$), Yukarı Dudullu (−68%, $\Delta = -44,768$), and Yeni Çamlıca (−70%, $\Delta = -44,035$). The heatmap (Figure 8) confirms the spatial concentration of growth in the north-western Beylikdüzü and Başakşehir corridors, and of decline in established Ümraniye mahalle. The spatial distribution of the top 20 rising and top 20 declining mahalle, which distinguishes the European peri-urban corridor from the Asian inner-ring belt, is

mapped in Map M4, with the named mahalle listed by group in the heatmap (Figure 8) is retained as a complement for the year-on-year timing it uniquely conveys.

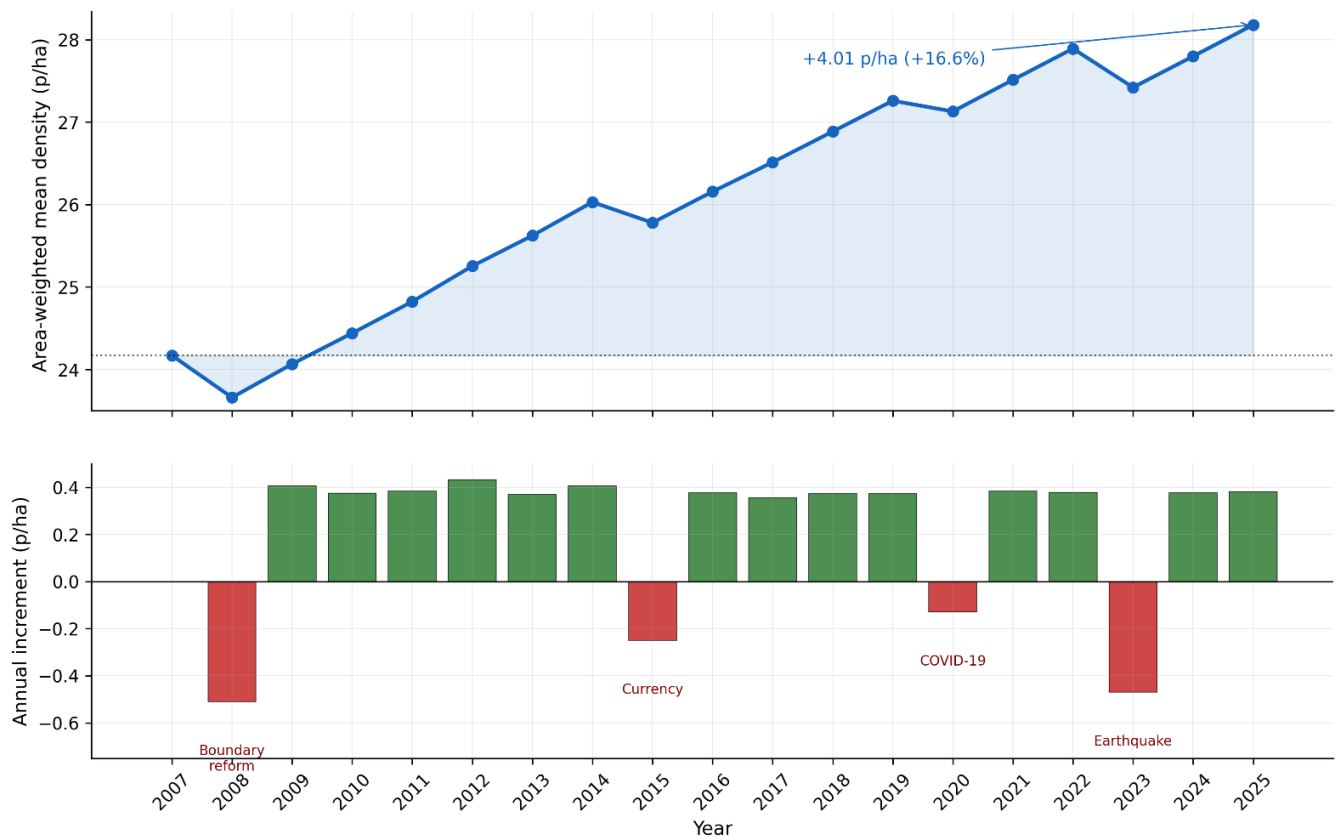


Figure 6. Waterfall chart: city-wide population density change, Istanbul mahalle 2007–2025 (area-weighted mean, p/ha). **(Top):** cumulative level. **(Bottom):** annual signed increment. Area-weighted mean = $\Sigma(\text{density} \times \text{area}) / \Sigma(\text{area})$ across 847 mahalle. Data: TURKSTAT ADNKS 2007–2025; MAKs shapefile (UTM 35 N). (1 person/ha = 100 persons/km²).

4.5. Phase Analysis: Early Versus Late-Period Growth Regimes

The phase diagram (Figure 9) maps the joint distribution of early period slopes (2007–2013) and late-period slopes (2019–2025). Q1 (Continued Growth, $n = 302$, 36%) clusters tightly along the positive diagonal, confirming sustained growth momentum in Başakşehir, Beylikdüzü, Tuzla, and Pendik. Q2 (Reversed: Rise → Decline, $n = 251$, 30%) contains mahalle that grew in 2007–2013 but have since plateaued or declined, signalling suburban saturation in many Ataşehir and inner-ring mahalle. Q3 (Recovered: Decline → Rise, $n = 99$, 12%) contains post-reform Ümraniye mahalle whose late-period positive slopes reflect organic population infill. Q4 (Continued Decline, $n = 195$, 23%) captures persistently declining mahalle predominantly in Üsküdar, Bahçelievler, Güngören, and Esenler. Notably, 71% of all mahalle cluster within ± 0.4 k/year of the origin in both periods, confirming that Istanbul’s aggregate demographic stability is genuine and that dramatic headline figures are driven by a small number of extreme outliers.

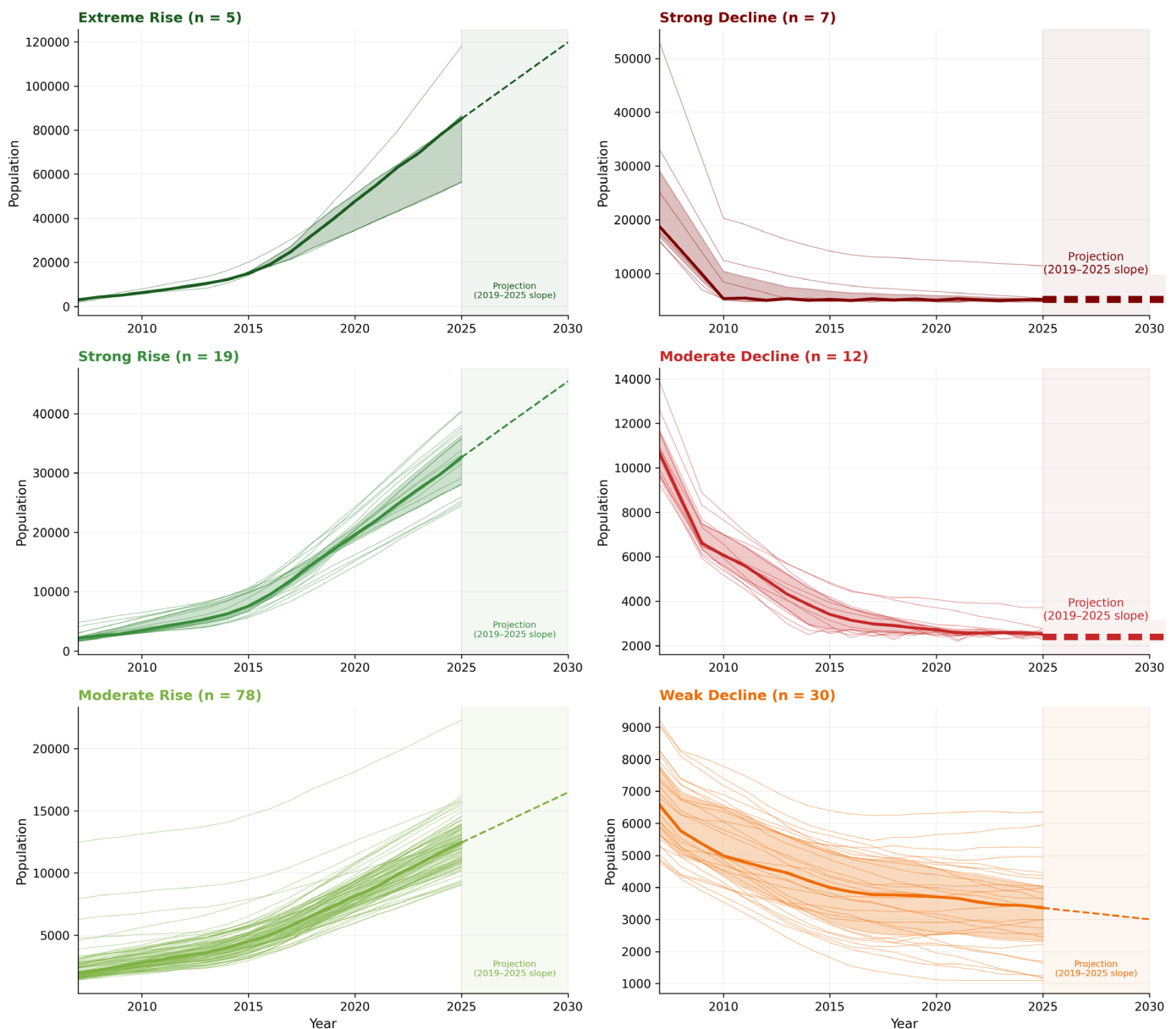


Figure 7. Mahalle population trajectories by change group, Istanbul 2007–2030. **(Left column):** growth groups (Extreme Rise, $n = 5$; Strong Rise, $n = 17$; Moderate Rise, $n = 64$). **(Right column):** decline groups (Strong Decline, $n = 6$; Moderate Decline, $n = 10$; Weak Decline, $n = 352$). Thick line = group median; shaded band = IQR; thin lines = individual mahalle. Dashed = linear projection on 2019–2025 slope. Data: TURKSTAT ADNKS 2007–2025.

4.6. Demographic–Structural Vulnerability: Cross-Classifying Population Change and Seismic Risk

The preceding subsections establish where Istanbul’s population is growing and contracting; translating these dynamics into seismic risk additionally requires intersecting them with the built environment’s structural vulnerability. To this end, each mahalle is cross-classified along two axes: its 2007–2025 population trajectory, collapsed into growing, stable, and declining classes, and a Disaster Risk Index (DRI) computed directly from the IBB/IMM scenario building damage forecast in the seismic loss estimation database underlying [31]. The DRI is defined as the building-weighted severe-damage ratio: the share of a mahalle’s building stock expected to reach the complete or extensive HAZUS damage states, obtained by spatially aggregating the grid-level forecast to mahalle boundaries (capturing 99% of the approximately 1.17 million forecast buildings). Mahalle in the upper tercile of this

ratio (≥ 0.040) are classified high-DRI. Because it is a per-building damage intensity, this index is complementary to, rather than identical with, the population-exposure ranking reported in [31]. Of the 806 mahalle for which both damage and population data were available, 269 (33.4%) were classified high-DRI. The cross-tabulation (Table 3) reveals a statistically significant association between demographic trajectory and seismic risk ($\chi^2(4) = 21.2, p < 0.001$; Cramér's $V = 0.115$). The share of high-DRI mahalle rises monotonically across the trajectory spectrum, from 26.0% of growing to 33.2% of stable and 44.7% of declining mahalle, indicating that population loss is concentrated in the most hazardous building stock: the older, higher-density inner-ring neighbourhoods that combine fragile construction with out-migration. A robustness check excluding 39 mahalle with fewer than 200 residents, whose growth rates are unstable on small denominators, left the association substantively unchanged ($n = 767$; $\chi^2(4) = 17.0, p = 0.002$). The converse exposure is equally consequential for planning: approximately 1.91 million residents (2025) inhabit mahalle that are simultaneously high-DRI and still growing, while 5.55 million reside in high-DRI mahalle in total. Seismic risk is therefore accumulating along two distinct fronts entrenched in declining inner-city cores and expanding in growing peripheral and coastal mahalle, each implying a different mitigation strategy. This cross-classification is mapped in Map M5 and tabulated per mahalle in Supplementary Materials.

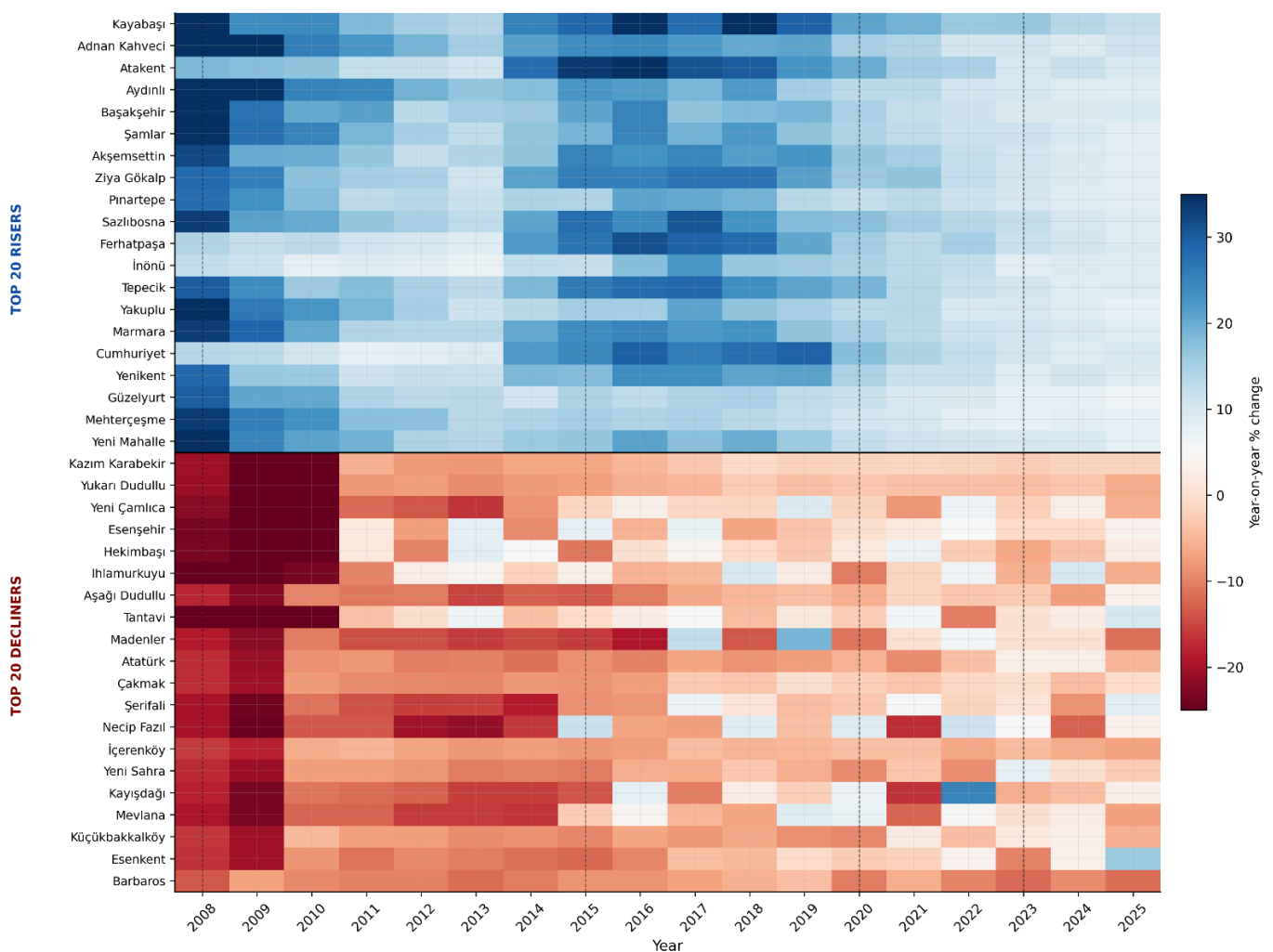


Figure 8. Annual population change rate heatmap: top 20 rising and top 20 declining mahalle, Istanbul 2008–2025. Cell = year-on-year % change. Blue = growth; red = decline. Values are clipped at $-25\%/+35\%$ for the colour scale. Dashed verticals = major shock years. Data: TURKSTAT ADNKS 2008–2025.

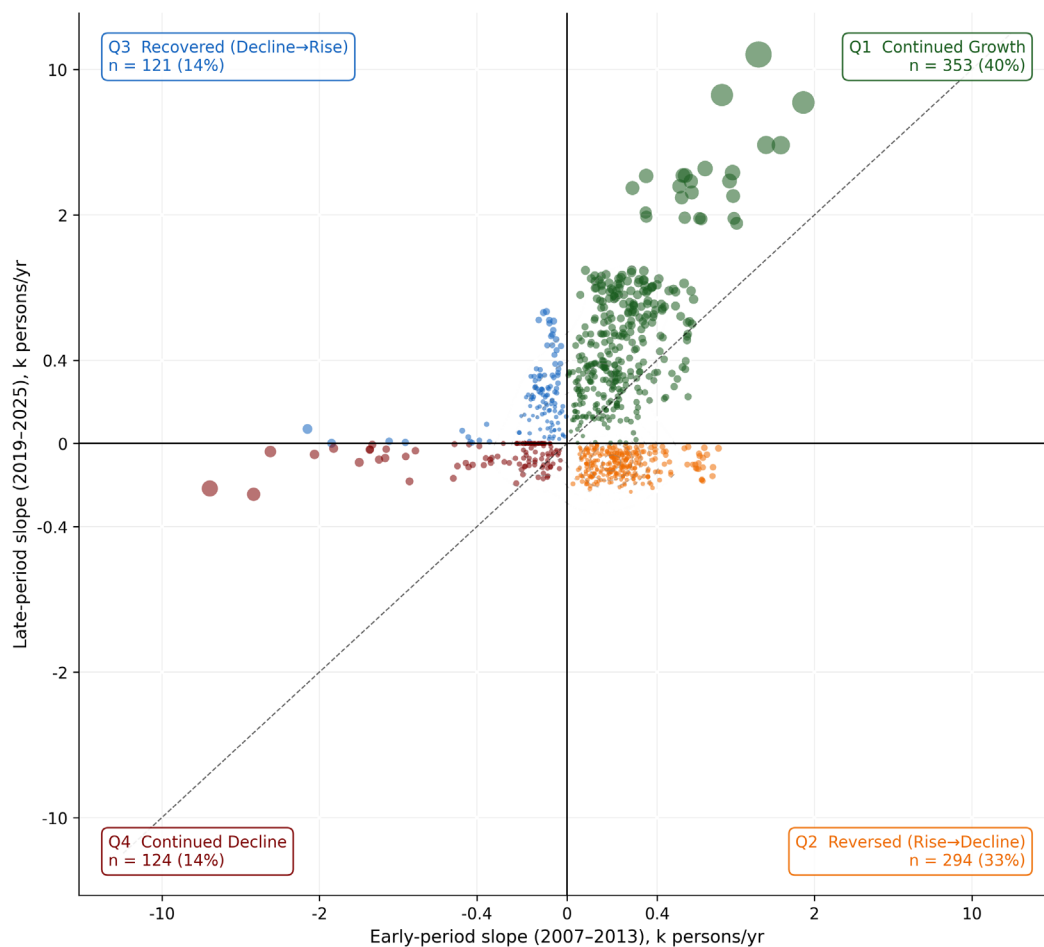


Figure 9. Phase diagram: early (2007–2013) vs. late (2019–2025) population growth slopes, Istanbul mahalle ($n = 847$). Bubble size = $|\Delta P|$ 2007–2025. KDE contour rings show density of points. Q1 Continued Growth ($n = 302$, 36%), Q2 Reversed ($n = 251$, 30%), Q3 Recovered ($n = 99$, 12%), Q4 Continued Decline ($n = 195$, 23%). Symmetric log (symlog) scaling: linear within ± 0.4 k/yr, logarithmic beyond. Dashed diagonal = equal slope ($y = x$). Data: TURKSTAT ADNKS 2007–2025. The symmetric log transform is linear within ± 0.4 k persons/year, so the mahalle clustered near the origin are shown without compression and are logarithmic beyond that, to accommodate the extreme outliers.

Table 3. Cross-classification of 806 mahalle by 2007–2025 demographic trajectory and Disaster Risk Index (DRI) tier (Pearson $\chi^2(4) = 21.2$, $p < 0.001$).

Total	High DRI	Moderate DRI	Low DRI	Trajectory
308	80	107	121	Growing
292	97	100	95	Stable
206	92	62	52	Declining
806	269	269	268	Total

5. Scenario Framework: Parameterisation and Assumptions

The scenario multipliers introduced in the following subsections are not free parameters but are calibrated against documented historical analogues and the empirical regularities established in Section 4. The economic stress scenarios are anchored to Turkey's 2018–2019 currency crisis, during which the lira lost roughly 30% of its value; the construction sector, a principal driver of Istanbul's peripheral growth, contracted by about 8.7% year-on-year in the final quarter of 2018; and household consumption fell by roughly

8.9% year-on-year in that quarter [34]. This episode supplies an observed magnitude for the dampening of peripheral growth momentum applied under moderate economic stress. The seismic scenarios draw their displacement and casualty assumptions from the structural vulnerability and damage estimates of the companion risk assessment [31] and from the published literature on Istanbul earthquake loss modelling. The specific multiplicative factors and the spatial rules used to redistribute displaced population are reported with each scenario below; their precise numerical values reflect the modelling team's calibration choices and should be read as transparent, adjustable assumptions rather than estimated coefficients.

5.1. Baseline Continuation (S0)

S0 preserves the 2019–2025 OLS slope for each trajectory group unchanged through 2035, representing a world in which Istanbul continues along its established suburban-expansion trajectory with no structural shocks or major policy interventions. The Extreme Rise group continues approaching saturation at approximately 120,000 persons/mahalle; the Moderate Rise group expands at +0.6 k/year; and the decline groups continue slow attrition at −0.2 to −0.3 k/year. The projected city-wide population under S0 reaches approximately 15.8–16.2 million by 2035, consistent with TURKSTAT's official medium-variant projection.

5.2. Moderate Economic Stress (S1)

S1 models sustained macroeconomic stress comparable to the 2018 Turkish currency crisis but lasting the full 2025–2035 period. A growth dampening factor of 0.70 is applied to all positive-slope groups (30% reduction in growth rate) and a slope amplification factor of 1.20 is applied to negative-slope groups. Net immigration from other Turkish provinces is assumed to slow by 30%; peripheral fringe growth is halved. Under S1, city-wide population reaches approximately 15.2–15.6 million by 2035. The 0.70 factor, representing a sustained 30% reduction in positive-growth momentum, is calibrated to the 2018–2019 currency crisis cited above and is deliberately moderate: it is milder than the most severe attenuation in the historical record, since realized city-wide growth over 2019–2025 (encompassing the COVID-19 disruption and the 2023 contraction) fell to roughly one-tenth of its 2010–2019 trend an extreme reserved for the compound-shock scenario S3.

5.3. Major Seismic Event (S2)

S2 introduces a probabilistic $M_w \geq 7.0$ rupture on the North Anatolian Fault beneath or near the Sea of Marmara. The seismic risk literature estimates the conditional probability of such an event over the next 30 years at 35–70% [3,4], making this scenario not merely plausible but arguably likely within the modelling horizon. The demographic impact pathway operates through three mechanisms: (i) immediate displacement of 200,000–500,000 persons from vulnerable inner-city mahalle (predominantly Fatih, Zeytinburnu, Avcılar, and Bakırköy) with high concentrations of pre-code, non-ductile reinforced concrete (RC) building stock; (ii) medium-term absorption in the outer-ring suburban corridor, generating a 2–3-year demand surge of 15–25% above S0 rates in the Moderate Rise group; and (iii) gradual recovery, with inner-city decline-group slopes set to −1.5 to −2.0 k/year for three years post-event before returning to S0 rates. The displacement magnitude is anchored in the building damage forecast: 200,000–500,000 corresponds to the residential population of buildings expected to sustain complete ($\approx 180,000$ residents) to complete-and-extensive ($\approx 615,000$ residents) damage. Displaced households are allocated to receiving mahalle by a suitability-weighted gravity rule in proportion to residential absorption capacity and inverse seismic risk concentrating absorption in the low-DRI outer-ring corridor (the Moderate Rise group, principally Başakşehir, Beylikdüzü, and Tuzla), following standard

small-area downscaling practice [15]. The -1.5 to -2.0 thousand persons/year post-event decline rate corresponds to the upper tail of observed neighbourhood contraction: declines of this magnitude occurred in roughly 3% of all mahalle-year transitions during 2007–2025, against a median decline of -0.11 thousand/year.

5.4. Combined Shock (S3)

S3 superposes the economic stress of S1 and the seismic disruption of S2, representing a scenario in which earthquake recovery is complicated by fiscal constraints, inflation, and reduced household income. The demand surge in outer-ring mahalle is dampened as households cannot afford new peripheral housing at the rate assumed in S2, and inner-city recovery is slower. Under S3, city-wide population growth nearly stalls at approximately 15.0–15.4 million by 2035, the lowest of any scenario.

5.5. Urban Renewal Policy (S4)

S4 models a state-led urban renewal intervention based on Türkiye's Risky Area programme under Law No. 6306 (Urban Transformation Law, 2012) [35], applied at a greater scale and speed than has historically been realised. The top-50 highest-risk inner-city mahalle are assumed to undergo accelerated building replacement with higher floor area ratios, generating a densification increment of +500 to +1500 persons/mahalle/year from 2027 onward. Simultaneously, a regulatory cap on new residential approvals in the top-20 outer-fringe mahalle is applied from 2026, dampening fringe growth to 50% of S0. S4 is the only scenario to generate positive deviation in the stable-middle zone of the Zipf deviation plot by 2035.

6. Scenario Results

6.1. Rank-Size Distribution Under Scenarios

Under S0, the Zipf deviation profile continues to amplify the empirical U-shape. By 2035, the projected deviation at rank 1 reaches approximately +0.22 (+66% above 2007), and at rank 892 exceeds +0.65 (+346%). The aggregate Zipf exponent drifts marginally toward -1.24 . Under S1, upper-tail deviation reaches approximately +0.17 by 2035 (one-third less than S0), and lower-tail deviation is compressed to approximately +0.52. Under S2, the post-earthquake years generate a temporary W-shape in the deviation profile, with a depression in the mid-upper rank range (inner-city damage zone) combined with a spike in the outer-ring absorption zone, before resolving back toward a U-shape within approximately five years. S4 is the only scenario to show positive deviation in the stable-middle zone (ranks 50–300) by 2035, generated by risky area densification. This stable-middle reversal is reported as a modelled projection of the S4 parameterisation rather than as an observed pattern.

6.2. Density Inequality and Concentration Under Scenarios

Under S0, Q2 (suburban fringe) continues its rapid ascent, reaching an index of approximately 220–240 by 2035, while Q5 (hyper-dense inner city) declines to approximately 80. Under S1, both Q2 growth and Q5 decline are moderated but the inversion is not reversed. Under S2, the seismic event generates a temporary Q5 density collapse followed by partial recovery; Q2 density spikes in absorption years then moderates. S4 is the only scenario in which Q5 density is projected to stabilise or modestly increase from 2027, as Risky Area regeneration adds dwelling units and population to high-density districts. The Gini coefficient remains broadly stable across all scenarios except S2, where post-event displacement generates a temporary spike that subsides within approximately five years.

6.3. Spatial Redistribution Patterns

The north-western Başakşehir corridor continues to absorb population under all scenarios: 1.5–2.0 k/year under S0 and S4, slowing to 1.0–1.4 k/year under S1, and temporarily accelerating under S2 as displaced households seek alternative housing. The eastern Ümraniye–Ataşehir zone presents complex scenario-dependent dynamics: under S4, the riskli alan programme targets several Ümraniye mahalle for renewal, generating projected growth of +0.3 to +0.5 k/year from 2027, a sign reversal that would move them from Q4 toward Q3 status. The historic inner city (Fatih, Üsküdar, Beşiktaş, Kadıköy, Bahçelievler) remains in the stable-middle zone under all scenarios, though several high-vulnerability districts may experience temporary population loss under S2 that is only partially reversed by recovery-phase reconstruction.

7. Discussion

7.1. The Structural Anatomy of Istanbul's Demographic Redistribution

The empirical analysis exposes a demographic structure that aggregate statistics consistently misrepresent. Istanbul's approximately three-million-person population growth between 2007 and 2025 was concentrated at the two extremes of the size hierarchy: the very largest mahalle grew through state-directed suburban production; the very smallest through peri-urban expansion and administrative subdivision; and the established middle tier was effectively insulated by housing stock constraints and residential inertia. This dual-ended growth model describes a city undergoing simultaneous centrifugal suburbanisation (upper tail) and peripheral colonisation (lower tail), while its historic urban core maintains demographic equilibrium.

The near-stability of the aggregate Zipf exponent would, in isolation, suggest a well-behaved power-law system undergoing minor structural change. The deviation-from-baseline analysis demonstrates that this stability is deceptive: it is produced by the mutual cancellation of upper-tail concentration and lower-tail proliferation across a stable middle. A single-exponent Pareto model is insufficient to characterise the distributional dynamics; a two-component or piecewise power-law model distinguishing the upper tail, middle mass, and lower tail would more accurately represent the observed redistribution, consistent with theoretical predictions of simultaneous elite concentration and peripheral expansion [1,2,6].

7.2. Implications for Scenario Analysis and Urban Planning

The scenario analysis yields three findings with direct planning relevance. First, the baseline trajectory (S0) amplifies existing inequalities: if current trends continue, the density inversion in which the least-dense outer suburbs densify fastest while the hyper-dense inner city loses population will deepen further by 2035. Second, the seismic scenario (S2) reveals an important risk asymmetry: the mahalle most vulnerable to structural damage (Fatih, Zeytinburnu, Avcılar, Bahçelievler, Bakırköy) are predominantly located in the stable-middle zone, where demographic inertia has preserved existing populations despite substandard building stock. A major earthquake would thus strike precisely at the portion of the distribution that is otherwise least dynamically active, generating a disproportionate displacement shock. Third, S4 is the only scenario to partially reverse the density-gradient inversion by stimulating inner-city growth, but this requires sustained institutional delivery capacity under Law No. 6306 that current governance arrangements have not reliably demonstrated. Under S2, displacement demand is projected to be absorbed mainly by the outer-ring corridor; however, where displaced inner-city households cannot afford peripheral housing, particularly under S3's combined economic stress, demand instead concentrates in lower-cost, already-dense inner districts, raising crowding and worsening

housing inequality there, so the corridor's absorption capacity is contingent on affordability and not on physical supply alone.

7.3. Limitations

Several limitations warrant acknowledgement. The scenario projections are constructed at the trajectory-group level and do not model mahalle-to-mahalle migration flows explicitly; a micro-simulation approach would be more appropriate for fine-grained redistribution modelling. The seismic scenario relies on a simplified displacement-and-absorption framework without spatially explicit building damage patterns, which would require integration with geotechnical ground motion amplification maps and building stock vulnerability registers [29]. The analytical sample excludes newly created mahalle, potentially underestimating lower-tail growth in recent years. Finally, the framework does not model international migration explicitly, which has become an increasingly important driver of Istanbul's population dynamics following the influx of Syrian refugees from 2014 onward. Finally, the model operates on total population counts and does not resolve age structure; an ageing inner-city core and a youthful suburban fringe would differ in natural increase and in post-shock recovery capacity, so age-disaggregated, cohort-based modelling is a priority extension.

8. Conclusions

This paper has presented a multi-method empirical characterisation of Istanbul's intra-urban demographic dynamics for 2007–2025 and extended this baseline into a scenario-based framework projecting four alternative demographic futures to 2035. The empirical analysis documents a structurally distinctive U-shaped deviation from the Zipf baseline: growth concentrated at both extremes of the mahalle size hierarchy, with the broad middle tier of established inner-city districts functioning as a demographic anchor. This pattern is accompanied by an inversion of the density gradient: the lowest-density suburban fringe quintile recorded a 51% density gain over the study period, while the highest-density hyper-urban core quintile lost 12% of its 2007 density.

The scenario analysis demonstrates that these structural patterns are not self-correcting under plausible alternative futures. The baseline continuation amplifies the U-shape. Economic stress compresses growth rates without reversing the structural pattern. The seismic scenario generates temporary disruptions that ultimately reinforce the suburban absorption trajectory. Only the policy scenario produces a partial reversal of the density-gradient inversion, contingent on institutional delivery capacity that current governance arrangements have not reliably demonstrated.

The methodological contribution of this paper is the deviation-from-baseline Zipf plot as a diagnostic complement to the standard rank-size slope. When applied to intra-urban data, this representation serves as a spatial X-ray of demographic redistribution within the size hierarchy, making visible the structural anatomy of growth that the OLS slope absorbs and conceals. Future work should integrate this diagnostic tool with spatial regression modelling, micro-simulation of household migration decisions, and geotechnical risk assessment to produce a fully integrated framework for urban population risk analysis in Istanbul and comparable megacities at the frontier of demographic and physical vulnerability.

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draft preparation, K.Y.A. and S.K.; writing—review and editing, all authors; visualisation, Ç.G. and C.M.S.; supervision, K.Y.A.; project administration, K.Y.A.; funding acquisition, K.Y.A. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

The following abbreviations are used in this manuscript:

Meaning	Abbreviation
Address-Based Population Registration System (Adrese Dayalı Nüfus Kayıt Sistemi)	ADNKS
Coefficient of Variation	CV
Interquartile Range	IQR
Spatial Address Registry System (Mekânsal Adres Kayıt Sistemi)	MAKS
North Anatolian Fault	NAF
Ordinary Least Squares	OLS
Mass Housing Administration of Türkiye (Toplu Konut İdaresi)	TOKİ
Turkish Statistical Institute	TURKSTAT

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