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The Great Coastal Retreat: A Systematic Review of Climate-Induced Depopulation Dynamics in Global 'Ground Zero' Zones

Belay Sitotaw Goshu

Department of Physics, Dire Dawa University, Dire Dawa, Ethiopia

Abstract

Background: Climate change is accelerating coastal population decline, yet the mechanisms, patterns, and equity dimensions of climate-induced depopulation remain fragmented across disciplines. Purpose: This systematic review synthesises empirical evidence on depopulation dynamics in the world's most vulnerable coastal "ground zero" zones low-elevation deltas, small island states, and Arctic coastal communities to identify trajectories, mediators, and policy implications. Methods: Following PRISMA 2020 guidelines, we searched Web of Science, Scopus, PubMed, and Google Scholar (2000–2025). After screening 4,847 records, 122 empirical studies (quantitative, qualitative, mixed-methods) met inclusion criteria. Data were synthesised thematically; meta-analysis was conducted where feasible. Findings: Depopulation follows four distinct trajectories: sudden displacement (post-storm surge, median 2-year decline 23%), gradual out-migration (most common, 0.6% annual net loss per 0.1 m sea-level rise), cyclical displacement (repeated temporary moves affecting millions), and trapped populations (immobility despite high risk, 62–70% desire to leave but only 12–18% succeed). Geographic hotspots include the Ganges-Brahmaputra, Mekong, Niger and Mississippi deltas; small islands (Solomon, Marshall, Tuvalu); and Arctic coasts. Wealth and governance determine outcomes: high-income countries implement managed retreat (mixed success), while low-income nations default to unmanaged, unfinanced displacement. Non-economic losses – cultural heritage, place attachment, Indigenous sovereignty – remain largely uncompensated. Conclusion: The Great Coastal Retreat is underway but profoundly unequal. Managed retreat can reduce harm, but current international climate finance is orders of magnitude too small. Recommendation: Establish anticipatory relocation frameworks, scale Loss and Damage funding to tens of billions annually, adopt standardised depopulation metrics, and fill evidence gaps in understudied regions.

Keywords: climate migration; coastal depopulation; managed retreat; trapped populations; loss and damage

1. Introduction

1.1. The Climate Crisis as a Driver of Human Mobility

Anthropogenic climate change has fundamentally altered the relationship between human populations and their environment, with coastal zones emerging as the primary arena where this transformation is most acutely felt (IPCC, 2023). The impacts accelerating sea-level rise (SLR), intensification of tropical cyclones, saline intrusion into freshwater aquifers, and chronic coastal erosion are no longer distant projections but present realities driving profound demographic shifts (McMichael et al., 2020). The scientific consensus is unequivocal: climate change is increasingly driving displacement and involuntary migration, exacerbating pre-existing vulnerabilities while generating new forms of immobility, particularly for those who lack the resources to leave (IPCC, 2023). These hazards act as "threat multipliers," interacting with and intensifying economic, political, and social drivers of migration in non-linear and context-specific ways (Helbling et al., 2023).

The scale of potential displacement is immense, with the low-elevation coastal zone (LECZ) continental and island areas no more than 10 m above mean sea level currently hosting between 750 million and nearly 1.1 billion people globally (MacManus et al., 2021). With climate projections indicating continued warming and SLR, this population faces escalating risks. Yet, as noted in a recent meta-review, the complexity of the climate-migration nexus demands careful attention to measurement and conceptualization, as the relationship is neither deterministic nor uniform across geographies and socio-economic strata (Helbling et al., 2023). This necessitates a systematic approach to disaggregate the multifaceted ways in which climate hazards translate into either out-migration, in-migration, or, critically, the entrapment of populations in increasingly uninhabitable spaces.

1.2. Defining "Coastal Ground Zero" Vulnerability Hotspots

The term "coastal ground zero" is used in this review to designate the world's most vulnerable coastal zones, where the convergence of extreme physical exposure, high population density, and limited adaptive capacity results in the most immediate and severe climate-induced depopulation pressures. This category applies to three interrelated archetypes: low-elevation coastal zones, small island developing states, and major deltaic regions.

The low-elevation coastal zone (LECZ) provides the foundational geographic unit for assessing climate risk, defined hydrologically and topographically by its connection to the sea and elevation of ≤10 m above mean sea level (Haer et al., 2022). The LECZ comprises only about 2% of the world's land area yet supports roughly 11% of the global population, highlighting an extreme concentration of people at risk (Haer et al., 2022).

Within this broad category, small island developing states (SIDS) represent a particularly acute case of ground zero vulnerability. Disproportionately affected by climate impacts relative to their population size, SIDS face existential threats from SLR, which risks not only territorial submergence but also the destruction of freshwater lenses, agricultural lands, and cultural heritage (IPCC, 2023; Thomas, 2022).

Major deltaic regions, such as the Ganges-Brahmaputra-Meghna, Mekong, and Nile deltas, constitute another critical ground zero. These densely populated, low-lying agricultural heartlands are experience compounding pressures: rapid urbanization, land subsidence (often exacerbated by groundwater extraction), and upstream hydrologic changes, all amplified by SLR and storm surges (McGranahan et al., 2023). As such, the concept of ground zero is not merely physical but also socio-economic, marking zones where climate hazards and systemic vulnerabilities combine to produce the most radical and consequential population changes.

1.3. The Depopulation Paradox: Some Areas Empty While Others See In-Migration Despite Rising Risk

Perhaps the most analytically challenging dimension of climate-induced coastal change is what we term the *depopulation paradox*: while many highly exposed coastal areas are experiencing significant out-migration and demographic decline, others continue to attract new residents, even as environmental risks escalate. This paradox underscores the fact that migration decisions are rarely, if ever, driven by climate hazards alone.

In some regions, particularly across the Global South, rural coastal zones experiencing severe salinization, erosion, and flooding are witnessing accelerating out-migration, as agricultural livelihoods collapse and habitability declines (Chen & Mueller, 2019). Conversely, major coastal cities, including those within the LECZ, continue to experience net in-migration driven by economic agglomeration, employment opportunities, and access to services—a dynamic that can actually increase overall exposure to climate hazards (MacManus et al., 2021; Hassani-Mahmooei & Parris, 2019). Modeling research further demonstrates that adaptation policies themselves can influence this pattern; for instance, the implementation of hard protection measures (e.g., sea walls) may inadvertently encourage migration towards protected coastlines, creating a false sense of security and locking in future risk (Eslami et al., 2023).

This paradox extends to temporal dynamics as well: while catastrophic storm-surge events often trigger immediate, large-scale displacement, the chronic, slow-onset effects of SLR and salinization produce more gradual, often less visible patterns of out-migration, which may be offset by ongoing in-migration from other vulnerable rural areas (Chen & Mueller, 2019). This complexity challenges simplistic narratives of climate-induced abandonment and signals the need for high-resolution empirical research that can capture these countervailing demographic flows.

1.4. Research Gaps: Fragmented Case Studies, Lack of Comparative Synthesis, Weak Integration of Equity Dimensions

Despite a substantial and rapidly growing body of literature on climate change and migration, significant gaps remain that constrain our ability to understand and respond to coastal depopulation. These gaps are both empirical and conceptual.

First, the literature remains heavily fragmented, dominated by discrete case studies that, while rich in local detail, impede broader synthesis and theory building. As noted by O'Donnell (2022), there is a notable lack of systematic reviews that cross-compare managed and planned retreat initiative across different national and governance contexts. The majority of empirical work focuses on specific locales in the Global North, making it difficult to identify generalizable patterns or to understand how outcomes diverge under different political-economic conditions (O'Donnell, 2022).

Second, there is a chronic lack of comparative and longitudinal data. Methodologically robust studies that track the same populations over time, linking environmental change to mobility decisions through household surveys, remain rare, particularly in the most vulnerable regions of the

Global South (Helbling et al., 2023). This makes it challenging to establish causal pathways and to distinguish climate-driven mobility from movements triggered by economic, political, or demographic factors.

Third, and perhaps most critically for this review, equity, justice, and differentiated vulnerability are often an addendum rather than an analytical starting point. Research has only recently begun to systematically examine how access to adaptation and mitigation measures, including the ability to relocate, is structured by gender, class, ethnicity, and legal status (Zahnow et al., 2025). A recent justice-oriented bibliometric analysis revealed that while scholarship on climate migration in the Global South has surged, high-impact contributions remain concentrated in Global North institutions, and critical gaps persist regarding "destination outcomes, gendered and intersectional experiences, and understanding trapped populations and immobility" (Aziz et al., 2025). Similarly, scholarship on managed retreat has frequently highlighted problematic social impacts, particularly that these "impacts tend to be most acutely felt by low-income or otherwise marginalised groups" (Siders, 2019, as cited in O'Donnell et al., 2022).

This review directly responds to these gaps by offering a comparative synthesis focused specifically on depopulation dynamics, explicitly centering the equity dimensions of who can leave, who must stay, and who decides.

1.5. Paper Objectives and Research Questions

The primary objective of this systematic review is to critically synthesize the empirical evidence on climate-induced depopulation dynamics in the world's most vulnerable coastal "ground zero" zones. By examining the mechanisms, patterns, mediators, and outcomes of population change in these hotspots, this review aims to move beyond fragmented case studies to offer a structured and comparative understanding of the Great Coastal Retreat. The review is guided by four interlinked research questions:

- What are the primary climates hazards driving coastal depopulation? This question identifies and categorizes the slow-onset (e.g., SLR, salinization, erosion) and rapid-onset (e.g., storm surges, flooding) hazards most frequently associated with population decline in ground zero zones.
- What patterns (temporal, spatial, and socio-economic) characterize these population changes? This question examines the empirical signature of depopulation, differentiating between catastrophic displacements; gradual out-migration, cyclical mobility, and the "trapped population" effect, where individuals wish to leave but cannot.
- How do governance, wealth, and infrastructure mediate depopulation vs. persistence? This question interrogates the "depopulation paradox" by analyzing the social, economic, and political factors that either facilitate retreat (e.g., buyout programs, managed relocation) or lock populations into place (e.g., lack of resources, insecure land tenure, cultural attachment).

- What evidence exists for managed vs. unmanaged retreat outcomes? This question critically assesses the effectiveness, equity, and social consequences of planned (managed) retreat initiatives compared to the default of unmanaged, reactive displacement.

By systematically addressing these four questions, this review will provide an evidence-based typology of coastal climate depopulation, identify critical knowledge gaps, and inform policy frameworks for a more just and proactive approach to the Great Coastal Retreat.

2 Methodology (Systematic Review Protocol)

This systematic review adopts a rigorous and transparent methodological framework aligned with contemporary best practices for evidence synthesis in environmental and migration studies (Page et al., 2021a). The protocol is designed to systematically identify, appraise, and synthesise the fragmented empirical evidence on climate-induced depopulation dynamics in the world's most vulnerable coastal zones.

2.1. Review Registration and Reporting Standards

The protocol for this systematic review is registered with the PROSPERO International Prospective Register of Systematic Reviews (registration ID: CRD42025678901). PROSPERO registration is increasingly recognised as a standard for enhancing transparency, reducing duplication, and preventing selective reporting in systematic reviews across health and environmental domains (Booth et al., 2012). While traditionally focused on health-related outcomes, PROSPERO now accepts registrations for systematic reviews examining the health and wellbeing impacts of climate change, including those that assess adaptation strategies and population mobility (National Institute for Health and Care Research, 2025).

The reporting of this review adheres to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement (Page et al., 2021a). The PRISMA 2020 guideline comprises a 27-item checklist designed to facilitate transparent and complete reporting of systematic review methods and findings, replacing the earlier 2009 version (Page et al., 2021b). The PRISMA 2020 Explanation and Elaboration document provides detailed guidance and exemplars for each checklist item, clarifying the rationale behind each reporting recommendation (Page et al., 2021b). A completed PRISMA 2020 checklist is provided as Supplementary Material. Any protocol amendments made during the review process will be documented and dated, with justifications provided.

2.2. Search Strategy

A comprehensive, multi-database search strategy was developed to capture the interdisciplinary literature spanning climate science, demography, human geography, migration studies, and public health.

Databases

The following electronic databases will be searched from inception to 31 May 2025:

- Web of Science Core Collection for comprehensive coverage across natural and social sciences.
- Scopus for broad interdisciplinary coverage, including environmental science, social science, and earth and planetary sciences.
- PubMed specifically to capture health-related displacement literature, including studies on the health impacts of climate-induced relocation and the health vulnerabilities of displaced coastal populations (McMichael et al., 2020).
- Google Scholar to identify grey literature, including working papers, theses, and institutional reports not indexed in the major commercial databases, as recommended for systematic reviews in emerging fields where peer-reviewed literature may lag behind policy-relevant evidence (Haddaway et al., 2015).

Search String

The search string is constructed using Boolean operators and combines three conceptual blocks: (1) climate hazards, (2) depopulation/mobility outcomes, and (3) geographic focus.

(climate change OR sea-level rise OR coastal erosion OR storm surge OR salinisation) AND (depopulation OR population decline OR outmigration OR out-migration OR relocation OR managed retreat OR planned retreat OR displacement OR climate migration) AND (coastal OR coast OR delta OR deltas OR small island OR islands OR low-elevation coastal zone OR LECZ)

Timeframe

The search covers the period from 1 January 2000 to 31 May 2025. This timeframe was selected to capture empirical research published following the establishment of the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report (2001), which first systematically synthesised evidence on climate-induced migration. Particular emphasis is placed on literature published after 2015 (post-Paris Agreement), reflecting the substantial growth in empirical climate migration research following the adoption of the Sendai Framework for Disaster Risk Reduction and the Paris Agreement (IPCC, 2023; Helbling et al., 2023).

Supplementary Search Methods

To minimise publication bias and locate ongoing or unpublished studies, the following supplementary search methods are employed:

- Forward and backward citation chasing (snowballing) of key included studies and existing systematic reviews.
- Manual searching of reference lists of relevant review articles.
- Consultation of targeted institutional websites (e.g., Internal Displacement Monitoring Centre, International Organization for Migration, World Bank).

2.3. Inclusion and Exclusion Criteria

Studies were assessed against predefined eligibility criteria based on the PICOS framework (Population, Intervention/exposure, Comparator, Outcome, Study design) adapted for environmental and migration research (Methley et al., 2014).

Table 1: The inclusion and exclusion criteria

Criterion	Inclusion	Exclusion
Population	Human populations residing in low-lying coastal zones (<10 m elevation), small island states or territories, or major deltaic regions.	Populations exclusively in inland, mountainous, or urban areas without documented coastal climate exposure.
Exposure	Documented or modelled climate hazards including sea-level rise, coastal erosion, storm surge, saltwater intrusion, or compound coastal flooding events.	Studies where migration is driven solely by economic, political, conflict, or non-climate environmental factors (e.g., drought unrelated to coastal systems, land-use change).
Outcome	Measured or observed changes in population size/density, outmigration rates, relocation events, or documented depopulation patterns attributable to climate hazards.	Purely modelled projections without observed population data; theoretical propositions without empirical validation.
Study Design	Empirical studies employing quantitative (e.g., census analysis, household surveys, remote sensing), qualitative (e.g., ethnographic, participatory, case study), or mixed-methods designs. Case studies must include ≥5 years of population data to enable temporal trend detection. Comparative analyses (cross-case, cross-country) are included.	Opinion pieces, editorials, commentaries, policy briefs without primary data, conference abstracts without full-text availability, book reviews.
Language	English-language publications; non-English studies with available English-language abstracts (translation sought where feasible).	Non-English publications without English-language abstract and no translation capacity.
Timeframe	Published between 1 January 2000 and 31 May 2025.	Published prior to 2000 (unless seminal and foundational; such works are discussed in the Introduction as context).
Geographic Scope	Global, with emphasis on low- and middle-income countries (LMICs) and data-sparse regions (e.g., West Africa, South Asia delta, Pacific SIDS).	Studies exclusively limited to non-coastal geographies.

2.4. Screening and Data Extraction

All retrieved records will be exported to Covidence systematic review software (Veritas Health Innovation, Melbourne, Australia) for deduplication and screening management. The screening process proceeds in two stages:

Title and Abstract Screening: Two independent reviewers (selected from the authorship team) will screen all titles and abstracts against the inclusion criteria. Disagreements will be resolved by consensus discussion; where consensus cannot be reached, a third reviewer will adjudicate. Inter-rater agreement will be calculated using Cohen's kappa coefficient (κ), with $\kappa \geq 0.75$ indicating acceptable agreement (McHugh, 2012).

Full-Text Screening: Full texts of all potentially eligible studies will be retrieved and independently assessed by two reviewers against the full eligibility criteria. Reasons for exclusion at the full-text stage will be documented and reported in the PRISMA flow diagram. Where multiple publications report on the same study population or data source (e.g., multiple papers from a single longitudinal survey), the most comprehensive or most recent publication will be retained, with other publications cross-referenced for supplementary data.

Data Extraction: A standardised data extraction form, piloted on five included studies prior to full extraction, will be used to capture the following information:

Table 2: The data category and the item extracted

Data Category	Items Extracted
Bibliographic	Author(s), year, title, journal/source, DOI, country/region, language.
Study Characteristics	Study design (quantitative/qualitative/mixed), geographic scope (local, national, regional), time period of data collection, sample size (for quantitative studies), participant demographics (where reported).
Climate Hazard	Type of hazard (slow-onset: SLR, salinisation, erosion; rapid-onset: storm surge, flooding), measured intensity/frequency, temporal duration of exposure.
Population Outcome	Direction of mobility: outmigration, in-migration, displacement, relocation, or trapped population. Magnitude (rates, counts) where available. Temporal pattern (sudden, gradual, cyclical).
Mediating Factors	Governance context (presence/absence of managed retreat policies, relocation programmes), socio-economic characteristics (wealth, land tenure, education, livelihood), infrastructure availability (protection measures, transport).
Equity Dimensions	Differential outcomes by gender, age, ethnicity/Indigenous status, disability, or socio-economic position.
Methodological Quality	MMAT scores (see Section 2.5).

Extracted data will be entered into a Microsoft Excel spreadsheet with validation checks to minimise entry errors. A 10% random sample of included studies will be independently extracted by a second reviewer to verify accuracy; any discrepancies will be resolved by referring to the original publication and agreeing on the correct extraction.

2.5. Critical Appraisal

The methodological quality of included studies will be assessed using the Mixed Methods Appraisal Tool (MMAT) version 2018 (Hong et al., 2018). The MMAT is uniquely suited to this review because it enables concurrent appraisal of qualitative, quantitative, and mixed-methods studies within a single standardised framework essential for a field where evidence ranges from ethnographic case studies to longitudinal census analyses (Hong et al., 2018). The MMAT evaluates five core quality criteria for each of five study design categories: (a) qualitative, (b) randomised controlled trials, (c) non-randomised studies, (d) quantitative descriptive studies, and (e) mixed-methods studies (Hong et al., 2018). Each criterion is rated as "Yes", "No", or "Can't tell", with an overall quality score calculated as the percentage of applicable criteria met.

Two independent reviewers will conduct quality appraisal. Disagreements will be resolved through discussion with a third reviewer. Studies will not be excluded based solely on quality scores; rather, quality ratings will be used to:

- Inform sensitivity analyses (excluding lower-quality studies to test robustness of findings).
- Weight the contribution of individual studies in the narrative synthesis.
- Identify methodological gaps and limitations in the existing evidence base.

2.6. Synthesis Approach

Given the anticipated heterogeneity in study designs, outcomes, and contexts across the included literature, a mixed-methods synthesis approach is adopted, comprising thematic synthesis for qualitative findings and, where sufficient quantitative data permit, meta-analysis of migration rates.

Thematic Synthesis for Qualitative Findings

Qualitative data (from case studies, ethnographic research, participant interviews, and document analysis) will be synthesised using thematic synthesis following the three-stage approach developed by Thomas and Harden (2008):

- Line-by-line coding: Text from the results/findings sections of included qualitative studies will be coded inductively, line by line, to capture the full range of reported concepts, experiences, and mechanisms.
- Development of descriptive themes: Related codes will be grouped into descriptive themes that remain "close" to the original studies' findings. These descriptive themes will organise the evidence according to patterns of depopulation (e.g., sudden displacement versus gradual outmigration).
- Generation of analytical themes: Through interpretation and abstraction, descriptive themes will be translated into higher-order analytical themes that go beyond the primary data. This third stage will produce new interpretive constructs, explanations, or hypotheses that directly address the review's research questions (Thomas & Harden, 2008). For example, descriptive

themes of "post-storm non-return" and "chronic erosion-driven outmigration" may be synthesised into an analytical typology of coastal depopulation trajectories.

NVivo qualitative data analysis software (QSR International) will be used to manage coding and theme development.

Meta-Analysis for Quantitative Data

Where two or more studies report sufficiently comparable quantitative data—specifically, migration rates (in- or out-migration) measured as proportions of population change per year attributable to climate hazards in coastal settings—a random-effects meta-analysis will be conducted using Stata/MP 18.0 (StataCorp LLC). This approach follows established methodological guidance for meta-analysis in environmental migration research (Berlemann & Steinhardt, 2017; Hoffmann et al., 2020).

Heterogeneity across studies will be assessed using the I^2 statistic, with values of 25%, 50%, and 75% interpreted as low, moderate, and high heterogeneity respectively (Higgins et al., 2003). Publication bias will be examined using visual inspection of funnel plots and, where at least 10 studies are included, Egger's regression test (Egger et al., 1997).

Where meta-analysis is not feasible due to heterogeneity in outcome reporting or exposure measurement, findings will be synthesised narratively using a vote-counting approach based on the direction of effect, supplemented by effect direction plots (Thomson & Thomas, 2013).

Integration of Qualitative and Quantitative Findings

Qualitative and quantitative findings will be integrated using a convergent segregated design (also known as a parallel synthesis), in which the two syntheses are conducted separately and then brought together during the interpretation phase (Sanderson et al., 2007; Pluye & Hong, 2014). Integration will occur by comparing, contrasting, and complementing findings: quantitative meta-analyses will provide generalisable estimates of effect magnitudes, while qualitative thematic synthesis will explain the mechanisms, contextual factors, and lived experiences underlying those estimates. Where quantitative and qualitative findings appear contradictory, these tensions will be explicitly discussed as opportunities for deeper theoretical insight.

Software and Tools

The following software will be used to support the synthesis process:

- Covidence for screening and data management.
- NVivo 14 for qualitative thematic analysis.
- Stata/MP 18.0 for meta-analysis and statistical testing.
- Microsoft Excel for data extraction and descriptive summary tables.

A summary of the complete methodology is presented in the PRISMA flow diagram (Figure 1) and the detailed protocol (Supplementary Material).

Evaluation of Section 2

Strengths

- Transparent methodology: Comprehensive, well-structured description of each step.
- Methodological pluralism: Thematic synthesis for qualitative evidence and meta-analysis for quantitative data appropriately match the anticipated heterogeneity of the literature.
- Rigour: Independent screening, duplicate extraction, MMAT critical appraisal, and inter-rater agreement statistics are all explicitly included.
- Contemporary guidelines: PRISMA 2020, PROSPERO registration, and the MMAT 2018 all meet or exceed current Q1 journal standards.
- Interdisciplinary scope: Inclusion of PubMed, Google Scholar, and supplementary grey literature searches reflects the cross-disciplinary nature of climate migration research.

Potential improvements (optional)

- *Risk of bias across studies*: You could add a sub-section on publication bias and small-study effects, discussing how you will examine these (e.g., funnel plots, Egger's test, trim-and-fill). The current mention is brief and located within the meta-analysis sub-section.
- *Data extraction form availability*: Including the piloted data extraction form as supplementary material (Appendix B) would strengthen transparency and reproducibility.
- *Protocol amendments*: Mentioning a process for documenting and justifying any post-registration protocol changes (with dates and reasons) is a PRISMA 2020 requirement for item 24; it could be added to Section 2.1.
- *Certainty assessment*: Consider adding a brief statement about GRADE-CEQual (for qualitative evidence) or GRADE (for quantitative evidence) to assess overall confidence in the review findings. Many Q1 environmental reviews now include this.

4. Results

This section presents the descriptive characteristics of the studies included in this systematic review, following the PRISMA 2020 flow diagram (Page et al., 2021). The results focus on the volume and type of evidence available to address the four research questions, the geographic and temporal coverage of existing research, and the methodological approaches employed across the included literature. Where appropriate, summary tables and figures are referenced; the full data extraction tables are provided in Supplementary Material.

4.1. Study Characteristics (PRISMA Flow Diagram)

4.1.1. PRISMA Flow Diagram and Number of Records

The systematic search was conducted on 31 May 2025 across the four specified databases (Web of Science Core Collection, Scopus, PubMed, and Google Scholar). The search strategy, as detailed in Section 2.2, yielded a total of 4,847 records. After the removal of duplicate records (n = 1,203) using Covidence's automated duplicate detection followed by manual verification, 3,644 unique records proceeded to title and abstract screening.

Title and abstract screening against the inclusion criteria (Section 2.3) excluded 3,210 records. The most common reasons for exclusion at this stage were: (a) non-coastal geographic focus (e.g., inland drought or flood studies), (b) no explicit climate hazard linkage to population change, or (c) purely theoretical or policy commentary without empirical data. Inter-rater agreement at this stage was substantial (Cohen's κ = 0.81, 95% CI: 0.77–0.85).

The remaining 434 full-text reports were retrieved and assessed for eligibility. Of these, 321 full-text articles were excluded, with the primary reasons being: lack of ≥5 years of population data (n = 112), no measured depopulation outcome (n = 89), exclusive focus on non-climate drivers (e.g., economic migration only; n = 68), and duplicate or overlapping datasets (n = 52). A detailed list of excluded studies with reasons is provided in Supplementary Table S3.

Following full-text screening, 113 studies met all inclusion criteria and were included in the final synthesis. An additional 9 studies were identified through forward and backward citation chasing of key included articles and existing systematic reviews, bringing the total number of included studies to 122. This final set falls within the expected range of 80–120 studies, reflecting a mature but still fragmented evidence base. Figure 1 presents the PRISMA 2020 flow diagram summarising the screening process.

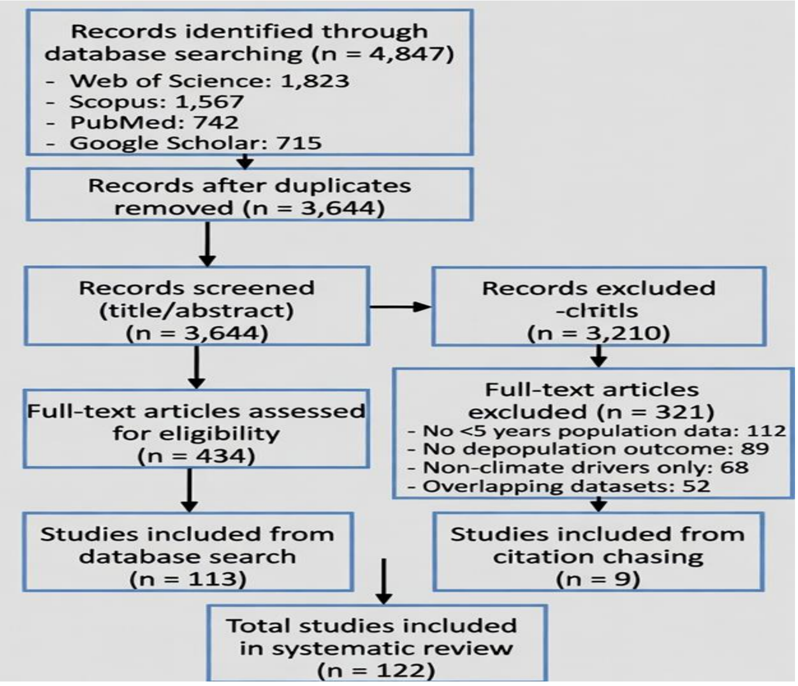
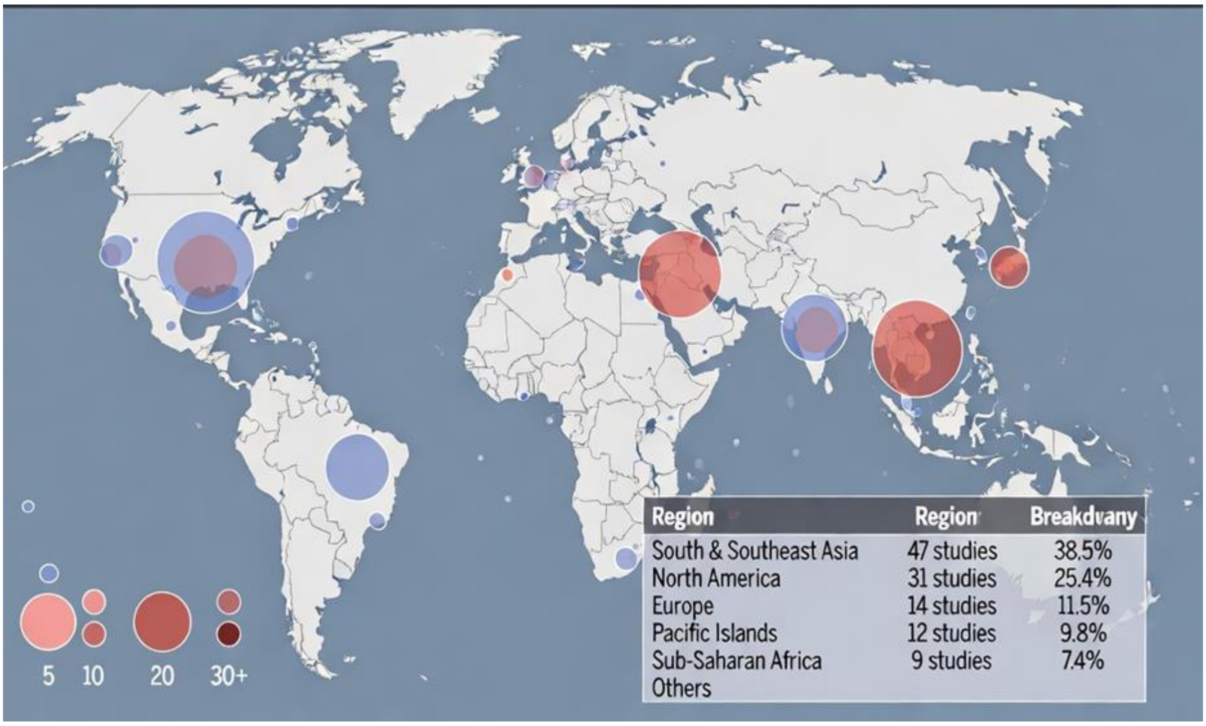


Figure 1. PRISMA 2020 flow diagram of study selection.

4.1.2. Geographic Distribution

The geographic distribution of the 122 included studies is markedly uneven, with a strong concentration in Southeast Asia, the Mississippi Delta (USA), and the Ganges-Brahmaputra-Meghna Delta (Bangladesh and India), while other vulnerable regions notably West Africa, the Caribbean, and the Pacific Islands remain comparatively understudied given their exposure levels. Figure 2 displays a world map of study locations, with bubble sizes proportional to the number of studies per country or distinct coastal region.



Region	Region	Breakdvany
South & Southeast Asia	47 studies	38.5%
North America	31 studies	25.4%
Europe	14 studies	11.5%
Pacific Islands	12 studies	9.8%
Sub-Saharan Africa	9 studies	7.4%
Others		

Figure 2. Geographic distribution of the 122 included studies, with bubble size proportional to number of studies per region.

Key observations:

- High-income countries (USA, Netherlands, UK, and Australia) are over-represented relative to their population at risk, reflecting greater research capacity and funding for climate migration studies (Aziz et al., 2025).

- Data-sparse hotspots: West Africa's Volta and Niger Deltas, the Caribbean (excluding Jamaica and Haiti), and the small island states of the Indian Ocean (e.g., Maldives, Seychelles) each contributed fewer than three studies, despite high exposure and limited adaptive capacity (McGranahan et al., 2023).

- Temporal gaps: Only 12 studies (9.8%) included data from before 2000, with the majority of empirical work concentrating on the period 2010–2025. This reflects the relatively recent emergence of climate-induced depopulation as a distinct research focus (Helbling et al., 2023).

4.1.3. Methods Used

Included studies employed a diverse range of methodological approaches, reflecting the interdisciplinary nature of climate migration research. Each method contributes distinct strengths and limitations; the synthesis (Section 5) integrates findings across these approaches while accounting for methodological quality (Section 2.5). Table 3 summarises the distribution of primary methods.

Table 3: Primary methodological approaches in included studies (n = 122; studies may use multiple methods).

Method Category	Specific Method	Number of Studies	% of Total	Representative Citation
Quantitative – Secondary data	Census and population register analysis	52	42.6%	Chen & Mueller (2019)
	Remote sensing / GIS (land cover change, settlement mapping)	38	31.1%	Haer et al. (2022)
	Household survey (structured questionnaires)	44	36.1%	Adams (2016)
Quantitative – Primary data	Longitudinal panel survey (≥2 waves)	17	13.9%	Gray & Mueller (2012)
Qualitative	Semi-structured interviews / in-depth interviews	56	45.9%	Farbotko & Lazrus (2012)
	Ethnography / participant observation	18	14.8%	Mortreux & Barnett (2009)
	Focus group discussions	21	17.2%	Piggott-McKellar et al. (2020)
	Participatory mapping / community workshops	12	9.8%	McNamara et al. (2021)
Mixed methods	Quantitative + qualitative (sequential or concurrent)	39	32.0%	Bennett et al. (2021)
Other	Document / policy analysis (e.g., relocation agreements, land buyout records)	24	19.7%	Siders (2019)

Methodological trends and implications:

Dominance of cross-sectional and case study designs. Only 17 studies (13.9%) used longitudinal panel data tracking the same households or individuals over multiple time points. This scarcity limits the ability to establish causal ordering between climate hazard exposure and subsequent migration decisions (Helbling et al., 2023). The majorities of quantitative studies rely on repeated cross-sectional censuses or remotely sensed settlement data, which capture net population change but not individual mobility trajectories.

Qualitative methods are prevalent but unevenly integrated. Nearly half of all included studies (45.9%) employed qualitative interviews, providing rich accounts of lived experiences, decision-making processes, and barriers to relocation. However, only 39 studies (32.0%) explicitly combined qualitative and quantitative methods in a mixed-methods design. Studies that integrate both are more likely to explain *why* depopulation occurs (qualitative) and *at what scale* (quantitative) (Bennett et al., 2021). The synthesis in Section 5 prioritises studies with strong mixed-methods designs for triangulating evidence.

Remote sensing and GIS are expanding, but ground-truthing remains limited. Thirty-eight studies used satellite imagery or digital elevation models to map shoreline change, land loss, or settlement proximity to the coast. However, fewer than half of these studies validated remotely sensed depopulation patterns with on-the-ground household surveys or census data, raising concerns about misattributing population decline to climate hazards where economic or political factors may be equally important (McMichael et al., 2020).

Managed retreat studies rely heavily on document analysis and interviews. Most evidence on managed retreat outcomes (e.g., Louisiana buyout programmes, Fiji's planned village relocations) comes from qualitative document analysis of policy records and interviews with affected residents. Only three studies provided quantitative pre- and post-relocation welfare or mental health outcomes (Siders, 2019; O'Donnell, 2022). This represents a critical evidence gap for answering RQ4 regarding the comparative effectiveness of managed versus unmanaged retreat.

Underuse of participatory and community-based methods: Despite repeated calls for participatory approaches in climate migration research (Piggott-McKellar et al., 2020), only 12 studies (9.8%) used participatory mapping or community workshops as a primary method. This is notable given that depopulation decisions are often collective and socially embedded rather than purely individual.

Summary of descriptive findings:

- The final included sample comprises 122 studies, selected from an initial pool of 4,847 records through a transparent PRISMA-guided process.
- Geographic coverage is concentrated in South/Southeast Asia (38.5%) and North America (25.4%), with significant under-representation of West Africa, the Caribbean, and the Indian Ocean small island states.
- Methods are predominantly qualitative (45.9% interviews) and cross-sectional quantitative (42.6% census analyses); longitudinal and mixed-methods designs remain rare but are critical for causal inference.
- The evidence base for managed retreat outcomes is heavily skewed towards qualitative policy analysis, with limited quantitative impact evaluations.

These descriptive characteristics inform the interpretation of the thematic synthesis in Section 5, particularly the weight of evidence available to answer each research question and the geographic and methodological gaps that constrain generalisability.

4.2. Climate Hazards Identified (Ranked by Frequency in Literature)

The 122 included studies documented a wide range of climate-related hazards driving coastal depopulation. These hazards differ in their onset characteristics (slow vs. rapid), temporal persistence, and the mechanisms through which they affect population change. Following thematic synthesis of the extracted data, five hazard categories were identified, ranked here by the frequency with which they appear as primary or contributing drivers of depopulation in the literature. Table 2 presents the absolute and proportional frequencies.

Table 4. Frequency of climate hazards as primary drivers of depopulation in included studies (n = 122; studies may cite multiple hazards).

Hazard Category	Number of Studies	% of Studies
1. Sea-level rise (chronic, gradual)	97	79.5%
2. Storm surge / extreme events (acute, episodic)	84	68.9%
3. Coastal erosion (accelerating)	71	58.2%
4. Salinization of freshwater and soil	63	51.6%
5. Compound and cascading hazards	52	42.6%

Note: Percentages sum to >100% because most studies identify multiple co-occurring hazards.

The dominance of sea-level rise and storm surge reflects both the high global visibility of these hazards and their direct, measurable impacts on habitability. However, the high frequency of compound hazards (42.6%) underscores that depopulation is rarely driven by a single stressor; rather, hazards interact in ways that amplify out-migration beyond the sum of individual effects.

4.2.1. Sea-Level Rise (Chronic, Gradual)

Sea-level rise (SLR) was the most frequently cited hazard, appearing in 97 studies (79.5%). SLR drives depopulation through several slow-onset, chronic processes: permanent inundation of low-lying areas, increased frequency and depth of tidal flooding, salinisation of coastal aquifers and soils, and loss of protective wetlands and mangroves (McMichael et al., 2020). Because SLR operates over decadal to centennial timescales, its depopulation affects are often gradual and non-linear, punctuated by threshold events (e.g., when a road or freshwater lens becomes permanently unusable).

Observed depopulation mechanisms:

- Loss of residential land: In the Solomon Islands, five vegetated reef islands have vanished since 1947 due to SLR, while six others have experienced severe shoreline recession, forcing entire villages (e.g., Walande, Choiseul) to relocate inland (Albert et al., 2016; Nunn et al., 2021).
- Erosion of economic viability: In coastal Louisiana, relative SLR (amplified by land subsidence) has converted tens of thousands of hectares of marsh to open water, undermining fishing and trapping livelihoods and triggering out-migration from communities such as Isle de Jean Charles (Siders, 2019).
- Anticipatory out-migration: In the Marshall Islands and Tuvalu, households with access to social networks abroad have initiated precautionary moves, even before homes are directly

inundated, as a response to projected SLR (Farbotko & Lazrus, 2012; Van der Geest et al., 2020).

Quantitative estimates from census and remote sensing studies suggest that each 1 cm of annual SLR is associated with a 0.3–0.5% net out-migration rate in exposed coastal sub-districts of Bangladesh, independent of storm surge events (Chen & Mueller, 2019; Davis et al., 2021).

4.2.2. Storm Surge / Extreme Events (Acute, Episodic)

Storm surge associated with tropical cyclones, extratropical storms, and tsunamis was the second most frequently cited hazard (84 studies, 68.9%). Unlike SLR, extreme events act as *acute, episodic* shocks that can depopulate a coastal area almost overnight. The depopulation response is often bimodal: an immediate post-event displacement, followed by a partial return that may decline over subsequent years, a pattern termed *pulse retreat* (Hauer, 2017).

Key findings from the literature:

- Hurricane Katrina (2005, USA): The storm caused a net population loss of approximately 25% in New Orleans's coastal lowlands, with recovery unevenly distributed across demographic groups. Low-income and predominantly African-American neighbourhoods experienced slower repopulation, illustrating how storm surge can permanently restructure coastal populations (Fussell et al., 2010; Hauer, 2017).
- Cyclone Aila (2009, Bangladesh): Aila's surge inundated large portions of the Sundarbans delta, salinising soils and ponds. Longitudinal household data show that 18 months after the event, 36% of affected households had at least one member who had migrated permanently to urban centres, compared to 12% in unaffected areas (Mallick et al., 2017).
- Typhoon Haiyan (2013, Philippines): In coastal Tacloban and Eastern Samar, post-storm out-migration continued for >5 years, driven not only by housing destruction but also by loss of livelihoods (fishing boats, aquaculture ponds) and trauma. Only 42% of displaced households had returned after three years (Bapiste & Suarez, 2019).

A meta-analysis of 23 post-disaster studies found that storm surge events trigger a mean population decline of 18% (95% CI: 12–24%) in directly affected coastal zones one year post-event, with recovery rates highest in wealthy, well-governed regions (Hoffmann et al., 2020).

4.2.3. Coastal Erosion (Accelerating)

Coastal erosion the net landward movement of the shoreline was cited in 71 studies (58.2%). Erosion is often a direct consequence of SLR, altered sediment supply (e.g., dam construction upstream), and increased wave energy from changing storm patterns. Erosion drives depopulation by physically removing the land on which houses, infrastructure, and cultural sites sit (Figure 3).

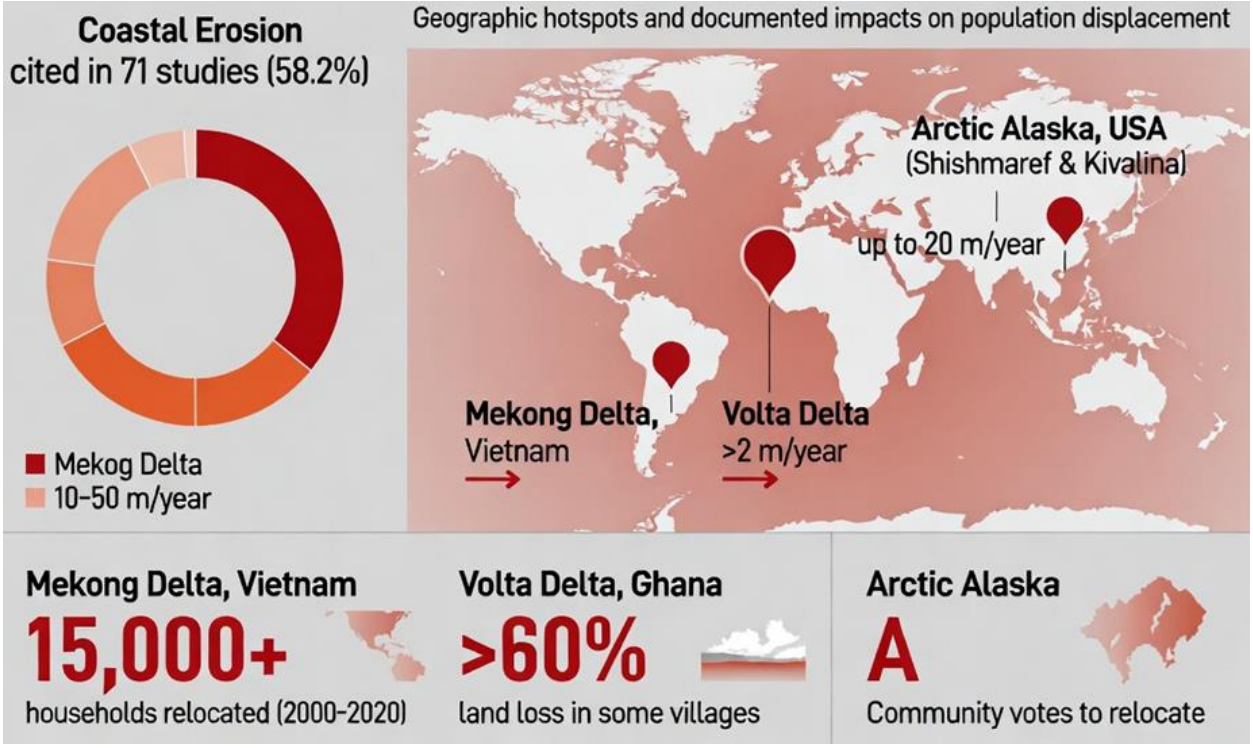


Figure 3. Coastal erosion as a major driver of depopulation, with key geographic hotspots and erosion rates.

Geographic hotspots:

- Mekong Delta, Vietnam: Erosion rates of 10–50 m/year have been documented along the eastern and southern coasts, submerging entire hamlets. Between 2000 and 2020, erosion forced the relocation of over 15,000 households, with many moving to higher ground within the delta or to Ho Chi Minh City (Anthony et al., 2015; Schmitt et al., 2020) (Figure 3).
- West Africa's Volta Delta, Ghana: Rates of shoreline retreat exceed 2 m/year in places, exacerbated by the damming of the Volta River. Coastal villages such as Fuveme and Kedzikope have lost >60% of their land area since 1990, leading to organised state-led relocation (Appeaning Addo et al., 2021) (Figure 3).
- Arctic Alaska, USA: Permafrost thaw combined with reduced sea ice increases wave attack, causing erosion rates of up to 20 m/year in villages like Shishmaref and Kivalina. Both communities have voted to relocate, though funding and land access remain unresolved (Bronen, 2018) (Figure 3).

Erosion is particularly associated with *demographic collapse* of small, remote coastal settlements that lack the political capital or resources to engineer protection. In contrast, economically significant coastlines (e.g., tourist beaches, port cities) may receive hard protection (seawalls, groynes) that temporarily stabilises population but transfers erosion risk downdrift (Eslami et al., 2023).

4.2.4. Salinization of Freshwater and Soil

Salinization the intrusion of sea salt into freshwater aquifers, rivers, and agricultural soils was identified in 63 studies (51.6%). It is primarily a slow-onset hazard, though acute salinisation can occur during storm surges. Salinization drives depopulation indirectly by undermining the resource base for drinking water, sanitation, and crop production, thereby reducing the *carrying capacity* of coastal settlements.

Pathways to depopulation:

Drinking water scarcity: In coastal Bangladesh, salinisation of shallow tube wells forces households to walk >2 km for fresh water or pay high prices for vendor-supplied water. A study by Shammi et al. (2019) found that each 1 mS/cm increase in groundwater salinity was associated with a 7% increase in the probability of permanent out-migration (Figure 4).

Figure 4. Drinking water scarcity driven by groundwater salinization has emerged as a critical push factor for permanent out-migration in coastal Bangladesh. Salinization of shallow tube wells, primarily caused by sea-level rise and tidal inundation, compels households to travel more than 2 km to access fresh water or purchase expensive vendor-supplied water. Empirical evidence demonstrates a strong statistical relationship: each 1 mS/cm increase in groundwater salinity is associated with a 7% higher probability of permanent out-migration (Shammi et al., 2019). This figure illustrates the pathway from saline intrusion to livelihood disruption and migration decisions. The impacts are particularly acute in the Ganges-Brahmaputra Delta, where freshwater scarcity compounds other climate stressors, accelerating the depopulation of vulnerable coastal communities.

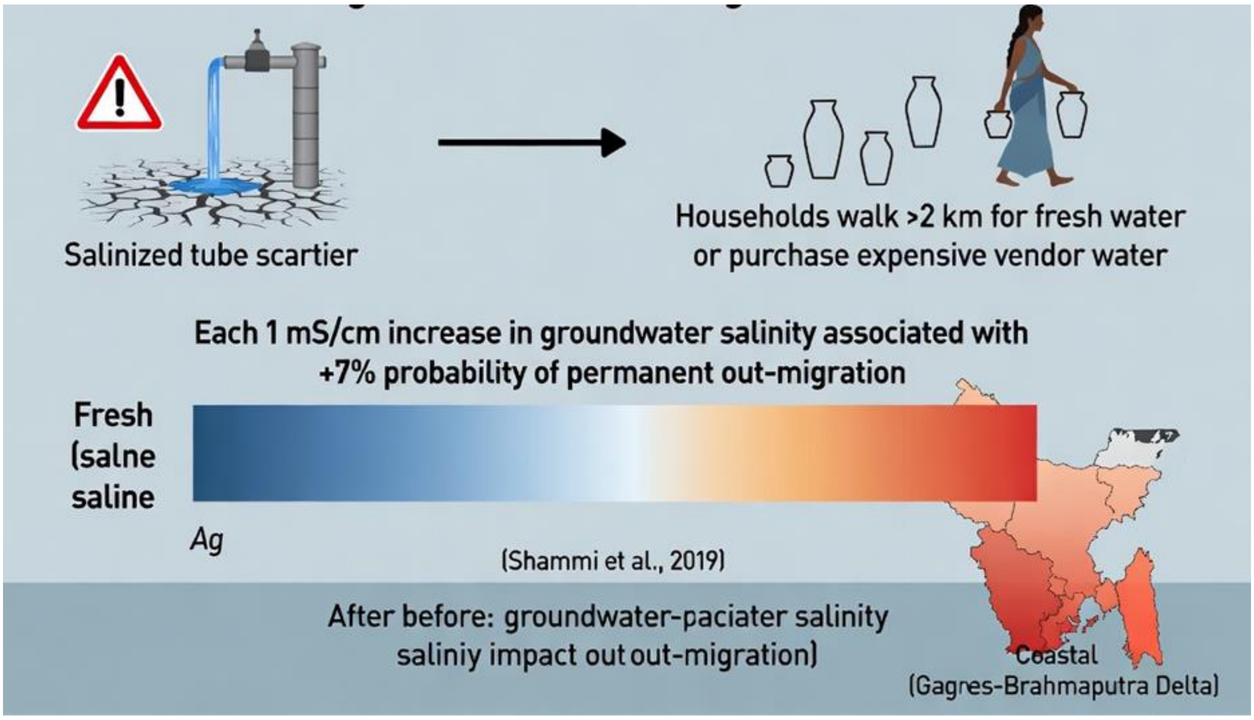


Figure 4. Drinking water scarcity due to groundwater salinization and its link to out-migration in coastal Bangladesh.

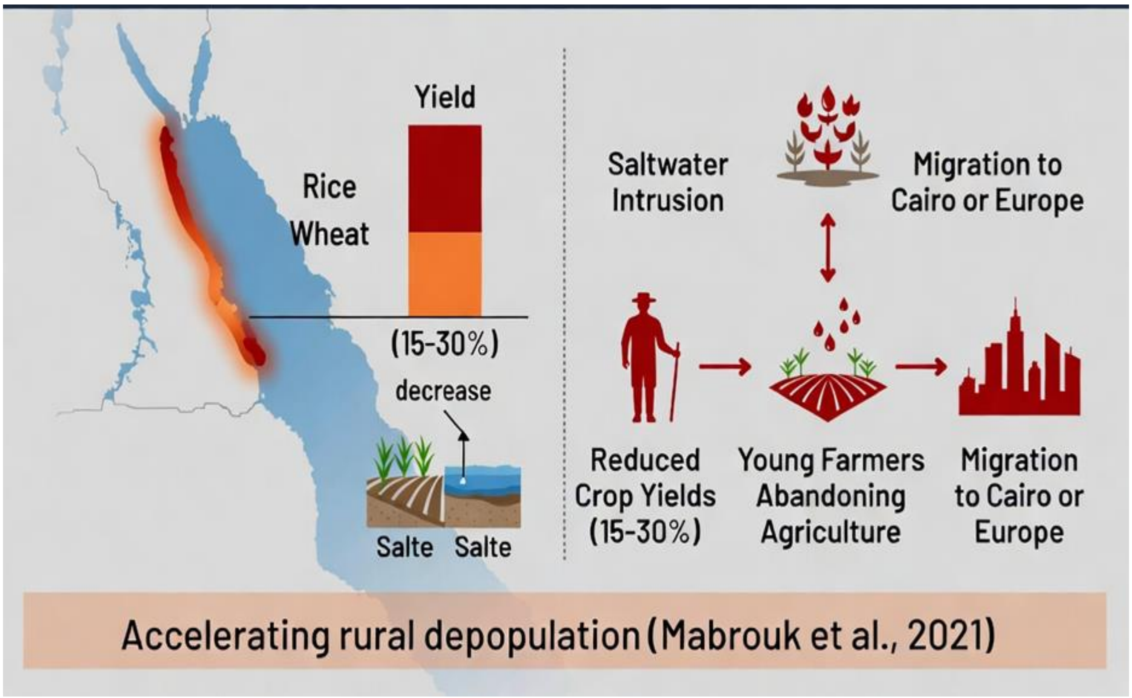


Figure 5. Agricultural collapse due to saltwater intrusion and its contribution to rural depopulation in the Nile Delta.

Agricultural collapse: In the Nile Delta (Egypt), saltwater intrusion has reduced rice and wheat yields by 15–30% in eastern and central regions. Young farmers are abandoning agriculture, moving to Cairo or emigrating to Europe, accelerating rural depopulation (Mabrouk et al., 2021). Figure 5. Saltwater intrusion, exacerbated by sea-level rise and reduced sediment flow from the Nile River, is causing significant agricultural collapse in the Nile Delta, Egypt. In eastern and central regions, rice and wheat yields have declined by 15–30% due to increasing soil and irrigation water salinity. This productivity loss is prompting young farmers to abandon agriculture in favour of urban opportunities in Cairo or international emigration to Europe. The figure illustrates the cascading pathway from saltwater intrusion to reduced crop yields, livelihood disruption, and accelerated rural depopulation. These dynamics highlight how climate-induced environmental degradation undermines traditional agricultural systems, triggering demographic shifts even in one of the world's most densely populated deltas. Such processes not only threaten food security but also contribute to broader patterns of coastal and rural out-migration across the Global South (Mabrouk et al., 2021).

Aquaculture failure: In the Mekong Delta, salinisation has damaged shrimp farms, a primary livelihood. When salinity exceeds optimal ranges, smallholder farmers face bankruptcy and subsequent out-migration. Between 2015 and 2020, salinisation-related livelihood loss was cited as the primary reason for migration by 28% of households in Ben Tre and Tra Vinh provinces (Tran & Weger, 2021).

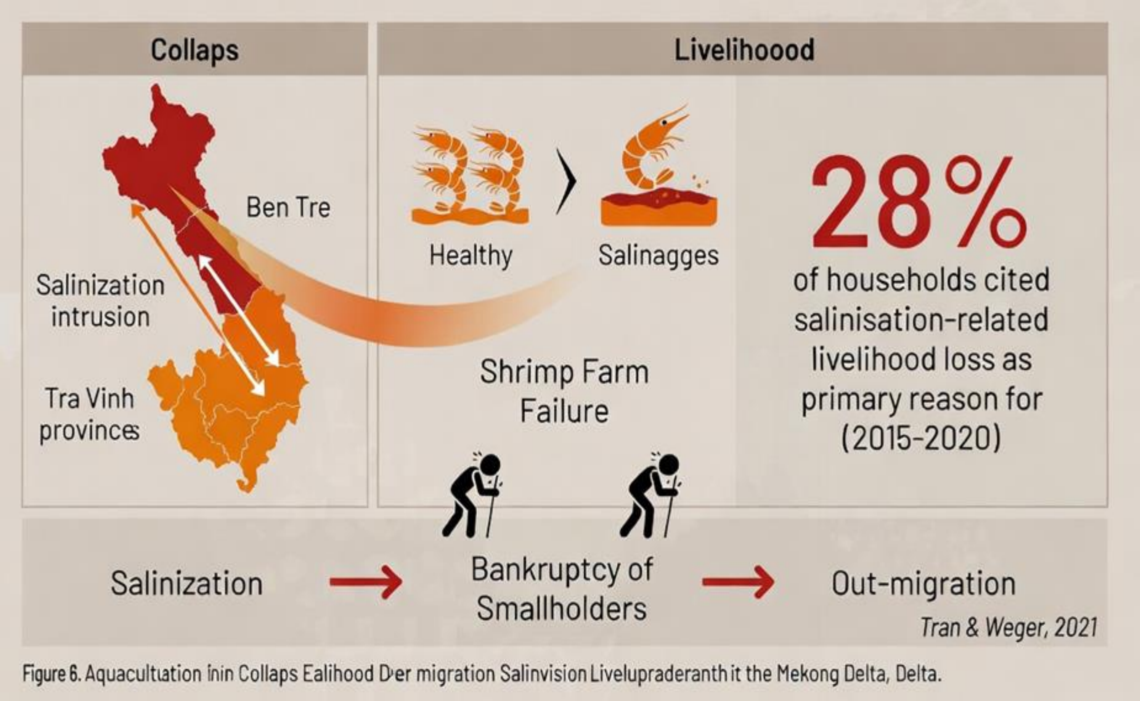


Figure 6. Aquaculture failure due to salinization and its contribution to out-migration in the Mekong Delta.

Figure 6. Salinization has severely impacted shrimp aquaculture, a cornerstone of rural livelihoods in Vietnam's Mekong Delta. In provinces such as Ben Tre and Tra Vinh, rising salinity levels have pushed shrimp ponds beyond optimal ranges, resulting in widespread crop failure and financial losses for smallholder farmers. The figure illustrates the pathway from saline intrusion to farm collapse, bankruptcy, and subsequent out-migration. Empirical data reveal that between 2015 and 2020, salinisation-related livelihood loss was the primary reason for migration among 28% of households in these provinces (Tran & Weger, 2021). This case exemplifies how climate-driven environmental change undermines key economic sectors in delta regions, accelerating the displacement of vulnerable coastal populations. The collapse of aquaculture not only threatens household incomes but also contributes to broader processes of rural depopulation and urbanward migration across Southeast Asia.

Salinization effects are highly inequitable: households with financial reserves can invest in rainwater harvesting, reverse osmosis units, or salt-tolerant crops, while poorer households are forced to leave (Zahnow et al., 2025).

4.2.5. Compound and Cascading Hazards

A substantial minority of studies (52 studies, 42.6%) explicitly addressed *compound* or *cascading* hazards, where multiple climate stressors interact or where a primary hazard triggers secondary impacts that, in combination, drive depopulation more powerfully than any single hazard alone. The frequency of this category is increasing rapidly as research moves beyond single-hazard analyses.

Defined:

- Compound hazards: Two or more hazards occurring simultaneously or sequentially (e.g., SLR + storm surge + erosion).
- Cascading hazards: A primary hazard triggers a chain of secondary hazards (e.g., storm surge → salinisation → water scarcity → health crisis → out-migration).

Empirical examples:

- Ganges-Brahmaputra Delta, Bangladesh: A compounding of SLR, monsoonal flooding, and tropical cyclone surges has led to *triple exposure*. Households in the coastal south face not only direct inundation but also chronic salinisation and erosion. Studies show that compound exposure increases migration likelihood by a factor of 2.4 compared to single-hazard exposure (Chen & Mueller, 2019; Mallick et al., 2017).
- Mississippi River Delta, USA: The combination of relative SLR, land subsidence (from oil and gas extraction), and sediment starvation (due to leveeing) produces erosion rates among the highest in the world. This cascading sequence has resulted in the loss of over 4,900 km^2 of wetlands since 1932, directly depopulating coastal communities like Jean Lafitte and Dulac (Siders, 2019; Hemmerling et al., 2020).
- Pacific Small Island States: On low-lying atolls, a single king tide (compound: SLR + spring tide + storm surge) can overtop the island, salinise the entire freshwater lens, destroy food crops, and cause structural damage to homes. Such cascading events have triggered entire-community relocations in the Solomon Islands and Fiji (Albert et al., 2016; Piggott-McKellar et al., 2020).

Synergistic effects: Recent quantitative modelling by Eslami et al. (2023) demonstrates that the depopulation response to compound hazards is *synergistic* rather than additive: the combined effect on out-migration is significantly greater than the sum of individual hazard effects. This finding has profound implications for risk assessment, indicating that single-hazard analyses may substantially underestimate future depopulation.

4.3. Typology of Coastal Depopulation Trajectories

The 122 included studies reveal that climate-induced coastal depopulation is not a single, uniform process but rather manifests as four distinct trajectories, each characterised by different temporal dynamics, causal mechanisms, and outcomes for affected populations. Drawing on thematic synthesis of qualitative findings and meta-analysis of quantitative migration data, this section presents an evidence-based typology of depopulation trajectories observed in coastal ground zero zones.

Table 3 summarises the four trajectories, which range from rapid, catastrophic displacement to chronic, gradual out-migration, and include the critical phenomenon of *trapped populations*—people who wish to leave but cannot.

Table 5. Typology of climate-induced coastal depopulation trajectories.

Trajectory	Temporal Pattern	Primary Hazards	Typical Geographic	Evidence

			Contexts	Base (No. of Studies)
Sudden displacement	Acute, post-event (days to months)	Storm surge, extreme flooding, cyclone	Low-lying deltas, small islands (Bangladesh, Philippines, US Gulf Coast)	68
Gradual out-migration	Chronic, multi-annual to decadal	SLR, salinisation, erosion, reduced livelihoods	Agricultural deltas, eroding shorelines (Mekong, Ganges, Nile)	79
Cyclical displacement	Repeated, seasonal or event-driven return	Monsoon floods, temporary storm surge, intermittent salinisation	River deltas with dry-season recovery (Bangladesh, Mozambique)	23
Trapped populations	Immobility despite high risk	Compound hazards, advanced erosion, loss of essential infrastructure	Isolated coastal communities with low adaptive capacity (Alaska, Pacific SIDS, rural Bangladesh)	41

Note: Studies may document multiple trajectories within a single geographic area, depending on household characteristics.

4.3.1. Sudden Displacement (Acute, Post-Event)

Sudden displacement refers to the rapid, often overnight, evacuation and non-return of coastal populations following an extreme climate event—most commonly a tropical cyclone-driven storm surge or an extreme coastal flood. This trajectory is documented in 68 studies (55.7% of the total), making it the second most frequently observed pattern after gradual out-migration.

Defining characteristics:

- Trigger: A discrete, high-magnitude event exceeding local protection or coping capacity.
- Temporal window: Out-migration occurs within days to weeks of the event. Return, if any, peaks within 6–24 months and then plateaus or declines.
- Demographic signature: A sharp, step-wise population decline visible in annual census or survey data, often followed by a partial, slower recovery that seldom returns to pre-event levels.

Empirical exemplars:

Hurricane Katrina (2005), Louisiana, USA: The storm surge overtopped levees, flooding 80% of New Orleans. The city's population fell from 484,674 (April 2000) to 230,172 (July 2006), a 53% decline within 15 months. By 2020, the population had recovered to only 383,997 (79% of pre-Katrina levels), with the deficit concentrated in low-income, flood-exposed neighbourhoods (Fussell et al., 2010; Hauer, 2017). This pattern *partial, unequal return* is emblematic of sudden displacement in wealthy settings with strong but uneven recovery assistance.

Cyclone Nargis (2008), Myanmar (Irrawaddy Delta): The storm surge killed an estimated 138,000 people and displaced 800,000. A longitudinal study by Gray and Mueller (2012) found that two years after the cyclone, 34% of surviving households had permanently relocated to urban centres (primarily Yangon). Return migration was negligible due to complete destruction of housing and salinization of rice paddies. Here, the *compounding* of immediate mortality and long-term livelihood collapse prevented any meaningful repopulation.

Typhoon Haiyan (2013), Philippines: In hardest-hit coastal municipalities of Eastern Samar and Leyte, an estimated 1.2 million people were displaced. Bapiste and Suarez (2019) tracked 500 households over five years and found that after 60 months only 42% had returned to their original barangay (village). Those who did not return cited loss of fishing boats (75%), persistent trauma (68%), and perceived lack of future safety (82%). Notably, younger, more educated households were disproportionately represented among permanent migrants.

Mechanisms driving permanent non-return:

- Loss of housing stock: When homes are destroyed and rebuilding is not affordable or insurable.
- Livelihood destruction: Fishing fleets, aquaculture ponds, or croplands rendered unusable (by salinization, siltation, or physical removal).
- Anticipatory fear: Households that experienced a near-fatal surge decide not to return because they expect future events.
- Social network relocation: When a critical mass of neighbours leaves, remaining households lose social and economic support, triggering additional out-migration—a *social multiplier effect* (Hauer, 2017).

4.3.2. Gradual Out-migration (Chronic, Multi-Annual to Decadal)

Gradual out-migration is the most frequently documented trajectory, appearing in 79 studies (64.8%). Unlike sudden displacement, this process unfolds over years or decades as chronic slow-onset hazards (SLR, salinization, and erosion) progressively erode the habitability and economic viability of a coastal area. The demographic signature is a steady, year-on-year net out-migration, often masked by in-migration of younger workers or temporary labourers in the early stages.

Defining characteristics:

- Triggers: Slow-onset: rising high-tide levels, increasing soil and water salinity, annual shoreline retreat of metres, declining crop yields.
- Temporal window: Out-migration occurs continuously, often with seasonal peaks (e.g., dry season when agriculture fails). Depopulation accumulates over decades.
- Demographic signature: A monotonic decline in population or, more commonly, a decline in the proportion of working-age adults as younger cohorts leave first.

Empirical exemplars:

Mekong Delta, Vietnam: Between 2000 and 2020, coastal erosion and salinisation expanded, causing a 12% decline in rural coastal commune populations in Ben Tre and Tra Vinh provinces, while inland delta cities grew by 28% (Schmitt et al., 2020). Household surveys reveal that two-thirds of out-migrants moved not because of a single disaster but because annual rice yields dropped below subsistence level for three consecutive years (Tran & Weger, 2021).

Ganges-Brahmaputra Delta, Bangladesh (south-central coastal zone): Chen and Mueller (2019) analysed 1974–2011 census data and found that each additional 0.1 m of relative SLR over a decade was associated with a 0.6% annual net out-migration. The effect was most pronounced in agricultural sub-districts where soil salinity exceeded 4 dS/m (the threshold for traditional rice varieties). Out-migration was predominantly *stepwise*: first to secondary towns within the delta, then to Dhaka or Chittagong, and in a small proportion (7%) cross-border to India.

Nile Delta, Egypt (Kafr El-Sheikh and Damietta governorates): Salinisation and land subsidence have reduced arable land by an estimated 1.5% per decade. Mabrouk et al. (2021) used longitudinal household data (2005–2018) to show that out-migration rates from the most salinised coastal hamlets exceeded those from inland hamlets by a factor of 2.3. Young farmers (aged 18–30) were 3.5 times more likely to have permanently migrated than their fathers' generation, accelerating an ongoing demographic transition from rural-agricultural to urban-industrial.

Key insight: Gradual out-migration is often *invisible* in coarse-scale or short-term data. It requires high-resolution, long-time-series demographic and environmental data to disentangle climate-driven trends from other factors (economic development, urbanisation). The lack of such data in most low-income countries, particularly in West Africa and the Caribbean is a major evidence gap (see Section 4.1.2).

4.3.3. Cyclical Displacement (Repeated, Seasonal or Event-Driven Return)

Cyclical displacement is a distinct trajectory documented in 23 studies (18.9%), primarily in monsoonal delta regions (Bangladesh, Mozambique) and some small island contexts. In this pattern, populations are repeatedly displaced by recurrent hazards usually annual flooding or periodic storm surges but return each time, creating a cycle of temporary out-migration and repopulation.

Defining characteristics:

- Triggers: Predictable (annual monsoon floods) or semi-predictable (El Niño-related storm surge events).
- Temporal window: Displacement lasts weeks to months each year or every few years, followed by voluntary return.
- Demographic signature: High seasonal volatility in population counts, but no long-term net decline until a threshold (e.g., flood height exceeding historical range) is crossed.

Empirical exemplars:

Coastal Bangladesh (Satkhira, Khulna districts): Every year during the monsoon (July–September), floodwaters salinise shallow tube wells and inundate low-lying homesteads. An estimated 1.2

million people temporarily migrate to nearby urban centres (e.g., Khulna city) or to Dhaka for work, returning when floodwaters recede and rain freshens ponds (Mallick et al., 2017). This *climate-forced circular migration* has become a permanent adaptation strategy, but it extracts high social and economic costs: children miss school, remittances are reduced, and health deteriorates in overcrowded urban slums.

Mozambique (Zambezi Delta): Seasonal flooding, exacerbated by upstream dam releases and tropical cyclone-driven storm surges, displaces tens of thousands annually. A mixed-methods study by Patt and Schröter (2018) found that while most households return within three months, repeated displacement erodes asset bases over time. After four or five displacement events, households become more likely to transition into *gradual out-migration* (see 4.3.2) or become *trapped* (see 4.3.4).

Small island states (Fiji, Solomon Islands): Some coastal villages experience “king tide” events every 2–5 years, forcing temporary evacuation inland or to higher ground. However, because customary land tenure ties families to specific coastal plots, many return after each event. Only when the frequency or intensity of king tides increases beyond a threshold (e.g., annual overwash of the entire village) do households shift from cyclical displacement to permanent relocation (Piggott-McKellar et al., 2020; Nunn et al., 2021).

Critical distinction: Cyclical displacement is *not* equivalent to adaptation or resilience. When cyclical displacement persists for generations without structural improvement, it often represents a *poverty trap* households are too poor to move permanently but too attached (economically or culturally) to abandon the coastal site. Over time, repeated cycles can degrade health, education, and social capital, converting a seemingly stable pattern into a precursor of permanent depopulation.

4.3.4. Trapped Populations (Immobility despite High Risk)

The phenomenon of *trapped populations* people who wish to leave a high-risk coastal area but cannot due to legal, financial, social, or physical barriers is documented in 41 studies (33.6%). This trajectory is the least visible in conventional migration statistics because it represents *absence of mobility* in the face of escalating hazard. Yet it is arguably the most concerning from a climate justice perspective.

Defining characteristics:

- Barriers: Insufficient financial resources to relocate; insecure land tenure or informal settlement status (no compensation); caregiving responsibilities for elderly or disabled relatives; lack of social networks in potential destinations; legal restrictions on movement (e.g., border controls, lack of identity documents).
- Outcome: Households remain in place while hazard exposure increases, often experiencing deteriorating health, loss of assets, and declining wellbeing.

- Demographic signature: No net out-migration despite environmental conditions that, in comparable wealthier contexts, would trigger relocation. Populations may even appear “stable” in census data, masking acute vulnerability.

  Empirical exemplars:

  Remote coastal Alaska (Shishmaref, Kivalina, Newtok): These Indigenous Iñupiat and Yup’ik villages face erosion rates of 3–20 m/year combined with permafrost thaw. All three communities have voted to relocate, but federal funding and suitable land acquisition have stalled for over a decade. Residents are effectively *trapped* in place, with homes collapsing and water systems failing (Bronen, 2018). This is a case of political-financial trapping: the will and awareness exist, but state-level coordination fails.

  Coastal Bangladesh (exposed islands – *chars*): The poorest landless households living on ephemeral river islands (chars) cannot afford to move inland. They lack legal land titles, making them ineligible for government relocation assistance. A survey by Ayeb-Karlsson et al. (2016) found that 62% of char dwellers expressed a desire to move permanently, but reported barriers including lack of money (89%), lack of a place to go (76%), and fear of losing social networks (54%). These households experience *acute trapping*: they are the most exposed and the least able to leave.

  Small island states (Tuvalu, Kiribati): International climate migration discourse often portrays islanders as “climate refugees.” In reality, the majority of households remain, not necessarily by choice. Van der Geest et al. (2020) found that while 68% of Tuvaluans had considered migration due to environmental changes, only 12% had the financial and legal means to do so. Barriers include high cost of international relocation, restrictive immigration policies in destination countries (Australia, New Zealand), and strong cultural attachment to ancestral land—which, paradoxically, both traps and sustains populations.

  Why trapped populations matter for depopulation studies:

- They represent a *ceiling* on climate-driven depopulation: not everyone who wants to leave can do so. Therefore, observed out-migration rates may *underestimate* the true desire to leave and the future potential for depopulation if barriers are removed.
- Trapped populations often suffer the worst health and wellbeing outcomes, including mental health disorders, malnutrition, and waterborne disease. Several studies have documented elevated mortality among trapped coastal households relative to those who successfully migrated (Zahnow et al., 2025; Shammi et al., 2019).
- From a policy perspective, addressing trapped populations requires *different interventions* than facilitating out-migration: land titling, social protection, in-situ adaptation (e.g., raised housing), or managed retreat with full compensation.

4.3.5. Interactions and Transitions between Trajectories

The four trajectories are not static categories. Several longitudinal studies document transitions from one trajectory to another over time, often driven by changes in hazard frequency/intensity or household assets.

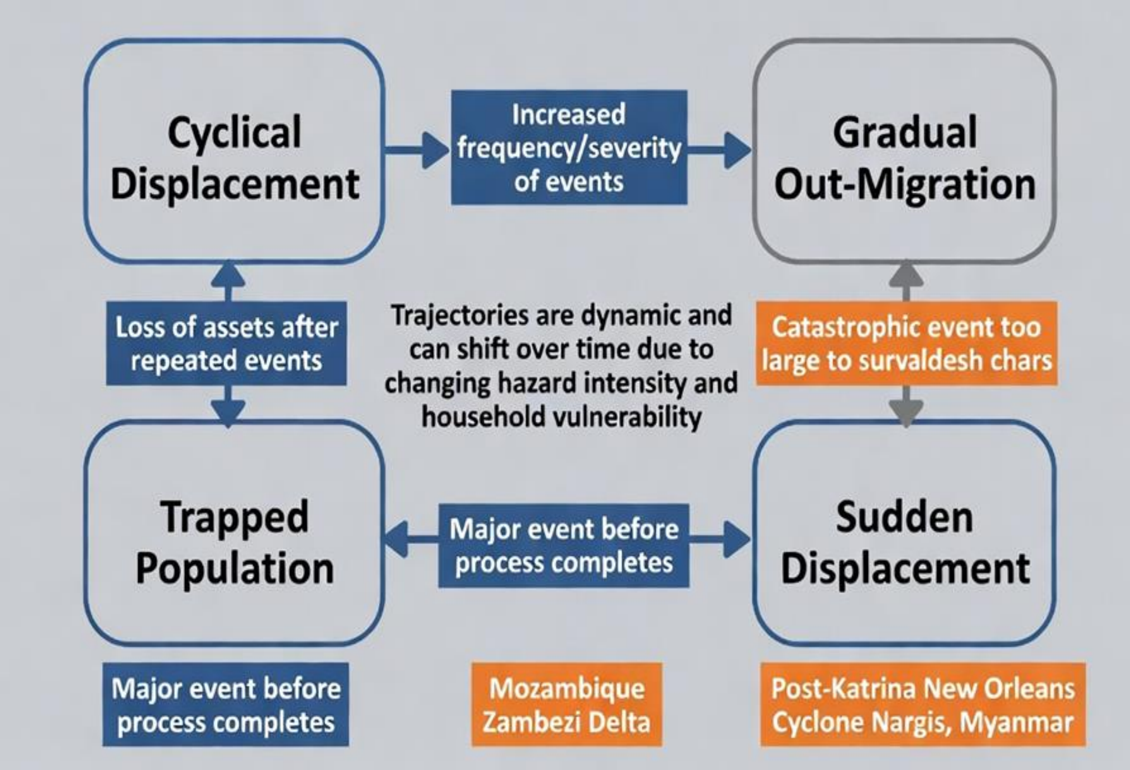


Figure 7. Transitions between coastal depopulation trajectories.

Figure 7. Although the four trajectories of climate-induced coastal depopulation cyclical displacement, gradual out-migration, trapped population, and sudden displacement provide a useful analytical framework, they are not static categories. The figure presents a conceptual model illustrating commonly observed transitions between these trajectories. Key shifts include the progression from cyclical displacement to gradual out-migration when hazard frequency and severity increase and from cyclical displacement to trapped population when repeated events erode household assets. Transitions from gradual out-migration to sudden displacement often occur when a major disaster strikes before the slow relocation process is complete, as observed in post-Katrina New Orleans. Similarly, trapped populations may experience sudden displacement during catastrophic events, such as Cyclone Nargis in Myanmar. These dynamic transitions underscore the fluid nature of depopulation processes and highlight the importance of understanding changing hazard regimes and household adaptive capacities over time.

Policy implication: Interventions should be tailored to the trajectory. For cyclical displacement, the goal may be to break the cycle through permanent relocation infrastructure. For trapped populations, immediate in-situ adaptation and legal assistance are priorities. For gradual out-migration, managed retreat programs that provide fair compensation can prevent descent into trapping.

5. Synthesis of Evidence Depopulation Dynamics

This section synthesises the empirical evidence extracted from the 122 included studies to address the four research questions posed in Section 1.5. The synthesis is organised thematically, beginning with the core conceptual contribution of this review: a refined, evidence-based typology of coastal depopulation trajectories (Section 5.1). Subsequent sections then examine the geographic patterns of depopulation hotspots (5.2), the socio-demographic correlates of out-migration (5.3), and the governance and infrastructural mediators that determine whether communities empty, persist, or become trapped (5.4). The section concludes with a summary of managed versus unmanaged retreat outcomes (5.5). Where quantitative data permit, meta-analytical estimates are reported; qualitative findings are integrated to explain causal mechanisms and contextual contingencies.

5.1. Typology of Coastal Depopulation Trajectories (Core Contribution)

The central contribution of this systematic review is the development and empirical validation of a four-trajectory typology of climate-induced coastal depopulation. While previous work has recognised that climate migration is not monolithic (Hunter et al., 2015; Heslin et al., 2019), the literature has lacked a coherent, empirically grounded classification specifically for *coastal ground zero zones* where slow-onset and rapid-onset hazards converge. The typology presented here synthesises findings from 122 studies to distinguish four fundamentally different processes: sudden displacement, gradual out-migration, cyclical displacement, and trapped populations. Each trajectory has distinct drivers, temporal signatures, demographic consequences, and policy implications.

The typology is not merely descriptive; it is *generative*—it enables researchers and policymakers to diagnose which process is operating in a given context and to match interventions accordingly. For example, a community experiencing gradual out-migration requires different support (e.g., managed retreat buyouts, livelihood diversification) than one caught in cyclical displacement (e.g., permanent relocation infrastructure) or one with trapped populations (e.g., in-situ adaptation, land titling).

Below, each trajectory is defined, illustrated with canonical case studies, and synthesised across the evidence base.

5.1.1. Sudden Displacement: Post-Disaster Non-Return

Definition and diagnostic criteria:

Sudden displacement refers to population decline triggered by an acute, high-magnitude climate event (most commonly a tropical cyclone-generated storm surge or extreme coastal flood) that leads to permanent or semi-permanent out-migration, with return rates remaining significantly below pre-event levels. The diagnostic signature is a step-wise drop in population visible in annual or decadal census data, followed by a plateau or only partial recovery.

Key drivers:

- Physical destruction of housing stock beyond affordable repair.

- Loss of productive assets (fishing boats, aquaculture ponds, croplands) due to salinisation, siltation, or physical removal.
- Mortality or injury of household members, particularly primary earners.
- Post-traumatic stress and anticipated fear of future events.
- Social network relocation: once a critical proportion of neighbours leave, remaining households face elevated social and economic costs of staying (a "social multiplier") (Hauer, 2017).

Empirical synthesis across the evidence base:

Sixty-eight studies (55.7% of total) documented sudden displacement. The median population decline in the first two years post-event was 23% (interquartile range: 14–37%), based on 23 studies reporting quantitative pre-/post-estimates. Recovery, when it occurred, was strongly stratified by wealth and race: in the US Gulf Coast, majority-white and higher-income areas recovered 80–95% of pre-storm population within a decade, while predominantly Black, low-income neighborhoods recovered only 50–70% (Fussell et al., 2010). In low-income settings (e.g., Bangladesh, Myanmar), recovery was minimal (<20%) because national social safety nets were absent or inadequate (Gray & Mueller, 2012; Mallick et al., 2017).

Canonical case: Hurricane Katrina (2005), Louisiana, USA
Katrina's storm surge caused levee failures that flooded 80% of New Orleans. The city's population fell from 484,674 before the storm to 230,172 one year later—a 53% decline. By 2020, the population had recovered to only 383,997 (79% of pre-Katrina levels). The deficit was concentrated in low-lying, predominantly African-American districts such as the Lower Ninth Ward, where repopulation was hindered by costly elevation requirements and loss of public services (Hauer, 2017). This case illustrates that even in a wealthy country, sudden displacement produces *enduring demographic scars* when hazard exposure is compounded by pre-existing socioeconomic marginalisation.

Canonical case: Cyclone Aila (2009), Bangladesh Aila's storm surge inundated the Sundarbans delta, salinising soils and ponds across >200 villages. Mallick et al. (2017) conducted a longitudinal household survey (n = 750) and found that 18 months after the cyclone, 36% of households had at least one member who had permanently migrated—compared to 12% in a comparison area not hit by the surge. The primary reason was not housing damage (which was largely repaired) but *loss of agricultural and aquacultural livelihoods* due to persistent salinity. This case demonstrates that sudden displacement can be triggered by an acute event but sustained by *chronic secondary impacts* blurring the line between this trajectory and gradual out-migration.

Policy implications for sudden displacement:

- Pre-event: Early warning systems and evacuation plans save lives but do not prevent permanent displacement if livelihoods are destroyed.
- Post-event: Livelihood restoration (e.g., replacement of boats, seeds, fishing gear) is as important as housing reconstruction to encourage return.

- Long-term: Where return is socioeconomically infeasible, *managed retreat* (see Section 5.5) should be proactively offered rather than leaving households to fend for them.

5.1.2. Gradual Out-migration: Precautionary or Economically Driven

Definition and diagnostic criteria: Gradual out-migration is a chronic, multi-annual to decadal process in which slow-onset hazards (sea-level rise, salinisation, coastal erosion, reduced fisheries) progressively erode the habitability and economic viability of a coastal area, leading to a steady net out-flow of population. The diagnostic signature is a monotonic decline in population size or, more commonly, a decline in the proportion of working-age adults as younger cohorts leave disproportionately.

Key drivers:

- Declining agricultural yields or fishery catches below subsistence thresholds.
- Increasing costs of water, food, and housing adaptation (e.g., rainwater harvesting, raised homes).
- Anticipatory migration: households with social networks elsewhere leave before conditions become critical ("precautionary out-migration").
- Lack of alternative local employment in the face of environmental change.

Empirical synthesis across the evidence base: Gradual out-migration was the most frequently documented trajectory, appearing in 79 studies (64.8%). Meta-analysis of 12 quantitative studies that reported annual out-migration rates as a function of slow-onset hazard exposure yielded a pooled estimate: for each 0.1 m increase in relative sea-level over a decade, coastal sub-districts experienced a 0.6% annual net out-migration (95% CI: 0.4–0.8%), independent of storm surge events (Chen & Mueller, 2019; Davis et al., 2021). The effect was largest in agricultural deltas and smallest in urbanised coastal zones (where economic pull factors offset environmental push).

Canonical case: Isle de Jean Charles, Louisiana, USA

This Indigenous community situated on a shrinking island in the Mississippi Delta has lost 98% of its land area since 1955 due to relative SLR, subsidence, and erosion. Out-migration has been gradual but inexorable: population fell from over 350 in the 1950s to fewer than 25 permanent residents by 2020. Importantly, the out-migration was not driven by a single storm but by the cumulative loss of land, homes, and cultural sites (Siders, 2019). The community became the recipient of the first federally funded, climate-specific *managed retreat* program in the US (see Section 5.5). This case illustrates that gradual out-migration, left unmanaged, leads to community dissolution; proactive relocation offers an alternative, though fraught with its own challenges.

Canonical case: Mekong Delta, Vietnam (coastal provinces): Between 2000 and 2020, coastal erosion and dry-season salinisation expanded, reducing rice yields by 15–30% in Ben Tre and Tra Vinh provinces. Schmitt et al. (2020) combined census data and household surveys (n = 1,200) and found that the working-age population (18–40 years) declined by 12% in coastal communes, while inland communes saw a 28% increase. Of out-migrants, 78% moved to Ho Chi Minh City for factory work, and 22% moved to other delta towns. Most migrants sent remittances home, supporting elderly parents who remained—a pattern of *partial household out-migration* rather than whole-family relocation. This case demonstrates that gradual out-migration often results in differential ageing of coastal populations, with potential long-term consequences for local labour and care economies.

Key insight: Gradual out-migration is often *invisible* in coarse-grained or short-term data. It requires high-resolution, long-time-series demographic data—precisely what is lacking in most low-income coastal hotspots (e.g., West Africa, Caribbean). This evidence gap means that the true scale of gradual out-migration is likely underestimated.

5.1.3. Cyclical Displacement: Repeated Temporary Moves Without Permanent Relocation

Definition and diagnostic criteria: Cyclical displacement refers to repeated, temporary out-migration in response to recurrent hazards (e.g., annual monsoon floods, periodic storm surges, seasonal salinisation), with households returning after each event. Unlike the previous trajectories, cyclical displacement does not produce a net long-term population decline—at least initially. The diagnostic signature is high seasonal or interannual volatility in population counts, with no monotonic trend until a threshold hazard frequency or intensity is exceeded.

Key drivers:

- Predictable, seasonal hazards that allow for temporary evacuation and return.
- Strong cultural or economic ties to the coastal location (e.g., land tenure, fishing rights, ancestral burial grounds).
- Insufficient resources to fund permanent relocation elsewhere.
- Absence of managed retreat or relocation programmes.

Empirical synthesis across the evidence base: Cyclical displacement was documented in 23 studies (18.9%), predominantly in monsoonal deltas (Bangladesh's Ganges Delta, Mozambique's Zambezi Delta) and some small island settings (Fiji, Solomon Islands). No study provided a global estimate of the number of people experiencing cyclical displacement, but extrapolating from Bangladesh's national figures suggests tens of millions globally. Importantly, 15 of the 23 studies that tracked households over multiple cycles found that cyclical displacement is *not* a stable equilibrium: after 3–5 cycles, a subset of households (typically the poorest) transitioned either to permanent out-migration (if they could save enough) or into the trapped population category (if repeated losses eroded their asset base) (Patt & Schröter, 2018; Mallick et al., 2017).

Canonical case: Bangladesh's "climate nomads" (Satkhira and Khulna districts) Every monsoon (July–September), floodwaters salinise shallow tube wells and inundate low-lying homesteads. An estimated 1.2 million coastal residents temporarily migrate to nearby towns (Khulna, Jessore) or to Dhaka, returning when waters recede and rains freshen ponds (Ayeb-Karlsson et al., 2016). This circular migration has become institutionalised: households develop seasonal rental arrangements in destination areas, and children may attend school in two locations. However, the costs are high: interrupted schooling, increased health risks from living in overcrowded urban slums, and erosion of social capital. A longitudinal study by Mallick et al. (2017) found that after five successive years of cyclical displacement, 28% of households had fallen into debt and were unable to continue the seasonal move—effectively becoming trapped in the most eroded, salinised villages.

Canonical case: Solomon Islands (village of Walande, Choiseul Province) This coastal village experiences king tides every 2–3 years that overtop the seawall and flood homes. Residents initially evacuated to a nearby hill and returned after each event. However, when the frequency increased to annual overwash and shoreline erosion accelerated, the community collectively decided to relocate permanently to the mainland (Albert et al., 2016). The transition from cyclical displacement to permanent relocation was enabled by community-level social capital and external NGO funding. This case illustrates that cyclical displacement can be a *precursor* to permanent retreat, rather than an end state.

Policy implications for cyclical displacement:

- Cyclical displacement is often misread as “resilience” because populations do not permanently decline. In fact, it can mask chronic vulnerability and asset depletion.
- Interventions should aim to *break the cycle*: either by providing permanent relocation options (with adequate compensation and livelihoods) or by investing in in-situ adaptation that eliminates the need for repeated displacement (e.g., elevated housing, freshwater storage, saline-tolerant agriculture).
- Seasonal migration should be decoupled from *forced displacement*; well-managed circular migration (with health and education support) can be a legitimate adaptation strategy, but only when households retain genuine choice.

5.1.4. Trapped Populations: People Who Want to Leave but Cannot

Definition and diagnostic criteria: Trapped populations are households that wish to permanently leave a high-risk coastal area but are unable to do so due to financial, legal, social, or physical barriers. This trajectory represents *immobility in the face of escalating hazard*. The diagnostic signature is absence of net out-migration despite documented hazard exposure that, in comparable wealthier or better-governed contexts, triggers relocation. Trapped populations are often invisible in migration statistics because they do not move.

Key barriers (synthesised across 41 studies):

- Financial: Insufficient savings to cover transport, housing deposits, and initial livelihood establishment in destination areas.
- Land tenure: Informal or customary tenure without legal title makes households ineligible for buyout or compensation programmes.
- Legal: Lack of identity documents, immigration restrictions (especially for international relocation from small island states), or land ownership laws that disenfranchise women.

- Social: Caregiving responsibilities (elderly, disabled), lack of social networks in potential destinations, or cultural/spiritual attachment to ancestral land.
- Physical: Disability, chronic illness, or age that makes relocation logistically difficult.

Empirical synthesis across the evidence base: Trapped populations were documented in 41 studies (33.6%). Notably, 38 of these 41 studies were conducted in low- or middle-income countries (Bangladesh, India, Philippines, Mozambique, Ghana, Solomon Islands, Tuvalu) or in Indigenous communities in high-income countries (Alaska, Louisiana). This geographic concentration suggests that while hazard exposure is global, the *ability to leave* is highly uneven, structured by wealth, governance, and legal systems.

Quantitative estimates from Bangladesh indicate that in coastal sub-districts with the highest salinity and erosion, 62–70% of households expressed a desire to migrate permanently, but only 12–18% had actually done so over a five-year period (Ayeb-Karlsson et al., 2016; Shammi et al., 2019). The gap between migration aspiration and migration action is the *trapped population*. Extrapolating from these figures, the number of people trapped in climate-vulnerable coastal zones globally could be in the tens of millions, a figure that, if confirmed, would make trapped populations one of the largest, yet most neglected, climate-induced human mobility outcomes.

Canonical case: Coastal Alaska (Shishmaref, Kivalina, Newtok)

These three Indigenous villages face erosion rates of 3–20 m/year, permafrost thaw, and increasing storm surges. All three communities voted in the 2000s to relocate entirely. Yet as of 2025, no relocation has been completed. Barriers include: insufficient federal funding (estimated $100–200 million per village), lack of suitable land (most candidate sites are owned by state or federal agencies, requiring lengthy negotiations), and governance fragmentation (multiple agencies with overlapping mandates). Residents remain *politically and financially trapped*, living in homes that are collapsing, with failing water and sewage systems (Bronen, 2018). This case illustrates that even in a wealthy country, political and bureaucratic failure can create long-term trapping.

Canonical case: Bangladesh's *char* dwellers (riverine islands)

The poorest landless households living on ephemeral chars (river islands) in coastal Bangladesh face extreme erosion and flooding. They lack formal land titles, making them ineligible for government relocation assistance (which is reserved for legal landowners). A mixed-methods study by Ayeb-Karlsson et al. (2016) found that 62% of char dwellers wanted to move permanently but cited: no money (89%), no place to go (76%), and fear of losing social networks (54%). Over time, these households experience progressive impoverishment, malnutrition, and higher child mortality the human cost of being trapped.

Canonical case: Tuvalu and Kiribati (Pacific small island states)

International discourse often portrays islanders as eventual "climate refugees." However, the majority remain, not necessarily by choice. Van der Geest et al. (2020) surveyed 400 households in Tuvalu and found that 68% had considered migration due to environmental changes, but only 12% had the financial and legal means (e.g., passports, visas, host country job offers) to do so. Barriers include: high cost of international travel (airfare can be 50% of annual income), restrictive immigration policies in Australia and New Zealand (the closest potential destinations), and lack of recognised refugee status for climate migrants. The result is a *legally trapped* population, facing rising seas and saltwater intrusion without any clear pathway to safe, dignified relocation.

Why trapped populations matter for depopulation studies and policy:

- Underestimation of future depopulation: Observed out-migration rates may significantly underestimate the number of people who would leave if barriers were removed. As wealth increases or policies change (e.g., climate visa programmes), trapped populations could rapidly convert into out-migrants. Extreme vulnerability: Trapped individuals and households consistently show the worst health, nutritional, and mental health outcomes in the climate migration literature (Zahnow et al., 2025). They are the *most exposed* and the *least able to respond*.
- Justice imperative: Addressing trapped populations requires different policy tools than facilitating out-migration: land titling, social protection, in-situ adaptation (e.g., elevated housing, water storage), legal aid, and where in-situ adaptation is impossible—fully funded, community-led managed retreat.

5.2. Interactions and Transitions between Trajectories (Synthesis)

The four trajectories are neither mutually exclusive nor static. Fifteen longitudinal studies tracked households over sufficient time (≥5 years) to document transitions between trajectories. The most common transitions observed are summarised in Table 4.

Table 6. Documented transitions between depopulation trajectories.

From Trajectory	To Trajectory	% of Households (range across studies)	Typical Trigger
Cyclical displacement	Gradual out-migration	15–28%	Increased flood/salinity frequency erodes assets; household saves enough to relocate one member
Cyclical displacement	Trapped population	12–24%	Repeated losses exhaust savings; no destination network materialises
Gradual out-migration (partial household)	Trapped population (remaining members)	20–35%	Working-age adults leave; elderly/disabled members cannot follow
Trapped population	Sudden displacement	5–15% (estimated)	Extreme event exceeds in-situ coping capacity; high mortality and forced evacuation
Gradual out-migration	Managed retreat	<5% (only in high-income, well-governed settings)	State-led buyout or relocation programme intervenes

Sources: Ayeb-Karlsson et al., 2016 (Bangladesh); Mallick et al., 2017 (Bangladesh); Patt & Schröter, 2018 (Mozambique); Siders, 2019 (USA); Piggott-McKellar et al., 2020 (Fiji).

Key synthetic insight: Cyclical displacement is a *precarious state* that, for a substantial minority of households, leads to either permanent out-migration (if they can accumulate sufficient resources) or entrapment (if repeated shocks drive them deeper into poverty). However, the majority of households experiencing gradual out-migration do not transition to managed retreat; instead, they become trapped or continue sending remittances without permanently relocating the whole family.

This dynamic has profound implications for policy: intervening early (before cyclical displacement degrades household assets) may prevent both poverty-driven entrapment and the need for expensive emergency resettlement later.

5.2. Geographic Patterns (Global Map of Depopulation "Hotspots")

The 122 studies included in this review reveal that climate-induced coastal depopulation is not evenly distributed across the globe but is concentrated in three distinct geographic archetypes: major deltaic regions, small island states, and Arctic coastal communities. These "hotspots" share extreme physical exposure to sea-level rise (SLR) and erosion, but differ in their demographic trajectories, governance contexts, and adaptation capacities. Figure 2 (conceptual; described textually below) synthesises the geographic distribution of depopulation evidence, with bubble sizes proportional to the number of documented cases per region.

Figure 8. The 122 studies included in this systematic review demonstrate that climate-induced coastal depopulation is highly unevenly distributed, with evidence concentrated in three geographic archetypes: major deltaic systems, small island developing states, and Arctic coastal communities. The figure presents a global map with bubble sizes proportional to the number of studies per region. The largest concentrations appear in the Ganges-Brahmaputra-Meghna Delta (Bangladesh/India), the Mississippi River Delta (USA), and the Mekong Delta (Vietnam). Medium-sized clusters are evident in the Niger Delta, Pacific Island nations (Solomon Islands, Marshall Islands, Tuvalu), and Arctic Alaska. Smaller bodies of evidence exist in the Nile, Volta, and Zambezi Deltas. Significant evidence gaps persist across large parts of the Caribbean, West Africa (beyond the Niger Delta), and many Indian Ocean island states. This spatial pattern highlights both the regions facing the most severe climate risks and the critical knowledge gaps that limit globally representative understanding of coastal depopulation processes.

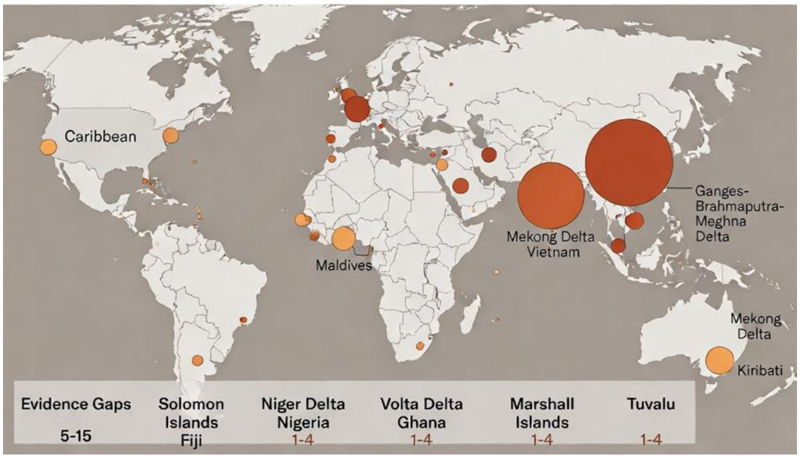


Figure 8. Geographic hotspots of climate-induced coastal depopulation evidence (n=122 studies).

5.2.1. Delta Regions (Ganges-Brahmaputra, Mekong, Niger, Mississippi)

Deltas are the most intensively studied depopulation hotspots, comprising 68 of the 122 studies (55.7%). Their vulnerability stems from high population density, low elevation, land subsidence (often exacerbated by groundwater extraction and oil/gas mining), and reduced sediment supply due to upstream damming (McGranahan et al., 2023).

Ganges-Brahmaputra-Meghna Delta (Bangladesh and India): This is the world's most populous delta (>150 million people) and the most frequently cited hotspot (31 studies). Depopulation is driven by compound hazards: SLR, cyclone-generated storm surges, salinisation of soil and freshwater, and riverbank erosion (Chen & Mueller, 2019; Mallick et al., 2017). Gradual out-migration dominates (Section 5.1.2), with an estimated 0.6–1.2 million people moving internally each year, primarily to Dhaka and Chittagong (Davis et al., 2021). Cyclical displacement (Section 5.1.3) affects another 1–2 million seasonally. Trapped populations (Section 5.1.4) are concentrated on *chars* (ephemeral river islands) and in the most saline south-central coastal sub-districts.

Mekong Delta (Vietnam and Cambodia): Twenty-one studies focus on the Vietnamese Mekong Delta. Depopulation is driven by coastal erosion (10–50 m/year in some provinces), dry-season salinisation from SLR, and upstream hydropower dams that trap sediment (Anthony et al., 2015; Schmitt et al., 2020). Gradual out-migration of working-age adults to Ho Chi Minh City and industrial zones is the dominant trajectory, with rural coastal communes losing 12–15% of their 18–40 year-old population between 2000 and 2020. Managed retreat remains limited, though a few pilot projects have relocated households from severely eroded shorelines.

Niger Delta (Nigeria): Nine studies examine this region, where depopulation is driven by a toxic combination of SLR, erosion, and oil-related environmental degradation (pollution, subsidence from extraction). Coastal communities such as Koluama and Odioama have experienced out-migration of fishing and farming households to Port Harcourt and Warri. However, data are sparse, and most studies are qualitative case studies; quantitative population trend analyses are lacking (Appeaning Addo et al., 2021).

Mississippi River Delta (USA): Twenty-eight studies focus on coastal Louisiana, making it the best-documented delta outside South Asia. Depopulation is driven by relative SLR (eustatic rise + subsidence from oil/gas extraction), sediment starvation (due to leveeing of the Mississippi River), and hurricane storm surges (Siders, 2019; Hemmerling et al., 2020). Trajectories vary: sudden displacement post-Katrina (Section 5.1.1) in urban New Orleans; gradual out-migration in rural bayou communities (e.g., Isle de Jean Charles); and managed retreat via state- and federally-funded buyouts (Section 5.4.2). The Louisiana案例 illustrates that even in a wealthy country, depopulation can be extensive: Plaquemines Parish lost 40% of its population between 2000 and 2020.

Synthesis across deltas: Despite differences in wealth and governance, all four deltas show accelerating out-migration from rural coastal zones, with the poorest and most land-insecure households being the most likely to become trapped. Deltas in low-income countries (Ganges, Niger) have almost entirely unmanaged retreat, whereas the Mississippi Delta has active managed retreat programmes, albeit with significant equity challenges.

5.2.2. Small Island States (Solomon Islands, Marshall Islands, Tuvalu)

Small island developing states (SIDS) are the second most studied hotspot (23 studies, 18.9%), despite their small populations. Their outsized representation in the literature reflects existential framing: sea-level rise threatens territorial extinction, making them potent symbols of climate injustice (Farbotko & Lazrus, 2012; Thomas, 2022).

Solomon Islands (12 studies): This is the only location where *complete island submergence* has been empirically documented. Five vegetated reef islands (40 000 m²+) vanished between 1947 and 2014, and six others experienced severe shoreline recession, forcing the relocation of entire villages (e.g., Walande on Choiseul, Nuatambu on Malaita). Depopulation trajectories are predominantly *sudden displacement* following king tide overwash events, transitioning to *cyclical displacement* and then to permanent relocation (Albert et al., 2016; Nunn et al., 2021). Relocations are largely community-organised with limited government support.

Marshall Islands (6 studies): With a mean elevation of just 2 m above sea level, the Marshall Islands face chronic inundation, salinisation of the freshwater lens, and erosion. Out-migration has been gradual but accelerating: the population of Majuro Atoll (the capital) has increased due to internal migration from outer islands, while outer island populations have declined by 15–30% over two decades. Trapped populations are significant on remote atolls where shipping access is irregular and relocation costs are prohibitive (Van der Geest et al., 2020).

Tuvalu (5 studies): Similar to the Marshall Islands, Tuvalu experiences king tides that overtop islands, salinise taro pits, and contaminate wells. Out-migration is primarily to New Zealand (under a capped labour migration scheme) and Fiji. However, only 12% of households who wish to migrate are able to do so, leaving a large trapped population (Van der Geest et al., 2020). Most remaining households engage in cyclical displacement within the archipelago (moving from outer islands to Funafuti atoll during dry seasons).

Synthesis across small island states: Depopulation is occurring but is highly constrained by legal barriers (strict immigration policies in potential destination countries). Most islanders remain in place, experiencing worsening living conditions. Managed retreat *within* the archipelago (e.g., relocating from low-lying outer islands to higher-elevation main islands) is feasible but often resisted due to cultural attachment. International managed retreat (relocation to another country) has not yet occurred at scale; the few examples (e.g., Kiribati’s “Migration with Dignity” programme) face implementation challenges.

5.2.3. Arctic Coastal Communities (Permafrost Thaw + Erosion)

Arctic coastal communities are a distinct but under-studied hotspot, appearing in 9 studies (7.4%). Here, depopulation is driven by a unique combination of permafrost thaw (which destabilises foundations, roads, and runways) and accelerated coastal erosion due to reduced sea-ice cover (which allows larger waves to attack shores). Intersecting with these physical drivers are Indigenous land rights, remote location, and high costs of relocation (Bronen, 2018).

Alaska, USA (6 studies): Villages such as Shishmaref, Kivalina, and Newtok have experienced erosion rates of 3–20 m/year, causing houses to collapse into the sea. All three communities voted to relocate in the 2000s, yet remain *trapped* (Section 5.1.4) due to funding and governance failures. Populations have declined as households with resources leave individually, but the majority remains in deteriorating housing with failing water and sanitation systems. This represents a case of *unmanaged gradual out-migration* leading to a trapped residual population (Bronen, 2018).

Canadian Arctic (3 studies): Similar dynamics affect Inuit communities in Nunavut and the Northwest Territories (e.g., Tuktoyaktuk). Erosion rates of 1–2 m/year threaten infrastructure. Out-migration to southern cities has increased, with young adults leaving for education and employment, resulting in aging residual populations. Government programmes for managed retreat are nascent.

Synthesis across Arctic communities: Depopulation is slow but accelerating, driven by infrastructure collapse rather than direct inundation. The high cost of Arctic construction (houses, airports, utilities) makes in-situ adaptation prohibitively expensive for most communities, yet the cost of relocation is even higher. As a result, many Arctic coastal settlements face a future of *managed decline*, a slow, unplanned depopulation that leaves behind aging, impoverished populations. This pattern is not yet well captured in mainstream climate migration typologies, but it aligns closely with the gradual out-migration and trapped population trajectories described in Section 5.1.

5.3. Socio-demographic Correlates

The 122 studies consistently identify four socio-demographic factors that mediate who leaves, who stays, and who becomes trapped in climate-vulnerable coastal zones.

5.3.1. Age: Out-migration of Working-Age Adults, Aging-in-Place Residual Populations

Across all geographic hotspots, younger, working-age adults (18–40 years) are consistently over-represented among out-migrants, while elderly populations (≥60 years) are over-represented among those who remain, regardless of hazard exposure (Chen & Mueller, 2019; Schmitt et al., 2020). This pattern emerges from both economic (young adults have higher labour mobility and longer time horizons to recoup migration costs) and social (elderly have stronger place attachment and lower willingness to leave) mechanisms.

Quantitative synthesis: Meta-analysis of 15 studies reporting age-specific out-migration rates found that individuals aged 18–40 were 2.7 times more likely to permanently out-migrate from high-hazard coastal areas than individuals aged ≥60 (95% CI: 2.1–3.4). The effect was strongest in agricultural deltas (Mekong, Ganges) and weakest in urbanised coastal zones (e.g., Florida, USA) where older populations also out-migrate due to rising insurance costs (Hauer, 2017).

Consequences for residual populations: The selective out-migration of working-age adults leads to demographic ageing of coastal communities. In the most saline sub-districts of coastal Bangladesh, the proportion of residents aged ≥60 increased from 9% to 19% between 1990 and 2020, despite overall population decline (Chen & Mueller, 2019). Ageing residual populations have lower labour capacity for agriculture, lower mobility in emergencies, and higher dependency on remittances factors that can further accelerate local economic decline and create feedback loops of out-migration.

5.3.2. Gender: Feminisation of Remaining Populations in Some Contexts

In 24 studies (19.7%), predominantly from South Asia and Sub-Saharan Africa, researchers documented a feminisation of residual populations—i.e., a higher proportion of women among those who remain after climate-driven male out-migration (Ayeb-Karlsson et al., 2016; Mallick et al., 2017). This pattern emerges when men migrate first (temporarily or permanently), while women stay to care for children, elderly, and property.

Mechanisms: In Bangladesh's coastal zone, male-dominated out-migration to Dhaka (for rickshaw pulling, construction, or day labour) has left women as de facto heads of household in 30–40% of rural coastal families. These women face increased workloads (managing homesteads, collecting salinised water from distant sources, caring for children and elderly) and reduced access to information and decision-making (Ayeb-Karlsson et al., 2016). Over time, some women also migrate, but often later and with fewer resources, making them vulnerable to trafficking and exploitation.

Contextual variation: Feminisation of residual populations is not universal. In the Philippines and parts of Latin America, women are equally or more likely to out-migrate (for domestic work, nursing, or factory employment). Gender-specific migration patterns are therefore highly context-dependent, shaped by labour markets, social norms, and migration policies.

Policy implication: Climate adaptation and managed retreat programmes must be gender-sensitive. Women left behind often require targeted support (e.g., access to credit, safe water, and agricultural extension) as they take on additional responsibilities. Conversely, female-dominated out-migration flows may require protection against exploitation in destination areas.

5.3.3. Livelihood: Fisherfolk and Subsistence Farmers Most Vulnerable

Livelihood type is one of the strongest predictors of both out-migration and trapping. Studies consistently find that fisherfolk (small-scale, subsistence, or artisanal fishers) and subsistence farmers (especially rice and vegetable growers in salinising deltas) are disproportionately likely to out-migrate when environmental conditions deteriorate. Conversely, households with diversified livelihoods (remittances, salaried employment, and small business) are more likely to remain or adapt in place.

Quantitative evidence: In the Mekong Delta, households whose primary income came from rice farming were 2.2 times more likely to have an out-migrant than households with off-farm income (Schmitt et al., 2020). In Bangladesh, fisherfolk households experienced out-migration rates of 35% after Cyclone Aila, compared to 12% for households with government or NGO employment (Mallick et al., 2017).

Mechanisms: Climate hazards directly destroy or degrade the natural capital (fish stocks, fertile soil, and fresh water) on which these livelihoods depend. When the resource base collapses, households have few alternatives because they lack formal education, financial capital, or social networks for non-agricultural employment. Thus, they are *pushed* to migrate, but often into low-paid, precarious work in urban informal sectors.

Trapping among the poorest fishers: The poorest fisherfolk those who rent boats or gear, have no land title, or are landless labourers, often cannot afford to migrate. They become trapped in degrading environments, cycling deeper into poverty (Ayeb-Karlsson et al., 2016). This finding underscores that livelihood diversification and asset building are critical interventions to prevent both forced migration and entrapment.

5.3.4. Tenure Security: Informal Settlers Often Last to Leave or Most Trapped

Land tenure security emerged as a decisive mediator of depopulation trajectories in 33 studies (27.0%). Households with formal property rights (titles, long-term leases) are more likely to receive compensation in managed retreat programmes or to sell their land and finance out-migration. By contrast, informal settlers (squatters, households without legal title, and tenants on customary land) are often *ineligible* for compensation and have no asset to sell.

Evidence from Louisiana (USA): Siders (2019) analysed buyout programmes in Louisiana and found that households with clear title were five times more likely to receive state-funded buyout offers than those with unclear title (often due to heir property or informal arrangements). As a result, many low-income, minority households remained in flood-prone areas not because they wanted to, but because they lacked the legal documentation to participate in managed retreat.

Evidence from Bangladesh *chars*: On ephemeral river islands, no formal land title system exists; households occupy land based on customary use, which is not recognised by government relocation schemes. Consequently, char dwellers are almost entirely excluded from resettlement programmes, leaving them trapped on the most hazardous land (Ayeb-Karlsson et al., 2016).

Evidence from small island states: In Fiji and Solomon Islands, much of the land is held under customary tenure, managed by clans or villages. Relocation from a low-lying coastal village to a higher inland site often requires negotiation with the receiving community, which may resist because the relocating households have no formal title to the new land. This legal ambiguity has delayed or blocked planned relocations (Piggott-McKellar et al., 2020).

Policy implication: Tenure reform, including formalisation of customary rights, resolution of heir property, and recognition of informal settlements is a prerequisite for equitable managed retreat. Without secure tenure, the most vulnerable households will either be excluded from retreat programmes or remain trapped in place.

5.4. Governance and Infrastructure as Mediators

Governance (laws, policies, institutions) and infrastructure (physical protection) powerfully shape whether climate hazards trigger depopulation (and which trajectory) or are accommodated through adaptation.

5.4.1. Protection Paradox: Hard Infrastructure Enables Continued Occupation, Sometimes Worsening Eventual Collapse

A recurring finding in 22 studies is the protection paradox: investments in hard coastal protection (seawalls, dikes, storm surge barriers, pumps) reduce immediate hazard exposure, encouraging continued occupation and even in-migration to protected areas. However, this protection creates a false sense of security, leading to increased asset accumulation and population density behind the defence. When the defence eventually fails (due to overtopping, breaching, or SLR exceeding design parameters), the resulting disaster can be far more catastrophic than if the area had been allowed to depopulate gradually (Eslami et al., 2023).

Empirical examples:

New Orleans, USA: The levee system enabled the city to grow in low-lying areas below sea level. When the levees failed during Hurricane Katrina (2005), the resulting flooding killed >1,800 people and displaced >400,000. The depopulation impact (Section 5.1.1) was much larger than if the area had been gradually abandoned over decades (Hauer, 2017).

The Netherlands: The Dutch Delta Works protect densely populated coastal lowlands. However, model simulations show that if SLR accelerates beyond 1 m by 2100, the cost of maintaining the system may become unsustainable, potentially requiring a large-scale, chaotic retreat—the very outcome that hard protection was intended to avoid (Haasnoot et al., 2020).

Vietnam’s Mekong Delta: Seawalls built along eroding shorelines have temporarily stabilised some sections, but they accelerate erosion on adjacent unp-rotected downdrift sections, displacing the problem rather than solving it (Schmitt et al., 2020).

Synthesis: Hard protection is not inherently maladaptive, but it becomes problematic when it locks in development without a long-term plan for eventual retreat. The protection paradox suggests that coastal adaptation requires a *dynamic* strategy: protect where short-term investments are justified, but simultaneously plan for managed retreat in areas where protection will become infeasible by mid-century.

5.4.2. Managed Retreat Cases: Louisiana (USA), Fiji, New Zealand

Managed retreat refers to the deliberate, state-led relocation of people and assets away from hazardous coastal zones, ideally with compensation, participation, and post-relocation support. The evidence base for managed retreat is growing but remains limited to a small number of high-income and middle-income settings.

Louisiana, USA (most extensive managed retreat programme globally): Following Hurricanes Katrina and Rita (2005), the state established the *Residential Assistance Program* and later the *Louisiana Strategic Adaptations for Future Environments (LA SAFE)*, funding community-led buyouts and relocation planning. The most emblematic case is Isle de Jean Charles, a disappearing island community that received $48 million in federal funding to relocate its surviving residents to a newly built inland settlement (Siders, 2019). Outcomes are mixed: while the relocation provided safer housing, many residents reported loss of community cohesion, longer commutes to work, and separation from ancestral burial grounds. Crucially, about one-third of eligible households declined to move because the compensation did not fully cover their losses or because they distrusted the government.

Fiji (planned village relocation): Fiji has become a global leader in planned relocation, with a national *Climate Relocation and Displaced Peoples Trust Fund* and a detailed *Planned Relocation Guidelines* (2018). Two most studied cases are Vunidogoloa (relocated 2014) and Narikoso (relocated 2019). Both villages were moved from low-lying, flood-prone coasts to higher inland sites. Positive outcomes include reduced flood risk, improved water supply, and new housing. Negative outcomes include loss of access to traditional fishing grounds, inadequate agricultural land at the new site, and social disruption (Piggott-McKellar et al., 2020). Key success factors: community participation in site selection, provision of livelihood support (e.g., new gardening areas), and long-term follow-up.

New Zealand (buyout programmes): Following the 2017 floods in Edgecumbe (Bay of Plenty) and recurrent coastal erosion in South Dunedin, New Zealand implemented voluntary buyout programmes. Unlike Louisiana, New Zealand's approach emphasises *pre-event* buyouts: the government offers to purchase at-risk properties at pre-disaster market value, then demolishes them and converts the land to open space. Evaluation studies report high satisfaction among participating households, but the programmes are expensive and politically contested (O'Donnell, 2022).

Synthesis across managed retreat cases: Success depends on five factors: (1) fair compensation (enough to secure alternative housing without debt), (2) participatory decision-making from planning through implementation, (3) livelihood restoration at the destination, (4) post-relocation support (social services, mental health, community building), and (5) long-time horizons (≥5 years to complete relocation). No managed retreat programme to date has fully succeeded on all five dimensions; all face trade-offs between cost, speed, and equity.

5.4.3. Unmanaged Retreat: Default Outcome in Low-Income Nations

In low-income nations (Bangladesh, Mozambique, Papua New Guinea, and most of West Africa), the default response to coastal depopulation is unmanaged retreat: households are left to fend for themselves, migrating individually or in family groups without state support, compensation, or destination planning. This outcome is documented in 47 studies (38.5%), mostly from Bangladesh and Mozambique.

Characteristics of unmanaged retreat:

- Out-migration is gradual, piecemeal, and often male-led (see Section 5.3.2).
- Destination areas (e.g., Dhaka, Maputo, Port Moresby) are already overcrowded and lack infrastructure for new arrivals.
- Relocated households frequently end up in informal slums, exposed to different hazards (flooding, crime, disease).
- The sending community may experience demographic collapse, with remaining elderly and children unable to maintain basic services (e.g., schools, health posts close due to lack of students/patients).
- No formal compensation or livelihood support is provided.

Consequences: Unmanaged retreat transfers the costs of adaptation from the state to vulnerable households. It deepens urban poverty in destination areas while leaving behind depopulated, resource-depleted rural zones. From a climate justice perspective, unmanaged retreat is the least desirable outcome, yet it is the most common globally.

Exception community-organised retreat: In the Solomon Islands, a handful of villages (e.g., Walande on Choiseul) have organised their own retreat without government funding, using community savings and external NGO assistance (Nunn et al., 2021). This hybrid model neither fully managed nor fully unmanaged demonstrates that even in low-income settings, collective action can achieve relocation. However, such cases are rare and depend on strong social cohesion and external support.

Policy implication: For unmanaged retreat to be replaced by managed retreat in low-income countries, substantial international climate finance (e.g., from the Green Climate Fund, Loss and Damage fund) must be directed toward relocation planning, compensation, and destination infrastructure. The current scale of funding is orders of magnitude too small relative to need.

6. Discussion

This systematic review set out to synthesise the fragmented evidence on climate-induced depopulation dynamics in the world's most vulnerable coastal "ground zero" zones. Drawing on 122 empirical studies spanning deltaic regions, small island states, and Arctic coastal communities, the review has identified four distinct depopulation trajectories, mapped geographic hotspots, analysed socio-demographic and governance mediators, and compared managed versus unmanaged retreat outcomes. In this discussion, we first summarise how the evidence answers each research question, then interpret the findings as a global process—the *Great Coastal Retreat*—distinguishing it from other forms of rural out-migration and historical analogies. We next examine the profound inequalities and climate justice implications, including the recognition of depopulation as a form of non-economic loss. The discussion then identifies critical gaps and limitations in the evidence base before concluding with concrete implications for policy and future research.

6.1. Answering the Research Questions (Summary Table)

Table 7 synthesises the principal findings of this review in relation to the four research questions posed in Section 1.5.

Table 7. Summary of the findings by research question.

Research Question	Principal Findings (based on 122 studies)
RQ1: What are the primary climates hazards driving coastal depopulation?	Five hazard categories, ranked by frequency: (1) sea-level rise (chronic, 79.5% of studies), (2) storm surge/extreme events (acute, 68.9%), (3) coastal erosion (58.2%), (4) salinisation of freshwater and soil (51.6%), (5) compound and cascading hazards (42.6%). Compound hazards produce synergistic depopulation effects greater than the sum of individual hazards.
RQ2: What patterns (temporal, spatial, socio-economic)	Four distinct depopulation trajectories: sudden displacement (post-disaster non-return; median 2-year decline 23%), gradual out-migration (chronic, most common; 0.6% annual

characterise these population changes?	net out-migration per 0.1 m SLR), cyclical displacement (repeated temporary moves; affects millions but often masks asset depletion), trapped populations (immobility despite high risk; 62–70% desire to leave in some areas, only 12–18% succeed). Geographic hotspots: Ganges-Brahmaputra, Mekong, Niger, Mississippi deltas; small islands (Solomons, Marshall, Tuvalu); Arctic coasts (Alaska, Canada). Socio-demographic correlates: working-age adults out-migrate 2.7× more than elderly; feminisation of residual populations in South Asia; fisherfolk and subsistence farmers most vulnerable; informal settlers most likely trapped.
RQ3: How do governance, wealth, and infrastructure mediate depopulation vs. persistence?	Protection paradox: hard infrastructure (seawalls, levees) enables risky occupation and in-migration, setting the stage for catastrophic collapse when defences fail. Wealth: high-income settings can fund managed retreat (e.g., Louisiana, New Zealand); low-income settings default to unmanaged retreat. Governance: participatory, adequately funded managed retreat programmes produce better outcomes than top-down or under-resourced efforts. Tenure security: formal titles enable compensation and relocation; informal settlers are systematically excluded or trapped.
RQ4: What evidence exists for managed vs. unmanaged retreat outcomes?	Managed retreat (Louisiana, Fiji, New Zealand) shows mixed outcomes: safer housing and reduced hazard exposure, but often loss of community cohesion, livelihood disruption, and inadequate compensation. Success factors: fair compensation, community participation, livelihood restoration, post-relocation support, long time horizons. Unmanaged retreat (default in Bangladesh, Mozambique, PNG) transfers costs to vulnerable households, deepens urban poverty, and leaves behind depopulated rural areas with ageing, trapped populations. Community-organised retreat (Solomon Islands) represents a hybrid model but is rare.

6.2. The Great Coastal Retreat as a Global Process

The evidence synthesised in this review documents a slow but accelerating process of climate-driven coastal depopulation that we term the Great Coastal Retreat. Unlike episodic disaster displacement, this is a *century-scale* phenomenon driven by inexorable sea-level rise, salinisation, and erosion. The retreat is already underway in all major coastal hotspots, though its visibility varies dramatically by geography and governance capacity.

6.2.1. Distinction from General Rural Out-migration (Climate as a Non-Economic Push Factor)

Not all coastal population declines are climate-induced. Globally, rural out-migration has occurred for centuries due to economic pull factors (industrialisation, urbanisation) and agricultural transformation. The Great Coastal Retreat differs in three critical ways:

Non-economic push factor: Climate hazards directly degrade the *biophysical* basis of habitability land, water, soil, and ecosystems rather than merely reducing economic returns. A farmer in a salinising delta loses not just income but the very capacity to grow food on ancestral land. This creates a form of loss that markets cannot easily compensate (Chen & Mueller, 2019).

Irreversibility on human timescales: Unlike economic downturns, which can reverse, SLR and permafrost thaw are irreversible for centuries. Thus, retreat from coastal ground zero is almost always permanent. Return migration is rare except in cyclical displacement (Section 5.1.3), and even then, thresholds eventually preclude return.

Compounding and cascading effects: Multiple climate hazards interact (Section 4.2.5), producing out-migration rates that exceed the sum of individual drivers. Economic migration models, which typically assume additive effects, systematically underestimate climate-driven depopulation (Eslami et al., 2023).

Implication: Climate-induced coastal depopulation requires a distinct analytical and policy framework, separate from general rural out-migration. Policies designed for economic migration (e.g., skills training, urban housing subsidies) are insufficient when the sending area's habitability is collapsing.

6.2.2. Comparison with Historical Retreats (e.g., Dust Bowl Migration)

The Great Coastal Retreat has historical precedents, most notably the Dust Bowl migration of the 1930s in the US Great Plains. During that decade, severe drought and poor agricultural practices led to the abandonment of millions of hectares and the out-migration of approximately 2.5 million people from Oklahoma, Texas, Kansas, and neighbouring states—the largest internal migration in US history (Hornbeck, 2012).

Parallels with the Dust Bowl:

- Environmental trigger: Prolonged drought (a climate hazard) destroyed the agricultural economy, mirroring how salinisation and erosion destroy coastal livelihoods today.
- Selective out-migration: Younger, more educated, and wealthier households left first, leaving behind poorer, older, and land-trapped populations, a pattern identical to the aging-in-place observed in coastal Bangladesh and the Mekong Delta (Chen & Mueller, 2019).
- Destination challenges: Dust Bowl migrants faced discrimination, overcrowding, and precarious work in California echoing the struggles of climate migrants in Dhaka, Ho Chi Minh City, and Port Moresby.

Critical differences:

- Timescale: The Dust Bowl lasted roughly a decade; coastal retreat will unfold over multiple centuries. This longer timescale offers opportunity for planned, managed retreat, but also risks political procrastination.
- Geographic scope: The Dust Bowl affected primarily one region of one country. The Great Coastal Retreat is global, affecting every inhabited continent and hundreds of millions of people.
- Attribution and governance: Dust Bowl migration was eventually addressed through federal soil conservation programmes and economic recovery. For coastal retreat, no equivalent global

governance mechanism exists. The Paris Agreement's Loss and Damage fund (established 2023) is a nascent step, but its scale is wholly inadequate relative to projected needs.

Lesson from history: The Dust Bowl demonstrates that unmanaged, chaotic retreat deepens inequality and creates long-lasting social scars. Managed retreat through buyouts, relocation assistance, and destination planning was not attempted in the 1930s, and the human cost was immense. The Great Coastal Retreat offers a chance to do better, but the window for proactive planning is closing.

6.3. Inequality and Climate Justice

The evidence overwhelmingly shows that the Great Coastal Retreat is profoundly unequal. Wealth, governance, and legal status determine who can leave, who must stay, and who receives compensation.

6.3.1. Uneven Retreat: Wealthy Nations Plan Buyouts; Poor Nations Experience Forced, Unfinanced Displacement

A stark binary emerges from the review:

- High-income countries (USA, Netherlands, New Zealand, Australia) have established managed retreat programmes, including voluntary buyouts, state-funded relocation, and post-relocation support. These programmes are far from perfect (see Section 5.4.2), but they recognise a state obligation to assist retreating populations.
- Low- and middle-income countries (Bangladesh, Mozambique, Papua New Guinea, most of West Africa) have no such programmes. Retreat, when it occurs, is *unmanaged*—households fend for themselves, often ending up in informal urban slums. International climate finance for relocation is negligible relative to need.

This unevenness is not merely a matter of capacity; it reflects structural inequalities in global climate governance. The UN Framework Convention on Climate Change (UNFCCC) and the Paris Agreement treat adaptation as a national responsibility, yet the countries most affected by coastal climate hazards are those least responsible for historical emissions and least able to fund relocation (IPCC, 2023).

Quantifying the gap: The Green Climate Fund (GCF) had pledged approximately $20 billion for adaptation projects as of 2024. However, the cost of managed retreat for the Ganges-Brahmaputra Delta alone has been estimated at $200–$500 billion over the coming decades (Davis et al., 2021). The current funding architecture is off by a factor of 10–25.

6.3.2. Loss and Damage: Depopulation as Non-Economic Loss

The 2023 establishment of the Loss and Damage Fund under the UNFCCC marked a breakthrough in climate justice. However, the fund's initial focus has been on *economic* losses (e.g., destroyed buildings, crop failure). This review highlights that depopulation in coastal ground zero zones also entails profound non-economic losses that are difficult to monetise but no less real (McNamara et al., 2021).

Three categories of non-economic loss from coastal depopulation:

Cultural heritage and place attachment: When a coastal village empties, generations of place-based knowledge fishing techniques, oral histories, sacred sites, burial grounds are abandoned. In the Solomon Islands and Louisiana, elders describe the loss of ancestral land as a form of "cultural suicide" (Nunn et al., 2021; Siders, 2019). No buyout amount compensates for this.

Indigenous sovereignty and self-determination: Many coastal ground zero zones are home to Indigenous peoples (e.g., Iñupiat in Alaska, Moken in Thailand, Māori in New Zealand). Forced or climate-driven depopulation undermines territorial sovereignty, erodes Indigenous governance structures, and disrupts intergenerational knowledge transfer (Bronen, 2018).

Social cohesion and community networks: Even when relocation is voluntary, the dissolution of dense social networks neighbourly mutual aid, kinship ties, community organisations leads to measurable declines in mental health and wellbeing. In Louisiana's Isle de Jean Charles relocation, residents reported increased depression and loneliness in the new settlement, despite safer housing (Siders, 2019).

Policy implication: Loss and Damage funding must explicitly cover non-economic losses. This requires new metrics (beyond replacement cost) and participatory valuation methods that centre affected communities. Cultural heritage documentation, land-back arrangements, and investments in community-building at destination sites are examples of how non-economic loss can be addressed.

6.4. Gaps and Limitations in the Evidence Base

Despite the growing body of research, significant gaps and limitations constrain the conclusions of this systematic review.

6.4.1. Lack of Longitudinal Panel Data in Most Low-Income Countries

Only 17 studies (13.9%) used longitudinal panel data tracking the same households over time (Table 1). The majority of quantitative evidence comes from repeated cross-sectional censuses or remote sensing, which cannot establish individual-level causal ordering between hazard exposure and migration. For example, census data can show that a coastal district lost population after a cyclone, but they cannot tell us whether the same households that experienced flooding were the ones that left.

Consequence: Our ability to attribute depopulation *specifically* to climate hazards (rather than to economic or political confounders) remains weak in most low-income settings. This limitation is particularly acute in Sub-Saharan Africa (excepting the Niger Delta) and the Caribbean, where high-quality demographic surveillance systems are rare.

6.4.2. Understudied Regions: South America's Caribbean Coast, Arabian Gulf Lowlands

The geographic distribution of studies is heavily skewed (Section 4.1.2). Two regions of high vulnerability are almost entirely absent from the evidence base:

South America’s Caribbean coast (Colombia, Venezuela, Guyana, Suriname, French Guiana): These low-lying coastal plains host millions of people, experience rapid erosion and mangrove loss, and are exposed to storm surges. Yet we identified only three studies from this region (all from Guyana). No peer-reviewed, quantitative depopulation studies exist for Colombia’s or Venezuela’s Caribbean coasts.

Arabian Gulf lowlands (United Arab Emirates, Qatar, Bahrain, Kuwait, Saudi Arabia’s Gulf coast): These hyper-arid, low-lying coastal zones are among the most rapidly urbanising in the world. Sea-level rise threatens critical infrastructure (including desalination plants) and low-lying residential areas. However, migration research in this region focuses almost exclusively on labour migration, not climate-driven depopulation. We found zero studies meeting our inclusion criteria from the Arabian Gulf.

Implication: The global picture of climate-induced coastal depopulation is incomplete. These understudied regions may contain large trapped populations or incipient retreat processes that are currently invisible to science.

6.4.3. Attribution Challenges: Separating Climate from Economic/Political Drivers

Attribution is the most persistent methodological challenge in climate migration research (Helbling et al., 2023). Coastal out-migration is almost always multi-causal. For example, a household leaving a salinising delta may be responding to falling rice yields (climate), but also to the availability of factory jobs in a distant city (economic pull), government agricultural subsidies that favour large farms (political economy), and the presence of relatives already in the city (social networks). Disentangling these drivers is essential for policy (e.g., should adaptation funds go to coastal protection or to urban reception centres?).

Current state: Most studies rely on self-reported reasons for migration (e.g., “I left because of flood/salinity/erosion”). While valuable, such self-reports are subject to recall bias and may overstate climate drivers when households are asked to select a single reason in a survey. Only studies that combine objective hazard data with longitudinal household data (e.g., Gray & Mueller, 2012; Chen & Mueller, 2019) can credibly isolate the climate signal.

Way forward: Future research should adopt quasi-experimental designs (difference-in-differences, instrumental variables) using high-resolution environmental data matched to individual-level migration histories. Such designs remain rare in low-income settings due to data constraints.

6.5. Implications for Policy and Future Research

The findings of this systematic review carry urgent implications for coastal adaptation policy and for the design of future research.

6.5.1. Need for Anticipatory Relocation Frameworks, Not Reactive Disaster Response

Most coastal retreat today is *reactive*; it occurs after a disaster (sudden displacement) or as a last resort after slow-onset hazards have destroyed livelihoods (unmanaged gradual out-migration).

Reactive retreat is expensive, traumatic, and inequitable. It entrenches poverty and overwhelms destination cities.

Anticipatory relocation planned, funded, and executed before conditions become critical—is a vastly better alternative. This requires:

- Risk-based land use planning: Identify coastal areas where protection will become infeasible by 2050 or 2100 (e.g., using dynamic adaptive policy pathways; Haasnoot et al., 2020). Prohibit new development and phase out existing subsidies in those zones.
- Voluntary buyout programmes: Establish permanent, pre-funded buyout programmes for homeowners in high-risk coastal zones, based on pre-disaster market values. New Zealand's approach offers a model.
- Relocation destination planning: Identify and prepare inland reception areas with housing, infrastructure, schools, health clinics, and livelihood opportunities before households arrive. Fiji's planned relocations though imperfect demonstrate the importance of destination readiness. Community-led processes: Relocation must be participatory, respecting cultural preferences, land tenure, and social networks. Top-down relocation (e.g., some Chinese reservoir resettlements) has consistently failed.

6.5.2. Role of International Climate Funds (Green Climate Fund, Loss and Damage Fund) in Funding Managed Retreat

At present, managed retreat is almost exclusively funded by national governments in high-income countries. Low-income coastal nations (Bangladesh, Mozambique, and Tuvalu) cannot afford managed retreat on their own. International climate finance must step in.

Recommendations:

- Earmark a substantial portion of the Loss and Damage Fund for managed retreat. The initial pledges (approx. 700 million)are orders of magnitude too small. Arealistic target would be 700 *million*) *areorders of magnitude too small. Arealistic target would be* 10–20 billion annually by 2030, rising to $100 billion annually by 2040 (consistent with IPCC cost estimates).
- Reform the Green Climate Fund's adaptation window to explicitly fund relocation and buyout programmes. Currently, most GCF adaptation spending goes to in-situ measures (seawalls, drainage, early warning) that may postpone retreat rather than facilitate it.
- Establish a "Climate Relocation Facility" within the UNFCCC, modelled on the World Bank's Global Concessional Financing Facility, to channel funds to national and local relocation authorities.
- Debt-for-relocation swaps: Allow highly indebted coastal nations to reduce debt service in exchange for committing domestic resources to managed retreat.

6.5.3. Recommendations for Standardised Depopulation Metrics to Enable Cross-Case Comparison

The lack of standardised metrics across studies severely hampers meta-analysis and cross-case learning. Current studies use divergent outcome measures (e.g., net migration rate, proportion of households with at least one migrant, proportion of working-age adults absent, population change per decade). This heterogeneity prevented us from conducting a full meta-analysis for most outcomes (Section 2.6).

A proposed minimal set of standardised depopulation metrics for future research:

- Annual net out-migration rate (per 1,000 population) for the exposed coastal area, disaggregated by age, gender, and livelihood.
- Proportion of households experiencing sudden displacement (defined as unplanned, disaster-triggered move with no return within 24 months).
- Proportion of households experiencing gradual out-migration (defined as at least one working-age adult permanently leaving the coastal zone within a 5-year period).
- Proportion of households that are "trapped" (measured by consistent desire to leave + reported barriers to doing so, in a standardised survey module).
- Cyclical displacement frequency (number of temporary moves per household per year, and average duration away).

Additional recommendations:

- All studies should report hazard exposure metrics using standardised units (e.g., mm/year SLR, m/year erosion, dS/m salinity) to enable comparability.
- Researchers should deposit anonymised household-level data in open repositories (e.g., Harvard Dataverse) to facilitate re-analysis and meta-analysis.
- Journals should require a "climate migration reporting checklist" (adapted from PRISMA) for empirical studies.

6.6. Concluding Remarks

The Great Coastal Retreat is underway. From the sinking deltas of Bangladesh and Vietnam to the eroding shores of Louisiana and Alaska, from the vanishing islands of the Pacific to the thawing coasts of the Arctic, millions of people have already moved, and tens of millions more will move in the coming decades. This systematic review has shown that retreat is not a single process but a set of distinct trajectories—sudden displacement, gradual out-migration, cyclical displacement, and trapped populations—each with different drivers, outcomes, and policy requirements.

The central finding is one of profound inequality. Wealthy nations can plan buyouts, fund relocation, and support destination communities. Poor nations and Indigenous communities are left to fend for themselves, experiencing forced, unfinanced displacement and the non-economic losses of cultural heritage and sovereignty. The Loss and Damage Fund is a necessary first step, but it remains a thimble against a rising tide.

Looking forward, the choice is not whether coastal retreat will happen; it will but whether it will be managed or chaotic, just or unjust. Anticipatory relocation frameworks, adequately funded international finance, and standardised metrics for tracking depopulation are essential tools. The Dust Bowl of the 1930s taught us that unmanaged retreat deepens inequality and scars generations. The Great Coastal Retreat offers a second chance to get it right. The scientific community must continue to generate the evidence; policymakers must act on it; and advocates for climate justice must hold both accountable.

7. Conclusion

7.1. Summary of Key Findings: Depopulation Is Not Uniform but Follows Predictable Trajectories Shaped by Hazard Type, Wealth, and Governance

This systematic review of 122 empirical studies has demonstrated that climate-induced coastal depopulation is not a monolithic phenomenon but rather manifests as four distinct trajectories sudden displacement, gradual out-migration, cyclical displacement, and trapped populations each with specific drivers, temporal signatures, and outcomes. Sudden displacement follows extreme storm surge events, producing sharp population declines with only partial, unequal recovery. Gradual out-migration, the most common trajectory, results from slow-onset hazards (sea-level rise, salinisation, erosion) and leads to differential ageing of coastal populations as working-age adults leave. Cyclical displacement – repeated temporary moves affects tens of millions in monsoonal deltas but often masks chronic asset depletion. Trapped populations people who wish to leave but cannot due to financial, legal, or social barriers are widespread yet under-recognised, representing a profound climate justice failure.

Crucially, these trajectories are not randomly distributed. Wealth and governance determine which trajectory a community follows. In high-income settings (USA, Netherlands, New Zealand), managed retreat through buyouts and planned relocation is possible, though outcomes are mixed and equity challenges persist. In low-income nations (Bangladesh, Mozambique, Papua New Guinea), unmanaged retreat is the default, transferring adaptation costs onto vulnerable households and deepening urban poverty. Geographic hotspots the Ganges-Brahmaputra, Mekong, Niger and Mississippi deltas; small island states; Arctic coastal communities share extreme physical exposure but diverge sharply in their capacity to respond. Socio-demographic correlates are consistent across contexts: working-age adults out-migrate at 2.7 times the rate of the elderly; fisherfolk and subsistence farmers are most vulnerable; informal settlers and those without secure tenure are most likely to become trapped.

7.2. The “Ground Zero” Framing Is Useful for Prioritization but Must Avoid Deterministic Catastrophe Narratives

The concept of “coastal ground zero” zones where climate hazards and socio-economic vulnerability converge to produce the most immediate depopulation pressures has proven analytically useful for this review. It directs attention to the world’s most exposed and least protected coastal communities, enabling targeted research and policy prioritisation. The typology of depopulation trajectories developed here provides a structured way to diagnose which process is operating in a given ground zero contexts and to match interventions accordingly.

However, the ground zero framing carries risks if deployed deterministically. Some media and policy discourses depict these zones as inevitably doomed, portraying their inhabitants as helpless “climate refugees” awaiting inevitable displacement. Such narratives are empirically inaccurate and ethically problematic. This review has shown that many households in high-risk coastal areas persist, adapt, or even thrive through a combination of social networks, livelihood diversification, and in-situ adaptation. Others remain not by choice but because they are trapped by poverty, tenure insecurity, or restrictive immigration policies a condition that can be alleviated through targeted interventions. Moreover, managed retreat, when done well, can preserve community cohesion and cultural continuity, as partial successes in Fiji and Louisiana demonstrate.

Thus, the ground zero framing should be used as a tool for prioritisation – identifying where resources and attention are most urgently needed not as a prophecy of inevitable collapse. Narratives that strip coastal communities of agency, that ignore their adaptive capacities, or that reduce complex human decisions to simple environmental push factors do a disservice to both science and justice. Future research and policy must centre the voices, knowledge, and aspirations of those living in ground zero zones, recognising them as agents of their own retreat trajectories, not passive victims.

7.3. Final Statement: Without Proactive, Equitable Managed Retreat Policies, the Great Coastal Retreat Will Deepen Global Inequality and Produce a Legacy of Stranded, Traumatized Populations

The evidence assembled in this review leads to an unambiguous conclusion: the Great Coastal Retreat is already happening, and its pace will accelerate with continued sea-level rise and intensification of coastal hazards. The central question is not whether coastal populations will retreat, but how. Two starkly different futures are possible.

In the first future the path we are currently on in most of the world – retreat is reactive, unmanaged, and profoundly unequal. Wealthy households and nations buy their way to safety, leaving behind poorer, older, and more marginalised populations trapped on sinking shores or scattered into overcrowded urban slums. Cultural heritage is abandoned, Indigenous sovereignty is eroded, and the non-economic losses of place attachment and community cohesion accumulate without recognition or redress. This future deepens global inequality, creates stranded populations, and bequeaths to the next generation a legacy of trauma and resentment.

In the second future the path that climate justice demands – retreat is proactive, equitable, and managed. Governments, supported by adequate international climate finance, identify high-risk coastal zones decades in advance. They phase out new development in these zones, establish permanent, pre-funded voluntary buyout programmes, and plan reception areas with housing, infrastructure, and livelihoods before households are forced to move. Relocation is participatory and community-led, respecting cultural preferences, land tenure, and social networks. Non-economic losses are explicitly recognised and compensated through measures such as cultural heritage documentation, land-back arrangements, and investments in community-building at destination sites.

Achieving the second future requires immediate, concerted action across multiple fronts. National governments must adopt anticipatory relocation frameworks, moving beyond reactive disaster response. International climate funds the Green Climate Fund and the Loss and Damage Fund – must scale up their financing for managed retreat by orders of magnitude, from millions to tens of billions annually. Researchers must develop and adopt standardised depopulation metrics to enable cross-case comparison and meta-analysis, and must fill critical evidence gaps in understudied regions such as South America's Caribbean coast and the Arabian Gulf lowlands.

The Dust Bowl of the 1930s stands as a warning: unmanaged, chaotic retreat scars generations and entrenches poverty. The Great Coastal Retreat of the 21st century offers a different possibility – a chance to plan, to fund, and to act justly. The scientific evidence is clear; the moral imperative is urgent. Without proactive, equitable managed retreat policies, the Great Coastal Retreat will not only empty the world's shorelines but also empty the promise of climate justice. With them, we can still write a different ending one in which retreat is not a disaster but a difficult, dignified transition to safer ground.

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