Integrating ABM and GIS for Flood Evacuation Planning: A Systematic Review and Future Direction

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***Abstract*—This systematic review examines the integration of agent-based modeling (ABM) and Geographic Information Systems (GIS) in flood evacuation planning from 2015 through early 2025. This review aims to systematically evaluate how ABM and GIS have been integrated in flood evacuation research, identify methodological gaps, and propose a structured framework to guide future model development. Using PRISMA guidelines, 67 studies were selected and analyzed to uncover methodological trends, empirical gaps, and policy relevance in this growing research domain. Using the PRISMA 2020 framework, the analysis reveals a dominant reliance on mesoscopic modeling (43%), limited real-time data integration (17.9%), weak empirical validation practices (16.4%), and minimal machine learning adoption (4.5%). To structure the evolving landscape, a conceptual integration framework is proposed to classify studies by modeling scale, data fidelity, and validation strategy. This framework highlights a gradual shift toward behaviorally realistic, spatially precise, and policy-relevant evacuation models. Persistent challenges include limited validation practices, weak real-time responsiveness, and insufficient policy integration. Conclusions were drawn by identifying five research priorities: AI integration, real-time enhancement, multi-hazard modeling, empirical grounding, and participatory policy co-design. This review offers actionable insights for advancing robust, scalable, and operational ABM-GIS systems in disaster risk reduction.**

***Keywords*—Agent-based modeling; GIS integration; flood simulation; spatial modeling; evacuation dynamics; multi-agent systems**

I. Introduction

Floods are among the most frequent and devastating natural disasters globally, causing extensive loss of life, displacement, and damage to infrastructure. Rapid urbanization, climate change, and land-use transformation have intensified both the frequency and severity of flood events in recent years [1] [2]. Notable examples include the 2018 Kerala floods in India [3], 2017 Hurricane Harvey in Houston [4], and the 2020 inundation of Wuhan, China [5]. These disasters underscore the urgent need for robust evacuation planning tools that can adapt to dynamic, uncertain conditions.

Traditional evacuation models often rely on aggregate or static assumptions, limiting their ability to reflect real-time decision-making and heterogeneous human behavior [6]. In contrast, agent-based modeling (ABM) offers a bottom-up approach, simulating individual or group behavior in complex systems [7],[8]. When coupled with GIS, which enables spatial analysis and environmental representation, ABM becomes a powerful tool for flood evacuation planning, integrating human dynamics with terrain, infrastructure, and hazard data [9], [10].

Although the use of ABM-GIS integration in flood modeling has expanded over the past decade, existing reviews have primarily focused on general disaster modeling [11] or lack systematic synthesis across methodological, spatial, and policy dimensions [12],[13],[14]. Moreover, many studies remain invalidated, use outdated data sources, or fail to connect modeling outputs to operational policy frameworks [15][16].

This study addresses these gaps by presenting a systematic review of 67 studies published between 2015 and early 2025 that combine ABM and GIS in flood evacuation contexts. PRISMA [17] review protocol is applied to ensure transparency in study selection and synthesis of findings through a newly proposed Conceptual Integration Framework. This framework categorizes studies by modeling scale, data fidelity, and validation strategy, enabling structured comparison across cases.

The goal of this review is twofold: 1) to map the current landscape of ABM-GIS flood evacuation research and 2) to identify methodological gaps and strategic priorities for future work. The main goal is to guide researchers, planners, and decision-makers in designing more adaptive, empirically grounded, and policy-relevant flood evacuation systems.

II. Literature Review

Flood evacuation modeling has evolved significantly with the integration of agent-based modeling (ABM) and Geographic Information Systems (GIS), enabling the simulation of complex, spatially grounded, and behaviorally diverse human responses to hydrological hazards. Over the past two decades, ABM-GIS frameworks have been widely adopted in urban risk assessment, emergency management, and real-time evacuation decision support [18][19].

A. Progress in ABM-GIS Integration

Recent studies demonstrate increasing sophistication in coupling GIS-based spatial layers with ABM decision logic. Hydrodynamic models (e.g., SWMM, HEC-RAS) are often used to simulate flood propagation, while ABMs simulate agent movement and decision-making under dynamic hazard conditions [20][21]. GIS platforms have enhanced spatial

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realism, allowing building-level, road-level, and infrastructure-specific modeling of evacuation behaviors.

Furthermore, models have become more inclusive of multi-agent interactions, shelter dynamics, and transportation network constraints [22] [23]. This integration enables more granular analysis of evacuation bottlenecks and policy interventions, such as staggered alerts or shelter assignments.

B. Gaps in Behavioral and Empirical Rigor

Despite technical advances, many ABM-GIS studies rely on deterministic or static behavior rules. Psychological realism, such as risk perception, delayed response, or social influence, is often underrepresented [24]. Few models incorporate agent heterogeneity (e.g., age, mobility, risk attitude), and even fewer validate outputs against real-world evacuation data.

Moreover, real-time data streams, such as IoT sensors or mobile tracking, remain rare in ABM-GIS platforms due to integration complexity and data availability constraints. Consequently, many models are scenario-driven rather than adaptive or predictive, limiting their utility in time-critical decisions.

C. Limitations of Existing Reviews

While several reviews have assessed ABM or GIS in isolation or within broader disaster contexts (e.g., pandemics, wildfires), few focus specifically on their combined application in flood evacuation modeling. For example, [25] Lakmali et al., 2024 and [26] Noor et al. (2025) discussed ABM applications in disaster simulation but offered a limited spatial methodological synthesis. More recent works (e.g., Wikstrom et al., 2022) [27] reviewed ABM-GIS tools in infrastructure planning, not evacuation behavior.

Importantly, past reviews have not systematically analyzed modeling scales, data fidelity, and validation strategies critical for translating simulations into operational emergency tools.

D. Need for the Current Review

Given the increasing severity and frequency of flood events and the rising importance of anticipatory evacuation planning, there is an urgent need to map how ABM-GIS tools are being used, validated, and operationalized in flood contexts. This review addresses that need by:

- Synthesizing 67 peer-reviewed studies with a clear inclusion and exclusion protocol.
- Classifying studies across three core dimensions: modeling scale, data fidelity, and validation strategy.
- Visualizing trends, identifying research gaps, and proposing actionable future directions.

By doing so, this review not only summarizes the current state of ABM-GIS flood evacuation modeling, but also offers a diagnostic framework for improving the realism, responsiveness, and policy alignment of future simulations. Table I shows how this review differs from other existing reviews on the area.

TABLE I. COMPARATIVE OVERVIEW OF EXISTING ABM-GIS REVIEWS AND THE PRESENT STUDY

Study	Hazard Type	ABM-GIS Focus	Scope of Review	Gap Addressed by Current Study
[20]	Floods propagation	GIS and hydrodynamic models	Flood spread, hazard mapping	Does not focus on adaptive ABM mechanisms
[23]	Urban disasters	ABM	Transportation bottlenecks, network constraints	No GIS integration for flood-specific evacuation
[25]	General disaster	GIS	ABM applications in disaster simulation	No methodological synthesis of ABM and GIS flood evacuation modeling
[24]	General disaster behaviour	ABM (Behaviour focused)	Human behavior, risk perception, response delay	Limited GIS integration; lacks spatial realism and hydrodynamic context
[27]	Infrastructure	ABM-GIS tools	ABM-GIS in infrastructure planning	No focus on evacuation behavior/modeling
This study (2025)	**Flood evacuation**	**ABM-GIS (integrated)**	**modeling scale, data fidelity, and validation strategy**	**Focus on flood-specific ABM-GIS models with Conceptual Integration Framework**

III. METHODOLOGY

This review adopts the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) 2020 guidelines [17] to ensure transparency and methodological rigor in the identification, screening, and inclusion of studies. The review protocol was not pre-registered, but all search strategies and inclusion criteria are documented in this section for full reproducibility. Two reviewers independently screened titles, abstracts, and full texts. Discrepancies were resolved through discussion. Inter-rater agreement during the full-text screening phase was 91%, indicating high screening consistency.

A. Data Sources and Search Strategy

Literature was retrieved from four major academic databases: Scopus, Web of Science, IEEE, and Science Direct. The search spanned publications from January 2015 to May 2025, focusing on studies that integrate agent-based modeling and Geographic Information Systems in flood evacuation planning. Boolean search strings combined keywords related to agent-based models, GIS, and flooding scenarios. Table II summarizes the database-specific queries. Only peer-reviewed journal articles, review papers, and selected book chapters written in English were considered.

TABLE II. DATABASES SEARCH STRATEGIES USED FOR IDENTIFYING RELEVANT ABM-GIS FLOOD EVACUATION STUDIES.

Data Source	Search Strategies
Web of Science	(“Flood Evacuation Planning” OR “Flood Evacuation Modeling”) AND (“Agent-Based Modeling” OR “Agent-Based Model” OR “ABS”) AND (“Geographic Information System” OR “GIS”)
IEEE Xplore	(“Flood Evacuation” OR “Flood Rescue”) AND (“Agent-Based Modeling” OR “Agent-Based Modeling”) AND (“GIS” OR “Geographic Information System”)
Scopus	("Agent-Based Model" OR ABM) AND ("Geographic Information System" OR GIS) AND ("Flood evacuation")
Science Direct	(“Flood Evacuation Planning with Agent-Based Modeling and GIS”) OR (“Systematic Review” AND “Flood Evacuation” AND “Agent-Based Modeling”)

B. Inclusion and Exclusion Criteria

Studies were included in this review if they focused specifically on flood evacuation or flood response modeling, combined ABM with GIS, and produced spatially explicit modeling outputs. Conversely, studies were excluded if they addressed non-flood hazards such as wildfires or pandemics, lacked a simulation or modeling component, or were published as editorials, conference abstracts, or in languages other than English. A detailed summary of the inclusion and exclusion criteria is provided in Table III.

TABLE III. INCLUSION AND EXCLUSION CRITERIA FOR STUDY SELECTION.

Criterion Type	Inclusion	Exclusion
Publication type	Peer-reviewed journal articles, conference papers, or book chapters in English	Non-peer-reviewed, theses, reports, or non-English texts
Disaster type	Flood-specific evacuation or risk-reduction contexts	Other hazards (earthquakes, wildfires, tsunamis)
Methodology	Explicit integration of ABM and GIS, with empirical, simulated, or hybrid modeling outcomes	Purely equation-based, system-dynamics, or statistical models without ABM and GIS linkage
Data output	Studies providing measurable or model-based evacuation results	Conceptual papers without implementation or evaluation

C. Screening and Selection

The initial search yielded 215 records, which were imported into EndNote for de-duplication. After removing 32 duplicates, 183 articles were screened by title and abstract. A total of 83 full-text articles were assessed for eligibility, leading to 67 studies being included in the final synthesis. Fig. 1 visualizes the identification, screening, and inclusion stages used to select studies for this systematic review. Out of 215 records retrieved from Scopus (n = 123), IEEE Xplore (n = 27), Science Direct (n = 30) and Web of Science (n = 35), 67 studies met the inclusion criteria. Articles were excluded due to incomplete methods or data use (n = 97) and the absence of both GIS and ABM simulation components (n = 16).

D. Data Extraction and Synthesis

For each of the 67 included studies, key metadata were extracted, including the year of publication, geographic focus, modeling scale (micro, meso, or macro), level of data fidelity (e.g., static, dynamic, or real-time), validation strategy (empirical, scenario-based, or none), integration of artificial intelligence or machine learning, and the degree of policy relevance or stakeholder engagement. The extracted information was tabulated and thematically coded using an inductive approach to allow for the identification of patterns across the dataset. Summary statistics were then generated to quantify these patterns, and a Conceptual Integration Framework was developed to classify studies along the dimensions of modeling scale, data fidelity, and validation approach.

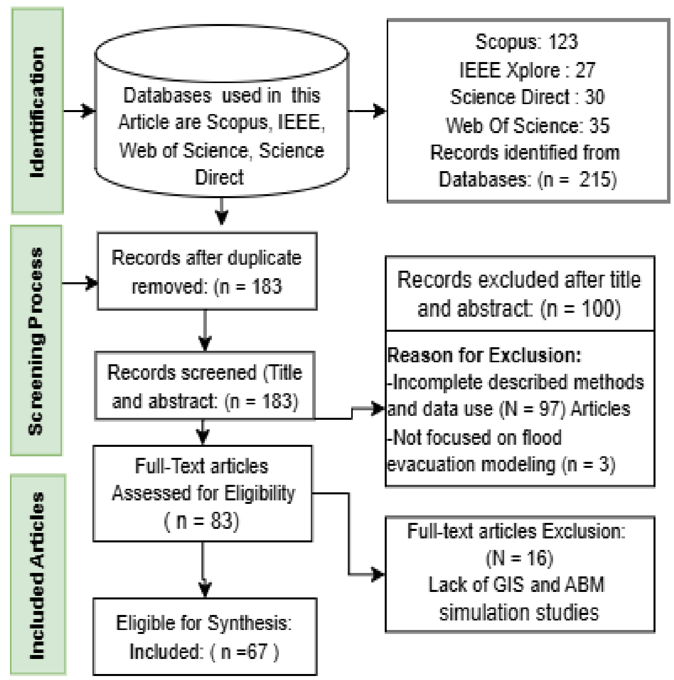

Fig. 1. Illustrates the systematic process used to identify, screen, assess, and include studies in this review of ABM-GIS integration for flood evacuation planning. Out of 215 initial records, 67 studies met the inclusion criteria based on methodological relevance, disaster type, and data integration requirements.

Due to the methodological diversity of the reviewed literature, no formal quality assessment tool (e.g., MMAT or GRADE) was applied. Instead, studies were qualitatively grouped based on the depth of empirical engagement and the transparency of their modeling processes. Table IV summarizes the data extracted from the selection process.

TABLE IV. SUMMARY OF STUDY SELECTION FROM DATABASE SEARCH RESULTS.

Database source	Initial Results	Screened Articles	Full-Text Reviewed	Included Studies
Web of science	35	30	16	14
IEEE Xplore	27	20	5	7
Scopus	123	113	45	33
Science Direct	30	20	17	13
Total	215	183	83	67

IV. Results

This section presents the descriptive and thematic findings from 67 studies integrating agent-based modeling (ABM) and Geographic Information Systems (GIS) for flood evacuation planning, published between 2015 and early 2025. The analysis is structured around publication trends, geographic distribution, methodological characteristics, validation strategies, and integration capabilities.

A. Publication Trends

The publication trajectory of ABM-GIS flood evacuation research over the past decade reflects both steady methodological maturation and a sharp recent increase in scholarly interest. As shown in Fig. 2, the number of publications remained relatively modest between 2015 and 2018, averaging four to five studies per year. A notable uptick began in 2019. The annual publication count peaks in 2025 (n = 15), more than triple the annual output of most prior years. This upward trend suggests growing recognition of ABM-GIS integration as a critical tool in disaster risk reduction, particularly in the face of escalating flood-related hazards driven by climate change and urban exposure. Beyond raw publication counts, thematic synthesis of the 67 reviewed studies reveals four dominant research orientations:

- Methodological integration of ABM and GIS frameworks;
- Geographic and contextual diversity in case study settings;
- Applications in flood policy, planning, and climate adaptation; and
- Limitations related to technical scalability, data availability, and behavioral realism.

Notably, all reviewed studies (100%) integrated both ABM and GIS components in their modeling workflows, underscoring the conceptual synergy between spatial data infrastructure and agent-based decision modeling. However, methodological depth and practical integration remain uneven across the literature. Only 17.9% of studies incorporated real-time data assimilation, 16.4% conducted empirical validation against observed evacuation behavior or outcomes, and a mere 4.5% integrated machine learning or artificial intelligence components to support decision-making under uncertainty. This sharp disparity between theoretical model development and operational implementation signals a critical research gap, particularly in translating simulation outputs into actionable, real-time policy tools.

B. Geographic Distribution

Fig. 3 illustrates the geographic distribution of case studies across 30 countries, revealing clear regional concentrations and gaps. China leads with the highest number of studies (n = 8), followed by the United Kingdom and the United States (n = 6 each), and India (n = 5). Several countries, including Canada, South Korea, Thailand, the Netherlands, and Japan, each contributed three studies. A diverse but sparse representation is observed across other regions, with two studies originating from countries such as Iran, Malaysia, Germany, Nepal, and Poland. Meanwhile, a long tail of countries, including Australia, Indonesia, Greece, Portugal, and the Russian Federation, appear only once in the dataset.

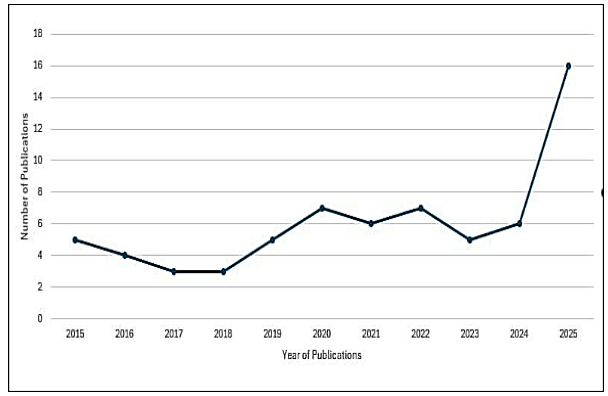

Fig. 2. Annual trends in ABM-GIS Flood Evacuation Publications (2015–2025) depict the yearly distribution of the 67 studies included in this review.

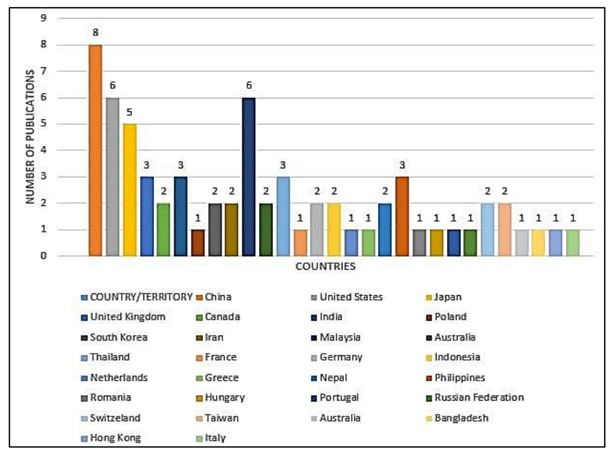

Fig. 3. Geographic distribution of ABM-GIS flood evacuation studies (2015–2025).

The data indicate that ABM-GIS flood evacuation remains heavily concentrated in high-income and upper-middle-income countries, particularly in East Asia, Western Europe, and North America. In contrast, low- and middle-income countries, despite being disproportionately affected by climate-induced flooding, remain underrepresented. This regional imbalance highlights a critical need for broader geographic engagement and increased research capacity in vulnerable regions such as Sub-Saharan Africa, Southeast Asia, and parts of Latin America.

C. Modeling Scale and Scope

The reviewed studies demonstrate a diverse application of modeling scales, reflecting the complexity and adaptability of ABM-GIS frameworks for flood evacuation scenarios. Modeling scale in this context refers to the level of agent aggregation and spatial resolution used to simulate evacuation dynamics, typically categorized as microscopic, mesoscopic, or macroscopic.

Among the 67 studies analyzed, mesoscopic models were the most prevalent, used in approximately 43% of cases. These models typically simulate groups of agents such as households or neighborhoods within bounded geographic areas. Their popularity stems from a pragmatic balance between behavioral realism and computational efficiency, making them particularly suitable for urban-scale evacuations.

Microscopic models, accounting for 34% of studies, simulate individual agents with high granularity, often including variables such as age, mobility constraints, or decision-making heuristics. While offering the highest level of behavioral fidelity, such models are typically computationally intensive and often limited to smaller spatial domains or hypothetical case studies. Nevertheless, they provide critical insights into individual response variability, agent interaction, and localized congestion patterns.

Macroscopic models used in 23% of the studies represent populations in aggregate form, often using flow-based or zone-level simulation. These are typically coupled with hydrodynamic flood models and employed in large-scale risk assessments or regional planning exercises. While less behaviorally nuanced, macroscopic models are valuable for policy analysis and scenario testing over wide geographic extents.

The distribution of modeling scales reveals a methodological trade-off between computational scalability and behavioral detail. Few studies demonstrated multiscale integration (e.g., linking macro-level planning with micro-level agent behaviors), which represents an important direction for future research. Furthermore, only a small subset of models incorporated dynamic scaling, adjusting resolution based on the phase of the flood or real-time data availability, suggesting further potential for methodological innovation.

D. Data Fidelity and Integration

The quality, resolution, and dynamism of data inputs play a central role in the effectiveness and realism of ABM-GIS flood evacuation models. Across the 67 reviewed studies, there was substantial variation in how spatial, behavioral, and environmental data were sourced, integrated, and updated.

Approximately 61% of the studies relied on static or semi-static data inputs. These typically included pre-existing land use maps, census demographics, transportation networks, and historical flood records. While such inputs are useful for scenario testing or long-term planning, they often fail to capture the evolving dynamics of real-time flood events or adaptive human behavior under stress. Only 17.9% of the reviewed studies integrated real-time or near-real-time data such as live rainfall feeds, remote sensing imagery, traffic congestion updates, or sensor-based river level monitoring. These studies demonstrated enhanced situational responsiveness but often faced challenges related to data availability, system interoperability, and model latency.

In terms of data integration architecture, most models embedded GIS data as static spatial layers within ABM environments, primarily using raster-based flood extents or vector-based infrastructure maps. A smaller subset employed bidirectional coupling mechanisms where ABM and GIS platforms dynamically exchanged inputs and outputs during simulation runs, allowing for continuous updates to hazard extents or agent decisions in response to environmental change.

Notably, only a few models demonstrated multi-source data fusion, combining satellite imagery, crowd-sourced reports, mobile GPS data, and hydrological sensors. These approaches, while technically demanding, offer a pathway to more adaptive and realistic evacuation simulations. The uneven adoption of real-time and high-fidelity data reflects a persistent gap between methodological potential and technical feasibility. Bridging this gap will require not only improved access to interoperable data streams but also a greater emphasis on data assimilation techniques, modular system architectures, and validation of input reliability. To illustrate how data source types influence modeling approaches, Table V summarizes a subset of representative studies categorized by their dominant data inputs, modeling strategy, and associated references. The table highlights how data availability, ranging from static GIS layers to real-time sensor streams, influences the design and focus of ABM-GIS flood evacuation models.

TABLE V. REPRESENTATIVE STUDIES CATEGORIZED BY DATA SOURCES AND MODELING APPROACH.

No. of Studies	Common Data Sources	Dominant Modeling Approach	Representative References
12	DEM, LiDAR, hydrodynamic models	GIS and ABM hybrid flood simulation	[57], [58], [59], [60]
6	OpenStreetMap, Sentinel-2 imagery	GIS-based multi-criteria + agent routing	[30], [61], [62]
7	Remote sensing and survey data	Policy-oriented ABM and GIS adaptation models	[63], [64], [64]
4	Open data sets, DEM	Community-scale pedestrian ABM	[65], [66], [6]
3	Sensor data, urban hydrology	Traffic-focused ABM	[67], [68]
3	Mixed databases	Comparative framework reviews	[69], [70]

E. Validation Strategies

Validation remains a critical yet underdeveloped component in ABM-GIS flood evacuation modeling. Of the 67 studies reviewed, only 16.4% employed empirical validation techniques comparing model outputs to observed evacuation behavior, historical flood outcomes, or survey-based data. These studies typically used post-disaster reports, GPS traces, traffic sensor data, or retrospective interviews to calibrate agent behavior and verify model outputs.

The majority of studies (over 50%) relied on scenario-based or face validation, in which model behavior is assessed against expert expectations, hypothetical benchmarks, or visual plausibility. While valuable for internal consistency checks and stakeholder communication, such methods lack the rigor and reproducibility needed for high-confidence decision support.

Cross-dimensional analysis shows that empirical validation was more common in microscopic models (34%) than in mesoscopic (43%) and macroscopic (23%) models. High-fidelity data integration was also more frequently associated with scenario-based rather than empirical validation, indicating clustering of methodological sophistication rather than balanced integration.

A small number of studies (approximately 10%) applied cross-model validation, comparing their ABM-GIS results to outputs from other simulation platforms (e.g., hydrodynamic models or system dynamics). These efforts improved model credibility but often lacked formal metrics or sensitivity analyses. Several barriers to robust validation were noted across the literature:

- Limited availability of real-time or post-event behavioral data.
- Ethical and logistical challenges in collecting ground-truth evacuation information.
- Lack of standard performance metrics, especially for complex human-environment interactions.

Only a minority of studies reported using statistical goodness-of-fit tests, confusion matrices, or spatial accuracy metrics. In many cases, the validation process was either omitted entirely or vaguely described, undermining transparency and reproducibility.

The limited emphasis on empirical validation reflects a broader issue in disaster modeling: a methodological bias toward model development over model testing. Without rigorous validation, even sophisticated simulations risk becoming academic exercises rather than operational tools. Future research must prioritize data-grounded calibration, quantitative error reporting, and transparent validation protocols, particularly if ABM-GIS tools are to inform real-world policy and emergency response.

F. ABM-GIS Methodological Capabilities

The methodological capabilities observed across the 67 reviewed studies highlight both the strengths and limitations of current ABM-GIS integration practices in flood evacuation modeling. Fig. 4 synthesizes the core features evaluated, including spatial resolution, behavioral realism, data integration, validation, computational performance, and policy relevance.

Most studies (83.6%) employed high-resolution GIS data such as road networks, building footprints, land use, and elevation, enabling detailed analysis of agent movement, bottlenecks, and evacuation routes. Behavioral realism varied widely: 74.6% included basic movement or crowd dynamics, but only 38.8% modeled adaptive or heterogeneous decision-making based on factors like risk perception, social influence, or individual constraints. Few studies incorporated empirically derived behavioral parameters or hazard-dependent scenario switching.

Regarding data integration, 65.7% of studies relied on static GIS layers, while only 17.9% integrated real-time or dynamic data sources. This gap continues to constrain the operational applicability of many models, especially in fast-evolving flood contexts. Model validation, as discussed in Section IV E, was another area of concern. While 43.3% of models conducted internal validation (e.g., sensitivity or scenario testing), only 16.4% employed empirical validation against observed data. This underscores the need for greater emphasis on robust, data-informed calibration and performance assessment.

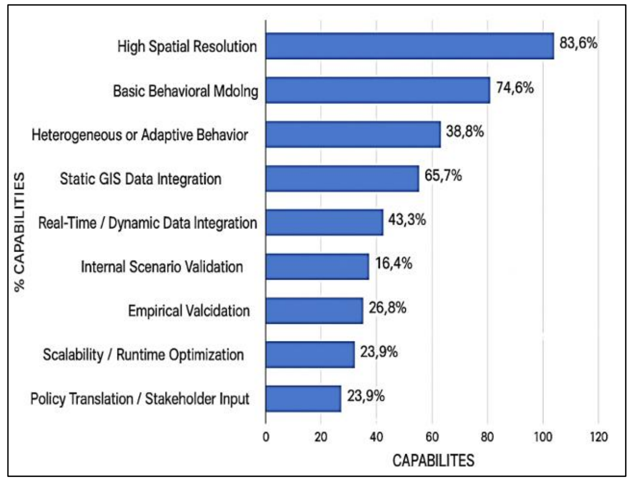

Fig. 4. Prevalence of key methodological capabilities across reviewed ABM-GIS Flood Evacuation Studies illustrates the percentage of studies (n = 67) exhibiting specific modeling capabilities, highlighting strengths in spatial resolution and basic behavior modeling, and gaps in real-time data integration and empirical validation.

In terms of computational performance, only 26.8% of studies addressed scalability or runtime efficiency, indicating that most models remain conceptual rather than real-time deployable. Similarly, policy translation and stakeholder engagement were limited (23.9%), raising concerns about practical relevance and adoption.

Overall, the analysis of methodological capabilities reveals a field that is advancing in spatial and behavioral complexity but still constrained by gaps in real-time responsiveness, empirical grounding, and stakeholder co-design. Addressing these limitations is essential for transitioning ABM-GIS systems from academic prototypes to operational decision-support tools.

To illustrate the diversity and depth of ABM-GIS modeling approaches in real-world contexts, Table VI summarizes selected case studies, outlining their integration frameworks, modeling focus, key contributions, and limitations, highlighting both methodological diversity and persistent gaps in realism, validation, and scalability.

G. Framework for Integrating Scale, Data, and Validation in ABM-GIS Models

To consolidate the methodological diversity observed across the 67 studies, a Conceptual Integration Framework was developed. This framework synthesizes findings across three core analytical dimensions modeling scale, data fidelity, and validation strategy and situates each study within a structured landscape of ABM-GIS flood evacuation modeling practices.

The modeling scale dimension captures the granularity of agent representation, distinguishing between microscopic models (individual-level), mesoscopic models (group-based), and macroscopic models (population aggregates). As described in Section IV C, mesoscopic approaches dominated the literature (43%), offering a balance between realism and computational tractability.

TABLE VI. COMPARATIVE SUMMARY OF SELECTED ABM-GIS FLOOD EVACUATION STUDIES

Author (Year)	Study Area	Model / Framework	Integration Focus	Key Findings / Contributions	Identified Limitations
[28]	Thailand	TU-FS Simulator	GIS-based flood mapping with ABM crowd simulation	Modeled large-scale pedestrian movement to optimize routes and shelter allocation during floods.	Limited to urban settings; did not consider behavioral diversity or multi-hazard context.
[29]	Nanning, China	SWMM-LISFLOOD + ABM	Hydrodynamic and GIS data coupled with ABM	Assessed pedestrian vulnerability and identified high-risk zones under dynamic flooding.	High computational cost; calibration challenges with real-time data.
[7]	Wuhan, China	Coupled Agent-Based Multi-Model Framework (CABMF)	Traffic and shelter data integration via GIS	Tested alternative evacuation strategies using spatially explicit ABM modeling.	Heavy computational demand; limited behavioral validation.
[6]	Kibera, Kenya	OpenStreetMap + DEM + ABM	Community-scale pedestrian simulation	Identified congestion points and suboptimal shelters in informal settlements.	Low-resolution open-source data; constrained by local data quality.
[30]	Nepal	GIS-based Analytic Hierarchy Process (AHP) + ABM	Flood-susceptibility mapping integrated with agent decisions	Prioritized evacuation corridors for high-risk areas; applicable with limited data.	Low-resolution DEM reduced route accuracy; static behavioral rules.
[31]	Coastal China	GIS + ABM for tsunami evacuation	Multi-hazard coupling (flood + landslide + liquefaction)	Demonstrated cross-hazard modeling capability within ABM and GIS framework.	Focused on specific hazard; limited to simulation, not validation.
[32]	China (Urban Metro)	GIS and ABM Transit Model	Infrastructure resilience analysis	Evaluated flood impacts on metro networks and rerouting efficiency.	Did not model passenger behavior diversity.
[33]	China (National Review)	Review of ABM and GIS frameworks	Policy-oriented, climate-adaptation focus	Highlighted potential for long-term risk and insurance modeling.	Conceptual; lacked empirical validation.
[34]	Hong Kong, China	ABM using AnyLogic platform integrated with GIS	Simulates self-evacuation under infrastructure failure	Developed an ABM incorporating household behavior diversity and infrastructure disruption.	Limited empirical validation
[35]	La Ciotat, France	SiFlo Model	GIS and ABM impact modeling	Quantified how awareness and maintenance reduce casualties (~30%).	Regional focus; simplified social behavior.
[36]	United Kingdom	Life Safety Model (LSM)	Dam-break simulation with GIS-ABM coupling	Measured effects of evacuation delay and congestion on mortality.	Requires high-quality DEM; computationally intensive.
[37]	Iran	Hybrid BIM and GIS and ABM	Behavioral and psychological modeling	Incorporated stress and social dynamics in evacuation after earthquakes.	Applied to earthquake context; limited flood transferability.

The data fidelity dimension assesses the type and dynamism of input data used. Models were classified as using low, medium, or high-fidelity data based on their use of static versus real-time information, sensor integration, and spatial resolution. Only 17.9% of studies achieved high data fidelity through real-time or dynamic input streams.

The third axis, validation strategy, reflects the extent and rigor of model verification. It distinguishes between empirical validation (against real-world observations), scenario-based validation, and no formal validation. Most studies (over 50%) relied on scenario-based validation, while only 16.4% employed empirical benchmarks.

By plotting studies across these three axes, the framework reveals distinct clusters and gaps. A central trend is the convergence toward spatially detailed, behaviorally rich, yet weakly validated models indicating methodological innovation without sufficient empirical grounding. Very few studies simultaneously demonstrated high fidelity, individual-level modeling, and rigorous validation.

The framework also exposes a structural limitation: few studies adopted hybrid approaches that span multiple scales, integrate dynamic data, and validate across both technical and behavioral dimensions. This lack of integration suggests that while the field is advancing in specific areas, systemic operational maturity remains limited. Ultimately, the Conceptual Integration Framework, as illustrated in Fig. 5, offers a diagnostic tool for positioning current research, identifying best practices, and directing future efforts toward comprehensive, validated, and policy-relevant ABM-GIS flood evacuation systems.

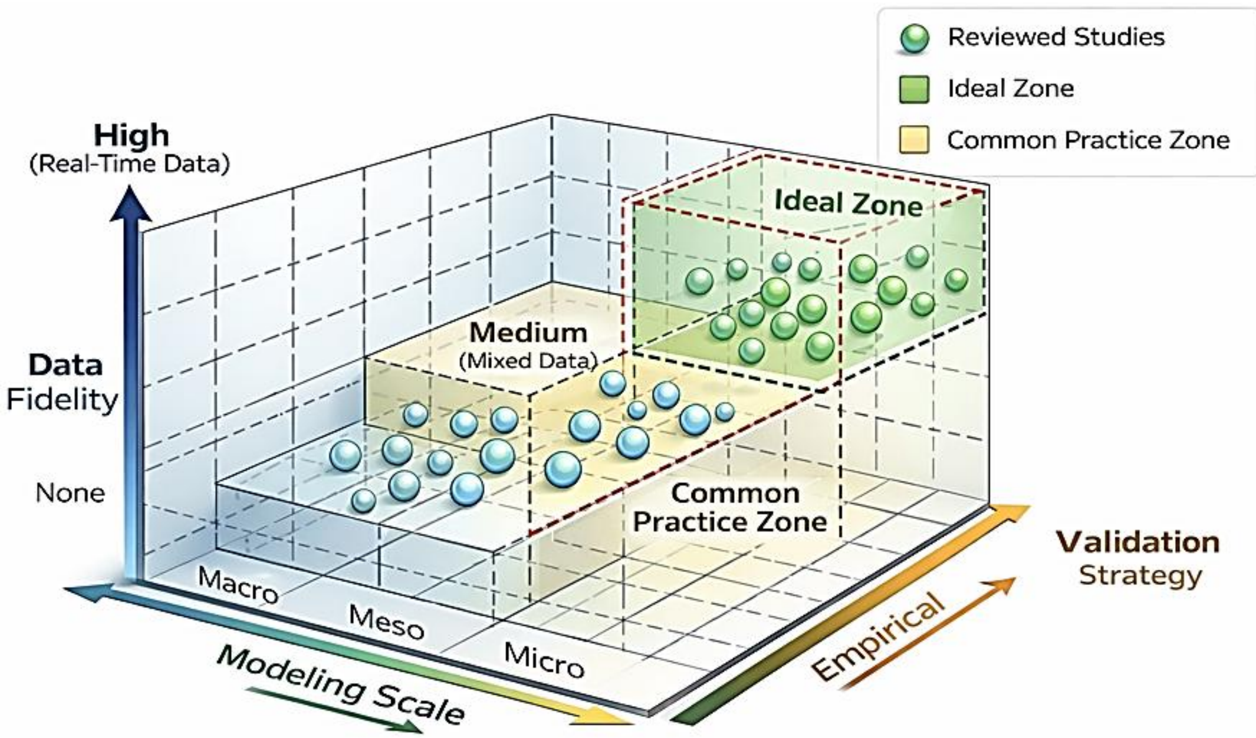

Fig. 5. Conceptual Integration Framework for ABM-GIS Flood Evacuation Models: A three-dimensional framework categorizing the 67 reviewed studies across modeling scale (macroscopic to microscopic), data fidelity (static to real-time), and validation strategy (none to empirical). The framework highlights dominant methodological clusters and identifies underdeveloped areas requiring future research.

H. Summary of Key Findings

The results of this review reveal a rapidly evolving field characterized by methodological diversity and growing sophistication in the integration of agent-based modeling and GIS for flood evacuation planning. While notable progress has been made in spatial resolution, behavioral modeling, and scenario-based applications, significant limitations persist. These include limited real-time data integration, inconsistent validation practices, and a lack of stakeholder engagement in model development. The Conceptual Integration Framework highlights clear trade-offs between fidelity, scale, and validation rigor emphasizing the need for more holistic, empirically grounded approaches. These findings collectively underscore a critical transition point for the field: from exploratory modeling toward operational decision-support systems that are robust, scalable, and grounded in real-world dynamics.

V. Discussion

The systematic review of 67 ABM-GIS flood evacuation studies demonstrates growing methodological innovation, particularly in spatial modeling and agent-based behavior representation. However, significant gaps persist in empirical grounding, real-time responsiveness, and operational integration. This discussion contextualizes those findings within current research trajectories and highlights the critical steps needed to evolve ABM-GIS models from academic prototypes into policy-relevant, adaptive systems.

A. Integration Advancements and Spatial Maturity

The field has matured notably in spatial fidelity and model sophistication. Over 80% of reviewed studies employed high-resolution GIS inputs such as DEMs, land use classifications, or detailed infrastructure networks. This reflects the increasing availability and accessibility of geospatial data and hydrodynamic models such as HEC-RAS or SWMM, which enhance terrain realism and flood dynamics. In many cases, spatial resolution enabled evacuation models to operate at building-level or street-level granularity, essential for identifying bottlenecks, exit points, and vulnerable zones in urban areas.

Concurrently, integration of GIS within ABM has improved in terms of layering, routing, and environment-agent interactions. However, in most studies, GIS is still used as a static input environment rather than a dynamically updating system. Real-time integration remains rare, and the use of GIS in feedback loops, such as adjusting flood depth or road blockage during simulation, is still largely absent.

B. Behavioral Realism and Modeling Scale Limitations

In terms of agent behavior, progress is mixed. While approximately 75% of studies modeled individual or group-level movement decisions, only a minority (less than 40%) introduced behavioral heterogeneity or psychological dynamics. Most models used deterministic rules (e.g., shortest-path algorithms or fixed compliance rates), overlooking decision uncertainty, social influence, or delayed response.

This undermines realism, as empirical studies show that evacuation behavior is often influenced by cascading cues, misinformation, or peer actions. There is a critical opportunity here to align ABM-GIS models with behavioral science, including risk perception theories and social contagion frameworks, to better emulate real-world complexities.

Additionally, the dominance of mesoscopic models, while efficient, may obscure fine-grained dynamics in dense urban environments or neglect macro-level impacts such as inter-jurisdictional flows. Multiscale or hybrid modeling approaches blending microscopic agent actions with regional-scale scenarios remain underutilized.

C. Validation and Data Assimilation Remain Critical Bottlenecks

Validation remains one of the weakest links in current ABM-GIS modeling. Despite methodological rigor in model design, only 16.4% of studies employed empirical validation strategies. The rest relied on scenario testing or visual plausibility. This validation gap weakens the credibility of simulation outputs and limits their utility in high-stakes planning contexts.

The main barriers include a lack of accessible post-event behavioral datasets, ethical challenges in observing real-time evacuations, and difficulty in matching dynamic model outputs with real-world baselines. Although some studies used field surveys or traffic counts, few integrated sensor-based evacuation data or mobile trace analytics.

Similarly, only a small subset of studies (17.9%) integrated real-time data sources (e.g., IoT sensors, remote sensing imagery, live weather feeds), despite the growing availability of such streams. Without real-time data assimilation, models remain static representations rather than responsive decision-support systems.

D. Limitations of the Review Methodology

Although this review followed PRISMA guidelines to ensure transparency in study identification and selection, a formal quality or risk-of-bias assessment tool (e.g., MMAT or GRADE) was not applied. This decision was primarily due to the methodological heterogeneity of the included studies, which span simulation-based modeling, hydrodynamic coupling, conceptual frameworks, and computational experiments that do not align neatly with conventional appraisal instruments designed for clinical or empirical research.

Nevertheless, this absence may influence the interpretation of research gaps, particularly regarding validation rigor. The reported validation prevalence reflects reporting patterns rather than a weighted assessment of study robustness. Future reviews would benefit from appraisal criteria specifically designed for ABM-GIS simulation research.

E. Policy Translation and Stakeholder Integration are Underdeveloped

Despite the theoretical potential of ABM-GIS models, only 23.9% of studies involved stakeholders or addressed implementation pathways. Even fewer aligned simulations with policy frameworks, emergency management protocols, or operational workflows. This represents a disconnect between scientific modeling and practical deployment.

Effective policy integration requires not just accurate models, but interpretable outputs, user-friendly interfaces, and stakeholder trust. Most reviewed studies stopped at visualizations or dashboards, without clear evidence of their use in drills, response plans, or municipal decision-making. Co-design processes, scenario walkthroughs, and participatory simulation remain the exception rather than the norm.

F. Research Priorities and Strategic Directions

To advance ABM-GIS flood evacuation modeling, five strategic research priorities emerge from the reviewed literature and are illustrated as follows:

1) Real-time IoT integration: Few models dynamically respond to live flood or mobility data. Integrating IoT sensors, satellite feeds, and traffic APIs would enable real-time updates to road conditions and hazard zones, improving the responsiveness of simulations.

2) Behavioral model enrichment: Agent behaviors are often simplistic, ignoring stress, uncertainty, or social influence. Future models should incorporate cognitive and psychological dimensions to better reflect real-world evacuation patterns.

3) Machine learning integration: ML methods can enhance model calibration, pattern recognition, and adaptive agent behavior. Reinforcement learning, in particular, can help agents learn optimal escape strategies over time, though interpretability must be preserved.

4) Multi-hazard modeling: Most simulations focus on single hazards. Incorporating cascading risks (e.g., power outages, pandemics) would allow for more realistic crisis planning and assessment of compound disaster scenarios.

5) Cloud computing and digital twins: Scalability remains a bottleneck. Cloud platforms and GPU-accelerated simulations can enable high-resolution, real-time modeling. Digital twins could support continuous monitoring and simulation of evolving emergencies.

This concise roadmap aligns emerging technologies with current modeling limitations, offering a practical foundation for building more adaptive, validated, and operationally integrated ABM-GIS systems

The reviewed studies and frameworks reveal both progress and ongoing gaps in ABM-GIS flood evacuation modeling. To summarize these findings, Fig. 6 presents key modeling components, typical methods, and recurring limitations offering a final lens to identify areas of innovation and those needing further development.

Table VII presents a strategic mapping of core challenges in ABM-GIS flood evacuation modeling alongside recommended solutions and anticipated outcomes. This synthesis aims to guide future work in developing empirically grounded, computationally efficient, and socially relevant simulation systems.

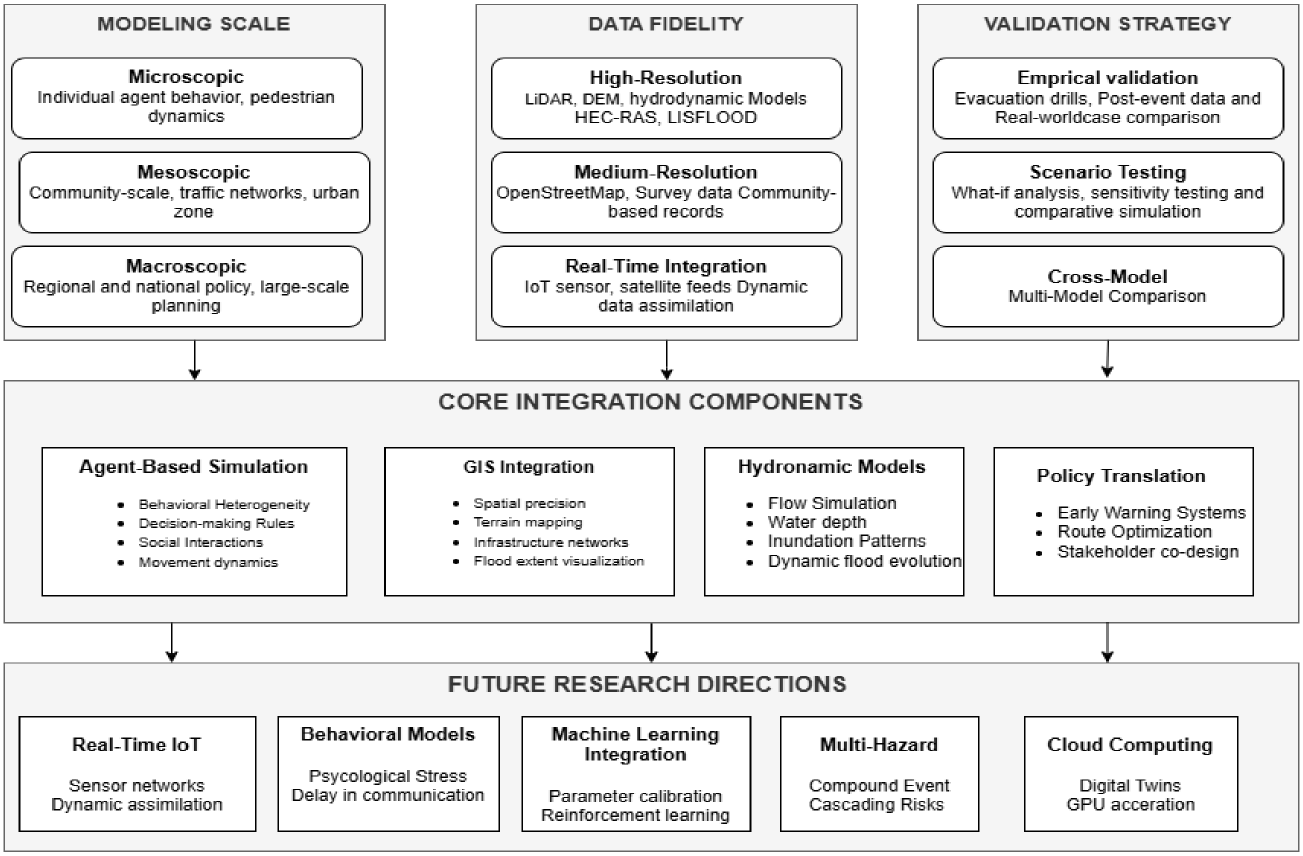

Fig. 6. Synthesis of ABM-GIS Modeling Practices, Core Integration Components, and Future Research Directions summarizes key dimensions of modeling scale, data fidelity, and validation strategy in ABM-GIS flood evacuation studies. The middle layer identifies essential integration components: agent simulation, GIS coupling, hydrodynamic modeling, and policy interfaces, while the bottom layer highlights six research priorities critical for advancing the field.

TABLE VII. STRATEGIC CHALLENGES, RECOMMENDED SOLUTIONS, AND EXPECTED OUTCOMES FOR ADVANCING ABM-GIS FLOOD EVACUATION MODELING

Research Focus	Key Challenge	Recommended Strategy	Expected Outcome	Ref.
Real-Time Data Integration	Static datasets limit responsiveness	Adopt IoT, UAV imagery, and satellite streams	Dynamic updates to ABM and GIS layers	[38], [39], [40]
Machine Learning Integration	Manual parameter tuning	Use reinforcement learning for behavioral adaptation	Self-calibrating models with faster simulation speeds	[41], [42], [43]
Multi-Hazard Modeling	Single-event focus	Link hydrologic, meteorologic, and infrastructure datasets	Cascading risk assessment	[44], [45], [46]
Behavioral Realism	Simplified decision rules	Integrate social-network and psychological factors	Culturally sensitive evacuation policies	[47], [48], [49]
Computational Scalability	High processing time	Parallel computing + cloud deployment	Real-time simulation capability	[50], [51], [52]
Validation Standards	Lack of benchmarks	Develop shared post-event datasets	Cross-model comparability	[53]
Policy Co-Design	Weak research	Participatory scenario planning with local agencies	Higher adoption of ABM and GIS outputs	[54], [55], [56]

VI. CONCLUSION

This review has critically examined 67 peer-reviewed studies that integrate ABM and GIS in the context of flood evacuation. The findings reveal clear progress in spatial resolution, agent-based behavior modeling, and hydrodynamic coupling. However, several persistent limitations hinder the operational utility of these models, including weak empirical validation, limited behavioral diversity, insufficient real-time data integration, and low policy engagement.

Through structured thematic synthesis and conceptual frameworks, the review identifies three core modeling dimensions: scale, data fidelity, and validation strategy that define the methodological landscape. Most studies emphasize spatial detail and heuristic agent behavior, yet few achieve comprehensive integration across all dimensions. Most remain static, proof-of-concept systems rather than fully adaptive, operational decision-support tools.

To address these challenges, the study outlines five strategic research priorities: real-time IoT integration, behavioral model enrichment, machine learning, multi-hazard coupling, and scalable cloud-based deployment. These priorities are not merely technical enhancements; they represent critical shifts toward empirical rigor, stakeholder relevance, and cross-disciplinary innovation.

As climate-driven flood risks intensify globally, the need for robust, adaptive, and context-sensitive evacuation models has never been more urgent. Future ABM-GIS systems must move beyond academic silos to become embedded components of anticipatory planning, real-time response, and long-term resilience strategies. This review provides a roadmap for that transition, bridging science, computation, and policy to strengthen disaster preparedness in the face of escalating uncertainty.

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