



Research article

Operationalization of a spatial interaction model to estimate the impact of community structure on resilience processes

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Abstract: Growing hazard exposures and deepening social disparities highlight the need for resilience frameworks that capture not only risk and vulnerability but also the processes through which communities adapt. Most existing indices rely on static indicators that describe socioeconomic or infrastructural conditions without representing the spatial and networked interactions that sustain adaptation and recovery. This paper operationalizes resilience as a process of dynamic interaction among people, infrastructure, and environment by advancing the Community Hazardscape and Amenity Placement in Provisioning of Improved Endpoints (CHAPPIE) framework. Using a production-constrained gravity model, CHAPPIE estimates potential benefit flows between households and resources within network constraints, thereby quantifying accessibility, connectivity, and equity as determinants of adaptive capacity. The paper aligns conceptual resilience capacities—education and information, basic provisioning, health and safety, and community cohesion—with measurable indicators and network metrics. By embedding spatial interaction theory within the resilience assessment, the framework provides a path toward quantifying resilience as a socio-ecological process rather than a static condition, illustrating how accessibility and structure shape adaptation potential.

Keywords: resilience processes; gravity model; network accessibility; community structure; socio-ecological systems; equity

1. Introduction

Natural hazards are increasing in frequency, intensity, and cost worldwide, magnifying risks for human and ecological systems [1,2]. Despite investments in mitigation, recovery outcomes remain uneven, particularly for communities already burdened by social inequities [3]. Traditional resilience indices describe community conditions through demographic, economic, and infrastructural indicators, yet they often fail to represent how these components interact to generate adaptive outcomes [4,5]. As a result, resilience continues to be interpreted largely as a static property rather than a reflection of dynamic processes describing how a place functions before, during, and after a disturbance [6,7].

Recent research in socio-ecological systems reframes resilience as an emergent capacity of interconnected networks [8–10]. From this perspective, resilience arises from feedback among social, physical, and ecological subsystems that distribute risk and benefit through flows of information, goods, and services. Understanding resilience, therefore, requires moving beyond inventories of assets toward representations of the interactions that enable or constrain adaptation. These flows are inherently spatial and represented by distance, infrastructure quantity and quality, and social connectivity, governing the capability and speed for resources to reach those in need [11,12].

1.1. From static indicators to interaction processes

Indicators remain valuable for benchmarking, but without incorporating the spatial and temporal dynamics of community systems, they cannot explain divergent recovery trajectories among communities with similar baseline conditions. For example, two neighborhoods may share comparable income levels and housing quality yet recover at vastly different rates after a flood due to one having redundant transportation and social networks while the other is isolated by limited access routes [13,14]. Capturing these differences requires models that couple resources with how those resources circulate through networks.

Spatial interaction and network models offer precisely this capacity. They represent flows between origins and destinations and quantify how connection strength declines with distance or friction. In resilience contexts, such models can capture how benefits like healthcare access or emergency response propagate through community structures and how disruptions cascade when networks fail [15,16]. Integrating these models into resilience assessment translates abstract capacities into measurable processes.

1.2. Purpose and research question

This study builds directly on the conceptual Community Hazardscape and Amenity Placement in Provisioning of Improved Endpoints (CHAPPIE) framework [17], which describes resilience as a process of interaction between households, resources, and infrastructure. The purpose of the present paper is to demonstrate how the framework could be operationalized by aligning it with measurable data and spatial modeling techniques. Considering this challenge, there are two research questions guiding this work: 1) How can the processes that generate community resilience be operationalized through measurable spatial interactions among households, resources, and infrastructure? 2) Is there adequate available data to effectively quantify the framework?

By addressing these questions, the paper advances resilience analysis from descriptive assessment toward process-based quantification. It positions CHAPPIE as both a conceptual bridge and a computational tool linking social vulnerability, infrastructure networks, and adaptive capacity within a unified socio-ecological model.

2. Data and methods

Resilience research has evolved from describing recovery capacity to exploring the dynamic processes that enable systems to persist and adapt amid change. This section establishes the theoretical foundation for conceptualizing resilience as an emergent property of socio-ecological systems shaped by spatial structure and interaction. It synthesizes literature on resilience-as-process, accessibility, and network theory to position the CHAPPIE framework within contemporary approaches that view communities not as static entities but as interconnected networks of people, infrastructure, and environment.

2.1. Resilience as a socio-ecological process

Resilience describes how systems absorb a disturbance, reorganize, and continue functioning while undergoing change [18]. In socio-ecological terms, it arises from the interdependence of human and natural systems and their ability to maintain feedback across scales [19,20]. Traditional assessments often treat these systems as static collections of assets, assuming that greater availability of resources equates to higher resilience. However, a growing body of literature emphasizes that how resources interact and how they are accessed, mobilized, and shared is equally important [6,8,21].

Within this paradigm, resilience emerges from processes of adaptation rather than states of stability. These processes include information exchange, social learning, mobility, and infrastructure connectivity. Measuring them requires capturing both structure (the spatial configuration of systems) and function (the flow of materials, people, and knowledge) [16,18]. This process-based framing aligns with general resilience concepts, which emphasize adaptability and transformability within complex, interconnected networks.

2.2. Community structure, accessibility, and equity

Community resilience depends on the organization and accessibility of resources across physical and social networks [22,23]. Accessibility is not merely the presence of a resource but the opportunity to benefit from it, shaped by distance, cost, infrastructure, and social barriers [12,24]. Inequities in these factors produce “friction” that limits adaptation. For example, health facilities may exist in a region, yet transportation, language, or cost barriers can render them functionally inaccessible.

Equity thus becomes central to resilience: Communities with similar exposure levels can experience dramatically different outcomes because of variation in accessibility [14]. Modeling resilience as a flow process captures this reality by linking the physical distribution of resources with social and infrastructural capabilities that enable their use.

2.3. *The role of networks in resilience*

Networks underpin nearly every resilience process. They include physical infrastructure (e.g., roads, utilities, broadband), ecological linkages (e.g., watersheds, green corridors), and social or informational ties. The resilience of these networks depends on their connectivity, redundancy, and modularity, properties well established in network science [15].

Communities with high connectivity can redistribute stress and reroute flows when disturbances occur, whereas fragmented or centralized networks are more prone to cascading failures [11,25]. In resilience modeling, network metrics such as centrality, betweenness, and clustering can represent these adaptive properties. By embedding them within spatial interaction models, accessibility becomes measurable not only by physical distance but by network topology and flow efficiency, capturing how structural position and connectivity influence the movement of benefits and information.

Theoretical perspectives on resilience emphasize that adaptation emerges from interactions among social, infrastructural, and environmental systems. Translating these concepts into measurable form requires a model capable of representing such interactions quantitatively. The next section introduces the CHAPPIE framework, which operationalizes these theoretical ideas through a spatial interaction model designed to capture the flow of benefits, risks, and adaptive capacity across community networks.

2.4. *Model development*

Building on the theoretical foundation established in the preceding section, this part of the paper translates the concept of resilience-as-process into a measurable spatial model. It introduces the CHAPPIE framework and explains how spatial interaction theory can be applied to represent adaptive processes as flows of benefit and risk. The section outlines the model's mathematical structure, its integration with network constraints, and its capacity to link social and infrastructural systems within a unified analytical framework.

2.4.1. Conceptual overview

The CHAPPIE framework assesses resilience as a balance between hazard exposure and benefit accessibility. It assumes that resilience increases when community members can efficiently access diverse, well-distributed resources and decreases when access is constrained by distance, infrastructure failure, or social barriers.

In CHAPPIE, households act as origins generating demand for resources, and community amenities (e.g., schools, clinics, and emergency facilities) act as destinations supplying benefits. Infrastructure networks (e.g., roads, utilities, communications) provide the pathways along which these flows occur. This approach unites socio-economic, infrastructural, and environmental dimensions of resilience within a single process-based framework.

2.4.2. Model formulation

CHAPPIE employs a production-constrained gravity model, a well-established spatial interaction formulation adapted here to represent benefit flows [26,27]. The model is defined in Eq 1.

$$T_{ij} = A_i O_i W_j^\alpha d_{ij}^\beta, \quad (1)$$

where,

$$A_i = \left[\sum_j W_j^\alpha d_{ij}^\beta \right]^{-1},$$

where T_{ij} is the estimate of the interaction share. A_i represents the relative location of origin i to the destinations j , where lower values indicate higher accessibility or interaction. O_i is the number of people per unit within the community (residential units). W_j is the vector of destination characteristics. d_{ij} is the distance (time or space) between i and j . α is the vector of population characteristics, and β is the vector of community characteristics.

This formulation quantifies potential benefit exchange, or the probability that a household can access a resource, subject to resource attributes, household attributes, and network constraints. By incorporating both physical distance and socioeconomic modifiers, it captures the relative accessibility of resources within real-world conditions.

2.4.3. Network constraints and socio-ecological context

To reflect actual community functioning, CHAPPIE constrains flows to follow existing infrastructure networks. Distances (d_{ij}) are measured along these networks, derived from physical and social attributes (e.g., congestion, broadband availability, income, language). This ensures that modeled interactions represent feasible pathways for resource exchange rather than simple proximity. It also allows for these attributes to be adjusted to test changes. Each origin and destination carries distinct socio-ecological attributes that shape interaction dynamics within the system. Population characteristics (α) include socioeconomic status, mobility, education, and health, capturing the demand-side variability in how residents engage with community resources. Community characteristics (β) represent collective governance, infrastructure quality, and environmental conditions, reflecting the broader contextual factors that influence accessibility and coordination. Resource attributes (W_j) capture the type, capacity, and quality of services available at destination nodes, representing the supply-side elements of the system. Together, these parameters define a network of potential interactions that operationalize the processes of resilience via distribution, access, and adaptation.

2.4.4. Scale and aggregation

Scale is a critical dimension of resilience measurement [20,28]. CHAPPIE is designed to operate across nested scales, from household parcels to neighborhoods and municipal boundaries, allowing aggregation without losing spatial variability. Each level reflects distinct but interrelated processes: Individual access, neighborhood connectivity, and community capacity. Aggregating these levels reveals emergent system behavior while preserving heterogeneity in exposure and benefit distribution.

Figure 1 presents the conceptual foundation of the CHAPPIE framework, showing how households (origins) interact with community resources (destinations) through a network of physical and social infrastructure. The schematic depicts the model's spatial interaction structure, in which each link represents a potential flow of benefits between households and resource nodes. These flows are governed by both spatial factors and socio-ecological modifiers. The strength of the connection

between any two points corresponds to the modeled interaction share T_{ij} , calculated through the production-constrained gravity equation from Eq 1.

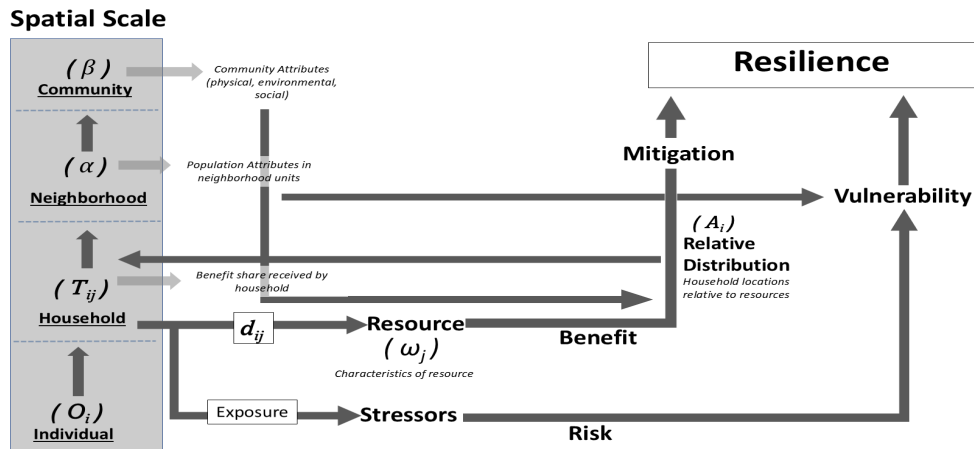


Figure 1. Conceptual schematic of the CHAPPIE framework showing households (origins), community resources (destinations), and infrastructure networks (edges). Flow intensity between nodes represents potential benefit exchange, constrained by distance and social friction. The model operationalizes resilience as the dynamic balance between risk (exposure) and adaptive capacity (accessibility).

Denser linkages and shorter network distances increase potential accessibility, reducing friction and enhancing adaptive capacity, whereas fragmented or elongated paths indicate higher friction and greater vulnerability. The schematic captures the central premise of CHAPPIE: That resilience arises from the structure and efficiency of interaction flows, which mediate the balance between exposure, capacity, and adaptation across interconnected socio-ecological systems.

While the CHAPPIE model establishes a conceptual framework for representing spatial interaction, its practical utility depends on how resilience capacities are defined and measured within that structure. The following section describes how key dimensions of resilience are operationalized through measurable indicators and aligned with model parameters to reflect adaptive processes in real communities.

2.5. Operationalizing resilience capacities

Having defined the model structure, this section describes how conceptual capacities are transformed into measurable components of resilience. It presents four primary capacities: Education and information, basic provisioning, health and safety, and community cohesion, and explains how each indicates a dynamic process of interaction between households, resources, and networks.

The CHAPPIE model translates resilience theory into quantifiable components by aligning capacities, or the social and physical processes enabling adaptation, with measurable data attributes. Rather than treating these as static characteristics, CHAPPIE defines each capacity as a dynamic exchange process among population, community, and resource variables. Each capacity corresponds to one or more model parameters (Tables 1–4), representing how accessibility and connectivity shape adaptive potential.

2.5.1. Education and information capacity

Information flow and learning highlight adaptive behavior in all socio-ecological systems. The education and information capacity reflects how well communities acquire, process, and share knowledge needed for preparedness and adaptation [25,29]. Table 1 summarizes the representative indicators used to operationalize the education and information capacity, aligning population, community, and resource variables with corresponding CHAPPIE model parameters.

In CHAPPIE, these processes are measured through population attributes (e.g., education levels, language proficiency, technology access), community attributes (e.g., investment in schools, communication infrastructure, emergency outreach), and resource attributes (e.g., schools, libraries, universities). Access to these resources indicates potential for information exchange and knowledge diffusion, which are core processes of adaptive capacity [9].

Table 1. Representative indicators for education and information capacity and their alignment with CHAPPIE model parameters.

Component	Example indicators	CHAPPIE parameters	Process function
Population	Educational attainment, English proficiency, internet or computer access	O_i, α	Knowledge base, communication capability
Community	Education spending, teacher–student ratio, broadband density	β	Network strength for information dissemination
Resources	Schools, libraries, community centers, postsecondary institutions	W_j, d_{ij}	Nodes for information flow and public learning

Information and education networks enhance resilience by reducing informational asymmetry and supporting rapid information dissemination during crises. In the model, higher connectivity between residents and knowledge hubs reduces friction and increases interaction share, signaling more efficient distribution of adaptive information.

2.5.2. Basic provisioning capacity

The basic provisioning capacity, outlined in Table 2, represents how effectively a community satisfies essential needs of food, shelter, utilities, and mobility. It captures both the distribution of goods and the infrastructure enabling movement and exchange. Access to employment, transportation, and basic services is the primary determinant of this capacity [30,31].

Table 2. Representative indicators for basic provisioning capacity.

Component	Example indicators	CHAPPIE parameters	Process function
Population	Income level, employment rate, housing cost burden	O_i, α	Resource demand and economic mobility
Community	Transit coverage, walkability, infrastructure investment	β	Efficiency of service distribution
Resources	Government offices, businesses, transit hubs	W_j, d_{ij}	Service and job accessibility nodes

Provisioning networks determine a community's ability to acquire necessities and sustain livelihoods. In CHAPPIE, the flow of provisions quantifies how household income and network accessibility jointly determine potential benefit acquisition. High friction from poor transportation or inequitable spatial planning reduces interaction share even when resources exist, reflecting unequal adaptive opportunities [24,32].

2.5.3. Health and safety capacity

Health and safety capacity measures are presented in Table 3, reflecting how effectively a community protects life and well-being through healthcare access, environmental quality, and emergency response. This capacity also reflects the flow of services and safety information that maintains public health and social stability [33,34].

Table 3. Representative indicators for health and safety capacity.

Component	Example indicators	CHAPPIE parameters	Process function
Population	Health status, insurance coverage, disability prevalence	O_i, α	Demand for health services and mobility limitations
Community	Crime rate, air/water quality, greenspace access	β	Environmental determinants of health and access.
Resources	Hospitals, clinics, EMS, parks, food outlets	W_j, d_{ij}	Resource nodes supporting physical and mental health

2.5.4. Community cohesion capacity

Table 4 details the indicators used to quantify community cohesion, emphasizing social connectedness, trust, and collective action as drivers of adaptive behavior. These are critical social processes that determine how communities mobilize during disruption [35,36]. Unlike purely physical attributes, cohesion operates through both spatial and aspatial networks, including volunteerism, civic participation, and digital connectivity [37,38].

Table 4. Representative indicators for community cohesion capacity.

Component	Example indicators	CHAPPIE parameters	Process function
Population	Social support networks, volunteerism, civic engagement	O_i, α	Collective potential for adaptive response
Community	Residential stability, economic inclusion, ethnic diversity	β	Structural support for place attachment
Resources	Cultural institutions, public spaces, community groups	W_j, d_{ij}	Physical and organizational nodes fostering connection

Cohesion converts social ties into functional adaptive capacity. CHAPPIE captures this through the density and accessibility of social nodes (e.g., civic centers, places of worship, nonprofits) that lower friction within the network and amplify connections among residents. Strong cohesion mitigates isolation and accelerates collective recovery [10,25].

2.5.5. Integrating capacities into the CHAPPIE model

Each capacity contributes to resilience through a measurable process of interaction. When aggregated, these flows describe the spatial distribution of potential benefits that counterbalance hazard exposure. The total resilience potential R_i for a neighborhood or community can be expressed as Eq 2.

$$R_i = \sum_{c=1}^4 \sum_j T_{ij}^{(c)} - H_i, \quad (2)$$

where $T_{ij}^{(c)}$ is the interaction flow for capacity c , and H_i represents hazard exposure or risk at origin i . This formulation conceptualizes resilience as a net process, which is represented as the sum of beneficial exchanges minus the stresses imposed by hazard exposures.

Figure 2 integrates the four resilience capacities within the CHAPPIE structure, illustrating how education, provisioning, health, and cohesion processes interact through shared infrastructure networks. Each capacity generates its own set of interaction flows between households (origins) and community resources (destinations), which are represented as directional connections weighted by accessibility and friction. The diagram integrates these capacity-specific flows into a composite network, where overlapping pathways reveal multifunctional infrastructure nodes that support multiple dimensions of resilience. For example, a school may simultaneously act as an educational node, an emergency shelter, and a hub of social cohesion, thereby reinforcing the interdependence among capacities.

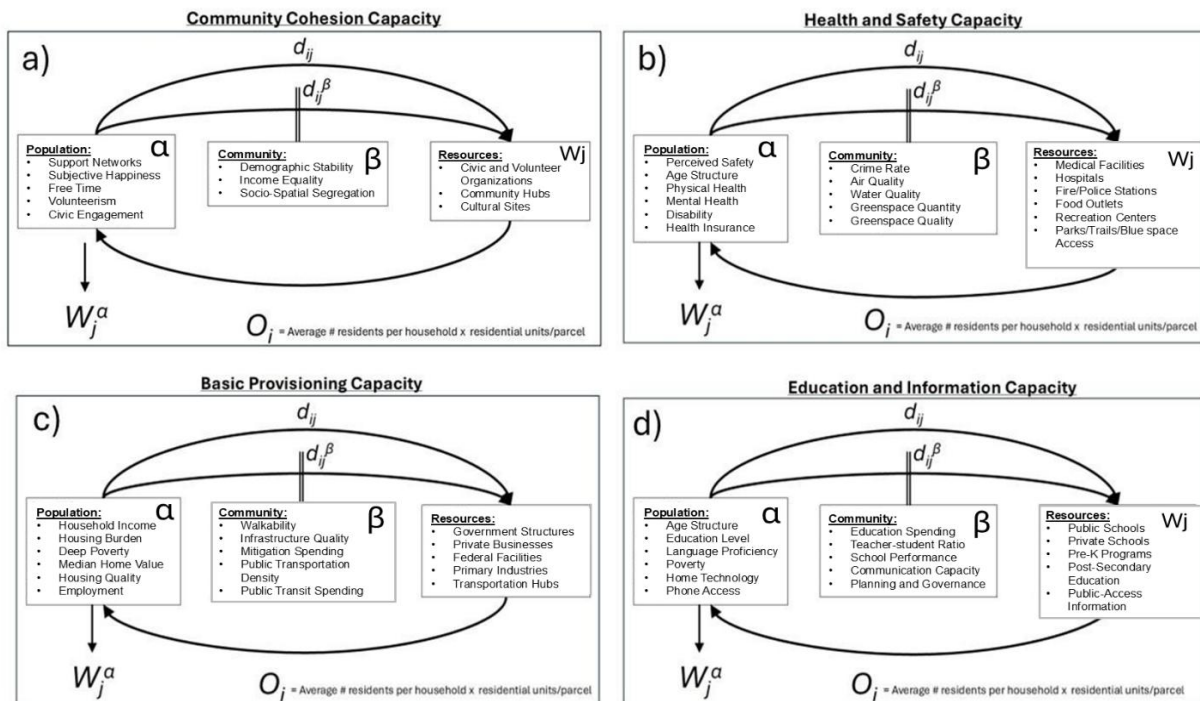


Figure 2. Integration of the four capacities within the CHAPPIE framework. Each capacity represents a process of interaction (education and information, provisioning, health and safety, cohesion). Network connectivity and accessibility modulate benefit flows, producing an emergent pattern of community resilience.

As depicted in Figure 2, resilience emerges from the cumulative strength and redundancy of these interaction flows. When aggregated across capacities, they form a spatially distributed web of benefit exchanges that represent the community's adaptive potential. This visual reinforces the concept of community resilience as a network process that is an outcome of how different systems interact, overlap, and mutually sustain one another under changing conditions. Having established how resilience capacities can be represented within the model, the next step is to demonstrate how these elements are implemented in practice.

3. Results

The CHAPPIE framework is designed to be operationalized using widely available demographic, infrastructure, and environmental datasets. This section outlines a generalized application pathway that can be adapted to local, regional, or national contexts. The goal is to demonstrate how the networked interactions among households, resources, and infrastructure, translate into measurable spatial processes that can be used to quantify resilience as an emergent property.

3.1. Define spatial extent and system boundaries

The first step is to define the study region, spatial units of analysis, and network extent. Depending on the purpose, CHAPPIE can be applied at parcel, census block, or neighborhood scales. Boundaries should reflect meaningful administrative or functional systems where governance and resource exchange occur [28]. For example, in a coastal community such as Escambia County, Florida, boundaries might align with evacuation zones or floodplain management districts.

Defining appropriate spatial scales ensures that modeled interactions correspond to real-world governance and service delivery processes. Scale mismatches where data or boundaries misalign with actual socio-ecological dynamics can distort resilience assessments [20]. CHAPPIE addresses this by nesting analyses: Household-level flows aggregate to neighborhoods, which in turn aggregate to municipalities, preserving both fine and broad spatial patterns.

3.2. Identify and classify network features

Next, spatial networks connecting origins (households) and destinations (resources) are delineated to represent the pathways through which benefits and risks flow. These networks encompass transportation infrastructure such as roads, transit routes, and pedestrian paths, typically derived from sources like OpenStreetMap or state departments of transportation. They also include utility systems sourced from agencies such as the U.S. Department of Energy or the Federal Communications Commission. In addition, natural systems such as floodplains, drainage basins, and ecological corridors are incorporated to capture the environmental linkages that influence connectivity and exposure across the landscape.

Each network segment is assigned friction values representing travel cost, congestion, or other frictional attributes. When available, dynamic datasets, such as real-time traffic, disaster closure maps, or broadband outage reports, can be used to simulate stress scenarios. Network topology metrics (e.g., betweenness centrality, redundancy, clustering) quantify structural resilience properties that modify the gravity function [11,15].

3.3. Attribute origins and destinations

Each household or population cluster (origin) is characterized by social and economic variables reflecting adaptive capacity, measured by income, education, vehicle ownership, health status, and digital access [3,30]. Destinations (resources) are classified by functional category and service radius corresponding to the four CHAPPIE capacities described earlier.

Resource data may be drawn from sources such as the U.S. Census Bureau's LEHD Origin-Destination Employment Statistics, Homeland Infrastructure Foundation-Level Data, or local planning inventories. Each destination receives a resource "attraction" score W_j , derived from its capacity (e.g., number of hospital beds, staff, or service population). These values directly inform the gravity model's interaction intensity T_{ij} .

3.4. Calculate interaction flows

The model calculates potential interaction shares between all origin–destination pairs within the defined network:

$$T_{ij} = A_i O_i W_j e^{-\beta d_{ij}}. \quad (3)$$

Accessibility is measured using network-based distances (travel time, friction) rather than Euclidean distance, ensuring realism in the estimation of benefit potential. The balancing factor A_i normalizes results so that the sum of flows from each origin equals its total population or demand. Each T_{ij} value represents a probabilistic share of benefit flow, or how likely a household is to access a given resource under normal conditions.

Multiple capacity layers can be analyzed separately (e.g., health vs. education) and later combined using weighted aggregation to represent total community benefit flow. The friction parameter (β) can be calibrated empirically using observed travel behavior or sensitivity analyses based on distance-decay relationships from regional travel models [26].

3.5. Integrate hazards and exposure

To link adaptive capacity with risk, CHAPPIE overlays modeled benefit flows with hazard exposure surfaces. These may include flood inundation maps, hurricane surge zones, heat exposure indices, or social vulnerability layers. Hazard data can be sourced from the FEMA, NOAA's NWS, or NASA's Earth Observing System.

The sum of potential interactions between origin-destination pairs (T_{ij}) across each of the four capacities will represent the overall adaptive capacity of the neighborhood or community. Hazard burden representing the exposure overlays, will be subtracted from the capacities, creating a resilience value (Eq 2).

3.6. Visualize benefit–risk distribution

Results can be visualized through choropleth and network flow maps that illustrate both the distribution of hazards and the connectivity of communities to the resources that mitigate or amplify those hazards. These visualizations enable diagnostic interpretation by highlighting spatial patterns of

access and risk. Areas characterized by high accessibility and low exposure typically represent resilient cores or well-connected hubs, whereas zones with low accessibility and high hazard potential reveal marginalized peripheries or “resilience deserts”. Regions exhibiting moderate accessibility often emerge as priority areas where targeted infrastructure investments can yield substantial improvements in adaptive capacity. Such spatial products are highly compatible with local planning workflows, as they can be produced using standard GIS tools such as ArcGIS Pro or QGIS and publicly available datasets.

3.7. Scenario analysis and monitoring

CHAPPIE can be extended to model future conditions or assess intervention impacts. By adjusting network friction (e.g., adding transit routes or closing roads) or modifying resource capacities, users can simulate changes in resilience potential over time. Scenario analysis allows planners to explore tradeoffs between mitigation investments and accessibility outcomes, aligning with adaptive management principles [7,14].

Because all variables are measurable and periodically updated, CHAPPIE also serves as a monitoring tool. Annual or decadal updates using new demographic, infrastructure, or hazard data can reveal whether resilience capacity is increasing, stable, or declining. When paired with empirical recovery metrics (e.g., housing return rates, service restoration), the model could provide predictive insights into community recovery trajectories.

3.8. Summary

This application pathway illustrates that CHAPPIE is readily implementable using open spatial data and standard analytical tools. It operationalizes resilience not as a single metric but as a set of measurable, network-dependent processes that reflect the ongoing exchange of benefits and risks across space and time. By embedding these interactions within policy and planning workflows, CHAPPIE offers a transparent, reproducible approach to resilience assessment that supports equity, adaptation, and systems thinking in community decision-making. Building on these methods, the following discussion interprets the broader implications of this approach for resilience theory, equity analysis, and planning practice, and explores how process-based assessment can inform more effective and inclusive policy decisions.

4. Conclusion

This section interprets the broader implications of the CHAPPIE framework for resilience science and policy practice. It discusses how operationalizing resilience as a network process reshapes understanding of adaptation, equity, and governance across spatial scales. The discussion connects theoretical advances to actionable insights for planners and decision-makers, emphasizing the framework’s potential to identify inequities, guide investments, and strengthen adaptive capacity within socio-ecological systems.

By framing resilience as an outcome of interacting flows, CHAPPIE demonstrates that adaptive capacity depends not only on what a community possesses but on how effectively it exchanges and mobilizes those assets. The model translates the abstract concept of resilience processes into quantifiable relationships among accessibility, connectivity, and exposure. These relationships

highlight that physical infrastructure and social organization function as parallel, and sometimes compensatory, networks of adaptation.

Resilient systems exhibit both redundancy and modularity, with multiple pathways for access and loosely coupled nodes that prevent cascading failure. The CHAPPIE formulation captures these traits by modeling alternative routes for benefit distribution and identifying where points of failure may exist. In practice, this allows planners to visualize how disruptions in one sector (e.g., road closures, power outages) reverberate through others, such as healthcare or communication.

At the municipal level, CHAPPIE supports several complementary applications that enhance resilience planning and decision-making. First, it enables the spatial prioritization of mitigation by mapping benefit flows and accessibility deficits, allowing planners to identify where new resources or infrastructure will produce the greatest marginal gains in resilience. Second, because CHAPPIE relies on measurable indicators, it facilitates the monitoring of resilience investments over time, helping to evaluate whether policy changes or capital improvements improve network efficiency and accessibility. Finally, the framework supports scenario testing through integration with hazard models, allowing practitioners to assess how network disruptions affect accessibility and adaptation under different planning strategies.

At regional scales, the framework supports multi-jurisdictional coordination. Resource flows frequently cross political boundaries; modeling them helps reconcile local planning decisions with broader system dynamics.

5. Discussion

Accessibility inequalities often mirror broader social disparities. High-income neighborhoods frequently enjoy redundant service networks, while marginalized communities remain dependent on limited and fragile infrastructure [38]. By measuring benefit potential rather than raw counts of resources, CHAPPIE exposes these inequities and quantifies who is positioned to respond and adapt, and who is left behind.

Equity-oriented resilience planning must therefore extend beyond hazard exposure reduction to include proactive investment in connectivity and service quality. The gravity-model approach provides a diagnostic lens to accomplish this. Low interaction probabilities (low T_{ij}) highlight structural barriers, including distance, cost, or policy neglect, that can be addressed through targeted interventions.

5.1. Limitations and research needs

While CHAPPIE offers a process-based advance, several limitations remain. First, weighting origin and destination attributes introduces uncertainty; empirical calibration through case studies is essential. Second, social friction factors such as trust, language, or discrimination remain difficult to quantify, yet substantially influence effective accessibility. Third, current implementation emphasizes spatial networks, whereas modern communities also operate through aspatial connectivity, including digital communication, remote work, and virtual social networks, which require novel data sources and metrics [39].

Future research should therefore focus on several areas that extend the framework's analytical and empirical reach. One priority is to integrate digital and cultural network measures into the spatial model, capturing aspatial forms of connectivity that influence adaptive capacity but are not currently

represented. Another is to couple model outputs with agent-based simulations to explore how individual and collective behaviors interact with spatial accessibility to shape resilience dynamics. Finally, the framework should be validated against post-disaster recovery data to empirically test whether modeled benefit flows correspond to observed recovery patterns and resilience outcomes.

5.2. Contributions to resilience science

This work contributes to resilience science both conceptually and methodologically in several key ways. It formalizes resilience as an interactive process that can be measured through modeled benefit flows, providing a concrete means of operationalizing dynamic adaptation. The framework integrates processes across multiple spatial scales, bridging household, neighborhood, and community dynamics within a single structure. By coupling social and physical infrastructure metrics through spatial interaction modeling, CHAPPIE captures the interconnected systems that shape adaptive capacity. The model also advances equity analysis by introducing a quantitative method for diagnosing structural inequality in access and resilience potential. Finally, it offers a reproducible analytical structure that can be implemented using open spatial data and standard GIS environments. Collectively, these advances move resilience research beyond static indices toward a dynamic, theory-driven understanding of how communities adapt to and recover from disturbance.

This paper operationalizes resilience as a process of interaction within socio-ecological systems. Through the CHAPPIE framework, spatial interaction modeling is used to represent the flow of benefits, services, and information across community networks. The model translates the theoretical capacities of education and information, basic provisioning, health and safety, and community cohesion into quantifiable variables that reflect how accessibility and connectivity shape adaptive potential.

By merging gravity-based modeling with resilience theory, CHAPPIE provides a means to observe resilience as it emerges from daily exchanges among people, infrastructure, and the environment. This approach reframes the assessment from what exists to how systems function, enabling equitable, data-driven decisions for mitigation and adaptation. Future applications will test the framework through case studies across diverse hazardscapes and governance contexts. As data availability and computational power expand, CHAPPIE offers a scalable pathway to measure, visualize, and strengthen resilience as a living, evolving process.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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The views expressed here are those of the authors and do not necessarily represent the U.S. Environmental Protection Agency. Mention of trade names or products does not imply endorsement.

Conflict of interest

The authors declare no conflict of interest in this paper.

Author contributions

Kyle Buck led the development of the manuscript, including conceptual framing, model design, analysis, and writing of the original draft. Justin Bousquin contributed to the conceptual development of the framework, provided critical feedback on structure and interpretation, and assisted with revisions and editing throughout the writing process.

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