Journal of Regional and City Planning
vol. 37, no. 2, page. 197-229, August 2026
DOI: 10.5614/jpwk.2026.37.2.5

Stress Testing the Resilience of Regional Spatial Structure to Hydrometeorological Disaster Disruptions: Empirical Evidence from West Sumatra

Tomi Eriawan[1]*, Lestari Setiawati[2]*, Wenny Widya Wahyudi[1]*, Meldi Romadhani[1]*, Alya Arianti Fresta[1]

[Received: 30 July 2026; 1st revision: 7 August 2026; accepted in final version: 13 August 2026]

Abstract. *Hydrometeorological disasters frequently disrupt transportation networks and threaten the functioning of regional spatial systems, particularly in geographically constrained regions. However, previous studies have primarily evaluated resilience from the perspective of transportation network performance, with limited attention to how transportation disruptions affect the continuity of hierarchical interactions among activity centers. This study assessed the resilience of the regional spatial structure in West Sumatra, Indonesia, by examining how hydrometeorological disaster disruptions influence regional connectivity under progressively increasing transportation network stress. An ex-post GIS-based stress-testing framework was developed using three disruption scenarios (conservative, moderate, and worst-case) to evaluate primary corridor functionality and alternative accessibility between the National Activity Center (NAC) and Regional Activity Centers (RACs). Changes in travel distance, travel time, and connectivity were analyzed to assess the continuity of hierarchical regional interactions. The results indicated that maintaining physical connectivity alone does not guarantee regional spatial structure resilience. Under moderate disruption, all origin-destination pairs remained connected; however, substantial travel-time increases revealed considerable deterioration in functional accessibility. Under the worst-case scenario, failure of critical primary corridors caused widespread network fragmentation and functional collapse of the regional interaction system. These findings demonstrate that regional spatial structure resilience depends not only on transportation connectivity but also on the ability of the transportation system to sustain hierarchical interactions among activity centers during disaster conditions. The proposed framework bridges transportation network analysis and regional spatial planning and provides a transferable approach for evaluating disaster resilience in mountainous and hazard-prone regions characterized by limited transportation redundancy.*

Keywords. *regional spatial structure, hydrometeorological disaster, transportation network resilience, stress testing, GIS network analysis.*

Introduction

Hydrometeorological disasters have become an increasing global concern due to the influence of climate change and human activities, such as deforestation, uncontrolled urbanization, and rising

[1]Department of Urban and Regional Planning, Faculty of Civil Engineering and Planning, Universitas Bung Hatta, Jl. Sumatera, Ulak Karang, Padang, West Sumatra 25133, Indonesia. *Corresponding author: romadhanimeldi@gmail.com
[2]Department of Industrial Engineering, Faculty of Industrial Technology, Universitas Bung Hatta, Jl. Gajah Mada No. 19, Olo Nanggalo, Padang, West Sumatra 25143, Indonesia.

greenhouse gas emissions. These conditions contribute to more frequent and intense extreme events, including floods, flash floods, landslides, and extreme rainfall (Xiong et al., 2024; Yaşar et al., 2025). Beyond causing physical damage, such disasters can also disrupt regional systems by interrupting transportation networks, reducing accessibility, and weakening spatial interaction between urban centers. These challenges are closely related to global efforts to achieve resilient infrastructure and sustainable regional development, particularly under Sustainable Development Goals (SDGs) 9 and 11, which emphasize infrastructure resilience, connectivity, and sustainable human settlements.

In many regions, spatial structures are organized through a hierarchy of activity centers connected by transportation networks that facilitate the movement of people, goods, and services across different spatial scales. The continuity of interaction between these centers strongly depends on the performance and reliability of transportation corridors. Consequently, disruptions to transportation infrastructure may not only affect local accessibility but also influence the broader functionality of regional spatial systems. Damage to roads and bridges can interrupt connectivity between activity centers, increase travel time, reduce logistics efficiency, and potentially isolate regions from major economics and service networks (Fang et al., 2025; Papilloud et al., 2024; Alabbad et al., 2021). Within this context, spatial structure plays a critical role in maintaining the functional integrations of regional systems by organizing the distribution of activity centers and transportation networks connecting them. Spatial structure therefore reflects not only physical arrangements of land use and infrastructure but also multidimensional relationships involving economic interaction, social connectivity, and regional functionality (Basile et al., 2021; Small et al., 2019).

In Indonesia, spatial structure planning is formally regulated through policies that guide the designation of hierarchical activity centers and the development of infrastructure networks at regional and national levels. These policies, as outlined in regional spatial planning documents, define the hierarchy of activity centers and connectivity patterns that support regional interaction and territorial integration. As long-term planning instruments, spatial plans serve as the primary guide for development direction and infrastructure investments over a period of up to twenty years. However, although spatial planning usually applies control and risk management principles, most conventional spatial planning frameworks are still developed under assumptions of relatively stable growth conditions and often provide limited consideration of how regional spatial structures would perform under extreme disruption (Juschten et al., 2021). This limitation raises concerns regarding the resilience of regional connectivity and the ability of spatial systems to maintain functional relationships between activity centers during hydrometeorological disasters.

Previous studies have widely explored the impacts of disasters on transportation systems, particularly in terms of accessibility loss, travel time changes, and disruptions to critical facilities. Most of these studies employed simulation-based approaches, while only a limited number utilized actual disaster events to examine how transport and spatial systems respond under real conditions (Liu et al., 2026; Papilloud et al., 2024). These studies have substantially advanced the understanding of transportation resilience by identifying how disasters affect mobility and accessibility. However, their primary emphasis remained on transportation network performance and localized accessibility, with relatively limited attention given to how these disruptions influence the continuity of hierarchical interactions among activity centers that underpin the regional spatial structure. Consequently, while transportation connectivity is widely recognized as an important component of disaster resilience, it remains unclear whether maintaining network connectivity alone is sufficient to preserve the functioning of the regional spatial structure during hydrometeorological disasters.

To address this gap, this study applied an ex-post stress testing approach to examine how actual hydrometeorological disaster events influence the continuity of regional spatial interactions through disruptions in transportation networks. Rather than focusing solely on transportation network performance or localized accessibility, the analysis evaluated system-level responses by integrating corridor functionality, connectivity continuity, and alternative accessibility under progressive disruption scenarios. Through this approach, the study investigated whether hierarchical interactions among activity centers can be maintained under different levels of disruption and explored the implications of these changes for the resilience of the regional spatial structure. By positioning transportation connectivity and accessibility as enabling conditions rather than the ultimate object of resilience assessment, this study contributes to growing discussion on disaster-resilient regional spatial planning and provides a broader perspective for understanding regional spatial structure resilience under hydrometeorological disaster conditions.

Literature Review

Hydrometeorological Disaster and Infrastructure Disruption

Hydrometeorological disasters encompass a wide range of events driven by atmospheric and hydrological processes, including floods, flash floods, landslides, and extreme rainfall. Under the influence of global climate change, these events are no longer regarded as isolated anomalies but have become increasingly frequent and intense. According to the World Meteorological Organization (WMO, 2021), the number of hydrometeorological disasters has increased fivefold over the past five decades, causing economic losses of approximately USD 3.64 trillion worldwide between 1970 and 2019. Beyond their economic consequences, these disasters disproportionately affect developing countries, where limited adaptive capacity increases the vulnerability of infrastructure systems and regional development. Recent studies further suggest that the intensification of the global hydrological cycle is expected to increase the frequency and severity of extreme precipitation events, reinforcing hydrometeorological disasters as one of the most significant threats to sustainable regional development (Xiong & Yang, 2024).

One of the most immediate consequences of hydrometeorological disasters is the disruption of transportation infrastructure, particularly strategic road corridors and bridges that support regional mobility and connectivity. Floods, landslides, and debris flows frequently reduce road capacity, interrupt traffic flows, and isolate areas. Empirical evidence demonstrates that flood-induced road inundation substantially decreases operating speeds and increases travel times. For example, Fu et al. (2025) reported that average vehicle speeds in Shanghai declined by 28-54% under different flood scenarios, disrupting between 47% and 92% of inter-zonal travel connections and generating commuter delay costs of up to USD 12 billion. Similarly, Liu et al. (2026) showed that the propagation of travel delays during extreme rainfall depends not only on rainfall intensity but also on drainage performance and the spatial configuration of the transportation network. Beyond operational disruptions, prolonged closures of major transportation corridors also generate broader socioeconomic consequences by restricting access to employment, healthcare, education, and markets, particularly for remote communities (Winter et al., 2016). These findings demonstrate that the consequences of hydrometeorological disasters extend well beyond physical infrastructure damage, affecting the operational performance and service continuity of regional transportation systems.

However, transportation disruptions caused by hydrometeorological disasters should not be viewed solely as infrastructure or mobility problems. Because transportation corridors constitute the physical links connecting hierarchical activity centers, disruptions to these corridors may also interrupt the spatial interactions that sustain regional systems. Reduced accessibility, longer travel times, and corridor failures can weaken the functional relationships among activity centers, even when parts of the transportation network remain physically connected (Shang et al., 2020). Consequently, understanding the impacts of hydrometeorological disasters requires moving beyond infrastructure damage assessment toward examining how transportation disruptions influence the continuity of regional spatial systems.

Regional Spatial Structure and Connectivity

Regional spatial structure refers to the spatial arrangement of activity centers and transportation networks that connect them within a regional system (Seleznov et al., 2025; Li et al., 2024; Rahmoun et al., 2024; Zhang et al., 2023). This concept is closely related to Central Place Theory (CPT), which explains how settlements and urban centers are organized hierarchically based on their functions and service coverage. Higher-order centers generally provide more specialized economic, administrative, and public services, while lower-order centers depend on these services through continuous spatial interactions (Berry et al., 1958). Consequently, regional spatial structure should be understood not only as the physical arrangement of activity centers and transportation infrastructure but also as a functional system that enables the movement of people, goods, services, and information across different hierarchical levels.

In many countries, regional development is organized through a hierarchy of activity centers with different functions and levels of service (Mishra et al., 2021; Tang et al., 2020). In Indonesia, this concept is formally applied through the spatial planning system, where activity centers are classified into National Activity Centers (NAC), Regional Activity Centers (RAC), and Local Activity Centers (LAC). Rather than representing merely an administrative classification, this hierarchy reflects the organization of regional functions and spatial dependencies. NAC generally accommodate higher-order economic, governmental, logistics, and public service provisions. As a result, interactions among these centers differ in intensity and functional importance, creating a regional system in which the continuity of higher-order interactions is essential for maintaining the overall functioning of the regional spatial structure.

The hierarchical relationships among activity centers are sustained through transportation networks that facilitate the movement of people, goods, and services across the regional system (Cattaneo et al., 2024). Interactions between NAC and RAC are particularly important because they support regional mobility, logistics distribution, administrative functions, and access to higher-level services, whereas interactions among RACs contribute to regional integration and provide alternative regional connections (Lee et al., 2025; Isya et al., 2025). Consequently, transportation connectivity is widely recognized as a fundamental component of regional spatial systems because it enables the continuity of spatial interactions among activity centers (Li et al., 2024; Chacon-Hurtado et al., 2020).

Transportation Network Analysis in Disaster Studies

Transportation network analysis has become one of the principal analytical approaches for investigating the impacts of disasters on transportation systems. By representing transportation systems as interconnected networks, this approach enables researchers to quantify how disruptions affect accessibility, connectivity, travel time, and overall network performance using graph-based indicators such as shortest path, centrality, and network robustness. Recent developments have further incorporated measures of network redundancy and real-time monitoring, enabling more comprehensive assessments of system performance under disruption (Auerbach & Kim, 2022; Furno et al., 2021).

A substantial body of research has applied network analysis to evaluate disaster-induced transportation disruptions by comparing baseline and disrupted network conditions. Graph-based methods have been widely used to assess accessibility to critical facilities, identify vulnerable populations, and quantify changes in travel time and connectivity following floods and other hazards (Alabbad et al., 2021; Papilloud et al., 2024). Similarly, studies evaluating different network reduction strategies have shown that disruptions affecting strategically important road segments produce disproportionately large declines in overall network performance (Kozhabek & Chai, 2025). These findings demonstrate the capability of network analysis to quantify the functional consequences of infrastructure disruptions beyond physical damage alone.

Recent studies have extended network analysis by integrating dynamic flood processes, historical disaster data, and multiple disruption scenarios. Fang et al. (2025) incorporated Internet of Things data to evaluate dynamic accessibility changes during extreme rainfall, while Xie et al. (2025) examined different landslide-induced road closure scenarios and identified substantial variations in network performance under different disruption levels. Zheng et al. (2025) further developed methods for identifying critical transportation corridors to support infrastructure prioritization and disaster preparedness. Together, these developments show that network analysis has evolved into a robust framework for evaluating transportation system responses under increasingly realistic disaster conditions.

Stress Testing Approach in Spatial Systems

Stress testing was originally developed in financial regulation to evaluate whether institutions could withstand extreme but plausible scenarios without triggering systemic failure. Owing to its ability to evaluate system performance under conditions beyond normal operation, the approach has subsequently been adopted across a wide range of disciplines, including medicine, engineering, and critical infrastructure planning (Linkov et al., 2022). Rather than assessing systems only under normal operating conditions, stress testing deliberately exposes them to predefined disruption scenarios that exceed routine operational conditions in order to identify vulnerabilities, system responses, and potential failure points before they occur in practice.

The application of stress testing to transportation and spatial systems has gained increasing attention in recent years. Existing studies commonly evaluate how disruption scenarios influence transportation system performance by comparing baseline and disrupted conditions using indicators such as accessibility, travel time, connectivity, and graph-based network metrics. For example, Aydin et al. (2018) integrated graph theory with stress testing to evaluate the resilience of urban transportation networks under earthquake scenarios, demonstrating that the approach can identify critical network components and spatial vulnerabilities. Similarly, Juschten et al. (2021) argued that climate-adaptive spatial planning requires assessment frameworks capable of evaluating system performance under multiple and interacting pressures that extend beyond normal planning assumptions. Collectively, these studies demonstrate that stress testing provides a systematic framework for examining how transportation and spatial systems respond under progressively more severe disruption scenarios.

Study Area

West Sumatra Province is located on the western coast of Sumatra, Indonesia, covering approximately 42,013 km^2 with a population of about 5.9 million (BPS, 2026). The province plays an important role in western Sumatra through a regional spatial system that relies heavily on road-based connectivity to support the movement of people, goods, and economic activities (Ansofino et al., 2022). Within the provincial spatial structure, Padang functions as the sole NAC, while several RACs, including Pariaman, Bukittingi, Payakumbuh, Solok, and Sawahlunto, support regional interactions across different parts of the province. Together, these activity centers form a polycentric regional system in which the continuity of transportation corridors is essential for maintaining regional connectivity (Gu et al., 2023; Curatella et al., 2020).

Unlike many other provinces in Indonesia, intercity mobility in West Sumatra depends almost entirely on the road transportation network, as railway services between major activity centers remain limited and maritime transport serves only selected coastal areas (Melasari et al., 2023). Consequently, disruptions to strategic road corridors have the potential to affect accessibility and connectivity across the regional spatial system due to the limited availability of equivalent alternative routes.

The province is characterized by mountainous terrain associated with the Bukit Barisan Range, where steep topography, high rainfall, and active geological processes contribute to frequent hydrometeorological hazards, particularly floods, flash floods, and landslides. A notable example occurred in May 2024, when flash floods in the Anai Valley severed the Padang-Bukittinggi national highway at multiple locations, disrupting one of the province's most important transportation corridors for more than two months (Utama, 2024). This event provides an appropriate case for examining how hydrometeorological disasters influence regional transportation connectivity and the functioning of the regional spatial system. **Figure 1.** Illustrates the location of the study area and the regional spatial structure of West Sumatra, including the hierarchy of activity centers and the primary transportation corridor connecting them.

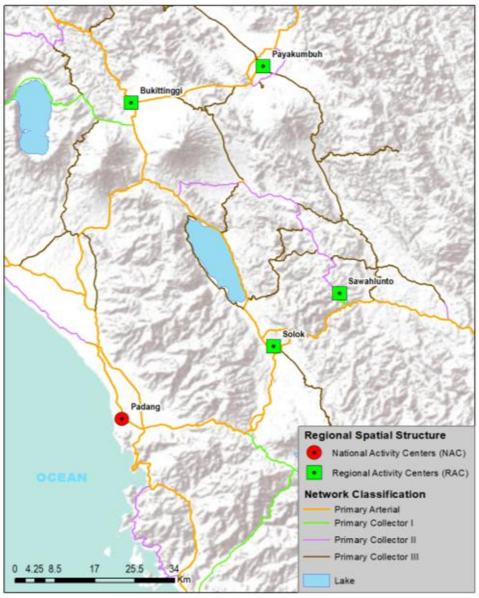

Figure 1. Study area

Data And Methods

Data Collection and Network Preparation

Three categories of spatial data were compiled to support the transportation network analysis: 1) regional spatial structure; 2) transportation networks; and 3) hydrometeorological disaster data. **Figure 2** presents the overall workflow of data preparation and analysis adopted in this study.

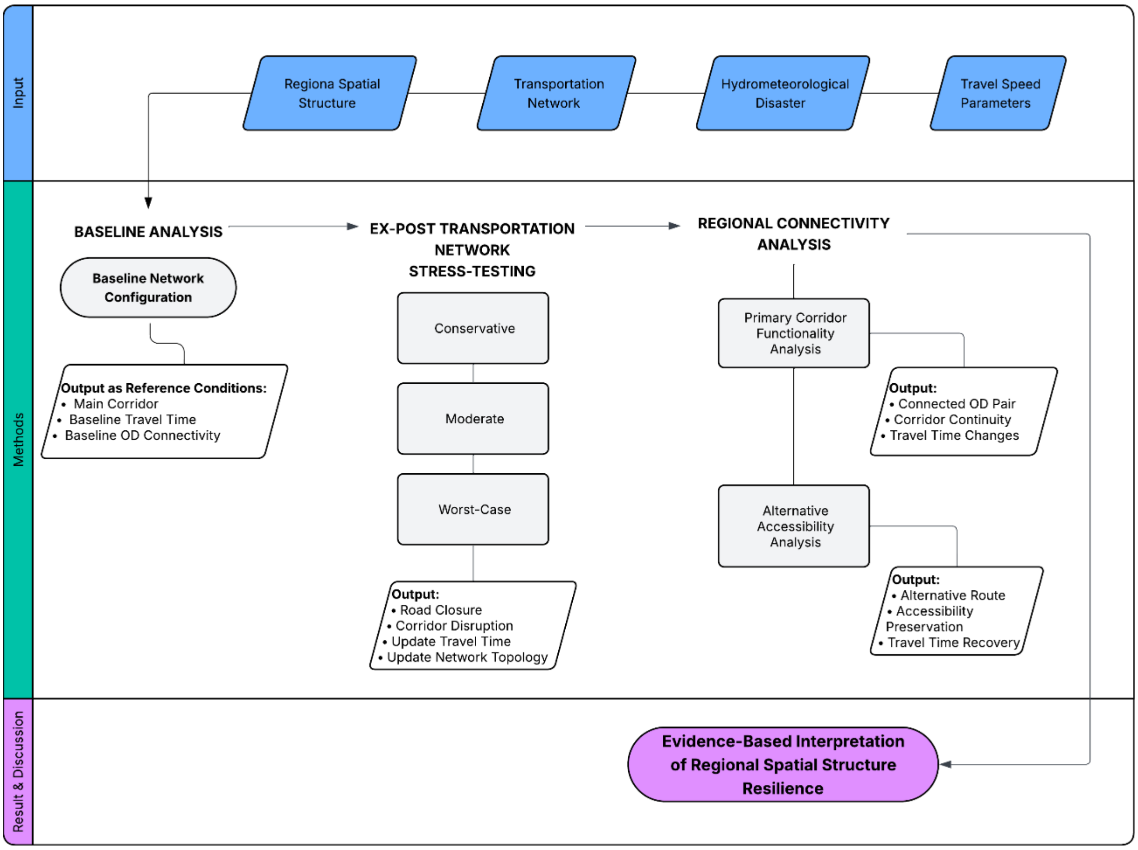

Figure 2. Overall workflow

The analysis focuses on the connectivity between Padang as NAC and five RACs, representing the principal hierarchical relationships within provincial spatial structure **(Table 1)**. These activity centers were selected because they constitute the primary regional interaction system in West Sumatra and served as the main origins and destinations for the connectivity analysis. Information on the hierarchy and functions of activity centers was obtained from the West Sumatra Provincial Spatial Plan (RTRW) 2025-2045.

Table 1. Hierarchical activity centers

Activity Center	Code	Hierarchy	Main Function
Padang	PDG	NAC	Metropolitan and provincial gateway
Pariaman	PRM	RAC	Coastal service center
Bukittinggi	BKT	RAC	Trade and tourism center
Payakumbuh	PYK	RAC	Regional service center
Solok	SLK	RAC	Highland service center
Sawahlunto	SWH	RAC	Cultural tourism center

Source: Adapted from West Sumatra Provincial Spatial Plan 2025-2045 (RTRW, 2025)

The transportation network data consisted of primary arterial roads and primary collector roads (Collector I-III), which form the principal corridors connecting activity centers throughout the province. The road network was obtained from the Regional Planning Agency and processed within a Geographic Information System (GIS) environment to create a routable network dataset. Prior to the analysis, the network underwent topology correction, connectivity checking, and attribute standardization to ensure consistency and continuity across all road segments.

Hydrometeorological disaster data, including flood, flash flood, and landslide events, were compiled from the National Disaster Management Agency (BNPB), the Ministry of Public Works (PU), the Regional Disaster Management Agency (BPBD), and related government reports. The disaster records used in this study correspond to hydrometeorological events occurring from 24 to 27 November 2025, the period for which a disaster emergency response status was declared in the affected areas. This defined time window provides a common temporal reference for the disruption analysis and avoids combining disaster events from different years or unrelated episodes. The dataset contains information on disaster locations and affected transportation infrastructure, including disconnected roads and bridges, flooded road sections, and corridors blocked by landslides. These data were spatially integrated with the transportation network to represent the observed disruption conditions during this specific disaster episode.

Because observed operating speed data were unavailable, travel speed for each road segment were estimated using the Indonesian Road Capacity Guidelines (Ministry of Public Works and Housing [PUPR], 2023). The estimation considered road type, lane width, side friction, roadside development intensity, road alignment, and vehicle category (**Table 2**). The resulting adjusted free-flow speeds were assigned to individual road segments to represent uncongested travel conditions and were subsequently used to estimate baseline travel times under normal operating conditions. These baseline travel times served as the reference for evaluating changes in corridor performance and regional connectivity under the disaster disruption scenarios.

Table 2. Variables used for travel speed estimation

Variable	**Description**
Road type	Function classification of road segments, including primary arterial and primary collector roads
Lane width	Effective lane width affecting vehicle movements and free-flow speed
Side friction	Intensity of roadside activities influencing traffic flow conditions
Roadside development intensity	Level of roadside land use and development activities along the corridor
Road alignment	Terrain characteristics of road segments, including flat, rolling, and mountainous conditions
Vehicle category	Passenger cars, small buses, larger buses, trucks, and motorcycles

Source: Adapted from the Indonesian Road Capacity Guidelines (PKJI, 2023)

Baseline Network Configuration

The baseline network configuration was established to represent normal transportation conditions prior to the introduction of disaster disruption scenarios. Establishing a baseline network before simulating disturbances is a common procedure in transportation resilience studies, as it provides the reference condition against which changes in network performance can be systematically evaluated. Previous studies have similarly defined baseline network conditions before introducing disruption scenarios to assess changes in accessibility, network functionality, and corridor performance (Zheng et al., 2025; Auerbach et al., 2022; Furno et al., 2021; Liu et al., 2020). In this study, the baseline served as the reference condition for evaluating changes in corridor functionality, travel time, accessibility, and regional connectivity throughout the stress-testing process.

A GIS-based network analysis was performed to identify the shortest routes connecting Padang as the NAC with each RAC, as well as the interconnections among RACs, using the primary arterial road network. These corridors represent the principal transportation links supporting regional interactions under normal operating conditions. For each origin–destination (OD) pair, the shortest travel distance and estimated travel time were calculated using the adjusted free-flow travel speeds. Travel time was estimated for several vehicle categories to represent passenger mobility and freight transportation under normal, uncongested traffic conditions.

The resulting baseline network configuration represents the normal functioning of West Sumatra's primary regional corridor system. Baseline travel distance, travel time, and route configuration were subsequently used as reference conditions for evaluating changes in corridor functionality under the disruption scenarios. Primary collector roads were introduced only during the alternative accessibility analysis to examine the extent to which secondary corridors could maintain regional connectivity when primary arterial network was disrupted.

Transportation Network Stress-Testing Scenarios

Following the establishment of the baseline network configuration, transportation network stress testing was conducted to evaluate how progressively severe hydrometeorological disruptions affect regional transportation corridors and regional connectivity. Stress testing has been widely adopted in transportation resilience studies because it enables system performance to be evaluated under increasingly severe disruption conditions rather than relying on a single failure scenario (Nasrazadani et al., 2025; Linkov et al., 2022). Previous studies have shown that transportation networks with limited redundancy are particularly sensitive to corridor failures, making progressive disruption scenarios essential for understanding how network functionality changes under different levels of hazard intensity (Rouhana et al., 2025). Therefore, the baseline network established in the previous stage served as the reference condition against which all disruption scenarios were evaluated.

Representing disaster impacts through multiple disruption scenarios also addresses the uncertainty associated with post-disaster transportation conditions. Transportation infrastructure rarely experiences uniform failure during hydrometeorological disasters; instead, disruption severity varies spatially according to hazard intensity and infrastructure conditions. Consequently, assuming complete network closure may overestimate accessibility losses and fail to represent actual post-disaster conditions (Papilloud et al., 2024). To capture this uncertainty, three progressively severe stress-testing scenarios were developed: conservative, moderate, and worst-case (**Table 3**).

Table 3. Transportation network stress-testing scenarios

Scenario	**Network Assumption**	**GIS Treatment**	**Description**	**Similar Approaches in Previous Studies**
Conservative	Only severe infrastructure damage causes disconnection	Restriction barrier	Roads and bridges with complete failure are treated as inaccessible	Furno et al. (2021), Alabbad et al. (2021).
Moderate	Severe infrastructure damage causes disconnection + partial accessibility remains on moderately affected corridors	Restriction barrier + added cost	Roads and bridges with complete failure are treated as inaccessible + flooded and landslide-affected roads remain accessible with reduced performance	Papilloud et al. (2024), Alabbad et al. (2021)

Scenario	**Network Assumption**	**GIS Treatment**	**Description**	**Similar Approaches in Previous Studies**
Worst-case	All affected corridors assumed inaccessible	Restriction barrier	The entire affected network treated as disconnected due to uncertainty conditions	Papilloud et al. (2024)

In the conservative scenario, only transportation segments with direct and substantial infrastructure impacts were assumed to be unavailable, while other affected segments remained operational. The moderate scenario assumed that severely damaged infrastructure remained closed, while road segments affected by flooding, flash floods or river runoff, or partial landslide obstruction remained operational but experienced reduced performance. Rather than removing these links from the network, additional travel-time penalties were assigned to affected segments to represent reduced travel speeds, temporary traffic management, debris clearance, and other operational constraints commonly observed following hydrometeorological disasters. Similar travel-time penalty approaches have been applied in GIS-based accessibility analyses to represent hazard-induced reductions in road performance under flood and landslide conditions (Popescu et al., 2025). This assumption is also consistent with empirical observations showing that flood- and landslide-affected roads may remain passable under restricted operating conditions before complete restoration is achieved (Petrucci et al., 2026).

Three disruption-specific travel-time penalties were applied to distinguish the assumed severity of different disaster conditions: 3 h for flash floods or river runoff, 1 h for flood inundation, and 3 h for landslides. The use of travel-time penalties to represent operational constraints on hazard-affected road segments is consistent with scenario-based disruption modelling; empirical depth-disruption functions have been used to translate flood conditions into reduced vehicle speeds and flood-induced delays rather than treating roads as simply open or closed (Pregnolato et al., 2017), while mesoscopic traffic simulations have similarly evaluated travel-time increases under road closures and speed reductions (Shahdani et al., 2022). The selected penalties are intentionally shorter than the full duration of disruption reported in empirical cases. For example, localized flood inundation has been reported to disrupt traffic for approximately half an hour even during relatively minor events (Pregnolato et al., 2016), while landslide-related road closures have persisted for fifteen days in Scotland (Postance et al., 2017), approximately three months following a highway cut-slope failure in southern Spain (Galve et al., 2025), and more than one year following the 2016 Kaikōura earthquake in New Zealand (Mason et al., 2021). These observations demonstrate that actual disruption and recovery durations can substantially exceed the temporal window represented in the present model. Accordingly, the 1–3 h penalties should not be interpreted as estimates of actual clearance or recovery times; rather, they represent standardized short-duration operational constraints within the stress-testing framework. This approach avoids assigning the full observed closure duration to every affected segment, which could produce disproportionately large cumulative penalties when multiple affected segments and concurrent or closely spaced disaster impacts occur along the same regional corridor. The selected penalties therefore provide a conservative and comparable representation of temporary operational degradation while allowing the analysis to focus on the relative effects of progressive network disruption on regional connectivity and accessibility. When multiple affected segments occurred along the same corridor, the corresponding penalties were accumulated to represent the combined effects of multiple disruptions on intercity travel performance.

Finally, the worst-case scenario assumed that all disaster-affected primary transportation corridors became inaccessible simultaneously, representing a counterfactual upper-bound stress-test condition rather than the historical simultaneous occurrence of all infrastructure failures. Similar progressive scenario frameworks have been adopted in transportation resilience studies to evaluate how network performance deteriorates under increasingly severe hazard conditions (Tang et al., 2024).

To evaluate the adaptive capacity of the regional transportation system, an alternative accessibility analysis was subsequently performed for the moderate and worst-case scenarios by incorporating the primary collector road network into the disrupted transportation system. Unlike conventional rerouting analyses that assume that secondary corridors remain fully operational, the collector road network was also subjected to the corresponding distribution scenarios because hydrometeorological disasters frequently affect both primary and secondary transportation corridors simultaneously. Consequently, the analysis evaluates not only whether alternative routes exist but also whether they remain sufficiently functional to maintain regional connectivity under progressively severe disruption conditions. The resulting network performance was then compared with the baseline condition to assess changes in corridor functionality and regional connectivity.

Regional Connectivity Analysis

The transportation network responses generated under each stress-testing scenario were analyzed through two complementary approaches: Primary Corridor Functionality Analysis and Alternative Accessibility Analysis. These analyses were designed to examine how disruptions influence corridor availability, travel distance, travel time, and accessibility between hierarchical activity centers under progressively severe network disruption scenarios. Similar analytical frameworks have been widely applied in transportation network studies to evaluate the consequences of infrastructure disruption on network functionality, accessibility, and route availability (Ahmed et al., 2020; Twumasi-Boakye et al., 2018; Pregnolato et al., 2016). Rather than directly measuring regional spatial structure resilience, the analyses provide empirical evidence describing changes in transportation network performance that subsequently form the basis for interpreting the resilience of the regional spatial structure.

The first analysis, primary corridor functionality analysis, evaluated the operational status of the principal regional transportation corridors connecting the NAC and RACs. The analysis determined whether each OD pair remained connected through the primary arterial road network under each disruption scenario. Corridor functionality was classified according to the availability of continuous routes linking activity centers after disaster-induced disruptions. This approach is consistent with previous transportation resilience studies that evaluated the impacts of critical corridor failures by examining changes in network connectivity, route continuity, and travel performance following infrastructure disruption (Twumasi-Boakye et al., 2018; Pregnolato et al., 2016). The resulting corridor conditions were subsequently compared with the baseline network configuration to identify the extent to which disruptions affected the principal regional transportation system.

The second analysis, the alternative accessibility analysis, examined the availability and performance of alternative travel routes after disruptions occurred along the primary arterial corridors. This analysis incorporated both primary arterial roads and primary collector roads (Collector I-III) to identify feasible alternative routes between activity centers under disrupted network conditions. Previous studies have shown that the availability of alternative routes plays an important role in reducing the impacts of transportation disruptions and maintaining network accessibility during hazard events (El Rashidy et al., 2019; Pregnolato et al., 2016). However, unlike conventional rerouting analyses that generally assume secondary routes remain fully operational, this study also subjected the primary collector network to the corresponding moderate and worst-case disruption scenarios, reflecting the possibility that hydrometeorological disasters simultaneously affect both primary and secondary transportation corridors. For each OD pair, the shortest feasible alternative route was identified, and the corresponding travel distance and estimated travel time were compared with the baseline network configuration to quantify changes in transportation network performance under disruption conditions.

Together, the two analyses provide complementary evidence describing how transportation networks respond to progressively severe hydrometeorological disruptions. The primary corridor functionality analysis identifies whether the principal regional corridors remain operational, while the alternative accessibility analysis evaluates the extent to which secondary corridors can compensate for disruptions to the primary network under realistic post-disaster conditions. The outputs from both analyses are subsequently integrated in results and discussion sections to interpret how changes in transportation network performance influence regional connectivity and the functioning of the regional spatial structure.

Results

Baseline Regional Corridor Performance

The baseline corridor performance analysis was conducted to examine how the existing transportation network supports interactions among activity centers under normal operating conditions. **Table 4** presents the baseline corridor characteristics based on origin-destination (OD) pairs, showing that these interactions are primarily supported by primary arterial roads, which function as the main regional movement corridors.

Table 4. Baseline corridor characteristics between activity centers

No	OD Pairs	Reference Corridor Sequence	Distance (km)	Estimated Travel Time (h)				
				PC	LB	ST	LT	M
NAC-RAC								
1	PDG–PRM	PDG–PRM	53.17	0.98	0.92	1.11	1.15	1.17
2	PDG–BKT	PDG–BKT	89.58	1.64	1.57	1.89	1.97	1.94
3	PDG–PYK	PDG–BKT–PYK	121.23	2.19	2.09	2.52	2.63	2.61
4	PDG–SWH	PDG–SLK–SWH	88.73	1.53	1.48	1.77	1.87	1.79
5	PDG–SLK	PDG–SLK	58.61	1.03	1	1.19	1.27	1.2
RAC-RAC								
6	PRM-BKT	PRM-BKT	80.74	1.41	1.36	1.63	1.71	1.67
7	PRM-PYK	PRM-BKT-PYK	112.37	1.97	1.88	2.26	2.36	2.33
8	PRM-SWH	PRM-PDG-SLK-SWH	140.1	2.35	2.26	2.73	2.87	2.79
9	PRM-SLK	PRM-PDG-SLK	109.96	1.85	1.79	2.16	2.27	2.19
10	BKT-PYK	BKT-PYK	31.62	0.55	0.52	0.63	0.65	0.67

No	OD Pairs	Reference Corridor Sequence	Distance (km)	Estimated Travel Time (h)				
				PC	LB	ST	LT	M
11	BKT-SWH	BKT-SLK-SWH	107.93	1.91	1.82	2.19	2.29	2.26
12	BKT-SLK	BKT-SLK	74.26	1.34	1.29	1.55	1.62	1.58
13	PYK-SWH	PYK-BKT-SLK-SWH	139.55	2.46	2.34	2.83	2.95	2.93
14	PYK-SLK	PYK-BKT-SLK	105.88	1.89	1.81	2.18	2.27	2.25
15	SWH-SLK	SWH-SLK	33.69	0.57	0.54	0.65	0.67	0.68

Notes: PC = passenger car, LB = large bus, ST = small truck, LT = large truck, M = motorcycle. For each OD pair, distance and travel time were calculated independently as the shortest network path between the designated origin and destination activity-center nodes. The reference corridor sequence identifies the regional corridors associated with the OD connection and should not be interpreted as a sequence of intermediate nodes used in the shortest-path calculation.

The results revealed considerable variation in corridor performance among OD pairs. Some activity centers are connected through relatively short travel distance and travel time, whereas others require substantially longer journeys despite belonging to the same regional system. For instance, the distance matrix indicated that corridors between Padang and Solok, as well as between Padang and Pariaman, represent some of the shorter intercity connections, while the corridors between Padang and Sawahlunto, Padang and Bukittinggi, and between Padang and Payakumbuh are comparatively longer. Differences in travel performance were consistently observed across all five vehicle categories. These variations in travel performance across vehicle types highlight the importance of incorporating multimodal perspectives when assessing regional accessibility, as user experiences differ substantially depending on vehicle characteristics and trip purpose (El-Maissi et al., 2020). The baseline travel matrices therefore provide an important benchmark for understanding how regional interactions are experienced by different transport users under normal conditions before transportation network stress-testing scenarios are introduced.

Primary Corridor Functionality under Progressive Disruption Scenarios

The following analysis evaluates whether the baseline corridors connecting activity centers remain functional under different disruption scenarios and how these disruptions influence travel performance and regional connectivity. **Table 5** summarizes the disaster-affected transportation segments identified along each baseline corridor, including the type of hydrometeorological disruption and the resulting corridor status. These observed impacts provide the empirical basis for interpreting the scenario-specific network responses.

Table 5. Disaster-affected transportation segments and corridor conditions

OD Pair		Main Corridor	Segment-Affected			Corridor Status
			Flash Flood / River Runoff	Flood Inundation	Landslide	
NAC-RAC	PDG–PRM	PDG–PRM	0	5	0	Disrupted
	PDG–BKT	PDG–BKT	5	2	2	Closed
	PDG–PYK	PDG–BKT–PYK	5	2	2	Closed
	PDG–SWH	PDG–SLK–SWH	0	1	2	Disrupted
	PDG–SLK	PDG–SLK	0	1	2	Disrupted
RAC-RAC	PRM-BKT	PRM-BKT	0	2	2	Closed
	PRM-PYK	PRM-BKT-PYK	0	2	2	Closed

OD Pair	Main Corridor	Segment-Affected			Corridor Status
		Flash Flood / River Runoff	Flood Inundation	Landslide	
PRM-SWH	PRM-PDG-SLK-SWH	2	4	2	Disrupted
PRM-SLK	PRM-PDG-SLK	2	4	2	Disrupted
BKT-PYK	BKT-PYK	0	0	0	Open
BKT-SWH	BKT-SLK-SWH	0	1	0	Disrupted
BKT-SLK	BKT-SLK	0	1	0	Disrupted
PYK-SWH	PYK-BKT-SLK-SWH	0	1	0	Disrupted
PYK-SLK	PYK-BKT-SLK	0	1	0	Disrupted
SWH-SLK	SWH-SLK	0	0	0	Open

Conservative Scenario

Under the conservative scenario, the regional transportation network maintained connectivity among all activity centers despite the assumed failure of severely damaged transportation infrastructure. No complete regional disconnection was observed, indicating that the primary corridor network continued to support physical connectivity between all OD pairs. This finding is consistent with previous studies showing that the removal of individual road segments does not necessarily lead to network fragmentation, as transportation systems are often able to preserve overall connectivity when alternative pathways remain available (Zhang et al., 2026; Mossoux et al., 2019). However, the impacts were unevenly distributed across the regional system. Only four OD pairs (PDG-BKT, PDG-PYK, PRM-BKT, and PRM-PYK) required rerouting through alternative primary corridors, whereas the remaining OD pairs continued to operate along their baseline routes, reflecting the localized nature of disruption impacts (**Table 6**).

Table 6. Changes in main corridor functionality under the conservative scenario

OD Pair	Connectivity Status	Alternative Main Corridor	Distance Change (km)	Travel Time Increase (%)
PDG–BKT	Maintained (reduced performance)	Available	+43.32	+43% – +47% (≈ 1.5×)
PDG–PYK	Maintained (reduced performance)	Available	+43.28	+28% – +34% (≈ 1.3×)
PRM-BKT	Maintained (reduced performance)	Available	+103.45	+126% – +128% (≈ 2.3×)
PRM-PYK	Maintained (reduced performance)	Available	+103.44	+90% – +92% (≈ 1.9×)
Remaining OD pairs	Maintained	Not required	0	0

The rerouting patterns further revealed the limited redundancy of the primary corridor system. Alternative connections relied heavily on a small number of substitute corridors, particularly those passing through SLK, highlighting their strategic role in sustaining regional connectivity during localized disruptions (**Figure 3**). Previous studies emphasized that route diversity is a key determinant of transportation network performance, as limited alternative pathways increase dependence on a small number of critical links (Mattsson & Jenelius, 2015). Consequently, the affected OD pairs experienced corridor distance increases of approximately 43-103 km, resulting in average travel time increases ranging from 28% to 128% relative to baseline conditions. Since travel time represents one of the principal components of transportation impedance, these increases indicate a reduction in functional accessibility between the affected activity centers, even though physical connectivity was preserved (Li et al., 2026; Pyatkova et al., 2019). Previous studies have similarly shown that longer travel times reduce the efficiency of passenger movement, freight distribution, and access to regional services, thereby constraining the effectiveness of regional interactions despite the continued existence of transport connections (Yang et al., 2023). Therefore, under the conservative scenario, the regional transportation network remained physically connected, but several hierarchical interactions were maintained with reduced operational efficiency rather than under normal baseline conditions.

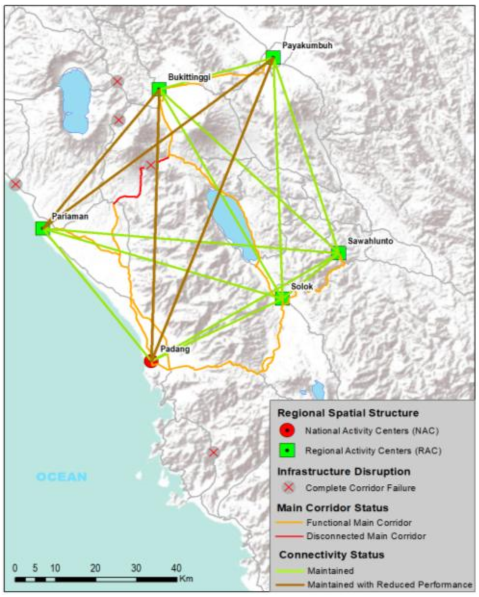

Figure 3. Main corridor functionality under conservative scenario

Moderate Scenario

Under the moderate scenario, regional connectivity between NAC and RACs was largely maintained despite the widespread impacts of hydrometeorological disruptions on the transportation network. However, transportation performance deteriorated substantially compared with the conservative scenario, reflecting the cumulative effects of severe damage, temporary traffic restrictions, reduced operating speeds, and localized flooding along the main corridors. Unlike the conservative scenario, the impact was no longer limited to a small number of rerouted OD pairs. Instead, almost all NAC-RAC and RAC-RAC connections experienced substantial increases in travel time, even when their baseline corridors remained available (see **Table 7** and **Figure 4a**). This pattern indicates that transportation disruptions affected not only corridor availability but also the operational performance of the regional network.

Table 7. Changes in main corridor functionality under the moderate scenario

OD Pair	Connectivity Status	Alternative Main Corridor	Source of Impact	Distance Change (km)	Travel Time Increase (%)
NAC-RAC					

OD Pair	Connectivity Status	Alternative Main Corridor	Source of Impact	Distance Change (km)	Travel Time Increase (%)
PDG–PRM	Maintained	Not required	Corridor delay	0	+513% – +652% (6.13× – 7.52×)
PDG–BKT	Maintained	Available	Rerouting + delay	+43.32	+554% – +683% (6.54× – 7.83×)
PDG–PYK	Maintained	Available	Rerouting + delay	+43.28	+415% – +512% (5.15× – 6.12×)
PDG–SWH	Maintained	Not required	Corridor delay	0	+374% – +473% (4.74× – 5.73×)
PDG–SLK	Maintained	Not required	Corridor delay	0	+551% – +700% (6.51× – 8.00×)
RAC-RAC					
PRM-BKT	Maintained	Available	Rerouting + delay	+103.45	+1239% – +1523% (13.39× – 16.23×)
PRM-PYK	Maintained	Available	Rerouting + delay	+103.44	+897% – +1102% (9.97× – 12.02×)
PRM-SWH	Maintained	Not required	Corridor delay	0	+557% – +708% (6.57× – 8.08×)
PRM-SLK	Maintained	Not required	Corridor delay	0	+705% – +894% (8.05× – 9.94×)
BKT-PYK	Maintained	Not required	No impact	0	0.00
BKT-SWH	Maintained	Not required	Corridor delay	0	+131% – +165% (2.31× – 2.65×)
BKT-SLK	Maintained	Not required	Corridor delay	0	+190% – +233% (2.90× – 3.33×)
PYK-SWH	Maintained	Not required	Corridor delay	0	+102% – +128% (2.02× – 2.28×)
PYK-SLK	Maintained	Not required	Corridor delay	0	+132% – +166% (2.32× – 2.66×)
SWH-SLK	Maintained	Not required	No impact	0	0.00

The magnitude of these impacts varied considerably across the regional network. The most severe effects were observed for connections involving PRM, an RAC located along the northwestern coastal corridor. The PRM-BKT and PRM-PRK OD pairs experienced the greatest deterioration in travel performance because movement had to be diverted to other remaining functional primary arterial corridors after the original corridor was disrupted. Consequently, these OD pairs recorded average travel time increases of 557% (6.57 times) and 1,523% (16,23 times), respectively, accompanied by additional travel distances of approximately 103 km. In comparison, the corresponding NAC-RAC corridors (PDG-BKT and PDG-PYK) experienced shorter detours of approximately 43 km, resulting in lower travel time increases of 415% (5.15 times) and 683% (7.82 times), respectively. These findings indicate that the impacts of hydrometeorological disruptions were unevenly distributed across the regional network, with the severity of performance deterioration largely influenced by the geographic position of activity centers and their dependence on a limited number of strategic primary arterial corridors. Similar spatial heterogeneity has been reported in previous transportation network studies, where peripheral nodes tended to experience greater accessibility deterioration than more centrally connected locations (Bergantino et al., 2024).

From a regional perspective, the moderate scenario demonstrates that preserving topological connectivity alone is insufficient to maintain equivalent levels of regional interaction. Although all hierarchical activity centers remained connected through the primary corridor system, the substantial deterioration in accessibility indicates that interactions between higher-order centers increasingly relied on slower and less efficient transportation conditions. Accordingly, the network continued to sustain hierarchical connectivity in a physical sense, while its operational capacity to facilitate regional interactions had already declined.

Worst-Case Scenario

Under the worst-case scenario, the primary arterial transportation network experienced extensive fragmentation, with 13 out of 15 OD pairs becoming disconnected (86.7%) (see **Figure 4b**). Unlike the moderate scenario, where all OD pairs remained physically connected despite substantial deterioration in travel performance, the simultaneous closure of all disaster-affected corridors fundamentally altered the connectivity configuration of the regional network. All five NAC-RAC connections were severed, while eight of the ten RAC-RAC relationships also became disconnected, leaving only two RAC-RAC pairs (BKT-PYK and SWH-SLK) connected through unaffected primary arterial corridors. These results indicate that the primary corridor network was no longer capable of maintaining continuous regional connectivity under extreme disruption conditions. Similar fragmentation patterns have been reported in previous transportation network studies, where simultaneous failures of multiple critical corridors separated transportation networks into disconnected components (Du et al., 2023; Loreti et al., 2022).

The connectivity losses were concentrated around Padang (PDG), resulting in the complete isolation of the province's only NAC from all RACs. As the principal regional hub supporting higher-order administrative, economic, logistics, and service functions, the loss of all NAC-RAC corridors eliminated direct transportation links between the provincial core and the surrounding regional centers. Consequently, regional interactions that normally depend on these strategic corridors could no longer be maintained through the primary arterial network, substantially reducing the network's ability to facilitate movement between major activity centers (Jeong et al., 2026).

Rather than functioning as a single integrated regional network, the remaining transportation system became fragmented into isolated sub-networks that were no longer connected to the provincial core. Although a limited number of regional connections remained operational, these isolated links were insufficient to sustain continuous interactions across the regional system because they no longer provide direct access to the NAC. This fragmentation pattern demonstrates how simultaneous failures of multiple critical primary arterial corridors can rapidly reduce network continuity, particularly in regions where higher-order activity centers depend on a limited number of strategic transportation corridors (He et al., 2021). Similar network fragmentation has been reported in previous transportation studies, where failures of critical links divided transportation systems into disconnected components and substantially reduced regional connectivity (Dong et al., 2022).

(a) Moderate scenario **(b)** Worst-case scenario

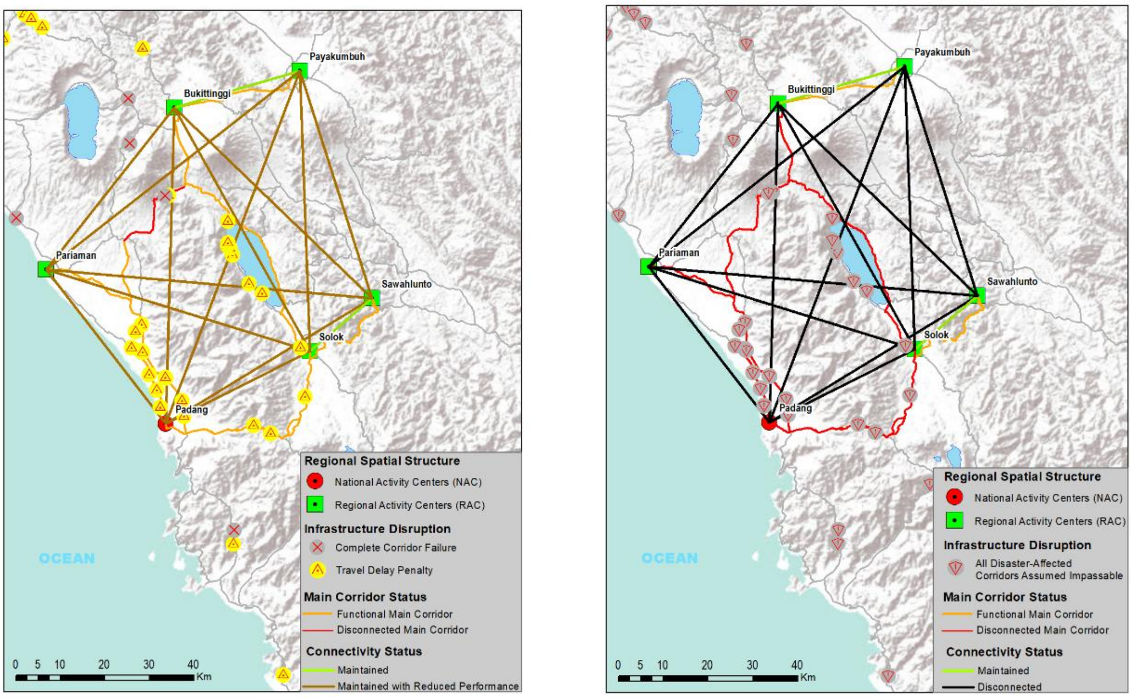

Figure 4. Main corridor functionality under disruption scenario

Alternative Accessibility under Progressive Disruption Scenarios

The primary corridor analysis demonstrated that maintaining physical connectivity alone does not necessarily preserve accessibility performance under disaster disruptions. However, transportation systems may continue to support regional interactions through secondary corridors when the main network becomes constrained. Therefore, this section examines the extent to which secondary collector roads can preserve accessibility and sustain functional linkages between hierarchical activity centers when the primary arterial corridors become disrupted.

Moderate Scenario

Under the moderate disruption scenario, the incorporation of primary collector roads demonstrated that the preservation of regional interactions depends not only on the availability of secondary connections but also their ability to maintain accessibility between activity centers. Although the broader transportation network provided additional routing options, these did not always translate into improved accessibility performance. Five distinct accessibility outcomes were identified: unchanged accessibility; no improvement; shorter but slower routers; partial recovery; and improved accessibility (**Table 8**). These outcomes indicate that the adaptive contribution of the secondary network varies considerably across OD pairs and depends not only on route availability but also on the geometric and operational characteristics of the available corridors (Florath et al., 2024).

Table 8. Accessibility recovery outcomes of alternative corridors under the moderate disruption scenario

OD Pair	ΔDist. Baseline (km)	ΔDist. Moderate (km)	ΔTT Baseline (%)	ΔTT Moderate (%)	Accessibility Outcome	Secondary Corridor Availability
NAC-RAC						
PDG–PRM	-4.52	-4.52	+679% – +864%	+27% – +28%	Shorter but slower	Available
PDG–BKT	+43.32	0	+554% – +683%	0	No improvement	Not available
PDG–PYK	+24.19	-19.09	+400% – +499%	-2% – -3%	Partial recovery	Available
PDG–SWH	0	0	+374% – +473%	0	No improvement	Not available
PDG–SLK	0	0	+551% – +700%	0	No improvement	Not available
RAC-RAC						
PRM-BKT	+98.98	-4.47	+1352% – + 1666%	+8% – +9%	Shorter but slower	Available
PRM-PYK	+79.86	-23.58	+964% – +1190%	+7%	Shorter but slower	Available
PRM-SWH	-4.51	-4.51	+625% – +794%	+10% – +11%	Shorter but slower	Available
PRM-SLK	-4.5	-4.5	+790% – +1003%	+11%	Shorter but slower	Available
BKT-PYK	0	0	0	0	Unchanged	Not required
BKT-SWH	-22.7	-22.7	-15% – -19%	-63% – -68%	Improved accessibility	Available
BKT-SLK	0	0	+185% – +233%	0	No improvement	Not available
PYK-SWH	-55.92	-55.92	-35% – -39%	-68% – -70%	Improved accessibility	Available
PYK-SLK	-19.1	-19.1	+116% – +150%	-6% – -8%	Partial recovery	Available
SWH-SLK	0	0	0	0	Unchanged	Not required

Notes: **ΔDist. Baseline** = DistanceAlternative – DistanceBaseline; **ΔDist. Moderate** = DistanceAlternative – DistanceModerate; **ΔTT** (%) = [(TTAlternative – TTReference) /TTAlternative] ×100, where Reference denotes either the baseline or moderated main-corridor condition. Negative values indicate improved performance, whereas positive values indicate deteriorated performance.

Two OD pairs (BKT-PYK and SWH-SLK) exhibited unchanged accessibility, as the primary arterial corridors connecting these activity centers were not affected by the identified disaster events. Consequently, no rerouting through the secondary transportation network was required and both travel distance and travel time remained identical to the baseline conditions. Four OD pairs (PDG-BKT, PDG-SWH, PDG-SLK, and BKT-SLK) showed no improvement, with travel distance and travel time remaining identical to those obtained from the disrupted primary arterial network. This occurred because no primary collector corridors were available to provide feasible alternative routes between these activity centers. As a result, the routing process continued to utilize the existing arterial corridors despite their disrupted operating conditions, leaving accessibility relative to the primary corridor analysis. These findings indicate that the adaptive capacity of the transportation network is spatially constrained by the availability of secondary corridors. Where no collector road alternatives exist, disruptions to the primary arterial network cannot be compensated through rerouting, causing accessibility to remain entirely dependent on the performance of the affected main corridors (He et al., 2021).

A more distinctive pattern emerged for five OD pairs (PDG-PRM, PRM-BKT, PRM-PYK, PRM-SWH, and PRM-SLK), which were classified as shorter but slower. Although the incorporation of the secondary transportation network reduced travel distances by approximately 4 to 24 km, travel times remained 7-28% longer than those obtained from the disrupted primary arterial corridors. This pattern was particularly evident for OD pairs originating from Pariaman (PRM). The alternative routes connecting PRM with Bukittinggi, Payakumbuh, Sawahlunto, and Solok continued to converge toward Padang before reaching their destinations. Although these routes were geometrically shorter, the corridors approaching Padang contained numerous disaster-affected road segments under the moderate scenario. Consequently, the cumulative travel-time penalties associated with these affected corridors offset the reduction in travel distance, resulting in no overall improvement in travel performance. These findings demonstrate that shorter travel distance alone does not necessarily translate into better accessibility because functional accessibility depends not only on route geometry but also on the operational condition of the corridors through which regional movement occurs (Mossoux et al., 2019; Kim et al., 2019; Moyano et al., 2018).

Two OD pairs (PDG-PYK and PYK-SLK) exhibited partial recovery, where travel times were reduced by approximately 2-8% relative to disrupted primary corridors but remained substantially higher than baseline conditions. These results indicate that, although the secondary network was able to alleviate part of the accessibility loss caused by disruptions to the primary arterial system, it was insufficient to fully restore pre-disaster travel performance. Consequently, interactions between the corresponding activity centers could continue under improved conditions, albeit with lower operational efficiency than under normal circumstances.

Finally, two OD pairs (BKT-SWH and PYK-SWH) demonstrated improved accessibility, where both travel distance and travel time became lower than under baseline conditions. This finding suggests that, for certain spatial configurations, the broader transportation network contains collector corridors capable of providing more efficient linkages than the primary arterial routes normally used under standard conditions. Rather than functioning solely as emergency detours, these secondary corridors can strengthen regional interactions by offering latent connectivity that remains underutilized during normal operating conditions (Prignano et al., 2026).

Overall, the moderate scenario demonstrates that the adaptive role of primary collector roads extends beyond providing physical alternatives to disrupted arterial corridors. Their contribution varies substantially across the regional network, ranging from no accessibility improvement to partial or even complete performance enhancement. More importantly, the results indicate that maintaining interactions between activity centers depends not simply on the existence of alternative routes, but also on the extent to which those routes are capable of preserving functional accessibility following disruptions to the primary transportation network (Wenxin et al., 2024; Chen et al., 2024; Anderson et al., 2022).

Worst-Case Scenario

Under the worst-case scenario, the contribution of the secondary transportation network to regional accessibility became substantially more limited than under the moderate scenario (**Table 9**). Of the fifteen OD pairs evaluated, only four RAC-RAC connections were restored through alternative corridors, whereas all NAC-RAC connections involving Padang remained disconnected. These findings indicate that, although the broader transportation network retained a limited capacity to restore local accessibility, it was unable to re-establish the principal regional connections that organize the provincial spatial system.

Table 9. Connectivity recovery and accessibility performance of alternative corridors under the worst-case scenario

OD Pair	Main Corridor Status	Alternative Corridor Status	Recovery Outcome	ΔDist. Baseline (km)	ΔTT Baseline (%)
BKT–PYK	Maintained	Maintained	Not required	0	0
BKT–SWH	Disconnected	Maintained	Fully restored	-22.7	-15% – -19%
BKT–SLK	Disconnected	Maintained	Partially restored	44.65	+58% – +62%
PYK–SWH	Disconnected	Maintained	Fully restored	-55.92	-35% – -39%
PYK–SLK	Disconnected	Maintained	Partially restored	6.07	+5% – +8%
SWH–SLK	Maintained	Maintained	Not required	0	0
Remaining OD pairs	Disconnected	Disconnected	Not restored	-	-

Notes: **ΔDist. Baseline** = DistanceAlternative – DistanceBaseline; **ΔTT Baseline** = [(TTAlternative – TTBaseline /TTBaseline] × 100. Negative values indicate improved performance, whereas positive values indicate deteriorated performance.

The restored OD pairs exhibited contrasting accessibility performance. BKT-SWH and PYK-SWH experienced both shorter travel distances and lower travel times than under baseline conditions, indicating that the available secondary corridors provided efficient substitutes for the disrupted arterial network (Guo et al., 2024). In contrast, BKT-SLK and PYK-SLK remained accessible only through substantially longer and slower routes, with travel distance increasing by approximately 6-45 km and travel times remaining 5-62% above baseline conditions. These results suggest that restoring physical connectivity alone does not necessarily restore accessibility performance, as the effectiveness of alternative routes depends on their operational characteristics as well as their spatial configuration (Pei et al., 2024).

More importantly, none of the alternative corridors succeeded in restoring connectivity between Padang and the surrounding RACs. This outcome indicates that the available secondary network lacks sufficient continuity to bypass the disaster-affected corridors leading to the provincial capital. Consequently, although local interactions among several RACs could still be maintained, the higher-order linkages connecting the provincial core with the remainder of the regional system could not be re-established through the existing secondary network.

Overall, the worst-case analysis demonstrates that the adaptive capacity of the secondary transportation network is highly uneven across the regional system. While it remains capable of preserving selected local interactions among RACs, its contribution is insufficient to recover the hierarchical connectivity centered on Padang. These findings indicate that the effectiveness of alternative accessibility depends not merely on the existence of secondary routes but also on their ability to reconnect the principal activity centers that structure regional interactions (Lee et al., 2025; Che et al., 2022).

Integrated Interpretation of Regional Connectivity under Progressive Disruption Scenarios

The five stress-testing conditions reveal a progressive transformation in regional connectivity as the severity of transportation disruption increases (**Table 10**). Under the conservative scenario, all 15 OD pairs remained connected, with the dominant impact limited to localized rerouting. The network therefore retained its overall connectivity and hierarchical interactions among activity centers were preserved. This pattern is consistent with the "robust yet fragile" property documented for infrastructure networks, whereby systems can remain robust against localized or random failures but become increasingly vulnerable when disruption becomes systematic (Yang, 2015). Under the moderate main-corridor scenario, connectivity was still maintained for all 15 OD pairs, but widespread travel-time degradation reduced corridor functionality. Thus, the regional spatial structure remained connected, although hierarchical interactions were maintained with reduced efficiency. This indicates that increasing disruption severity does not immediately produce physical disconnection, as network performance can deteriorate while connectivity is still preserved (Mattsson, 2015; Wang, 2019).

The introduction of alternative accessibility produced a different network response. Under the moderate alternative-accessibility scenario, all 15 OD pairs remained connected, but the outcomes were heterogeneous across the regional network. Some OD pairs benefited from shorter or more efficient alternative routes, whereas others experienced limited or no improvement because suitable secondary corridors were unavailable or because alternative routes remained dependent on disaster-affected approaches. Accordingly, the dominant network response was adaptive rerouting through secondary corridors. At the regional spatial level, hierarchical interactions could still be maintained through these alternatives, although their effectiveness varied substantially across OD pairs. This heterogeneous response is consistent with evidence that redundancy does not translate uniformly into resilience, as the contribution of alternative routes depends on network configuration and the spatial distribution of critical links and activity centers (Martin, 2021).

Table 10. Integrated assessment of regional structure resilience across progressive disaster disruption scenarios

Assessment Dimension	Conservative	Moderate (Main Corridor)	Moderate (Alternative Accessibility)	Worst-Case (Main Corridor)	Worst-Case (Alternative Accessibility)
Observed Network Performance					
Connected OD pairs (n = 15)	15	15	15	2	6

Assessment Dimension	**Conservative**	**Moderate (Main Corridor)**	**Moderate (Alternative Accessibility)**	**Worst-Case (Main Corridor)**	**Worst-Case (Alternative Accessibility)**
NAC-RAC connectivity	Maintained	Maintained	Maintained	Collapsed	Collapsed
RAC-RAC connectivity	Maintained	Maintained	Maintained	Partially maintained	Partially restored
Implications for Regional Connectivity					
Dominant impact	Localized rerouting	Widespread travel-time degradation	Heterogeneous accessibility outcomes	System-wide disconnection	Selective connectivity restoration
Dominant network response	Connectivity maintained	Corridor functionality reduced	Adaptive rerouting through secondary corridors	Network fragmentation	Partial functional recovery
Implication for regional spatial structure	Hierarchical interactions preserved	Hierarchical interactions maintained with reduced efficiency	Hierarchical interactions maintained through adaptive alternatives	Hierarchical structure collapsed	Local interactions partially restored, hierarchical structure not recovered

The most pronounced transformation occurred under the worst-case scenarios. When all identified disaster-affected primary corridors were assumed to be unavailable, only two of the fifteen OD pairs remained connected through the primary corridor system. The dominant impact was therefore system-wide disconnection, accompanied by network fragmentation and the collapse of the regional hierarchical structure. This outcome is consistent with previous findings that the coordinated loss of critical links can be substantially more damaging to network integrity than isolated failures (Yang, 2015; Vodak, 2018). When alternative accessibility was subsequently introduced, six OD pairs could be connected, indicating selective connectivity restoration. However, this recovery remained insufficient to restore the NAC–RAC relationships involving Padang, while only selected RAC–RAC interactions could be maintained or restored. The dominant network response was therefore partial functional recovery, with local interactions partially restored but the regional hierarchical structure remaining unrecovered. This finding highlights the importance of the position of restored links within the broader network hierarchy, as the recovery of individual connections does not necessarily restore the functions previously supported by strategically important corridors (Reggiani, 2022).

Taken together, **Table 10** demonstrates a clear progression in the response of the regional spatial system: maintained connectivity under localized disruption, reduced functional efficiency under widespread corridor degradation, adaptive rerouting under moderate alternative accessibility, network fragmentation under severe disruption, and partial functional recovery when secondary corridors are available under the worst-case condition. Importantly, connectivity status, network response, and spatial-structural implications do not necessarily change simultaneously. A network may remain connected while its functional efficiency declines and connectivity may be partially restored without recovering the hierarchical relationships that organize the regional system. The worst-case results should nevertheless be interpreted as a bounding stress-test condition rather than a reconstruction of a historically simultaneous failure, as the scenario deliberately assumes the concurrent unavailability of all identified disaster-affected primary corridors. Likewise, the observed lack of hierarchical recovery reflects a passive recovery condition without prioritization of strategically critical links. These qualifications are important for interpreting the results as an assessment of upper-bound vulnerability rather than as a prediction of actual post-disaster recovery trajectories.

Overall, the results demonstrate that increasing disruption severity produces qualitatively different responses across the regional system, from connectivity preservation to functional degradation, adaptive rerouting, fragmentation, and selective recovery. This progression provides the empirical basis for the following discussion, which considers why transportation connectivity and accessibility, although essential for diagnosing disruption, should not be treated as sufficient indicators of regional spatial structure resilience.

Discussion

Beyond Connectivity: Rethinking Regional Spatial Structure Resilience

The findings of this study raise a broader conceptual question regarding what should constitute resilience when the object of analysis is not the transportation network itself but the regional spatial structure that the network enables. Conventional transportation resilience assessments commonly rely on indicators such as connectivity, accessibility, travel time, and network efficiency to characterize system performance under disruption (Papilloud et al., 2024; Pregnolato et al., 2016). These indicators are essential for identifying the magnitude and distribution of transportation disruption, but they do not by themselves capture whether the spatial relationships supported by the transportation system remain functionally meaningful. For a regional spatial system organized around hierarchically differentiated activity centers, resilience therefore needs to be considered in relation to the continuity of the interactions that sustain this hierarchy.

This argument requires a distinction between the performance of the network and the function of the spatial system. He et al. (2021) and Shang et al. (2020) demonstrated that topological and operational measures can provide substantially different assessments of transportation network robustness. Jafino et al. (2019) further emphasized that infrastructure connectivity alone does not necessarily guarantee the continuation of broader accessibility and functional outcomes. These perspectives suggest that transportation indicators should be interpreted as evidence of the conditions under which spatial interactions occur rather than as direct measures of the resilience of those interactions. In a regional spatial context, the relevant question is therefore not simply whether a connection exists, but whether the transportation system continues to provide the level of access and interaction required by the hierarchical roles of the activity centers it connects.

The same principle changes how accessibility recovery should be interpreted. Accessibility is inherently relational, because it describes the ease with which locations can be reached through a network. However, an improvement in accessibility at one spatial scale does not necessarily imply recovery at another. Xu and Chopra (2023) showed that improvements in transportation accessibility do not automatically restore higher-order system functionality, while Bergantino et al. (2024) highlighted the possibility of localized accessibility recovery alongside persistent disruption at the broader regional scale. This distinction is particularly important for spatial planning because regional hierarchies are not formed simply by the existence of connections but by differentiated roles and patterns of interaction among centers. Consequently, an alternative route may improve local accessibility while still failing to reproduce the strategic regional relationship previously supported by a primary corridor.

This perspective also suggests that resilience should not be interpreted as a single condition that a regional system either possesses or loses. Rather, resilience can be understood as the capacity of the spatial system to preserve the functional relationships associated with its intended spatial structure when the conditions supporting those relationships are disturbed. A system may retain some interactions while losing others, maintain local relationships while losing higher-order connections, or adapt through alternative configurations without fully recovering its original hierarchy. Such differentiated responses indicate that resilience is inherently relational and spatially uneven. The relevant unit of assessment is therefore not only the road segment or network component but also the interaction between the disrupted network and the hierarchical relationships among activity centers.

Based on this interpretation, transportation connectivity, travel time, and accessibility can be positioned as intermediate mechanisms rather than ultimate measures of regional spatial structure resilience. Disaster disruption affects the availability and performance of transportation corridors; these changes alter the accessibility and travel conditions between activity centers; and the resulting changes determine whether the functional relationships embedded within the regional hierarchy can be sustained. This conceptualization places the regional spatial structure at the analytical endpoint rather than the transportation network itself. **Figure 6** summarizes this relationship by linking transportation disruption to changes in network conditions, accessibility, and ultimately the continuity of hierarchical spatial interactions.

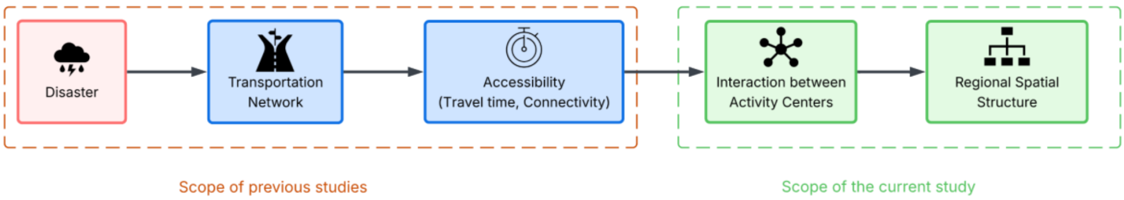

Figure 6. Conceptual framework: from network performance to regional spatial structure resilience.

The conceptual implication is that regional spatial structure resilience should be assessed according to the extent to which a region can sustain its intended hierarchy of interactions under changing transportation conditions. This does not diminish the importance of connectivity or accessibility. Instead, it places these indicators within a broader causal framework in which their significance depends on the spatial functions and hierarchical relationships they support. Such a perspective extends transportation-oriented resilience assessment toward a more explicitly spatial interpretation of resilience, in which the preservation of regional function is treated as the ultimate concern rather than the preservation of transportation infrastructure performance alone.

Towards Disaster-Resilient Regional Spatial Planning

The findings of this study suggest that disaster-resilient regional spatial planning should extend beyond the conventional objective of protecting transportation infrastructure toward maintaining the functional organization of regional systems during disruptive events. Existing resilience strategies have predominantly emphasized strengthening critical transportation assets, improving infrastructure robustness, and accelerating post-disaster recovery. While these measures remain indispensable, they primarily focus on the performance of individual infrastructure components. The present study demonstrates that transportation infrastructure should instead be understood as a functional system that enables interactions among hierarchical activity centers. Consequently, the primary objective of resilience-oriented regional spatial planning should be to preserve the continuity of these interactions rather than merely maintaining the physical integrity of transportation networks.

This perspective has important implications for regional spatial planning policies, particularly in regions where spatial structures are organized around hierarchical systems of National Activity Centers and Regional Activity Centers. Conventional spatial planning generally determines the hierarchy of activity centers based on economic functions, service provision, and administrative roles, while transportation corridors are designated to facilitate interactions among these centers. However, considerably less attention has been given to evaluating whether these hierarchical relationships remain functional under disaster conditions. The results of this study indicate that transportation corridors supporting higher-order interactions deserve greater consideration within spatial planning because disruptions affecting these corridors may weaken regional integration long before complete network failure occurs. Accordingly, resilience assessment should become an integral component of regional spatial planning by explicitly evaluating the robustness of hierarchical interactions under progressive disaster scenarios.

The findings further suggest that transportation investment priorities should be guided not only by engineering considerations or traffic demand but also by their contribution to sustaining regional spatial functions. Corridors connecting National Activity Centers with Regional Activity Centers warrant particular attention because disruptions affecting these links have disproportionately large consequences for regional integration. Likewise, secondary transportation networks should be developed strategically to provide functional redundancy capable of maintaining hierarchical interactions when primary corridors become disrupted rather than simply increasing overall network density.

Although this study focuses on West Sumatra, the proposed analytical framework is also relevant to other mountainous and hazard-prone regions that depend on a limited number of strategic transportation corridors. Similar geographical conditions exist in many countries, where limited network redundancy and recurrent hydrometeorological hazards create comparable challenges for regional connectivity. Consequently, the stress-testing framework presented in this study provides a transferable approach for integrating transportation network analysis with regional spatial planning.

Ultimately, the findings highlight that disaster-resilient regional spatial planning should be evaluated according to its ability to preserve the functional organization of regional systems rather than simply restoring damaged transportation infrastructure. Transportation connectivity, accessibility, and network redundancy remain essential components of resilience planning; however, their ultimate value lies in supporting the continuity of hierarchical interactions among activity centers. By explicitly integrating transportation stress-testing into regional spatial planning, resilience assessment can move beyond infrastructure-oriented evaluation toward a more comprehensive understanding of how regional systems continue to function under disaster conditions. This perspective provides a practical pathway for incorporating resilience considerations into spatial planning policies while also contributing to the broader discourse on disaster-resilient regional development.

Conclusion

This study investigated the resilience of regional spatial structure in West Sumatra by examining how hydrometeorological disaster disruptions influence the continuity of hierarchical interactions

among activity centers. Using ex-post stress-testing scenarios that progressively disrupted primary transportation corridors and evaluated alternative accessibility, the study demonstrated that regional spatial structure resilience cannot be adequately interpreted through conventional transportation performance indicators alone.
The results demonstrate that maintaining physical connectivity does not necessarily imply that regional spatial structure remains resilient. Although the transportation network continued to function under several disruption scenarios, progressive deterioration in travel performance reduced functional accessibility and weakened hierarchical interactions among activity centers. Moreover, the effectiveness of alternative accessibility depended not only on the availability of secondary corridors but also on their ability to sustain strategically important regional interactions. These findings indicate that regional resilience is determined by the continuity of hierarchical spatial interactions rather than by transportation connectivity alone.

Beyond its empirical findings, this study contributes a conceptual perspective on how regional spatial structure resilience should be interpreted under transportation disruption. The proposed framework repositions transportation connectivity, travel time, and accessibility as intermediate mechanisms through which disaster-induced disruptions influence the continuity of hierarchical interactions among activity centers, rather than as ultimate indicators of resilience. Consequently, regional spatial structure resilience is more appropriately understood in terms of the ability of the regional system to sustain its functional organization despite progressive degradation of transportation network performance. By explicitly linking transportation network analysis with regional spatial planning, this study bridges two research domains that have often been examined separately and provides a transferable analytical framework for evaluating disaster resilience in regional spatial systems.

From a regional spatial planning perspective, these findings highlight the importance of incorporating scenario-based resilience assessment into evaluation and development of regional spatial structures, particularly in regions that rely on a limited number of strategic transportation corridors. Rather than prioritizing transportation investments solely according to engineering characteristics or traffic demand, planning efforts should emphasize preserving the continuity of hierarchical interactions that support regional functions during disaster conditions. Although this study was conducted in West Sumatra, the proposed analytical framework is equally applicable to other mountainous and hazard-prone regions where complex topography, recurrent hydrometeorological hazards, and limited transportation redundancy create similar vulnerabilities. Integrating transportation stress-testing into regional spatial planning, therefore, provides a practical basis for strengthening disaster-resilient regional development under geographically constrained conditions.

Despite these contributions, several limitations should be acknowledged. First, the analysis evaluated changes in transportation connectivity and accessibility as proxies for the continuity of regional spatial interactions without explicitly assessing their subsequent socioeconomic consequences, such as logistics performance, public service accessibility, or regional economic productivity. Second, travel time was estimated using generalized operating speeds based on road hierarchy rather than segment-specific free-flow speeds derived from detailed operational traffic data. Accordingly, the estimated travel times should be interpreted as comparative indicators for evaluating relative accessibility changes across disruption scenarios rather than precise representations of actual operating conditions. Future research should integrate transportation network stress-testing with socioeconomic, logistics, and public service analyses supported by more detailed operational traffic data. Such integration would provide a more comprehensive understanding of how transportation disruptions propagate through regional systems and influence their long-term functionality, adaptability, and sustainability.

Ultimately, the resilience of regional spatial structure should not be evaluated solely by the ability of transportation networks to maintain connected but by their capacity to continuously sustain hierarchical interactions that enable regional systems to function under progressively increasing disaster risks.

Acknowledgements

This research was supported and funded by the Institute for Research and Community Service (*Lembaga Penelitian dan Pengabdian kepada Masyarakat* – LPPM) Universitas Bung Hatta through Grant/Contract No. 079/RIPKA-DRI/UBH/V-2026. The authors would like to express their sincere gratitude to LPPM Universitas Bung Hatta for providing the necessary financial support to complete this study.

Declaration Of Generative Ai Use in Writing

During the preparation of this work, the authors used Quillbot, developed by Learneo, Inc., to assist with paraphrasing and refining the language in certain sections. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the final content of the publication.

References

Ahmed, S., Dey, K. (2020). Resilience modeling concepts in transportation systems: a comprehensive review based on mode, and modeling techniques. *J Infrastruct Preserv Resil* 1, 8. https://doi.org/10.1186/s43065-020-00008-9

Alabbad, Y., Mount, J., Campbell, A., & Demir, I. (2021). Assessment of transportation system disruption and accessibility to critical amenities during flooding: Iowa case study.. *The Science of the total environment, 793*, 148476 . https://doi.org/10.1016/j.scitotenv.2021.148476

Anderson, M. J., Kiddle, D. A. F., & Logan, T. M. (2022). The underestimated role of the transportation network: Improving disaster & community resilience. *Transportation Research Part D: Transport and Environment*, *106*, Article 103218. https://doi.org/10.1016/j.trd.2022.103218

Ansofino, A., & Zusmelia, Z. (2022). Comparative and Competitive Advantages Analysis of Rubber as A Featured Product of West Sumatera to Support of Spatial Interaction. *Proceedings of the 1st International Conference on Economic and Education, ICON 2021, 14 – 15 December 2021, Padang-West Sumatra, Indonesia*. https://doi.org/10.4108/eai.14-12-2021.2318307

Auerbach, J., & Kim, H. (2022). Measuring Robustness and Coverage of Transportation Networks with Multiple Routes and Hubs. *Annals of the American Association of Geographers, 112*, 1741 – 1760. https://doi.org/10.1080/24694452.2021.2000357

Aydin, N. Y., Heinimann, H. R., Duzgun, H. S., & Wenzel, F. (2018). Integration of stress testing with graph theory to assess the resilience of urban road networks under seismic hazards. Natural Hazards, 91(1), 37–68. https://doi.org/10.1007/s11069-017-3112-z

Basile, R., Commendatore, P., & Kubin, I. (2021). Complex spatial economic systems: migration, industrial location and regional asymmetries. *Spatial Economic Analysis, 16*, 1 – 8. https://doi.org/10.1080/17421772.2021.1876911

Bergantino, A. S., Gardelli, A., & Rotaris, L. (2024). Assessing transport network resilience: empirical insights from real-world data studies. *Transport Reviews*, *44*(4), 834–857. https://doi.org/10.1080/01441647.2024.2322434

Berry, B., & Garrison, W. (1958). The Functional Bases of the Central Place Hierarchy. *Economic Geography, 34*, 145. https://doi.org/10.2307/142299

BPS-Statistics West Sumatra Province. (2026). Population by age group and sex in West Sumatra Province, 2022 [Data set]. https://sumbar.bps.go.id/id/statistics-table/3/WVc0MGEyMXBkVFUxY25KeE9HdDZkbTQzWkVkb1p6MDkjMw==/jumlah-penduduk-menurut-kelompok-umur-dan-jenis-kelamin-di-provinsi-sumatera-barat--2018.html

Cattaneo, A., Girgin, S., De By, R., McMenomy, T., Nelson, A., & Vaz, S. (2024). Worldwide delineation of multi-tier city–regions. *Nature Cities, 1*, 469 – 479. https://doi.org/10.1038/s44284-024-00083-z

Chacon-Hurtado, D., Kumar, I., Gkritza, K., Fricker, J., & Beaulieu, L. (2020). The role of transportation accessibility in regional economic resilience. *Journal of Transport Geography*. https://doi.org/10.1016/j.jtrangeo.2020.102695

Che, L., Xu, J., Chen, H., Sun, D., Wang, B., Zheng, Y., Yang, X., & Peng, Z. (2022). Evaluation of the Spatial Effect of Network Resilience in the Yangtze River Delta: An Integrated Framework for Regional Collaboration and Governance under Disruption. *Land*. https://doi.org/10.3390/land11081359

Chen, X., Ma, S., Chen, L., & Yang, L. (2024). Resilience measurement and analysis of intercity public transportation network. *Transportation Research Part D: Transport and Environment*, *132*, Article 104202. https://doi.org/10.1016/j.trd.2024.104202

Curatella, L., Fortunato, G., Pilogallo, A., Saganeiti, L., Santarsiero, V., Bonifazi, A., & Scorza, F. (2020). Polycentrism and Effective Territorial Structures: Basilicata Region Case Study. 1689-1696. https://doi.org/10.1007/978-3-030-48279-4_159

Du, C., Ouyang, M., Zhang, H., Wang, B., & Wang, N. (2023). Resilience patterns of urban road networks under the worst-case localized disruptions. *Risk Analysis*, *44*(10), 2333–2347. https://doi.org/10.1111/risa.14236

Dong, S., Gao, X., Mostafavi, A., & Fan, C. (2022). Modest flooding can trigger catastrophic road network collapse due to compound failure. *Communications Earth & Environment*, *3*(1), Article 38. https://doi.org/10.1038/s43247-022-00366-0

El-Maissi, A. M., Argyroudis, S. A., & Nazri, F. M. (2020). Seismic vulnerability assessment methodologies for roadway assets and networks: A state-of-the-art review. *Sustainability*, *13*(1), Article 61. https://doi.org/10.3390/su13010061

El Rashidy, R. A. H., & Grant-Muller, S. (2019). A composite resilience index for road transport networks. *Proceedings of the Institution of Civil Engineers – Transport*, *172*(3), 174–183. https://doi.org/10.1680/jtran.16.00139

Fang, X., Lu, L., Hong, Y., & Sun, P. (2025). Evaluating Dynamic Accessibility of Transportation Network Under Extreme Rainfall and Flooding: An Integrated Framework. *IEEE Internet of Things Journal, 12*, 38556-38568. https://doi.org/10.1109/jiot.2025.3587223

Florath, J., Chanussot, J., & Keller, S. (2024). Road accessibility during natural hazards based on volunteered geographic information data and network analysis. *ISPRS International Journal of Geo-Information*, *13*(4), Article 107. https://doi.org/10.3390/ijgi13040107

Fu, Y., et al. (2025). The economic impacts of flood-driven transportation delays. Transportation Research Part D: Transport and Environment. https://doi.org/10.1016/j.jtrangeo.2025.104436

Furno, A., Faouzi, N., Sharma, R., & Zimeo, E. (2021). Graph-based ahead monitoring of vulnerabilities in large dynamic transportation networks. *PLoS ONE, 16*. https://doi.org/10.1371/journal.pone.0248764

Galve, J. P., Pérez-García, J. L., Ruano, P., & et al. (2025). Applications of UAV Digital Photogrammetry in landslide emergency response and recovery activities: The case study of a slope failure in the A-7 highway (S Spain). *Landslides*, *22*(5), 1383–1396. https://doi.org/10.1007/s10346-024-02449-9

Gu, Y., Shi, R., Yan, Z., Li, Q., & Yue, Y. (2023). How to determine city hierarchies and spatial structure of a megaregion?. *Geo-spatial Information Science, 27*, 276 – 288. https://doi.org/10.1080/10095020.2022.2161425

Guo, M., Zhao, T., & Gao, Z. (2024). Pre-disaster resource allocation based on network topology and flow features. *Transportmetrica A: Transport Science*, 1–24. Advance online publication. https://doi.org/10.1080/23249935.2024.2344631

He, Z., Navneet, K., van Dam, W., & Van Mieghem, P. (2021). Robustness assessment of multimodal freight transport networks. *Reliability Engineering & System Safety*, *207*, Article 107315. https://doi.org/10.1016/j.ress.2020.107315

Isya, M., Refiyanni, M., Chaira, C., & Akhyar, A. (2025). Evaluation of the Road Transportation System in Supporting Connectivity between Activity Centers. *Construction Technologies and Architecture, 18*, 107 – 117. https://doi.org/10.4028/p-zq3quk

Jafino, B. A., Kwakkel, J., & Verbraeck, A. (2019). Transport network criticality metrics: A comparative analysis and a guideline for selection. *Transport Reviews*, *40*(2), 241–264. https://doi.org/10.1080/01441647.2019.1703843

Jeong, S., & Chang, J. S. (2026). Multidimensional connectivity of North Korean arterial roads. *Transportation Letters*. https://doi.org/10.1080/19427867.2026.2613233

Juschten, M., Reinwald, F., Weichselbaumer, R., & Jiricka-Pürrer, A. (2021). Developing an Integrative Theoretical Framework for Climate Proofing Spatial Planning Across Sectors, Policy Levels and Planning Areas. *Land*. https://doi.org/10.3390/land10080772

Kim, J., & Lee, B. (2019). More than travel time: New accessibility index capturing the connectivity of transit services. *Journal of Transport Geography*. https://doi.org/10.1016/j.jtrangeo.2019.05.008

Kozhabek, A., & Chai, W. (2025). Robustness assessment of urban road networks in densely populated cities. *Applied Network Science, 10*. https://doi.org/10.1007/s41109-025-00707-w

Lee, S., Jeon, J., Cho, K., & Im, J. (2025). Does Intercity Transportation Accessibility Matter? Its Effects on Regional Network Centrality in South Korea. *Land*. https://doi.org/10.3390/land14040873

Li, J., Chen, Z., Huang, G., & et al. (2026). A dynamic simulation framework for evaluating the impacts of urban flooding on transportation systems. *International Journal of Disaster Risk Science*, *17*, 182–196. https://doi.org/10.1007/s13753-026-00697-y

Li, Y., Liao, C., Li, X., & Guo, R. (2024). Understanding regional structure through spatial networks: A simulation optimization framework for exploring balanced development. *Habitat International*. https://doi.org/10.1016/j.habitatint.2024.103155

Li, Y., Teng, M., & Liu, Y. (2024). Spatial dynamics of transport accessibility and regional efficiency in the Yangtze River Delta Urban Agglomeration. *Scientific Reports, 14*. https://doi.org/10.1038/s41598-024-69974-4

Linkov, I., Trump, B. D., Pescaroli, G., & Hynes, W. (2022). Resilience stress testing for critical infrastructure. International Journal of Disaster Risk Reduction, 82, 103323. https://doi.org/10.1016/j.ijdrr.2022.103323

Liu, J., Lu, H., Chen, M., Wang, J., & Zhang, Y. (2020). Macro Perspective Research on Transportation Safety: An Empirical Analysis of Network Characteristics and Vulnerability. *Sustainability*. https://doi.org/10.3390/su12156267

Liu, J., Xu, Z., Wan, L., & MacAskill, K. (2026). *Road transport resilience under extreme rainfall: Integrating multiple impact factors and delay propagation*. International Journal of Disaster Risk Reduction. https://doi.org/10.1016/j.ijdrr.2026.106024

Loreti, S., Ser-Giacomi, E., Zischg, A., Klither, M., & Thaler, T. (2022). Local impacts on road networks and access to critical locations during extreme floods. *Scientific Reports*, *12*(1), Article 1552. https://doi.org/10.1038/s41598-022-04927-3

Martin, B., Ortega, E., Cuevas-Wizner, R., Ledda, A., & De Montis, A. (2021). Assessing road network resilience: An accessibility comparative analysis. *Transportation Research Part D: Transport and Environment*, *95*, Article 102851. https://doi.org/10.1016/j.trd.2021.102851

Mason, D., & Brabhaharan, P. (2021). Characterisation of transport resilience and measures to enhance resilience in the recovery after the 2016 Kaikōura earthquake. *Bulletin of the New Zealand Society for Earthquake Engineering*, *54*(2), 69–81. https://doi.org/10.5459/bnzsee.54.2.69-81

Mattsson, L.-G., & Jenelius, E. (2015). Vulnerability and resilience of transport systems – A discussion of recent research. *Transportation Research Part A: Policy and Practice, 81*, 16–34. https://doi.org/10.1016/j.tra.2015.06.002

Ministry of Public Works and Housing. (2023). Indonesian Road Capacity Guidelines (PKJI) (Guideline No. 09/P/BM/2023). Directorate General of Highways. https://binamarga.pu.go.id/uploads/files/1942/09pbm2023-pedoman-kapasitas-jalan-indonesia-.pdf

Mishra, S., Sahu, P., Pani, A., & Mehran, B. (2021). Spatial Planning Framework for Development of Rural Activity Centers: Method of Location Allocation, Effect on Trip Length, and Policy Implications. *Papers in Applied Geography, 7*, 372 – 391. https://doi.org/10.1080/23754931.2021.1901237

Melasari, J., P., Y., & Y. (2023). Accessibility Towards West Sumatra Tourism Area. *IOP Conference Series: Earth and Environmental Science, 1173*. https://doi.org/10.1088/1755-1315/1173/1/012049

Mossoux, S., et al. (2019). *Evaluating the effects of road network disruption on accessibility using iterative road segment removal.* Natural Hazards and Earth System Sciences, 19, 1251–1265. https://doi.org/10.5194/nhess-19-1251-2019

Moyano, A., Martínez, H., & Coronado, J. (2018). From network to services: A comparative accessibility analysis of the Spanish high-speed rail system. *Transport Policy, 63*, 51-60. https://doi.org/10.1016/j.tranpol.2017.11.007

Nasrazadani, H., Nogal, M., Adey, B. T., & et al. (2025). Prioritizing simulation-based stress tests to assess the resilience of transport systems: A computation-free methodology. *Journal of Infrastructure Preservation and Resilience*, *6*, Article 16. https://doi.org/10.1186/s43065-025-00128-0

Papilloud, T., Steiner, A., Zischg, A., & Keiler, M. (2024). Road network disruptions during extreme flooding events and their impact on the access to emergency medical services: A spatiotemporal vulnerability analysis. *The Science of the total environment*, 177140. https://doi.org/10.1016/j.scitotenv.2024.177140

Pei, S.-S., Zhai, C.-H., Hu, J., Wang, Z.-Q., & Xie, L.-L. (2024). Resilience assessment and enhancement of interdependent transportation-healthcare system: A spatial accessibility approach. *Transportation Research Part D: Transport and Environment*, *128*, Article 104090. https://doi.org/10.1016/j.trd.2024.104090

Petrucci, O., & Gariano, S. L. (2026). Road interruptions due to landslides and floods in Southern Italy. *Natural Hazards*, *122*, Article 209. https://doi.org/10.1007/s11069-026-08025-9

Popescu, C., & Bărbulescu, A. (2025). GIS-based accessibility analysis for emergency response in hazard-prone mountain catchments: A case study of Vărbilău, Romania. *Water*, *17*(19), Article 2803. https://doi.org/10.3390/w17192803

Postance, B., Hillier, J., Dijkstra, T., & Dixon, N. (2017). Extending natural hazard impacts: An assessment of landslide disruptions on a national road transportation network. *Environmental Research Letters*, *12*(1), Article 014010. https://doi.org/10.1088/1748-9326/aa5555

Pregnolato, M., Ford, A., & Dawson, R. (2016). Disruption and adaptation of urban transport networks from flooding. *E3S Web of Conferences*, *7*, Article 07006. https://doi.org/10.1051/e3sconf/20160707006

Pregnolato, M., Ford, A., Robson, C., Glenis, V., Barr, S., & Dawson, R. (2016). Assessing urban strategies for reducing the impacts of extreme weather on infrastructure networks. *Royal Society Open Science*, *3*(5), Article 160023. https://doi.org/10.1098/rsos.160023

Pregnolato, M., Ford, A., Wilkinson, S. M., & Dawson, R. J. (2017). The impact of flooding on road transport: A depth-disruption function. *Transportation Research Part D: Transport and Environment*, *55*, 67–81. https://doi.org/10.1016/j.trd.2017.06.020

Prignano, L., Fulminante, F., Galceran Puig, C., Candelas, P., & Cozzo, E. (2026). Roads and rivers. The importance of regional transportation networks for early urbanization in central Italy (950–500 BC). *Journal of Archaeological Science*, *161*, Article 106513. https://doi.org/10.1016/j.jas.2026.106513

Pyatkova, K., Chen, A. S., Butler, D., Vojinović, Z., & Djordjević, S. (2019). Assessing the knock-on effects of flooding on road transportation. *Journal of Environmental Management*, *244*, 48–60. https://doi.org/10.1016/j.jenvman.2019.05.013

Rahmoun, T., & Zhao, W. (2024). A New Model of a Spatial Structural Map for Re-Building Urban-Rural Links. *International Review for Spatial Planning and Sustainable Development*. https://doi.org/10.14246/irspsd.12.1_21

Reggiani, A. (2022). The architecture of connectivity: A key to network vulnerability, complexity and resilience. *Networks and Spatial Economics*, *22*(3), 415–437. https://doi.org/10.1007/s11067-022-09563-y

Rouhana, F., & Jawad, D. (2025). A spatial-network approach to assessing transportation resilience in disaster-prone urban areas. *ISPRS International Journal of Geo-Information*, *14*(7), Article 261. https://doi.org/10.3390/ijgi14070261

Seleznov, M., & Rudytsia, D. (2025). Design of Road and Transport Structures in Territorial and Regional Settlement Systems. *Municipal economy of cities*. https://doi.org/10.33042/2522-1809-2025-3-191-348-354

Shahdani, F. J., Santamaria-Ariza, M., Sousa, H. S., Coelho, M., & Matos, J. C. (2022). Assessing flood indirect impacts on road transport networks applying mesoscopic traffic modelling: The case study of Santarém, Portugal. *Applied Sciences*, *12*(6), Article 3076. https://doi.org/10.3390/app12063076

Shang, W.-L., Chen, Y., Song, C., & Ochieng, W. Y. (2020). Robustness analysis of urban road networks from topological and operational perspectives. *Mathematical Problems in Engineering*, *2020*, 1–12. https://doi.org/10.1155/2020/5875803

Small, M., & Adler, L. (2019). The Role of Space in the Formation of Social Ties. *Annual Review of Sociology*. https://doi.org/10.1146/annurev-soc-073018-022707

Tang, H. (2020). Regional Patterns and Hierarchical Tendencies: Analysis of the Network Connectivity of 63 Service-Oriented Tourist Cities in China. *Sustainability*. https://doi.org/10.3390/su12166532

Tang, J., Wu, S., Yang, S., & Shi, Y. (2024). Resilience assessment of urban road transportation in rainfall. *Remote Sensing*, *16*(17), Article 3311. https://doi.org/10.3390/rs16173311

Twumasi-Boakye, R., & Sobanjo, J. O. (2018). Resilience of regional transportation networks subjected to hazard-induced bridge damages. *Journal of Transportation Engineering, Part A: Systems*, *144*(10). https://doi.org/10.1061/JTEPBS.0000186

Utama, R. A. (2024, May 12). Akibat banjir bandang di Padang Panjang, jalur Padang-Bukittinggi masih lumpuh [Due to flash floods in Padang Panjang, Padang-Bukittinggi route remains paralyzed]. *Kompas.id*. https://www.kompas.id/artikel/en-akibat-banjir-bandang-di-padang-panjang-jalur-padang-bukittinggi-masih-lumpuh

Vodak, R., Bíl, M., & Křivánková, Z. (2018). A modified ant colony optimization algorithm to increase the speed of the road network recovery process after disasters. *International Journal of Disaster Risk Reduction*, *31*, 280–289. https://doi.org/10.1016/j.ijdrr.2018.04.004

Wang, Y., Zhan, J., Xu, X., Li, L., Chen, P., & Hansen, M. (2019). Measuring the resilience of an airport network. *Chinese Journal of Aeronautics*, *32*(12), 2694–2706. https://doi.org/10.1016/j.cja.2019.08.023

Wenxin., Lin, S., Ci, Y., & Li, R. (2024). Resilience evaluation and improvement of post-disaster multimodal transportation networks. *Transportation Research Part A: Policy and Practice*. https://doi.org/10.1016/j.tra.2024.104243

Winter, M. G., et al. (2016). The economic impact of landslides and floods on the road network. Procedia Engineering, 143, 1425–1434. https://doi.org/10.1016/j.proeng.2016.06.168

WMO. (2021). *Weather-related disasters increase over past 50 years, causing more damage but fewer deaths*. World Meteorological Organization. https://wmo.int/media/news/weather-related-disasters-increase-over-past-50-years-causing-more-damage-fewer-deaths

Xie, S., Yang, Z., Wang, M., Xu, G., & Bai, S. (2025). Evaluating the resilience of mountainous sparse road networks in high-risk geological disaster areas: A case study in Tibet, China. Applied Sciences, 15(5), 2688. https://doi.org/10.3390/app15052688

Xiong, J., & Yang, Y. (2024). Climate Change and Hydrological Extremes. *Current Climate Change Reports, 11*. https://doi.org/10.1007/s40641-024-00198-4

Xu, Z., & Chopra, S. S. (2023). Interconnectedness enhances network resilience of multimodal public transportation systems for Safe-to-Fail urban mobility. *Nature Communications*, *14*, Article 4291. https://doi.org/10.1038/s41467-023-39999-w

Yang, Y., Li, Z., Chen, Y., Zhang, X., & Wang, S. (2015). Improving the robustness of complex networks with preserving community structure. *PLOS ONE*, *10*(2), Article e0116551. https://doi.org/10.1371/journal.pone.0116551

Yang, L., Wang, X., Jiang, X., & Tatano, H. (2023). Assessing the regional economic ripple effect of flood disasters based on a spatial computable general equilibrium model considering traffic disruptions. *International Journal of Disaster Risk Science*, *14*(3), 488–505. https://doi.org/10.1007/s13753-023-00500-2

Yaşar, M., & Yiğit, M. (2025). Hydrometeorological Disasters in the Context of the Climate Crisis: A Regional Disaster Inventory Study in Türkiye. *Doğal Afetler ve Çevre Dergisi*. https://doi.org/10.21324/dacd.1559696

Zhang, L., Zuo, X., Wu, Z., Chen, C., Pan, Z., & Hu, X. (2023). The Spatial Structure and Driving Mechanisms of Multi-Source Networks in the Chengdu-Chongqing Economic Circle of China. *ISPRS Int. J. Geo Inf., 12*, 411. https://doi.org/10.3390/ijgi12100411

Zhang, X., et al. (2026). *Integrated assessments of transportation network resilience combining topological and functional performance metrics*. Transportation Engineering, 100420. https://doi.org/10.1016/j.treng.2026.100420

Zheng, S., Wang, J., Yang, X., & Lu, X. (2025). Key corridor identification in multi-objective highway networks based on feature lines. *International Journal of Industrial Engineering Computations*. https://doi.org/10.5267/j.ijiec.2025.8.008