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Article

Criticality disaster risk assessment for urban rail transport in Indonesia

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Abstract: The increasing frequency of extreme weather events due to climate change poses significant risks to urban rail systems, especially in disaster-prone regions like Indonesia. Urban railways, with limited rerouting options, are highly vulnerable to natural disasters such as floods, landslides, and earthquakes. These disruptions can cause cascading economic impacts, including infrastructure damage, productivity loss, and prolonged travel times. This study develops a methodological framework to assess disaster risk and climate vulnerability in urban rail systems, with Bandung, Indonesia, as the case study. The framework integrates Climate Vulnerability and Risk Assessment (CVRA) with the Movement and Place (M&P) framework, leveraging Geographic Information System (GIS) technology to identify and prioritize high-risk areas. CVRA evaluates hazards, exposure, and vulnerabilities, while M&P assesses the functional significance of transport nodes based on movement patterns and land use density. The combined analysis produces a risk matrix, enabling targeted mitigation strategies that integrate engineering solutions, urban planning, and policy interventions. Findings highlight critical vulnerabilities in Bandung's proposed LRT system, particularly at stations susceptible to earthquakes and landslides. Recommended mitigation measures include resilient infrastructure designs, strategic planning for high-risk zones, and stakeholder engagement for prioritization. This framework offers practical guidance for policymakers to enhance urban rail resilience, reduce climate-related risks, and ensure sustainable urban mobility. It serves as a scalable model for other cities in Indonesia and globally, supporting adaptive and sustainable transport systems.

Keywords: Movement & Place; urban rail transport; disaster; climate vulnerability; risk assessment

1. Introduction

Developing an urban railway transport infrastructure requires a massive amount of investment. Therefore, there is a need to incorporate the effect of climate change on design and operation. The data indicates the increase in the frequency and severity of extreme weather events, such as heavy rainfall and flooding. Meanwhile, the projections of annual rainfall may not significantly increase. These unpredictable natural events threaten the operational integrity of mass transit systems, particularly urban rail, which is highly susceptible to disruptions. Unlike road systems, rail networks have limited rerouting options, making them more vulnerable to prolonged operational outages during disasters. Such disruptions can have cascading economic effects, including loss of productivity, increased travel times, and costly repairs to damaged infrastructure.

Indonesia is geographically located in a ring of fire. We face significant challenges from natural disasters, such as earthquakes, floods, and landslides, which frequently disrupt our infrastructure and transportation systems, particularly urban rail transport (CFE-DMHA, 2021). Over the past two decades, Indonesia's disaster risk management framework has been developed and refined to address these hazards. Central to this framework is Law No. 24 of 2007 concerning Disaster Management, which mandates all levels of government, from national to local, to conduct disaster risk assessments as part of their planning processes. This legislation has established national and regional disaster management agencies (BNPB and BPBD) responsible for coordinating disaster risk reduction (DRR) efforts. Other relevant regulations, such as Law No. 26 of 2007 on Spatial Planning and Law No. 1 of 2011 on Housing and Settlement Areas, contribute to urban resilience by guiding land use, protecting disaster-prone areas, and incorporating disaster mitigation into spatial planning policies.

A significant gap in implementing DRR and CCA lies in data management and preparedness. Although Law No. 24 of 2007 explicitly requires accurate data collection and management as part of disaster preparedness, local governments often struggle with maintaining comprehensive disaster risk data, particularly concerning transportation infrastructure. National-level data platforms, such as BNPB's InaRISK and the Ministry of Agrarian and Spatial Planning's GISTARU, have made progress in providing up-to-date geospatial data.

A comprehensive and resilient approach to disaster risk management in urban rail transport is critical. This research aims to fill the existing regulatory and technical guidance gaps by developing a flexible methodological framework for assessing disaster risks and climate vulnerabilities in mass transit systems. The framework is designed to assist transport authorities in identifying "hotspots"—areas of critical vulnerability within the rail network—and to plan and implement engineering and non-engineering interventions to mitigate these risks.

This research seeks to provide policymakers and transport authorities with the necessary tools and frameworks to address these challenges, ensuring that urban mass transit infrastructure can withstand future disasters, thereby reducing social, economic, and environmental impacts. By improving urban rail transport systems' design, planning, and management, Indonesia can better protect its critical infrastructure and ensure more reliable and safe transportation for its urban populations.

2. Literature review

2.1. National hazards in Indonesia

Due to its complex tectonic setting and climatic conditions, Indonesia faces significant risks from various natural hazards, including earthquakes, tsunamis, volcanic eruptions, and flooding.

Earthquake hazards are exceptionally high along the Padang to Jakarta segment, Ambon, and northeast Palu, while intermediate risks are found in southeastern Yogyakarta, southwestern Bajawa, and Dili. Even in low-hazard areas such as Makassar and Praya, there remains a 10%–20% probability of experiencing earthquakes exceeding 7.0 Mw within the next 50 years (Pailoplee, 2017). These risks stem from Indonesia's position within a highly active tectonic zone where three significant plates (Eurasian, Indo-Australian, and Pacific) and one micro-plate (Philippine Plate) interact. Methods such as Probabilistic Seismic Hazard Analysis

(PSHA) are employed to assess earthquake hazards, combining earthquake catalogs and fault-line analysis to map potential risks (Susilo and Adnan, 2013).

Tsunami hazards are closely tied to seismic activity, as 90% of tsunamis in Indonesia are triggered by earthquakes (Pribadi et al., 2013). The highest tsunami risks for short return periods (100 years) are concentrated along the west coast of Sumatra, the south coast of Java, and the north coast of Papua. For more extended return periods (500–2500 years), the Sunda Arc poses the most significant threat due to its potential for high-magnitude earthquakes (Horspool et al., 2014).

Volcanic hazards are another primary concern, as Indonesia has 147 volcanoes, including 76 active stratovolcanoes, which account for 13% of the world's active volcanoes (Hariyono and S, 2018). These volcanoes exhibit diverse eruption characteristics, including lava domes, crater lakes, lethal gases, and caldera formations. Hazard assessments rely heavily on geomorphology, field studies, and event trees, as demonstrated in the studies of Sinabung, Merapi, and Semeru (Maeno et al., 2019). Local communities often use traditional wisdom to mitigate volcanic risks, adapting practices that align with specific eruption types and regional characteristics.

Flooding hazards remain one of Indonesia's most frequent and devastating natural disasters. For instance, the 2007 Jakarta floods were exacerbated by intense rainfall, with return periods of 150 to 300 years for 3-day storm events (Liu and Zipser, 2015). In the Citarum watershed, flood risks are dominated by moderate (44.15%) and high (42.25%) levels, influenced by factors such as rainfall, land use, soil infiltration, and slope (Fernandos et al., 2020). Effective flood mitigation requires updating intensity-duration-frequency (IDF) curves and utilizing rapid assessment models to identify vulnerable areas (Helmi et al., 2019).

Ina-Risk has developed national maps of disaster risks, such as earthquakes, volcanic eruptions, landslides, and floods, forming the basis for identifying vulnerable areas and planning mitigation strategies in this research.

2.2. Resilience in urban transport systems

Resilience in urban transport systems, particularly in rail networks, is essential to ensuring continuous functionality amid disruptive events such as natural disasters (Serdar et al., 2022). The concept of resilience refers to the capacity of a system to anticipate, prepare for, respond to, and recover from significant disruptions while maintaining essential operations. In this context, resilience is multi-dimensional, encompassing individual infrastructure elements, the connectivity between these elements, and their interactions with broader societal and environmental systems (World Bank Group, 2021b). Drawing from the World Bank guidelines on Disaster Risk Management in the Transport Sector (Nakat and Salim, 2015; Wu and Koh, 2023), it is crucial to understand how resilience integrates with urban transport, as each element—whether an individual railway station or the entire rail network—plays a role in enhancing or diminishing the overall system's resilience.

Urban rail transport infrastructure requires huge investments corresponding to different scales, times, and locations. Most of the metropolitan areas in Indonesia, i.e., Jakarta, Bandung, and Surabaya, are highly vulnerable to natural disasters due to the country's geographical location and climate patterns. Therefore, there is a need to incorporate the infrastructure's ability to withstand, recover from, and adapt to disasters. The transport infrastructure should have a significant resilience level for maintaining low interrupted mobility, particularly in urban areas. For instance, while the resilience of a single station could be assessed in terms of its structural integrity and ability to resume operations post-disaster, the broader resilience of the transport system includes the redundancy of routes and access points. A resilient transport system ensures access to essential services like hospitals, schools, and workplaces during emergencies, supporting economic and social mobility while minimizing disruptions.

2.3. Disaster risk management

Effective disaster risk management and climate adaptation strategies are essential to maintain urban mobility and economic productivity. Law No. 24 of 2007 on Disaster Management underscores the importance of disaster preparedness, while sector-specific guidelines are necessary for translating these frameworks into actionable measures for urban rail systems. Enhancing the resilience of transport infrastructure is about protecting physical assets and ensuring the continuity of services vital to urban populations (World Bank Group, 2015).

A structured approach to disaster risk management is necessary for urban rail systems, combining strategies such as Avoid–Mitigate–Restore–Offset (Stevenson and Weber, 2020; The World Bank, 2016). This framework helps in managing disaster risks at different stages of the infrastructure lifecycle:

- Avoiding hazards by situating rail lines in low-risk areas.
- Mitigating risks by designing resilient structures that withstand known hazards, such as floods or earthquakes.
- Restoring operations quickly after a disaster through rapid response and maintenance protocols.
- Offsetting residual risks by developing disaster preparedness and recovery plans to handle unexpected events effectively.

A significant challenge in disaster risk assessment is the inherent uncertainty associated with predicting the likelihood and impact of disasters, especially in climate change.

As climate projections remain uncertain, infrastructure designed today must account for potential future conditions that may exacerbate vulnerabilities, such as increased flooding or extreme weather events. Climate change introduces additional complexity to disaster risk management by increasing the frequency and intensity of natural disasters. For urban rail transport systems, this includes heightened risks of flooding, landslides, and extreme weather events that threaten operational continuity. In Indonesia, for instance, heavy rainfall and flooding pose significant threats to rail infrastructure, affecting the physical integrity of assets and the broader socio-economic systems reliant on these networks.

Decision-makers often face overdesigning or underdesigning infrastructure, which carries significant financial and operational risks. To mitigate this uncertainty, scenario-based analysis and Monte Carlo simulations can forecast various potential outcomes, providing more robust data for planning resilient infrastructure.

2.4. Climate vulnerability and risk assessment

Integrating climate adaptation into infrastructure planning is critical to ensuring that urban rail systems can withstand future climatic challenges. Strengthening resilience requires incorporating disaster risk reduction (DRR) and climate change adaptation (CCA) across the entire infrastructure lifecycle, from design and construction to maintenance and operation. The Climate Vulnerability and Risk Assessment (CVRA), supported by Geographic Information System (GIS) technology, provides a systematic approach to identifying and mitigating climate-related risks in urban rail systems.

CVRA evaluates transport network hazards, exposure, and vulnerabilities, prioritizing actions based on stakeholder input (World Bank Group, 2021a). The overall aim of this CVRA is to identify locations under various levels of risk in a way that aids in the targeting and prioritization of recommendations for structural and non-structural risk reduction measures. This can be applied to existing urban transport network management practices, integrating this methodology with existing asset management systems and processes and using this more locally to complete a climate audit of new transport sector investments (World Bank Group, 2021c). GIS plays a crucial role by enabling spatial analysis and visualization, allowing for more precise identification of areas within the transport network most susceptible to climate risks such as flooding, extreme weather, and rapid urbanization.

2.5. Movement and place

The 'Movement and Place' framework is derived from the 'Link and Place' approach adopted by Transport for London (2019), and is currently used in Victoria State in Australia to support transport network planning (Victoria State Government, 2019). The research employs the Movement and Place scoring method to evaluate risks within specific zones. This method analyzes movement patterns (e.g., the flow of people and goods) and the functional importance of particular locations (such as rail stations or corridors). By assessing these factors, high-risk areas within the transport network can be identified, essential for targeted risk management and mitigation efforts (Austroads, 2020).

By embedding these considerations into routine decision-making processes, Indonesia can enhance the resilience of its urban transport systems and mitigate the social and economic impacts of future disasters.

3. Methods

This study applies the CVRA approach to Bandung, chosen as the case study for this research due to its status as a growing urban center with an expanding rail transport system, exemplified by the planned LRT in Bandung City, as shown in **Figure 1**. Despite its development, Bandung faces notable climate vulnerabilities, including frequent flooding and other extreme weather events exacerbated by rapid urbanization.

These factors make it an ideal site for applying the CVRA and Movement and Place scoring methods.

This study utilizes various sets of data, including climatic data, urban transport data, and socio-economic data, all collected from multiple sources. The climatic data is obtained from the official government platform, Ina-Risk, which provides national maps of disaster risks, such as earthquakes, volcanic eruptions, landslides, and floods. The urban transport data is sourced from The Spatial Data Plan of the Mayor of Bandung City (2011–2031), while the socio-economic data is gathered from the official website of Badan Pusat Statistik Indonesia.

The GIS-based approach starts with collecting and preparing spatial data using ArcGIS Pro, including shapefiles, GeoJSON files, or raster data from InaRisk and transportation authorities. The data is analyzed with tools like overlay analysis to identify overlaps, such as flood-prone areas intersecting transport networks, while spatial join and buffering assess proximity to critical infrastructure. Maps are then created to visualize risk levels using symbology and heat maps, with tools like ArcGIS Pro also supporting analysis of elevation-based hazards like landslides. Multi-criteria decision analysis (MCDA) can further prioritize vulnerable locations through hierarchical layers. This approach highlights risks, supports evidence-based decisions, and aids in effective risk mitigation and urban planning.

The framework proposed in this study is not only versatile but also generalizable to different geographical and climatic conditions. Its design, which combines Climate Risk Vulnerability Assessment (CVRA) and Urban Transport Zone Scoring (Movement & Place), makes it adaptable to various contexts beyond rail-based systems. This flexibility allows the framework to be applied in diverse regions and cities with unique challenges and priorities.

Regarding the calculation methods for different types of disasters, the framework employs a uniform approach to integrate multiple hazards, but it also allows for hazard-specific adaptations when necessary. For instance, while the CVRA provides a standardized methodology for assessing risks, the parameters and indicators used can be tailored to address the unique characteristics of each hazard—whether it is flooding, landslides, earthquakes, or others. This ensures that the assessments remain relevant and precise for the specific context and type of disaster.

The adaptability of the framework is further supported by its demonstrated applications in diverse contexts. For example, Pregnolato et al. (2017) introduced a methodology to evaluate the costs of transport disruptions and the benefits of adaptation measures under current and future climate scenarios, illustrating its utility in mitigating climate risks. Similarly, Walker et al. (2011) utilized a GIS-based approach to identify vulnerabilities in transport systems, demonstrating the potential of spatial analysis tools to enhance decision-making and urban planning. In another example, Dvorak et al. (2020) explored a comprehensive evaluation method for environmental risks in the Czech Republic, showcasing the ability to address diverse hazards effectively.

Another research also demonstrates aligning approaches. Kagramanian et al. (2023) emphasize the importance of robust assessment tools for analyzing the criticality of transport networks under disaster conditions, which aligns with this study's focus on disaster risk assessment for Indonesia's urban rail systems and the need to identify critical nodes and links. Similarly, Bulková et al. (2024) highlight the use of GIS-based tools for risk assessment, showcasing the value of spatial visualization in identifying vulnerable areas. Building on these approaches, this study integrates GIS techniques to assess risks and provides targeted recommendations for enhancing the resilience of Indonesia's urban rail infrastructure.

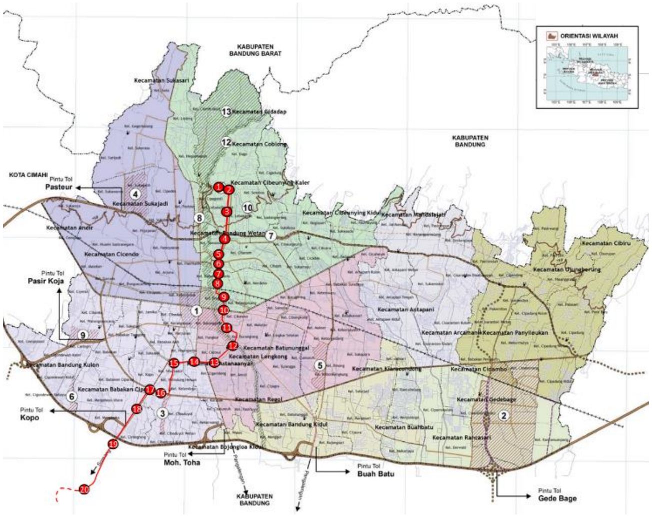


Figure 1. Planned route map for Bandung city LRT.

3.1. CVRA method: Step by step

The research framework begins with data collection, encompassing diverse sources such as climate data (temperature fluctuations, precipitation levels), urban transport data (passenger volume, infrastructure details), and socio-economic data (population density, land use). This data forms the foundation for analysis and is processed through GIS to create spatial visualizations. GIS technology allows researchers to identify key vulnerable areas within the rail network, highlighting zones susceptible to climate hazards like flooding or extreme weather conditions (Goodchild and Haining, 2004).

Following the GIS-based mapping, the CVRA method is applied to assess the vulnerability of the rail infrastructure to climate hazards. This involves evaluating factors such as the exposure of different parts of the rail network to risks like heatwaves or floods, the sensitivity of the infrastructure (e.g., age, maintenance), and the system's adaptive capacity to recover from climate-induced damage. This assessment helps prioritize areas that require immediate attention based on their vulnerability to disruptions.

Once the vulnerability analysis is completed, the Movement and Place scoring method is introduced to focus on risk evaluation within specific zones. This method assesses the movement patterns of passengers and goods through these zones and the significance of each location within the broader network (Diemer et al., 2018). Zones with high passenger flow or strategic importance, such as key stations, are identified as high-risk areas. The summary of CVRA process could be seen in Figure 2.

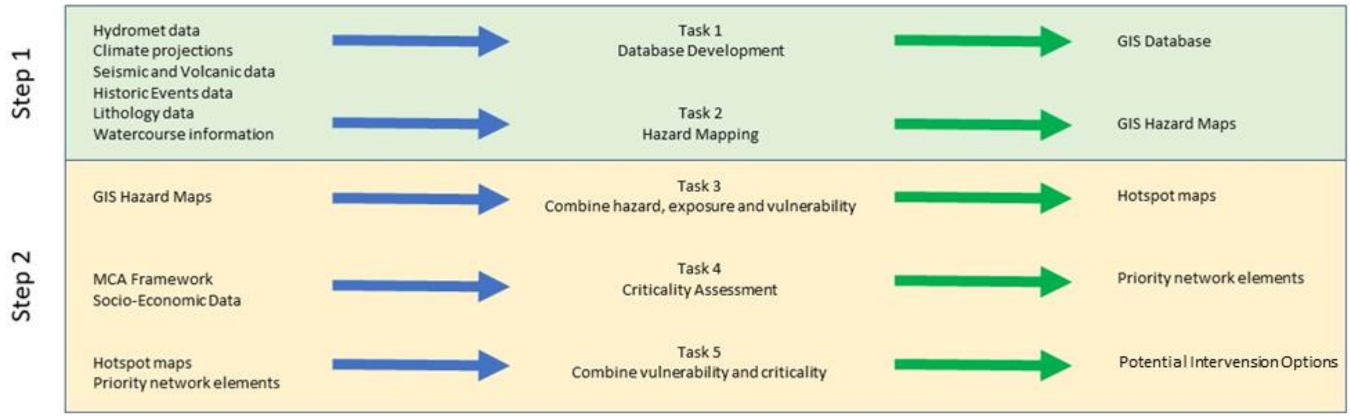


Figure 2. Summary of CVRA process.

3.2. Movement and place: Criteria and scoring

The Movement Score and Place Score are determined using criteria adapted from Austroads standards (Austroads, 2020), but we adjusted and simplified it into three groups based on Indonesia's regional autonomy framework: national and provincial levels, regional and city levels, and local or district levels. This simplification accounts for the varying complexities in transport planning and governance across different administrative tiers. The Movement Score is calculated using three key variables, as shown in **Table 1** and classified into M1, M2, and M3 categories, as outlined in **Table 2**.

Similarly, the Place Score evaluates population factors, demographics, and regional spatial development, as detailed in **Table 3**. The combination of Movement and Place Scores is visualized in **Figure 3**, which illustrates **criticality levels** for various areas based on the intersection of Movement (M1, M2, M3) and Place (P1, P2, P3) scores. High criticality zones (**red**) indicate areas requiring immediate attention and priority action, while moderate (**yellow**) and low (**green**) criticality zones guide resource allocation to mitigate risks effectively. This classification clearly focuses on prioritizing mitigation efforts in areas with the highest potential impact on transport operations and infrastructure resilience.

Table 1. Movement functions and score for urban railway.

Movement Function	**Score**		
	3	**2**	**1**
Strategic role in the mass transit network	Main Inter-city and regional station e.g. Bandung Station Hall	Municipal/regency capital station or other principal station e.g. Padalarang stations	District or Local station e.g. Rancaekek station
Service Diversity	Multi modal interchange	Limited interchange facilities	No interchange facilities
Usage/Patronage (a measure of the scale of passenger use)	High Train Headway < 15 min during peak hours	Medium Train Headway of 15–30 min during peak hours	Low Headway > 30 min usually for regional train during peak hours

Table 2. Definition of movement and its classification.

Movement Classification	Definition	Lower Boundary	Upper Boundary
M1	High or significant movement of people on intercity or regional routes, facilitating multi-modal exchange / intersections.	7	9
M2	Moderate movement of people on routes connecting several municipalities, and exchanges between different services of the same mode.	5	6
M3	Local movement without interchanges/exchanges of modes.	3	4

Table 3. Definition of place and its classification.

Place Classification	Definition	Note
P1	Highly important areas	National/provincial/municipal level government office building National/provincial/municipal level hospital National/provincial/municipal level military and police headquarter building Central business district Main District with population greater than 150,000 inhabitants within 700 m radius from the station
P2	Important areas with high-density land use	University or public schools Dense residential areas Municipal or lower level hospital Mosques, churches, and other worship building District with population between 50,000 and 150,000 inhabitants within 700 m radius from the station
P3	Semi-urban areas, with low-density land use	Scattered residential areas Agriculture mix residential areas District with population less than 50,000 inhabitants

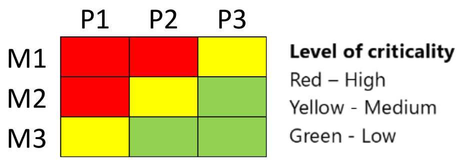


Figure 3. Level of criticality.

3.3. Risk calculation

After identifying the scores for exposure, criticality, and vulnerability of each network element, the three analyses are combined and mapped using GIS to identify the highest-risk sections or parts of the mass transit systems exposed to natural disasters and climate hazards. Risk calculation is necessary, and the result of this process will yield up to four priority lists, showing the priorities for mitigation. It is important to note that the three aspects should be combined using a simple formula, as shown in Equation (1). The equation for defining risk score is illustrated in Equation (1).

$$\text{Risk Score } i = \sum_{i=1}^{n} MP_n \; x \; (\sum_{j=1}^{3} E_{ij}) \tag{1}$$

where MP_n is the Movement and Place/Criticality Score for each station i; E_{ij} is the Exposure Score for each station i for every type of disaster j. i refers to each station; and j refers to a type of disasters, namely Landslides, Earthquakes, and Floods. The

Criticality and Exposure scores are assigned as follows: 1 for Low, 2 for Medium, and 3 for High.

The risk score will be between 1 and 27. These can be graded against the scale described below, as follows:

- A score of 27 represents very high risk, which requires very high priority of mitigation measures;
- A score between 18 and 27 represents high risk, which requires high priority of mitigation measures;
- A score between 10 and 19 represents medium risk, which requires medium priority of mitigation measures;
- A score of below 11 represents low risk, which requires low priority of mitigation measures.

This combination of aspects is shown in **Figure 4**, noting that the aim should always be to identify the elements that would lie in the bottom right-hand corner of this matrix.

Exposure \ Criticality	Low	Medium	High
Low	L	L	M
Medium	L	M	H
High	M	H	VH

Risk Score:
Red – Very High
Orange – High
Yellow – Medium
Green – Low

Figure 4. Combining exposure and criticality.

The final step in the framework is the development of risk mitigation strategies. Insights from the CVRA and Movement and Place scoring methods guide this phase, recommending solutions like infrastructure reinforcements, enhanced urban planning, or new policies to mitigate identified risks. These strategies are tailored to the specific vulnerabilities in the rail transport system to ensure that high-risk zones are addressed effectively. This approach ensures that areas vulnerable to climate impacts are identified and managed through evidence-based strategies. The detailed methodology is visualized in **Figure 5**, which outlines the process of vulnerability identification, risk assessment, and the development of mitigation strategies for Bandung's urban rail transport system.

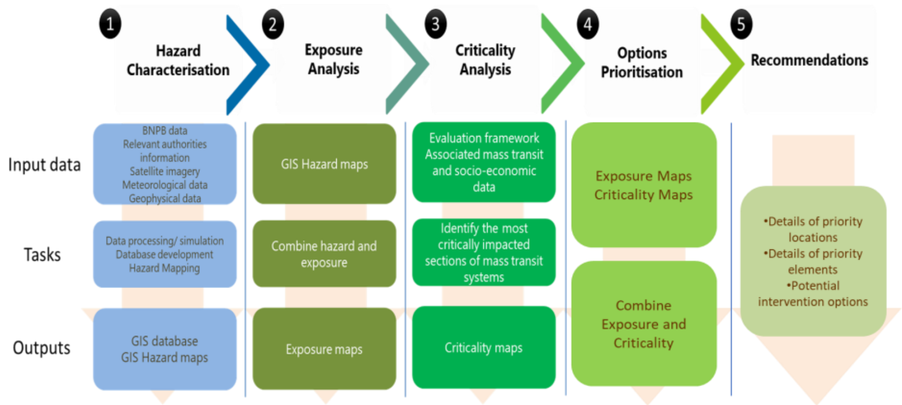


Figure 5. The process to mainstream resilience in mass transit system: Introduction to resilient mobility assessment and prioritization.

4. Discussion

It's important to include risk assessments in all stages to improve resilience in mass transit systems, from planning to maintenance. It involves looking at factors like hazard exposure, system weaknesses, disaster prevention designs, technology, and costs. Resilience should be assessed at three levels: examining network-wide infrastructure (like communication and power supply), evaluating operational elements (such as tracks and stations) for redundancy, and identifying vulnerable parts of the network (like tracks that need to be raised). This section offers a straightforward guide for government agencies and stakeholders to analyze hazards, assess how transit systems might be affected, pinpoint the most impacted areas, and prioritize actions to enhance resilience.

4.1. Exposure analysis

Spatial analysis plays a critical role in evaluating the exposure of mass transit systems to natural disasters and climate change, helping to identify vulnerabilities that may lead to asset damage or service disruptions. This analysis assesses how transit infrastructure and operations are exposed to various hazards, emphasizing preparedness and rapid recovery. The process begins with identifying potential hazards using tools like exposure checklists, which aid in pinpointing at-risk assets and services. While these preliminary assessments are not a substitute for comprehensive analyses, they serve as a foundation for discussions on resilience, guiding necessary actions, and fostering stakeholder collaboration.

Exposure analysis involves mapping hazards, overlaying transit assets against them, and assigning vulnerability scores based on each hazard's distinct impact across locations. In the context of the Greater Bandung LRT system, this analysis evaluates hazards such as volcanic eruptions, landslides, earthquakes, and floods, providing a range of exposure scores from low to high, as summarized in **Table 4**. While the elevated design of the Bandung LRT reduces flood exposure risks for stations like Kopo Sayati, Margahayu, and Karapitan, the accessibility and entrance points of these stations remain critical considerations. For instance, stations like Babakan Siliwangi demonstrate high earthquake exposure but lower exposure to other hazards, underscoring the need for tailored mitigation strategies for each hazard type.

Table 4. Four levels of investment priority.

Risk Calculation		Risk Priority Level	Risk Intervention	
Score	scale			
27	Very High Risk	Very High Priority	Essential Investment Plan	Should be implemented as a part of basic design of network
19–26	High Risk	High Priority	High Priority Plan	Should be implemented as soon as funding available
11–18	Medium Risk	Medium Priority	Extended Plan	Should be implemented, depending upon BCR, as soon as funding is available
3–10	Low Risk	Low Priority	Back Up Plan	Viable interventions, implemented only if funding becomes available

4.2. Movement and place/criticality analysis

The Movement & Place Analysis framework will help guide and classify the function consideration of the mass transit system. The M&P framework is not prescriptive. However, it enables meaningful engagement between government agencies to determine the strategic role of mass transit networks, both in the movement of people and serving as a place (a destination in its own right).

Movement classifications communicate the broad movement function of a mass transit system about its place function. The classification of M1 to M3 is determined by calculating a total score from three movement functions: 1) the station's strategic role in the network; 2) service diversity; and 3) usage, as described in **Tables 1** and **2**.

Based on the analysis results, four LRT stations are classified under category M1. The station with the highest movement score is Dago Station, with a score of 8, while the other three stations—Leuwipanjang, Kopo I, and Terminal Soreang—have a score of 7. In category M2, there are 15 stations, with Kopo II Station scoring six and the remaining 14 stations scoring 5. Meanwhile, category M3 includes seven stations with a movement score of 4.

Place categories are defined to identify three types of places according to their significance to the city or region and the density of land use surrounding the station, as described in **Table 3**. The Place Score is defined based on the station's population and location. For example, the stations from Babakan Siliwangi to Teuku Umar are situated in the Coblong District, which has a population of 116,575. This figure falls within the range of 50,000 to 150,000 residents, thus classifying the stations in the Coblong District as P2 category stations. A similar analysis was conducted for the stations from Sultan Agung to Braga, located in the Bandung Wetan District, which has a population of 37,970 residents, resulting in their classification as P3 category stations. Meanwhile, the stations from Jarak Harupat to Tugu Strawberry, located in the Katapang District with a population of 154,320 residents, are classified as P1 category stations. **Table 4** summarizes the Movement and Place score and total criticality of each LRT Station in Greater Bandung.

4.3. Risk calculation: Result

Vulnerability of each network element, the above three analyses are combined and mapped, using the GIS, to identify the highest risk sections or parts of the mass transit systems exposed to natural disaster and climate hazards. Given the diversity of hazards and how these affect different cities, it is recommended that separate indices be produced for each hazard–flooding, landslides, volcanoes and earthquakes. Using this method, the result of the process will be up to four priority lists, showing the priorities for flooding mitigation, landslide mitigation etc.

Figure 4 illustrate how to overlay the criticality and exposure against each hazard type. These calculations are completed within the GIS, utilizing data from mass transit networks, land use, and socio-economic data sets. **Table 4** depicts the risk assessment framework for intervention prioritization within a transport network. Risk levels are calculated based on various criteria explained in Equation (1), such as exposure, movement, and place/criticality. Each combination of these factors results in a risk score, determining the priority level for mitigation measures. In this way, interventions will be ranked into one of four categories (see section 3.3 Risk Calculation):

- Very high priority **(score: 27)**—effectively, are so crucial to the integrity of the network that they should be considered essential. It is recommended that, whilst value engineering should be undertaken on intervention measures, these measures do not need to be subject to cost-benefit analysis;
- High priority **(score: 19–26)**—these interventions are in areas with high or medium exposure and high or medium criticality. These interventions should be prioritized for further engineering and economic studies;
- Medium priority **(score: 11–18)**—in areas where either exposure or criticality are high or where both exposure and criticality are medium, these interventions should be considered for inclusion in maintenance programs or should be part of longer-term engineering and economic studies;
- Low priority **(score: 3–10)**—these interventions are in areas where either exposure or criticality is medium, with the other being low, or where both are low. These interventions should be held in reserve for future consideration.

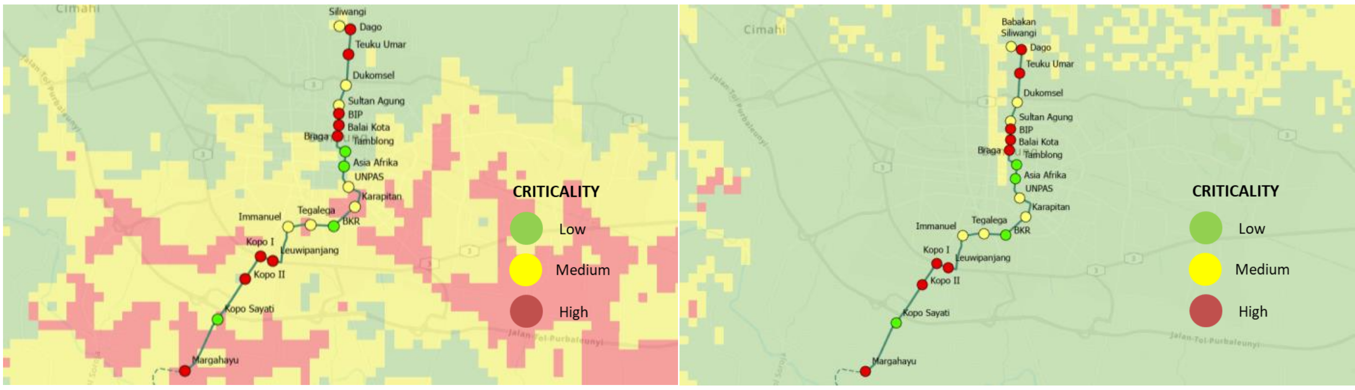
Table 4 presents four categories for prioritizing investment interventions based on risk levels: **Essential Investment Plan**, **High Priority Plan**, **Extended Plan**, and **Backup Plan**. These categories are tied to risk scores, with higher scores indicating more urgent needs. **Very High Risk (score 27)** requires immediate action as part of the network’s basic design. **High Risk (scores 19–26)** should be addressed as soon as funding is available. **Medium Risk (scores 11–18)** interventions depend on funding and the Benefit-Cost Ratio (BCR). Lastly, **Low Risk (scores 3–10)** measures are optional and implemented only if funding becomes available. This framework helps decision-makers allocate resources efficiently, focusing on the most critical areas first.

Table 5 shows that the assessed risks fall into medium and low categories. A risk score ranging from 10 to 19 represents a medium risk, necessitating a medium priority for mitigation measures. This means interventions for these risks should be included in maintenance programs or considered in long-term engineering and economic studies. On the other hand, a score below 11 indicates low risk, requiring low priority for mitigation measures. These interventions can be held in reserve for future consideration unless conditions change or additional factors arise that elevate their priority. **Figures 6 and 7** shows the criticality and exposure level against flooding, landslide, earthquake, and volcanic eruption along the planned route of Bandung City LRT.

Table 5. Exposure analysis, criticality analysis, and risk calculation for each LRT station in greater Bandung.

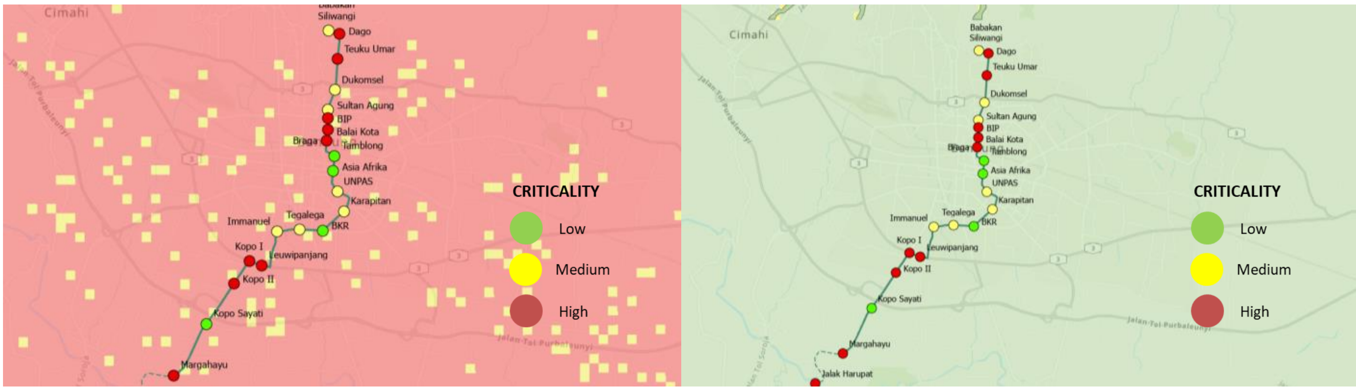
Station Name	Exposure				Movement & Place - Criticality				Risk Calculation	
	Volcanic Eruption	Landslide	Earthquake	Flood	Movement Score	District	Place Score	Total Criticality		
Babakan Siliwangi	None	Medium	High	Medium	M2	Coblong	P2	Medium	14	Medium Risk
Dago	None	Low	High	None	M1	Coblong	P2	High	12	Medium Risk
Teuku Umar	None	Low	High	Low	M2	Coblong	P2	Medium	10	Low Risk

Dukomsel	None	Low	High	Low	M3	Bandung Wetan	P3	Low	5	Low Risk
Sultan Agung	None	Low	High	Low	M3	Bandung Wetan	P3	Low	5	Low Risk
BIP	None	Low	High	Low	M2	Bandung Wetan	P3	Low	5	Low Risk
Balai Kota	None	Low	High	Low	M2	Sumur Bandung	P3	Low	5	Low Risk
Braga	None	Low	High	Low	M2	Sumur Bandung	P3	Low	5	Low Risk
UNPAS	None	Low	High	Medium	M2	Lengkong	P2	Medium	12	Medium Risk
BKR	None	Low	High	Medium	M3	Regol	P2	Low	6	Low Risk
Tegalega	None	Low	High	Medium	M2	Regol	P2	Medium	12	Medium Risk
Immanuel	None	Low	High	Medium	M2	Bojongloa Kidul	P2	Medium	12	Medium Risk
Leuwi-panjang	None	Low	High	Medium	M1	Bojongloa Kidul	P2	High	18	Medium Risk
Kopo I	None	Low	High	Medium	M1	Bojongloa Kidul	P2	High	18	Medium Risk
Kopo II	None	Low	High	Medium	M2	Babakan Ciparay	P2	Medium	12	Medium Risk
Kopo Sayati	None	Low	High	High	M3	Margahayu	P3	Low	7	Low Risk
Margahayu	None	Low	High	High	M2	Margahayu	P3	Low	7	Low Risk
Jalak Harupat	None	Low	High	Medium	M2	Katapang	P1	High	18	Medium Risk
Katapang	None	Low	High	Medium	M3	Katapang	P1	Medium	12	Medium Risk
Citaliktik	None	Low	High	Medium	M2	Katapang	P1	High	18	Medium Risk
Tugu Strawberry	None	Low	High	Medium	M3	Katapang	P1	Medium	12	Medium Risk
Tamblong	None	Low	High	Low	M3	Sumur Bandung	P3	Low	5	Low Risk
Asia Afrika	None	Low	High	Low	M2	Sumur Bandung	P3	Low	5	Low Risk
Karapitan	None	Low	High	High	M2	Regol	P2	Medium	14	Medium Risk
Kantor DPD Soreang	None	Low	High	Low	M2	Soreang	P2	High	10	Low Risk
Terminal Soreang	None	Low	Medium	Low	M1	Soreang	P2	High	12	Medium Risk



(**a**) (**b**)

Figure 6. Criticality and exposure against flooding **(a)** landslide; **(b)** hazards in Greater Bandung.



(**a**) (**b**)

Figure 7. Criticality and exposure against earthquake **(a)** volcanic eruption; **(b)** hazards in Greater Bandung.

5. Conclusion

Incorporating disaster risk management and climate resilience into urban rail systems is crucial for protecting infrastructure and ensuring reliable mobility in disaster-prone areas like Indonesia. This research highlights the growing vulnerabilities of mass transit systems to climate change and natural hazards, emphasizing the need for proactive measures. The Climate Vulnerability and Risk Assessment (CVRA) and Movement and Place (M&P) frameworks provide a structured approach to identify high-risk areas and prioritize risk mitigation strategies.

The risk analysis for Bandung’s transportation system reveals that earthquakes pose the highest threat, with 25 out of 26 stations classified under high risk. Floods rank as the second most significant hazard, affecting three stations at high risk, 12 at medium risk, and the rest at low risk. Landslides, while generally low risk, have one exception at Babakan Siliwangi station, which is categorized as medium risk. From the Movement and Place (M&P) perspective, seven stations hold high M&P scores, highlighting their strategic importance regarding location and activity levels.

The risk calculation identifies a maximum score of 18, marking the upper limit of medium risk and just below high risk (19). Notably, this score appears in stations with high M&P values, emphasizing the need for focused mitigation efforts to prevent escalation into high risk. For earthquake-prone stations, immediate actions such as implementing earthquake-resistant construction standards and early warning systems are crucial. Improving drainage systems, establishing clear evacuation routes, and enforcing flood management protocols are necessary for flood-prone stations.

By applying these methods in a case study of the Bandung LRT system, the research demonstrates how spatial analysis (Movement and Place) and disaster risk assessments can effectively address vulnerabilities of the transport system (rail network and station levels). The integration of GIS technology further enhances the precision of risk mapping, allowing for a comprehensive evaluation of exposure, criticality, and sensitivity to various hazards. The findings underscore the necessity of balancing technical, economic, and social considerations to ensure that urban rail systems are resilient to disasters and capable of sustaining urban mobility and productivity.

High M&P stations should be prioritized in mitigation plans to protect critical transport operations and user safety. A proactive risk management approach is key to minimizing disruptions and ensuring resilience. The findings offer valuable guidance for policymakers and transport authorities to design and manage rail infrastructure that can withstand future challenges, helping Indonesia protect urban transport systems, reduce socio-economic impacts, and ensure safe and reliable public transportation for its growing population.

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