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GIS-Based exposure assessment of primary roads and bridges to flood and landslide hazards in Central Java, Indonesia

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Abstract
The continuity of road transportation services is always threatened by flash flood and landslide in Central Java Province that is always exposed to disaster. This study proposes a province-wide GIS-based assessment to determine the most vulnerable road sections and bridges to these hazards. Road and bridge inventories were overlaid on the official BNPB hazard maps by using ArcGIS, and exposure levels were quantified by the length of the road segments and the number of bridges crossing the low-, medium-, and high-hazard areas. The definition of hazard used in this study is the spatial potential of occurrence, not to be understood as a measure of risk of network vulnerability. The results indicate that flash flood exposure is not limited to lowland corridors, but is also prevalent in upland corridors, and that there are significant exposures along riverine systems. In contrast, landslide exposure is more spatially concentrated along upland corridors associated with steep terrain. There are several corridors that are identified as multi-hazard hotspots, such as Karang Pucung – Wangon, Bumiayu – Salem and Kutoarjo – Bruno – Wonosobo. Overall, this study offers explicit spatial information regarding exposure to hazards of the primary road network, which can serve as a basis for prioritization of mitigation, monitoring, and further connectivity-based hazard vulnerability analysis.

Introduction

Regional infrastructure, such as roads and bridges, is an important factor for socioeconomic activities, mobility and disaster response. Road transportation systems are highly exposed to natural hazards, especially floods and landslides in Indonesia where complex geophysical and hydro-meteorological conditions are always present, which significantly affects the continuity of road transportation systems. These hazards are well known to be significant sources of disruption to transportation systems and to regional accessibility and emergency response capacity (e.g., Pyatkova et al. 2019; Koks et al. 2019; Chen et al. 2015).

Central Java Province is a context that is highly relevant to study these challenges. According to the National Disaster Management Agency (BNPB), the province recorded more than 8,300 disaster events between 2010 and 2024—the highest among all provinces in Indonesia. Further data from the Central Statistics Agency (BPS, 2024) show that floods and landslides make up about 51% of the total disasters. The variety of the topography of the province from coastal lowlands along the Java Sea to steep

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mountainous regions influenced by volcanic systems like Slamet, Sindoro, Sumbing, and Merapi–Merbau, leads to the existence of spatial variations in hazard conditions on the road network.

A number of previous studies have examined flood and landslide hazards in Central Java; however, these studies are typically limited to specific regions or hazard types. The studies conducted by Handayani et al. (2017, 2020) and Hermawan et al. (2023) for instance, examined the coastal flooding and land subsidence potential in the northern coastal cities and the flood and landslide potential in Semarang city, respectively. Landslide prone areas have also been identified in upland areas, such as Banjarnegara and Kebumen (Hadmoko et al., 2017; Isnaini, 2019; Zamroni et al., 2020). These studies offer important information on hazard characteristics, but are typically limited in geographic extent and do not explicitly quantify the provincial scale intersection of hazards with the main road network.

BNPB also generates province-level hazard maps regularly, using multi-criteria GIS-based assessments (e.g. BNPB 2015, 2021). Although these datasets are available, they are not often combined with detailed inventories of roads and bridges to enable infrastructure agencies to determine which specific segments and structures are vulnerable, and how. This leaves a disconnect between hazard information and its use in infrastructure planning, asset management and disaster preparedness.

In this context, exposure assessment is an analytical step of importance. It does not directly indicate risk or vulnerability of the network, but it indicates the spatial conditions in which this vulnerability may arise. Exposure analysis is a systematic process of connecting hazard layers with infrastructure networks to establish a baseline for determining critical locations that could need further evaluation regarding functionality, connectivity and resilience.

Given the strategic importance of the primary road network—as defined by the Indonesian Roads Law (2004), which connects major activity centers and supports regional mobility—this study focuses on national and provincial primary roads and bridges in Central Java Province. The analysis is conducted for the whole of the province, encompassing both northern lowland and southern upland areas to ensure that the different geomorphological conditions are covered.

Recent developments in GIS-based approaches have demonstrated the potential of integrating hazard information with transportation networks to support infrastructure risk analysis (e.g., Toma-Danila et al. 2020). But this type of integration is still not common in many regional settings, such as Indonesia, where hazard maps and infrastructure inventories are available, but are not systematically integrated. Based on these factors, there is a need for a systematic method that quantifies infrastructure exposure to spatial hazard information.

This study aims to achieve three major objectives: (1) estimate exposure of primary road segments and bridges to flood and landslide hazards at the provincial scale; (2) identify spatial hotspots of single and multi hazard exposure; and (3) provide a foundation for a connectivity-based vulnerability analysis of road networks. For these purposes, a GIS based spatial overlay approach is used to combine official hazard maps with road and bridge data. Results provide a systematic overview of where exposure is highest and provide an empirical foundation for infrastructure planning, prioritization and further analytical development.

Method

Study Area

Central Java Province is situated in the central region of Java Island (Figure 1) with a total area of 32,548 km² and is divided into 29 regencies and 6 cities. The province has a population of over 36 million people and a very varied topography ranging from the lowlands of the coast of the Java Sea to the highlands of the volcanic mountain systems of Mount Slamet, Mount Sindoro, Mount Sumbing and the Merapi–Merbabu complex.

The main road network in Central Java consists of national and provincial roads as arterial and collector roads that connect the main activity centers. The data from the Ministry of Public Works and Housing (MoPWH, 2022, 2023) and the Provincial Government of Central Java (2022, 2023) show that the network consists of around 1581 km of national roads and 2440 km of provincial roads. These roads represent the backbone of regional mobility and logistics.

Bridges are also a part of critical infrastructure in the network, in addition to road segments There are 858 national bridges and 2,078 provincial bridges in Central Java. Bridge location, structure and overall condition classification data were retrieved from official Bridge Management System (BMS) data from MoPWH (2023).

The analysis covers the entire province, including both northern lowland regions and southern upland areas. Lower-order road classes (e.g., primary local and sub-local roads) were excluded from the analysis due to their limited role in regional connectivity and to maintain consistency with the intended province-scale screening approach.

Hazard Data

The flood hazard data in this study is specifically for areas that are vulnerable to flash floods (banjir bandang) based on BNPB InaRISK platform. Flash floods have short warning times, high velocities, and high erosion potential and are especially significant for road and bridge structures located along river corridors and sloping terrain. The hazard layers classify exposure into three levels—low, medium, and high—based on multi-criteria analyses integrating rainfall, topography, land use, soil conditions, and historical disaster records (BNPB, 2021).

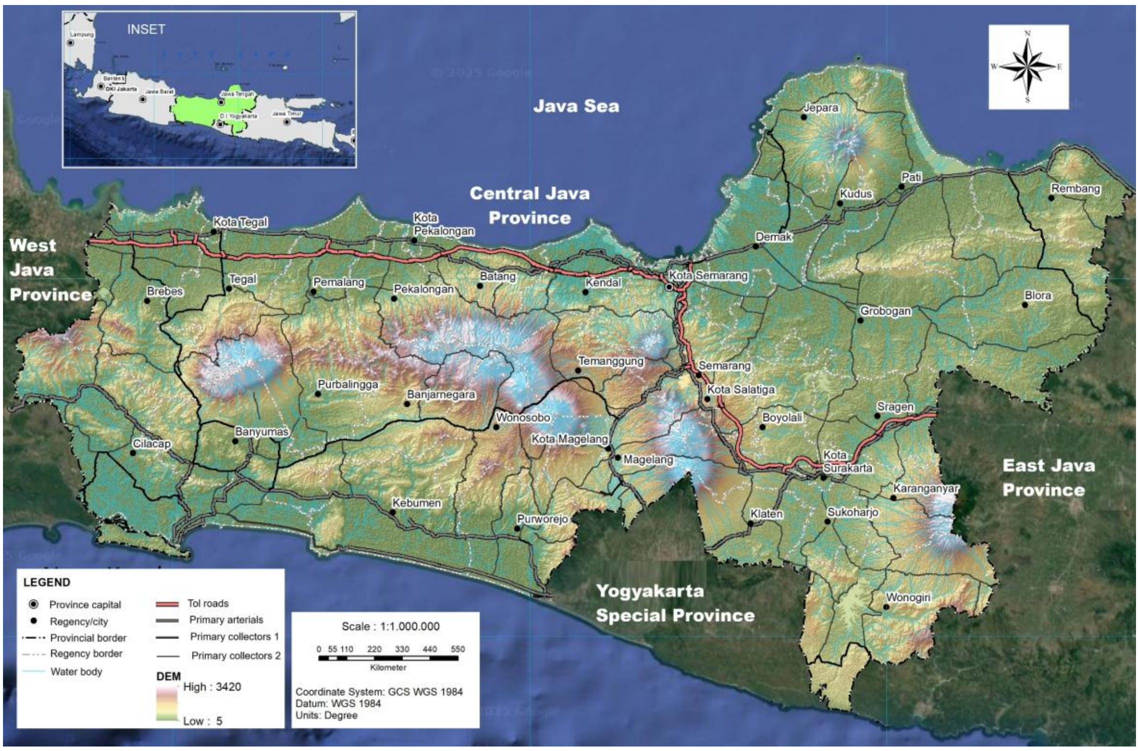

Figure 1. A map of Central Java Province showing its primary road network and geographical settings

GIS Preprocessing

Spatial preprocessing was performed in ArcGIS software (ESRI). All datasets were projected to the UTM Zone 49S coordinate system for spatial consistency. The following pre-processing steps were taken: Topology verification to ensure continuity of road polylines and to eliminate digitizing errors; Segmentation of road polylines into smaller segments to improve the overlay accuracy; Buffering of road centerline (5–10 m) to represent the physical road corridor to capture intersecting hazard zones; Snapping of bridge point locations to corrected road centerlines to ensure alignment during spatial analysis.

Exposure Analysis Procedure

A spatial overlay technique using GIS was used to estimate exposure of road segments and bridges to flood and landslide hazards. The analysis was performed on a per-hazard basis, to maintain the hazard-specific characteristics and to prevent aggregation bias.

Table 1. Procedure for exposure analysis

Step No.	Procedure	Remarks
1	Raster-to-vector sampling	Assignment of a hazard class to each road segment and bridge point by sampling the underlying hazard raster
2	Length-based exposure calculation (roads)	Calculation of total length of road within each hazard class through line-raster intersection
3	Count-based exposure calculation (bridges)	Determination of number of bridges intersecting each hazard class
4	Multi-hazard overlay	Identification of multi-hazard hotspot along road sections by combining both exposure layers

A non-weighted classification approach was used. This was done deliberately to maintain the original hazard classification given by BNPB and to not add subjective weighting assumptions. Exposure is then understood according to the spatial overlap between the extent of infrastructure and hazard zones, and especially in the medium and high hazard categories.

Table 1 outlines the analysis procedure, which involved four steps: (1) assigning hazard class to each road segment and bridge point using a raster sampling approach; (2) calculating the length of exposed road in each hazard class; (3) counting the number of bridges crossing each hazard class; and (4) identifying the multi-hazard exposure by overlaying the flood and landslide layers.

Identification of Hazard Hotspots

Hazard hotspots were identified based on cumulative exposure characteristics rather than individual hazard intensity alone. Road corridors were ranked according to the following criteria: total length of road segments intersecting hazard zones; concentration of exposure within medium- and high-hazard classes; presence of multi-hazard overlap; and spatial continuity of exposed segments.

This approach allows the identification of corridors where exposure is both extensive and spatially concentrated. It is important to note that this prioritization is indicative rather than prescriptive, as the analysis does not account for traffic volume, structural condition, or functional importance beyond network classification.

Uncertainty and Limitations

The hazard datasets used in this study are derived from province-scale models and are therefore subject to spatial resolution and classification uncertainties. While suitable for screening-level assessment, the boundaries between hazard classes may not fully capture local-scale variability.

In addition, the overlay process introduces potential alignment uncertainties between raster hazard layers and vector-based infrastructure data. The use of buffering and preprocessing steps helps reduce this effect but does not eliminate it entirely. These limitations do not invalidate the results; however, they imply that exposure values should be interpreted as indicative measures suitable for macro-level analysis rather than precise site-specific assessments.

Results

The findings of this study show that there are differences in exposure patterns at each hazard type and infrastructure type in the primary road network in Central Java Province. Flash flood exposure is identified to be more spatially widespread and highly correlated with high intensity hazard conditions, especially for bridge structures, when all the above are considered together. By contrast, landslide exposure is more spatially concentrated along upland corridors with a high proportion of road segments falling within the high hazard category, whereas the exposure of bridges to landslides is largely in the low to medium hazard category.

The differences suggest that hazard type and infrastructure characteristics combine to create varying spatial distributions and intensities of exposure, which in turn create varying spatial patterns across the network.

Flash flood Hazard Exposure on Primary Road Network

The flash flood hazard zones in Central Java Province are intersected by primary road segments which have a wide spatial distribution (Figure 2). The exposure is not only in coastal and lowland areas, but also along several upland corridors, which are the spatial characteristics of flash flooding processes in different terrain conditions.

The results indicate that flash flood exposure is both extensive and intensity-driven. Many of the most affected corridors are dominated by medium- to high-hazard classes, with the high-hazard category constituting a substantial proportion of the total exposed length. For example, the corridor Simpang Tiga Pejagan–Kanci–Ketanggungan–Tegal/Brebes exhibits approximately 7.53 km of exposed segments, of which nearly 80% fall within the high-hazard category. Similar patterns are observed in corridors such as Jepara–Keling and Karang Pucung–Wangon, where more than half of the exposure is associated with high hazard levels.

Table 2 summarizes the primary road corridors with the largest cumulative exposure to flash flood hazards. Several corridors—including Karang Pucung–Wangon, Kutoarjo–Bruno–Wonosobo, and Bumiayu–Salem—show consistently high exposure across multiple hazard classes, indicating both spatial continuity and intensity of hazard interaction along these routes.

Table 2. Top 10 primary road corridors exposed to flood hazards

Rank	Road Corridor	Low (km)	Medium (km)	High (km)	Total Exposed (km)
1	Sp.3 Pejagan–Kanci – Ketanggungan – Bts. Kab. Tegal/Brebes	0.32	1.30	5.92	7.53
2	Karang Pucung – Wangon	0.68	2.35	3.29	6.33
3	Kutoarjo – Bruno – Bts. Kab. Wonosobo	1.22	2.37	2.16	5.75
4	Bumiayu – Salem	0.65	1.92	2.33	4.91
5	Jepara – Keling	0.41	1.40	3.10	4.91
6	Keling – Tayu	0.34	1.05	2.10	3.50
7	Pemalang – Randudongkal	0.39	0.98	1.69	3.06
8	Purwokerto – Baturaden	3.47	0.54	–	4.01
9	Kesesi – Bantarbolang	0.47	1.61	1.40	3.48
10	Tol Pejagan – Pemalang	1.05	1.07	1.10	3.22

Note: – indicates no exposure in that hazard class

At the same time, variability in hazard composition is also evident. Certain corridors, such as Purwokerto–Baturaden, exhibit a higher proportion of low-hazard exposure relative to medium and high categories. This variation suggests that flash flood exposure is influenced by localized hydrological and topographical conditions, resulting in heterogeneous hazard intensity across the network. Collectively, the findings demonstrate that flash flood exposure in

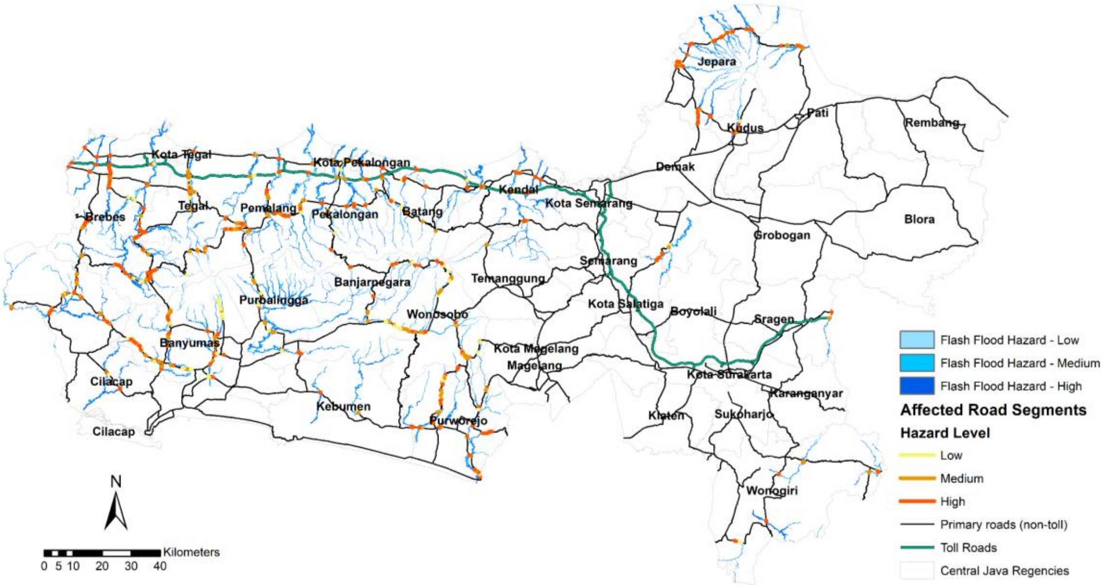

Figure 2. Flood hazard exposure of primary road network in Central Java Province

Central Java is not only widespread but also characterized by a strong presence of high-hazard segments in key corridors, highlighting the significance of flash flooding as a dominant hazard affecting the primary road network.

Flood Hazard Exposure on Bridges

Table 3 reports the flash flood hazard exposure to bridges by regency. There are 136 bridge structures in Central Java Province that are exposed to flash flood hazards, highly unevenly distributed across hazard levels (Figure 3). The high hazard class exposure is by far the largest, followed closely by the medium hazard class exposure, with the low hazard class exposure being quite small.

This distribution shows that a significant percentage of bridge infrastructure is located in an area with high intensity flash flood conditions. Bridge exposure is more concentrated in the high hazard class than in road segments where exposure is spread across the various hazard classes.

Table 3. Flash flood hazard exposure of bridges by regency (sorted by high hazard)

Regency	Low	Medium	High	Total
Brebes	0	2	22	24
Banyumas	0	10	16	26
Cilacap	0	1	12	13
Tegal	0	1	10	11
Kendal	3	3	9	15
Purworejo	0	5	7	12
Batang	1	1	6	8
Wonosobo	1	1	3	5
Jepara	0	0	3	3
Banjarnegara	1	3	3	7
Pekalongan	0	3	2	5
Pemalang	0	2	2	4
Kota Pekalongan	0	1	1	2
Kebumen	0	0	1	1

Regency with the largest number of exposed bridges are Banyumas (26 bridges), Brebes (24 bridges) and Cilacap (13 bridges). In these regencies, the number of exposed bridges is found to be in the high hazard category, which shows that there is a strong correlation between the position of the bridges and the flood hazard areas. Other regencies are also having significant exposures, such as Kendal

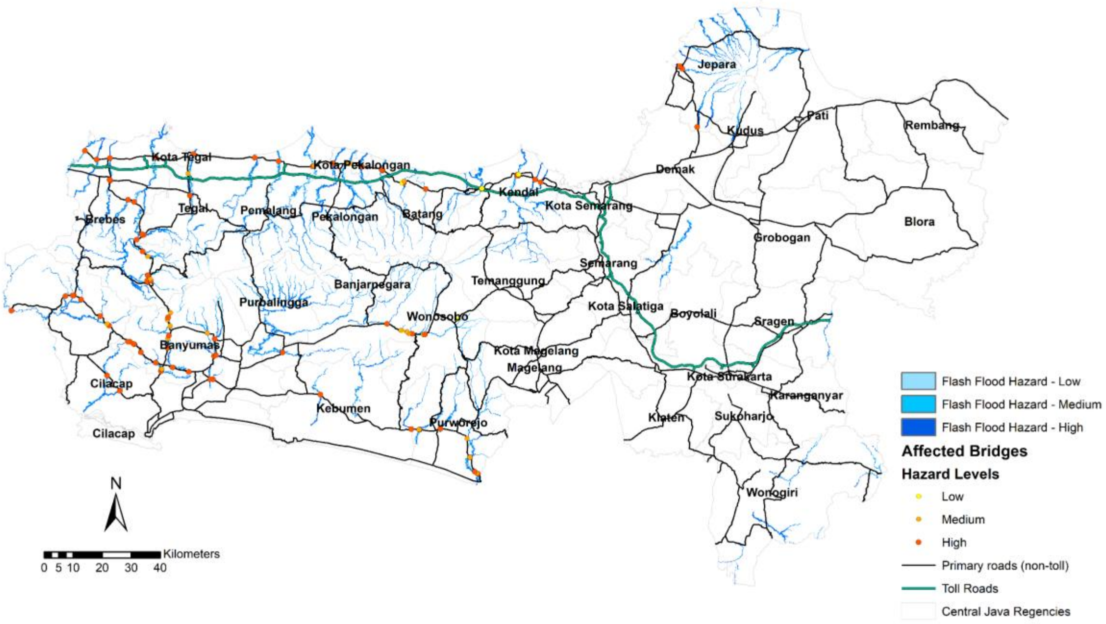

Figure 3. Flood hazard exposure of primary bridges in Central Java Province

(15 bridges), Purworejo (12 bridges) and Tegal (11 bridges) with more exposure differences between hazard classes. Meanwhile, there are several regencies that are relatively less exposed, where only a few bridges are affected.

Overall, the findings show that flash flood exposure on bridges is not only prevalent but also is highly concentrated in high-hazard conditions, suggesting a different exposure pattern than for road segments.

Landslide Hazard Exposure on Primary Road Network

The exposure of landslide hazard is more spatially concentrated than flash flood exposure (Figure 4). In total, there are about 484 km of road sections crossing landslide hazard areas in Central Java Province. The distribution of exposure is heavily skewed towards high hazard with about 60.6% of the total length exposed being in this category. The medium and low hazard classes account for approximately 22.6% and 16.8% respectively. This means that exposure to landslides, although not as geographically widespread as it could be, is very tightly coupled with an increased hazard intensity along certain road corridors.

Table 4 lists the main road corridors experiencing the highest total landslide exposure. The corridor Wiradesa – Kalibening has the highest exposure (above 40 km) and a significant part of it falls under high hazard level. Wadaslintang–Selokromo and Bumiayu–Sirampog corridors experience large exposure (>20 km) mostly in medium to high hazard classes. Some corridors are exposed to several levels of hazards, such as Kutoarjo–Bruno–Wonosobo, which reveal continuous landslide-prone corridors along mountainous roads.

The results overall show that landslide hazard exposure is spatially concentrated, high intensity and different from the more widespread but variable exposure pattern observed for flash flood hazards.

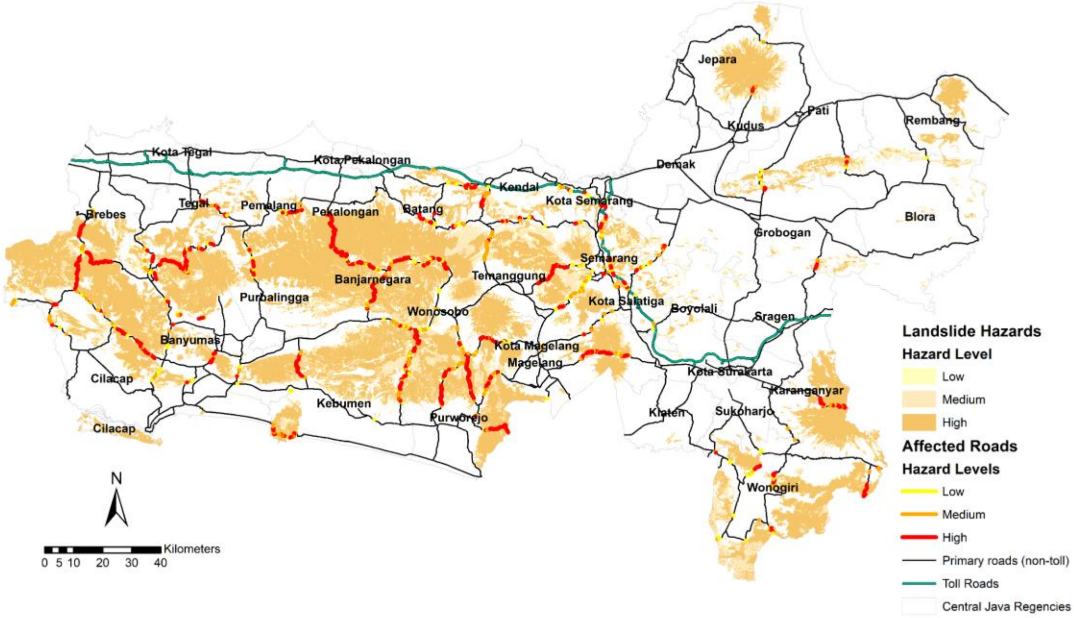

Figure 4. Landslide hazard exposure of primary road network in Central Java Province

Table 4. Top 10 primary road corridors exposed to landslide hazards

Rank	Road Corridor	Low (km)	Medium (km)	High (km)	Total Exposed (km)
1	Wiradesa – Kalibening (Bts. Kab. Banjarnegara)	2.25	5.99	32.51	40.75
2	Wadaslintang – Selokromo	2.04	4.95	18.14	25.14
3	Bumiayu – Sirampog	3.92	2.01	17.90	23.83
4	Banjarnegara – Wanayasa	1.77	3.51	12.96	18.24
5	Kutoarjo – Bruno – Bts. Kab. Wonosobo	2.39	3.59	10.37	16.35
6	Cilopodang – Salem	1.63	0.96	10.85	13.44
7	Bumiayu – Salem	0.42	1.66	12.83	14.90
8	Karanganyar – Tawangmangu – Kalisoro	1.31	0.41	8.84	10.57
9	Parakan – Patean (Bts. Kab. Kendal)	2.18	7.80	0.55	10.54
10	Kejajar – Dieng	0.89	0.02	6.27	7.18

Landslide Hazard Exposure on Bridges

Bridge exposure to landslide hazard is relatively small compared to flash flood hazard with 40 bridges located in the landslide hazard area (Figure 5).

The distribution of exposure is widely varied, and is quite different from exposure in flash flood conditions. Most exposed bridges are in the low hazard and medium hazard categories (about 52.5% and 37.5%, respectively), with about 10% in the high hazard category. This shows that the exposure of landslides on bridges is more or less correlated with a low to moderate hazard intensity.

The highest number of exposed bridges is found in Banyumas (9 bridges), Banjarnegara (8 bridges) and Wonosobo (6 bridges) regencies. But the bulk of these exposures are in low and medium hazard classes. Only limited number of regencies, like Batang and Wonogiri, show bridges in high hazard category, but the number of bridges in the high hazard category is still small (Table 5).

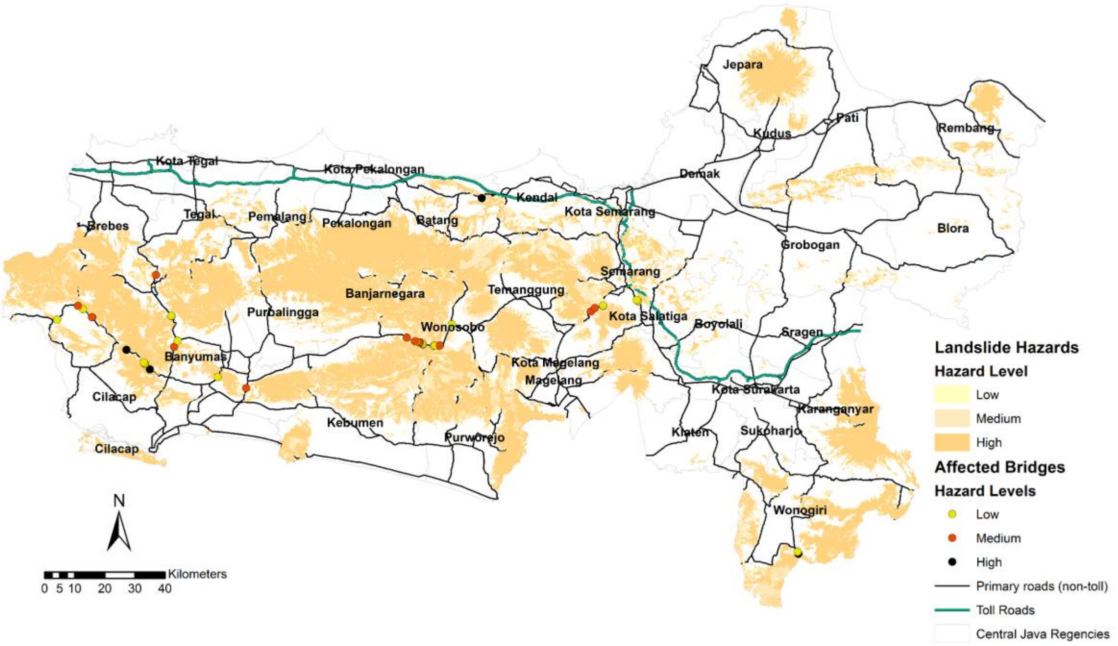

Figure 5. Landslide hazard exposure of primary bridges in Central Java Province

Table 5. Summary of landslide-exposed bridges by regency

Regency	Low	Medium	High	Total
Banyumas	5	2	2	9
Banjarnegara	3	5	0	8
Wonosobo	4	2	0	6
Semarang	4	1	0	5
Cilacap	2	3	0	5
Wonogiri	1	0	1	2
Temanggung	0	1	0	1
Brebes	2	1	0	3
Batang	0	0	1	1

Note: regencies not listed have zero landslide-exposed bridges

The results show that the exposure to landslide hazard is more restricted in terms of extent and is more often related to lower hazard intensities than is the exposure to flash flood hazard, which is dominated by higher hazard intensities. This distinction brings attention to the varying interactions between types of hazards and bridge infrastructure throughout the province.

Multi-Hazard Exposure of Primary Roads and Bridges

The overlay of flash flood and landslide exposure layers reveals several primary road corridors that are exposed to both hazard types (Figure 6). Selected representative corridors where overlapping exposure is seen are summarised in table 6.

There are several main corridors that have measurable exposure to flash flood and landslide hazards, such as the Karang Pucung–Wangon, Bumiayu–Salem, and Kutoarjo–Bruno–Wonosobo corridors. These corridors are where road segments overlap hazard areas related to hydrological processes (flash flooding) and geomorphological processes (slope instability), and they represent areas where two or more hazard mechanisms are spatially overlapping.

Other corridors like Wadaslintang–Selokromo and Cilopodang–Salem are mostly dominated by landslide exposure and also have flash flood prone segments at certain locations. On

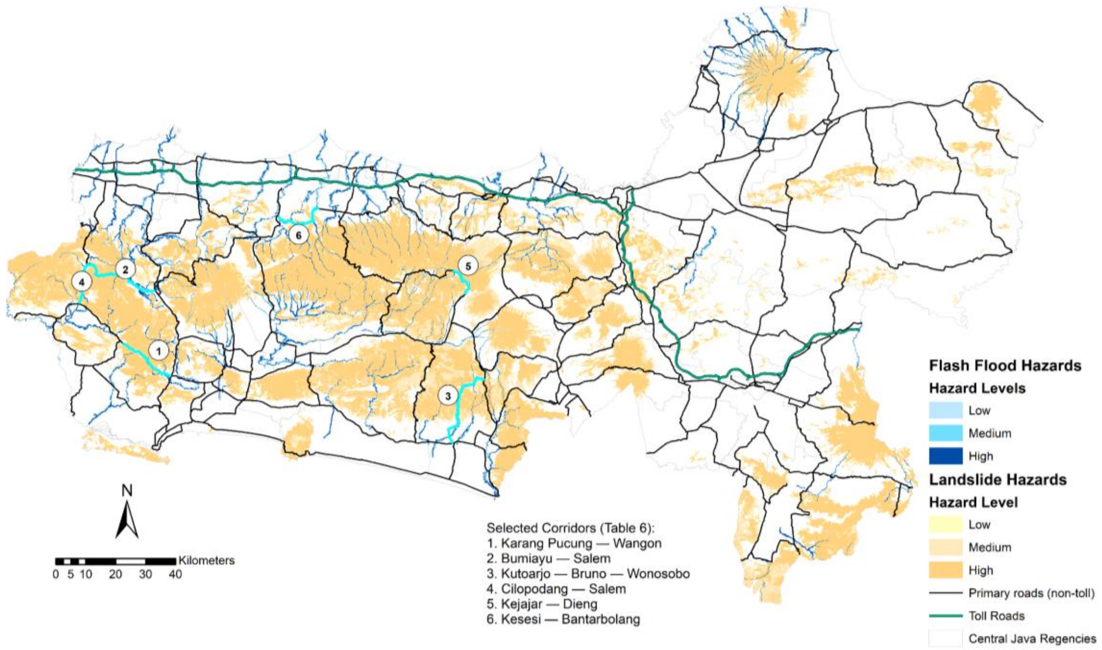

Figure 6. Multi-hazard exposure of primary road network: overlap of flash flood and landslide hazards

the other hand, corridors such as Jepara–Keling are mainly affected by flash flood hazard, and have a limited interaction with land slide prone area.

Table 6. Selected multi-hazard corridors with overlapping flash flood and landslide exposure

No	Road Corridor	Flash Flood Exposure (km)	Landslide Exposure (km)
1	Karang Pucung – Wangon	6.33	11.45
2	Bumiayu – Salem	4.91	14.90
3	Kutoarjo – Bruno – Wonosobo	5.75	16.35
4	Cilopodang – Salem	2.64	13.44
5	Kejajar – Dieng	2.88	7.18
6	Kesesi – Bantarbolang	3.48	6.43

Note: The table presents selected representative corridors identified from the highest exposure rankings in both hazard types.

Collecively, the results show that multi-hazard exposure is not uniformly distributed across the network but is concentrated along specific corridors where environmental conditions favor the coexistence of different hazard types. These corridors represent segments of the primary road network with overlapping exposure characteristics.

Discussion

In this study, the spatial exposure patterns of the main road network and bridges in Central Java Province are identified, which have strong spatial exposure patterns in line with the geomorphological characteristics of the area and in line with the results of previous studies.

The wide spread of flash flood exposed road segments in coastal and lowland regencies confirms the previous study stating that tidal flood, river overflow and inundation caused by drainage is frequent along the northern coast and major river basins of Java. (Handayani et al., 2017, 2020; Maryono and Hutomo, 2016; Hermawan et al., 2023). Meanwhile, the exposure to flash flood in upland corridors suggests that flood process in Central Java is not only related to lowland inundation but also due to steep terrain, heavy rainfall and fast accumulation of runoff. This observation builds on previous research by emphasizing the importance of localized hydrological response in the exposure to flooding along roads.

Landslide exposure, on the other hand, is more spatially concentrated and is mainly related to upland corridors with a steep gradient, highly weathered volcanic morphology and high rainfall intensity. This spatial distribution is similar to the previous assessment of landslide prone areas in Dieng Plateau, Serayu highlands and southern volcanic foothills. (Hermawan et al., 2023; Zamroni et al., 2020). Such a focus of landslide exposure along road corridors in the mountains has been identified in other countries, especially in humid tropical and mountainous areas (e.g., Goetz et al., 2015; Winter et al., 2016). The results also reveal that the majority of the exposure to landslides is under high hazard conditions, suggesting that corridors where landslides occur are not only concentrated, but also have high hazard intensity.

This study is a major contribution in that it has identified primary road corridors vulnerable to flash flood and landslide hazards. There are overlapping exposures in corridors like Karang Pucung–Wangon, Bumiayu–Salem, Kutoarjo–Bruno–Wonosobo, and Wadaslintang–Selokromo, which are areas where disruption could be intensified during intense rainfall. It is understood that the interaction of hydrological and geotechnical processes in the same corridors is an important amplifier of infrastructure risk in multi-hazard environments. (e.g., Gill and Malamud, 2016; Koks et al., 2019). The results confirm the need to address multiple hazard types as a whole, instead of single hazards mitigation measures alone.

The results also reveal distinct exposure characteristics between infrastructure asset types. It is found that bridges are disproportionately exposed to high hazard flash flood conditions especially in regencies of Banyumas, Brebes, and Cilacap. This is a sign of the vulnerability of bridge structures in active fluvial systems with high discharge, sediment transport and dynamic flow regimes. (Hadmoko et al., 2017). By contrast, the exposure to landslides on bridges is relatively small and is mostly linked to low to medium hazard categories. The difference indicates that road alignments in slopes and cut sections are more prone to landslide processes than those at valley bottoms. Previous studies (e.g., Winter et al., 2016; Loli et al., 2022) have reported similar differences in the effects of hazards on roads and bridges.

In general, this research shows that exposure analysis using GIS at the provincial level can be used to gain valuable information for identifying hazard exposed corridors and infrastructure elements at the provincial level. This finding confirms the results of previous research (e.g., Mardiah et al., 2017; Rachmawati, 2017) that, despite the increasing availability of hazard information in Indonesia via the BNPB's Hazard Assessment and InaRISK, integration with the infrastructure inventories in the context of risk-informed planning is not yet widely developed. This study helps to fill this operational gap by directly connecting hazard maps with road and bridge data.

Lastly, it should be noted that the results in this study are exposure conditions and not direct measures of network vulnerability or performance. Exposure is a measure of where infrastructure is at risk from hazards, but does not fully represent the impacts of functional disruption. Future research is thus needed to expand on this work by integrating connectivity-based vulnerability analysis, more detailed hazard data, and field validation to improve the estimation of the potential impacts of hazard-induced disruptions and to inform infrastructure resilience planning.

Practical Implications

Based on the results of this research, there are several implications that can be applied in infrastructure planning and management in hazard-prone areas like Central Java.

First, the GIS-based exposure analysis at the provincial level can be used as a decision support tool to identify hazard prone corridors and infrastructure elements. Multi-hazard corridors are areas where more than one hazard can be experienced, e.g. Karang

Pucung–Wangon, Bumiayu–Salem, and Kutoarjo–Bruno–Wonosobo, where the combination of the hazard exposure can further enhance the probability of disruption. Thus, such corridors can be regarded as priority areas for mitigation planning. Instead of using single-hazard strategies, integrated strategies at corridor level are recommended to tackle the multiple hazard mechanisms.

Secondly, the findings indicate a need for different approaches for different types of infrastructure. Regencies with high exposure to flash flood conditions are regencies that have bridges, for example Banyumas, Brebes, Cilacap, Kendal and Purworejo. To minimize the risk of service disruption, these structures may need to be reinforced, hydraulically assessed periodically, and monitored. These are especially crucial for keeping traffic moving during heavy rain.

Third, the exposure indicators obtained from this study can be used at the asset management level for risk-informed maintenance prioritisation and budget allocation by national and provincial road agencies. Infrastructure assets with higher exposure levels, especially those in medium and high hazard zones, can be prioritised to enhance the effectiveness of available resources for infrastructure maintenance.

Lastly, the hazard exposure maps created in this study can be used in emergency routing and service continuity planning. Authorities can use corridors identified as concentrated exposure to plan for alternate routes and contingencies for maintaining access to the region in case of a disaster.

Conclusion

This study is a GIS-based identification of flash flood and landslide exposure on road segments and bridges in the main road network of Central Java Province. The flash flood hazards are identified as being ubiquitous in both lowland and upland areas, while exposure to landslides is more spatially localized along upland and mountainous road alignments. A number of primary road corridors are identified as hotspots because they are exposed to both types of hazards, suggesting multi-hazard conditions along key transportation corridors.

The results include specific spatial data on the location and extent of exposure of the provincial primary road network to flash flood and landslide hazards. Bridge structures are found to be disproportionately exposed to high intensity flash flood conditions, and for landslides, road sections with slopes, cuts and embankments are exposed. These opposing trends illustrate the need to take into account hazard-specific and asset-specific characteristics in infrastructure planning and management.

This study is a GIS-based exposure assessment at the provincial level and as such does not assess the functional effects of hazard related disruptions on overall network performance. Rather, it serves as an evidence base to prioritize hazard-prone corridors for monitoring, hazard mitigation planning and further detailed assessment. Future studies are likely to expand on these results, add connectivity-based vulnerability analysis, more precise hazard information, and field testing to enhance infrastructure resilience planning.

Declaration Statement

The authors declare that ChatGPT (OpenAI) was used solely for language proofreading, grammar correction, and improvement of writing clarity during the preparation of this manuscript. All scientific content, including the study design, methodology, data analysis, interpretation of findings, and conclusions, was developed and verified exclusively by the authors. The authors take full responsibility for the accuracy, originality, integrity, and validity of the manuscript's content.

References

BNPB (2015). Study on Disaster Risks for Central Java Province 2016-2020 (in Bahasa Indonesia). National Agency for Disaster Management: Jakarta

BNPB (2021). Study on Disaster Risks for Central Java Province 2022-2026 (in Bahasa Indonesia). National Agency for Disaster Management: Jakarta

BNPB (2024). Kompilasi Data Jumlah dan Dampak Kejadian Bencana. https://data.bnpb.go.id/dataset/data-bencana-indonesia.

BPS. (2024). Jumlah Kejadian Bencana Alam Menurut Provinsi. https://www.bps.go.id/en/statistics-table/3/TUZaMGVteFVjSEJ4T1RCMlIyRjRTazVvVDJocVFUMDkjMw==/jumlah-kejadian-bencana-alam-menurut-provinsi--2023.html?year=2023.

Chen, X.-Z., Lu, Q.-C., Peng, Z.-R., & Ash, J. E. (2015). Analysis of Transportation Network Vulnerability under Flooding Disasters. Transportation Research Record: Journal of the Transportation Research Board, 2532(1), 37-44. https://doi.org/10.3141/2532-05

Gill, J. C. and Malamud, B. D. (2016): Hazard interactions and interaction networks (cascades) within multi-hazard methodologies, *Earth Syst. Dynam.*, 7, 659–679, https://doi.org/10.5194/esd-7-659-2016

Goetz, J. N., Brenning, A., Petschko, H., Leopold, P. (2015). Evaluating machine learning and statistical prediction techniques for landslide susceptibility modeling, *Computers & Geosciences*, 81, pp.1-11, https://doi.org/10.1016/j.cageo.2015.04.007.

Hadmoko, D. S., Lavigne, F., Sartohadi, J., Gomez, C., Daryono, D. (2017). Spatio-Temporal Distribution of Landslides in Java and the Triggering Factors. *Forum Geografi* 31 (1), 1 – 15. DOI: 10.23917/forgeo.v31i1.3790

Handayani, W., Chigbu, U. E., Rudiarto, I., Putri, I. H. S. (2020). Urbanization and Increasing Flood Risk in the Northern Coast of Central Java – Indonesia: an Assessment towards Better Land Use Policy and Flood Management. *Land* 9(10), 343. https://doi.org/10.3390/land9100343

Handayani, W., Rudiarto, I., Setyono, J. S., Chigbu, U. E., Sukmawati, A. M. (2017). Vulnerability assessment: a comparison of three different city sizes in the coastal area of Central Java, Indonesia. *Advances in Climate Change Research* 8(4), 286-296. https://doi.org/10.1016/j.accre.2017.11.002

Hermawan, F., Sulistyaningrum, E., Afchori, J. A., Yuniarto, R., et. al. (2023). Flooding and Landslide Potential Mapping of Public Housing after Landuse Change. *KoNTeks* 17 Vol. 1 No. 2. https://doi.org/10.62603/konteks.v1i2.33

Isnaini, R. (2019). Analisis Bencana Tanah Longsor di Wilayah Jawa Tengah. *Islamic Management and Empowerment Journal* 1 (2). 143 – 160. DOI: 10.18326/imej.v1i2.143-160

Koks, E.E., Rozenberg, J., Zorn, C. (2019). A global multi-hazard risk analysis of road and railway infrastructure assets. *Nat Commun* 10, 2677. https://doi.org/10.1038/s41467-019-10442-3

Loli, M., Kefalas, G., Dafis, S., Mitoulis, S. A., Schmidt, F. (2022). Bridge-specific flood risk assessment of transport networks using GIS and remotely sensed data, *Science of The Total Environment* 850, 2022, 157976, https://doi.org/10.1016/j.scitotenv.2022.157976

Mardiah, A.N.R., Lovett, J.C., Evanty, N. (2017). Toward Integrated and Inclusive Disaster Risk Reduction in Indonesia: Review of Regulatory Frameworks and Institutional Networks. In: Djalante, R., Garschagen, M., Thomalla, F., Shaw, R. (eds) Disaster Risk Reduction in Indonesia. Disaster Risk Reduction. Springer, Cham. https://doi.org/10.1007/978-3-319-54466-3_3

Maryono, Hutomo, I. A. (2016). Model Prediksi Kawasan Rawan Bencana di Kecamatan Karangkobar. *Jurnal Pembangunan Wilayah & Kota* 12(3), 303-314.

Ministry of Public Works and Housings, MoPWH (2022). Keputusan Menteri Pekerjaan Umum dan Perumahan Rakyat Nomor 430/KPTS/M/2022 tentang Penetapan Ruas Jalan dalam Jaringan Jalan Primer Menurut Fungsinya sebagai Jalan Arteri Primer dan Jalan Kolektor Primer-1

Ministry of Public Works and Housings, MoPWH (2023). Number of National Bridges Year 2023 https://data.pu.go.id/dataset/jumlah-jembatan-nasional

Provincial Government of Central Java (2022) Keputusan Gubernur Jawa Tengah Nomor 622/11 tahun 2022 tentang Penetapan Ruas Jalan dalam Jaringan Jalan Kolektor Primer-2 dan Jalan Kolektor Primer-3 sebagai Jalan Provinsi di Provinsi Jawa Tengah.

Pyatkova, K., Chen., A. S., Butler, D., Vojinovic, Z., Djordjevic, S. (2019). Assessing the knock-on effects of flooding on road transportation. *J. of Envi. Manag.* 244, 48-60. https://doi.org/10.1016/j.jenvman.2019.05.013

Rachmawati, T. A. (2017). Study on integrating disaster risk reduction in Indonesian municipal spatial planning. *IOP Conference Series Earth and Environmental Science* 70(1): 012046. DOI:10.1088/1755-1315/70/1/012046.

Roads Law, 38 Republic of Indonesia (2004). https://jdih.pu.go.id/internal/assets/assets/produk/UU/2014/10/UU38-2004.pdf

Toma-Danila, D., Armas, I., and Tiganescu, A.(2020). Network-risk: an open GIS toolbox for estimating the implications of transportation network damage due to natural hazards, tested for Bucharest, Romania, *Nat. Hazards Earth Syst. Sci.*, 20, 1421–1439, https://doi.org/10.5194/nhess-20-1421-2020

Winter, M. G., Shearer, B., Palmer, D., Peeling, D., Harmer, C., & Sharpe, J. (2016). The Economic Impact of Landslides and Floods on the Road Network. *Procedia Eng.*, 143, 1425-1434. https://doi.org/10.1016/j.proeng.2016.06.168

Zamroni, A., Kurniati, A. C., Prasetya, H. N. E. (2020). The assessment of landslides disaster mitigation in Java Island, Indonesia: a review. *Journal of Geoscience Eng., Envi., and Tech.* 5 (3) 124-128., https://doi.org/10.25299/jgeet.2020.5.3.4676