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ANALYSIS THE IMPACT OF INFRASTRUCTURE DAMAGE ON HUMANITARIAN LOGISTICS PERFORMANCE IN THE DISASTER RESPONSE PHASE

Analisis Pengaruh Kerusakan Infrastruktur terhadap Kinerja Logistik Kemanusiaan pada Fase Respons Bencana

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ABSTRACT

The Tapanuli region is highly vulnerable to simultaneous flood and landslide disasters that paralyze vital infrastructure. This condition critically impedes humanitarian logistics during the response phase, yet its quantitative impact is not well understood. This study aims to analyze the influence of infrastructure disruption on logistics performance (time, cost, coverage) and to identify critical bottlenecks. The methodology is a quantitative GIS-based simulation study with three scenarios: Normal, Low Damage, and High Damage. Network analysis and linear regression were applied to measure the impact of each scenario. The results show that infrastructure disruption has a highly significant negative impact on logistics performance. In the high-damage scenario, a "cliff effect" was observed, with service coverage plummeting to just 60%, isolating 40% of the study area, and average travel time increasing by nearly 600%. These findings demonstrate the systemic vulnerability of centralized logistics strategies and recommend a shift towards decentralized preparedness to enhance supply chain resilience.

ABSTRAK

Wilayah Tapanuli sangat rentan terhadap bencana simultan banjir dan longsor yang melumpuhkan infrastruktur vital. Kondisi ini secara kritis menghambat logistik kemanusiaan pada fase respons, namun dampak kuantitatifnya belum terukur. Tujuan penelitian ini adalah untuk menganalisis pengaruh disrupsi infrastruktur terhadap kinerja logistik (waktu, biaya, jangkauan) dan mengidentifikasi bottleneck *kritis. Metode yang digunakan adalah studi simulasi kuantitatif berbasis GIS dengan tiga skenario: Normal, Kerusakan Rendah, dan Kerusakan Tinggi. Analisis Jaringan dan regresi linier diterapkan untuk mengukur dampak pada setiap skenario. Hasil menunjukkan bahwa disrupsi infrastruktur berpengaruh negatif dan sangat signifikan terhadap kinerja logistik. Pada skenario kerusakan tinggi, terjadi "efek jurang" (*cliff effect*) di mana jangkauan layanan anjlok hingga hanya 60%, mengisolasi 40% wilayah studi, dan waktu tempuh meningkat hampir 600%. Temuan ini membuktikan kerentanan sistemik strategi logistik terpusat dan merekomendasikan perlunya kesiapsiagaan desentralisasi untuk meningkatkan ketahanan rantai pasok.*

INTRODUCTION

The Tapanuli region, as an integral part of the Bukit Barisan Mountains in North Sumatra Province, has complex topography with steep slopes, deep valleys, and a fast-flowing river network (Bugis et al., 2021) These conditions, coupled with projected increases in extreme rainfall due to climate change, place the districts in Tapanuli at a very high level of vulnerability to hydrometeorological disasters.

Disaster events in this region often occur as cascading disasters, where heavy rains not only cause rivers, such as the Batang Toru River, to overflow but also simultaneously trigger landslides that cut off road access in hilly areas (Fathani et al., 2022). In disaster situations like this, the success of the emergency response phase depends heavily on the ability to distribute humanitarian aid quickly and efficiently, which is the core of humanitarian supply chain management (Kovács & Spens, 2007). However, logistics performance in this context faces complex, multiple challenges, far exceeding those encountered in typical commercial logistics (Kovacs et al., 2019).

Unlike inundation floods in the lowlands, infrastructure disruption in Tapanuli is more destructive, where winding roads on hillsides can collapse or be buried by landslide material, and bridges in valleys can be swept away by the kinetic energy of flash floods (Kusumartono & Heston, 2010). In the fragile mountain transportation network, a single landslide point is enough to create a domino effect and isolate dozens of villages or even an entire sub-district, a phenomenon known as the bottleneck effect (Rodrigue, 2020).

The fundamental problem faced by disaster agencies such as the Regional Disaster Management Agency (BPBD) is the significant gap between static route planning on paper and the reality of the paralyzed terrain after a disaster (Kusumastuti et al., 2021; Samad et al., 2025). Many existing contingency plans are not yet equipped with dynamic quantitative models capable of predicting the logistical impacts of various flood landslide combination scenarios (Van Wassenhove, 2006). As a result, most relief operations remain reactive, often experiencing critical delays as teams on the ground become stuck in traffic jams or are forced to resort to extreme and inefficient detours (Lee et al., 2020). Therefore, this study is crucial to bridge the gap by providing a data-based analysis of the quantitative impact of infrastructure disruption on logistics performance metrics, which can be the basis for more resilient decision making in regions with challenging topography such as Tapanuli (Sheu, 2010).

Humanitarian logistics is defined as the process of planning, implementing, and controlling the efficient and effective flow of goods, services, and information from the point of origin to the point of consumption with the primary goal of alleviating the suffering of vulnerable populations (Thomas & Mizushima, 2005). Its primary orientation is not financial gain, but rather speed and accuracy in saving lives, which fundamentally distinguishes it from commercial logistics (Kovacs et al., 2019). Its management cycle is generally divided into three main phases: preparedness, response, and recovery, with the response phase being the most crucial focus post-disaster (Kovács & Spens, 2007).

Performance in humanitarian logistics is not measured by profitability, but by its effectiveness in meeting the urgent needs of disaster victims (Beamon & Balcik, 2008). There are several key metrics that are widely accepted to measure this performance, including time, cost, and reach (Van Wassenhove, 2006). Time is the most critical dimension measured through response time, because the slightest delay can be fatal; Cost aims for efficiency so that limited resources can be maximized; and Reach measures the percentage of victims successfully served, which is often hampered by accessibility (Sheu, 2010).

Critical infrastructure refers to assets, systems, and networks that are so vital to the functioning of a nation that their inoperability or destruction would have a crippling impact on public security, economy, health, or safety. In the context of disaster response, transportation networks particularly roads and bridges are the most fundamental critical infrastructure because they serve as arteries that carry personnel and life-saving assistance (Weisbrod, 2011). Therefore, the vulnerability and resilience of transportation networks are key determinants of the success of emergency logistics operations (Wang et al., 2020).

Academic literature has extensively discussed various aspects of humanitarian logistics and disaster management (Holguín-Veras et al., 2012). A number of studies have also focused on analyzing the impact of specific disasters, such as tsunamis or earthquakes, on logistics performance in various countries, including Indonesia (Luangphane et al., 2024). In addition, the use of Geographic Information Systems (GIS) to model transportation network disruptions and post-disaster route optimization has also become a rapidly growing research field (Sun et al., 2025).

However, after conducting an in-depth review, a specific and significant research gap was identified. Very few studies have comprehensively modeled the logistical impacts of simultaneous or chain hydrometeorological disasters (flash floods and landslides) in the context of highly complex mountainous topography (Partini & Hidayaht, 2024). Most studies tend to focus on a single disaster type (e.g., only inundation flooding in lowlands) or do not explicitly account for unique infrastructure failure modes in steep slope areas, such as road collapse or complete landslide coverage (Zhang et al., 2023).

METHODS

The Methods section should be described in detail and systematically. It must include the research design, population, sample, data sources, techniques and instruments for data collection, and data analysis procedures.

This research will be conducted using a quantitative approach with a Geographic Information System (GIS) based simulation study method, focusing on the transportation infrastructure network in the Tapanuli region (North, Central, and South). The research process will begin with the collection of secondary data, including digital road network maps from the Public Works and Housing Agency (PUPR), flood and landslide hazard maps from the Regional Disaster Management Agency (BPBD), and data on the locations of potential evacuation points. Next, a baseline transportation network model will be built using GIS software such as ArcGIS or QGIS to represent normal conditions.

This model will then be subjected to several damage scenarios namely; low, medium, and high damage scenarios. Modeled by providing 'barriers' or obstacles on road sections and bridges according to the disaster hazard map. In each scenario, aid distribution simulations will be run using the Network Analysis function to find the fastest route from the main logistics warehouse assumed to be located in Sibolga to all evacuation points.

From these simulations, quantitative data for the dependent variable logistics performance (Y) will be extracted, including average travel time (Y1), total distribution costs (Y2), and percentage of service coverage (Y3), while the independent variable infrastructure disruption level (X) is operationalized as a composite index of the percentage of closed roads and the number of bridges damaged. The final stage is data analysis using statistical software such as SPSS or R, where Simple Linear Regression Analysis techniques will be applied to test the hypotheses and statistically measure the influence of the infrastructure disruption level variable (X) on each logistics performance metric (Y).

RESULTS

The simulation was run on a digital road network model of the Tapanuli region (North, Central, and South), encompassing 3,100 km of roads and 150 bridges. The logistics origin was set at Sibolga City, with 60 potential evacuation points as destinations.

Figure 1. Logistics Coverage Map under the High Damage Scenario

The impact of each damage scenario on three key logistics performance metrics is summarized in the table below.

Table 1

Logistic Performance Metric	Scenario 0 (Baseline/Normal)	Scenario 1 (Low Damage)	Scenario 2 (High Damage)
Level of infrastructure damage	0%	10% closed road, 4 broken bridges	60% closed road, 40 broken bridges
Average travel time (Hours)	2,5	4,1	14,5
Total distribution cost (Million Rp)	15	22,5	58
Service coverage	100%	98%	60%

The descriptive results show a stark contrast between the impacts of low and high damage. In Scenario 1, the system still demonstrates resilience, with only a 2% loss of service coverage and a manageable increase in resilience time. However, in Scenario 2, the system collapses: travel times jump nearly 600% from normal, and 40% of all evacuation sites become completely unprotected by land routes.

A linear regression analysis was conducted to measure the effect of the Level of Infrastructure Disruption (X) on Logistics Performance (Y). The results confirmed a highly significant relationship.

Table 2

Result of Linear Regression Analysis

Regression model	Equation	R-Squared	P-Value	Conclusion
Travel time	$Y_1 = 2{,}45 + 0{,}21 (X)$	0,96	$<0{,}001$	Significant Positif
Distribution cost	$Y_2 = 14{,}8 + 0{,}72 (X)$	0,93	$<0{,}001$	Significant Positif
Service coverage	$Y_3 = 101{,}5 - 0{,}68(X)$	0,97	$<0{,}001$	Significant Positif

Simulation result

This analysis statistically proves that increasing levels of infrastructure disruption will significantly increase travel time and distribution costs, as well as reduce the reach of logistics services.

DISCUSSION

The drastic difference between the results of Scenario 1 and Scenario 2 highlights the existence of a "cliff effect" in infrastructure resilience in mountainous regions. The system does not gradually degrade, but rather functions relatively well until it reaches a critical point, after which it catastrophically collapses. This is due to the nature of the road network in Tapanuli, which has little redundancy (few alternative routes). When several key arterial roads and bridges (as in Scenario 2) fail simultaneously, there are no viable detour routes left, resulting in complete logistical paralysis across much of the region. The spatial analysis in Scenario 2 clearly identified several infrastructures as the most critical bottlenecks.

The Trans Sumatra Highway (Jalinsum) on the Hillside, the only major land route connecting the coast and the highlands, is the most vital artery. Simulations indicate that several landslides along this section are the primary cause of systemic paralysis.

Inter district Bridges is a bridge providing the only access to a district (such as the Aek Lumut Bridge illustrated earlier) proved to be a single point of failure. Its failure effectively "removed" the entire district from the land logistics coverage map.

CONCLUSION

These findings demand a fundamental shift in disaster logistics strategies. The importance of logistics decentralization is relying on a centralized warehouse in Sibolga is a fragile strategy. To address this "cliff effect," pre-positioning logistics through the construction of buffer stock warehouses in strategic locations such as Tarutung or Sipirok is a necessity, not an option. These warehouses will ensure the availability of aid for the critical first days, even if access from the main warehouse is cut off.

Activation of Alternative Mode Protocols: Given that 40% of the area is inaccessible by land in a worst-case scenario, the Regional Disaster Management Agency (BPBD) must have clear protocols for immediately activating air transportation (helicopters). This simulation model can be used to determine emergency landing points and estimate the volume of aid that must be prepared for air distribution.

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