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MORALITY BEFORE KNOWLEDGE

Integrating disaster risk into the economic valuation of strategic infrastructure: A case study of Yogyakarta International Airport under tsunami threat

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ABSTRACT
Background: In response to the increasing frequency of natural disasters and the urgency of climate adaptation, this study assesses the potential economic losses at Yogyakarta International Airport (YIA), a key National Strategic Project/*Proyek Strategis Nasional* (PSN) in Indonesia. Despite its critical role in promoting regional connectivity and economic growth, YIA is located in a high-risk seismic and tsunami-prone zone along the Indian Ocean. **Methods:** Using the Total Economic Value (TEV) framework, this research estimates direct and indirect losses resulting from a hypothetical disaster scenario, including waterlogging impacts on runways and aprons. The analysis integrates hazard exposure data, infrastructure vulnerability, and sectoral economic linkages, encompassing damage to assets, disruptions to tourism, and income loss during the recovery phase. **Findings:** Findings reveal that a single severe disaster could result in 429,746,360,380 rupiah losses, with cascading effects on local livelihoods and regional mobility. The study underscores the need for ex-ante disaster risk integration in infrastructure investment planning, contributing to the development of resilient and sustainable airport systems under Indonesia's long-term disaster risk reduction framework. **Conclusion:** This study concludes that Yogyakarta International Airport (YIA) is highly vulnerable to tsunami hazards, with potential for extensive infrastructure damage and significant direct and indirect economic losses, underscoring the urgent need to integrate disaster risk reduction into the planning and operation of critical infrastructure. **Novelty/Originality of this article:** This article lies in its application of the Total Economic Value (TEV) framework combined with hazard exposure analysis to comprehensively estimate both direct and indirect economic losses of Yogyakarta International Airport (YIA) as a National Strategic Project (PSN) in a tsunami-prone area.

KEYWORDS: disaster risk reduction; economic loss estimation; Yogyakarta International Airport; infrastructure resilience; tsunami risk.

1. Introduction

Indonesia is globally recognized as one of the most disaster-prone countries due to its unique geotectonic and climatological position. Located at the convergence of the Indo-Australian, Eurasian, and Pacific tectonic plates, the country is highly exposed to frequent seismic and volcanic activity. According to the National Disaster Management Agency (*Badan Nasional Penanggulangan Bencana*, BNPB), more than 22,000 disaster events were recorded between 2015 and 2023, resulting in over 30,000 fatalities and the displacement

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of approximately 40 million people. Climate-induced hazards such as floods and extreme weather events are also on the rise, exacerbated by deforestation, rapid urban expansion, and global warming.

In response to these escalating risks, the Government of Indonesia developed the National Disaster Management Master Plan 2020–2044 (*Rencana Induk Penanggulangan Bencana*, RIPB). The RIPB provides a comprehensive, forward-looking strategy to strengthen national resilience against natural hazards. It adopts a multi-sectoral approach integrating disaster risk reduction (DRR), climate adaptation, spatial planning, and investment frameworks. The plan also reinforces Indonesia's international commitments to the Paris Agreement, the Sendai Framework for Disaster Risk Reduction 2015–2030, and the Sustainable Development Goals (SDGs), particularly Goal 11 on sustainable cities and Goal 13 on climate action. Importantly, it emphasizes the integration of DRR into infrastructure development and mandates long-term financial investments to support risk mitigation and adaptive capacity.

At the same time, infrastructure development has been a central pillar of Indonesia's growth strategy. The National Strategic Projects (*Proyek Strategis Nasional*, PSN) initiative, coordinated by the Committee for the Acceleration of Priority Infrastructure Delivery (KPPIP), has been pivotal in driving economic transformation. Under the RPJMN 2020–2024, PSNs aim to expand basic service coverage, reduce regional disparities, and enhance competitiveness. By early 2023, 158 out of 210 PSNs had been completed, with a total investment of IDR 1,102 trillion (approximately USD 73 billion). These projects include energy systems, transportation networks, and airports serving as key economic gateways. However, the large-scale investments involved demand rigorous disaster risk assessments. According to the 2021 Indonesian Disaster Risk Index/*Indeks Risiko Bencana Indonesia* (IRBI), around 44.71% of PSNs are located in high-risk areas, and another 55.29% in moderate-risk zones. This spatial overlap between critical infrastructure and hazard-prone regions exposes systemic vulnerabilities that could undermine both long-term economic gains and public safety. Government mid-term evaluation reports have also raised concerns about the lack of robust risk modeling in early project design, particularly in coastal and seismic zones.

A critical example is the Yogyakarta International Airport (YIA), a flagship PSN in Kulon Progo Regency, Special Region of Yogyakarta. Commissioned in 2020 to replace the overburdened Adisutjipto Airport, YIA was designed to accommodate 20 million passengers annually and positioned as a gateway for international tourism and regional trade in southern Java. Yet, its strategic potential is overshadowed by significant geophysical risks. Situated less than 10 meters above sea level on the southern coast, YIA lies in close proximity to the Java subduction zone, one of the world's most active seismic belts. The Indonesian Meteorology, Climatology, and Geophysics Agency (BMKG) projects that a megathrust earthquake in this zone could generate tsunami waves exceeding 10 meters in height, reaching the shoreline in under 30 minutes. Historical records, including the 2006 Yogyakarta earthquake and previous Indian Ocean tsunamis, underscore the recurrent seismicity of the region (Irawan et al., 2021; Weniza et al., 2023). These conditions render YIA highly vulnerable to tsunami inundation, coastal erosion, and soil liquefaction, jeopardizing both physical infrastructure and the wider regional economy dependent on continuous airport operations (Fakhruddin et al., 2021; Wood et al., 2023)

Although YIA has not yet been directly impacted by a major disaster, its exposure profile warrants urgent policy and technical attention. Preliminary risk mapping by BNPB and international partners such as JICA and UNDP has identified critical vulnerability hotspots within and around the airport's operational zones. Moreover, climate projections suggest that coastal infrastructure in Java will increasingly face compound risks from sea-level rise, extreme rainfall, and seismic activity. The potential consequences of a tsunami strike on YIA are severe and multifaceted. On the airside, risks include runway cracking from seismic shaking, debris accumulation from tsunami waves, structural damage to the air traffic control tower and apron, erosion caused by ocean currents, and leakage from aviation fuel storage facilities. On the landside, threats extend to damage to terminals, parking areas, evacuation bottlenecks, and fire hazards from oil leakage or aircraft engine damage. Beyond these physical impacts, operational disruptions would trigger cascading socio-economic consequences, particularly in tourism, trade, logistics, and labor mobility, all of which are central to Yogyakarta's economy (Alam & Ali, 2023; Gupta, et al., 2022).

This study is therefore motivated by the urgent need to integrate DRR into infrastructure valuation and planning. We employ the Total Economic Value (TEV) framework to estimate potential economic losses from a tsunami-induced waterlogging event at YIA. Economic valuation methods for disaster losses are diverse. For instance, Khan et al. (2023), analyzed the effects of water depth, flood duration, flow velocity, and warning time on flood-related economic losses and proposed a non-traditional water-depth damage curve. Phong (2022), examined 3,000 units across residential, industrial, agricultural, and commercial areas in Bangkok and developed correlations between flood losses and inundation parameters. Oliveri et al. (2000) introduced empirical frequency–loss curves to evaluate flood damages. Kazama et al. (2010) applied numerical simulations and flood control manuals to estimate flood damage costs, while Middelmann (2010) studied combinatorial models for flood loss assessment. Notaro et al. (2014) further examined uncertainties in depth–damage curves using case studies in Cappalermo, Italy.

GIS and Remote Sensing (RS) technologies have also become important tools for loss assessment. De Jonge et al. (1996) applied GIS-based simulations to model flood depth and economic damages. Haq et al. (2012) combined socio-economic and spatial data with GIS/RS to estimate flood damages and map inundation extents. More recently, Llinas (2022) advanced the concept of information fusion tailored to both natural and human-made disasters, building on FEMA-led initiatives (Ayalke & Aprinar, 2023; Banihipati, 2020; Bot, 2021). This approach integrates fundamental geospatial data, socio-economic indicators, historical loss records, seismic and meteorological datasets, and real-time observations.

In addition, software-based and economic modeling approaches have been widely applied. Rose et al. (2005) highlighted the use of HEC-RAS, HEC-GeoRAS, and Computable General Equilibrium (CGE) models for assessing direct and macroeconomic impacts of meteorological disasters (Carrera et al., 2015; Mohammadia et al., 2014; Narayan, 2003; Wu & Guo, 2019; Sandoval, 2023; Sawngsupavanich, 2022). The Input–Output (IO) model is also widely used: Hallegatte (2008) adan Galbusera et al. (2023) estimated indirect losses from Hurricane Katrina using IO analysis, while Wu et al. (2019) applied abnormal IO tables to measure losses from the Wenchuan earthquake. Each model has distinct strengths and weaknesses: CGE models require extensive datasets and complex computations, while IO models demand fewer inputs and provide a clear structure for analyzing indirect economic losses across industrial sectors, making them particularly well suited for disaster loss evaluation (Okuyama, 2007; Ring et al., 2010; Weitzman, 2009). By quantifying both direct damages and indirect disruptions, such as service downtime, tourism contraction, and supply chain interruptions, this study aims to deliver evidence-based insights that can inform policy design, strengthen the resilience of strategic infrastructure, and guide future investment in hazard-prone zones (Mizutori, 2020).

The contribution of this paper is threefold. First, it demonstrates a structured methodology for integrating disaster risk into infrastructure valuation, bridging a critical gap between disaster science and infrastructure economics. Second, it generates empirical evidence on the scale and nature of potential tsunami-related economic losses at YIA, providing a foundation for resilience-oriented investment. Third, it offers policy-relevant recommendations for embedding DRR into the planning of National Strategic Projects in Indonesia. Ultimately, the case of YIA illustrates the broader imperative of aligning infrastructure development with disaster resilience to ensure that strategic investments enhance rather than undermine long-term sustainable development.

2. Methods

Yogyakarta International Airport (YIA) is located in Kulonprogo Regency, Special Region of Yogyakarta (DIY), covering an area of approximately 600 hectares. The airport lies along the southern coastline of Java Island, characterized by predominantly flat coastal morphology. The nearest coastal zones adjacent to YIA include Congot Beach and Glagah Beach, which serve as natural boundaries of the airport's surroundings. This geographical setting, while favorable for large-scale airport construction, simultaneously increases exposure to multiple coastal and seismic hazards (Koller, 2022). Several active faults are situated in the vicinity of the airport, thereby creating a significant potential for seismic hazards such as earthquakes and their secondary coastal impacts. Based on its geographical and geological conditions, the YIA coastal zone particularly around Glagah and Congot Beaches faces multiple hazards, including earthquakes, tsunamis, flooding, and coastal abrasion, as well as other events such as extreme weather and indirect consequences from volcanic eruptions (Islam et al., 2022). The combination of seismic and hydro-meteorological risks makes the YIA region highly vulnerable to disaster impacts (Lim et al., 2023; Frankhouser, 2021).

The southern region of Central Java, including Kulonprogo Regency and its surrounding areas, has long been recognized as one of the most seismically active regions in Indonesia. Its proximity to the subduction zone of the Indo-Australian and Eurasian plates further amplifies the tsunami risk, while low-lying coastal areas heighten susceptibility to inundation. This hazard context underscores the importance of incorporating comprehensive disaster risk assessments into the planning and operation of YIA, ensuring resilience not only for aviation facilities but also for the surrounding communities and economic activities (BNPB, 2019).

Fig. 1.Research location

Tsunami hazard modeling for the Yogyakarta International Airport (YIA) region was conducted using the Cornell Multi-Grid Coupled Tsunami Model (COMCOT), a widely recognized numerical model for simulating tsunami dynamics. COMCOT has been extensively applied in both research and operational contexts, including the 2004 Indian Ocean tsunami in Aceh (Rasyif et al., 2023) and the development of early warning system scenarios for the South China Sea (Lin et al., 2015). The model was employed to simulate tsunami wave propagation, arrival time, maximum wave amplitude, and inundation extent.

Data processing with COMCOT was carried out by the Indonesian Agency for Meteorology, Climatology, and Geophysics/*Badan Meteorologi, Klimatologi, dan Geofisika* (BMKG), which has adopted this tool for official tsunami hazard assessment and scenario development.

The tsunami hazard modeling in this study utilized several key datasets that served as boundary and initial conditions for the simulations. These included bathymetric data to represent seabed topography, Digital Elevation Model (DEM) data to capture coastal and nearshore terrain, and fault source parameters or deformation models that define the tsunami-generating mechanism associated with seismic rupture. These datasets were integrated into the COMCOT framework and processed numerically, with all computations executed using Fortran-based code to ensure efficiency and stability in solving large-scale simulations. The integration of these diverse datasets allowed the model to accurately reproduce the physical environment in which tsunami waves are generated and propagated.

At the core of COMCOT, the Nonlinear Shallow Water Equations (SWE) are employed as the governing hydrodynamic equations (Ward, 2011). These equations describe the conservation of mass and momentum in shallow water systems, providing the mathematical foundation for simulating tsunami generation, wave propagation across ocean basins, and subsequent inundation of coastal areas. Through this formulation, the model is capable of estimating critical parameters such as tsunami arrival times, maximum flow depths, and inundation extents, which are essential for assessing the potential impacts on Yogyakarta International Airport (YIA) and its surrounding coastal regions. By combining robust physical inputs with validated numerical methods, the modeling framework provides reliable outputs that form the basis for subsequent risk and economic impact assessments (Hoyos, 2022; Olbert et al., 2017).

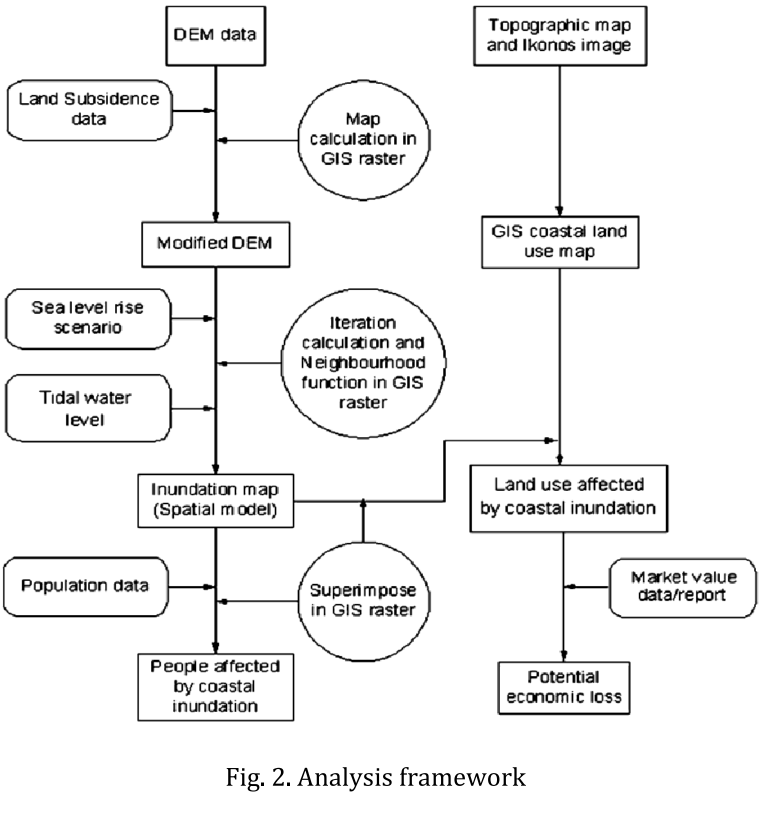

Fig. 2. Analysis framework

The coastal inundation and economic loss assessment employed an integrated geospatial and economic modeling framework. The foundation of the analysis was the Digital Elevation Model (DEM), which provides a gridded representation of coastal terrain. Since elevation data are sensitive to vertical ground movements, the DEM was corrected for land subsidence rates, producing a modified DEM. If z(x,y) denotes the original elevation at grid point (x,y) and s(x,y) the subsidence value, the corrected elevation is expressed as:

$$z^*(x,y) = z(x,y) - s(x,y) \quad \text{(Eq.1)}$$

Inundation scenarios were generated by incorporating tidal water levels and sea-level rise (SLR) projections into the modified DEM. The effective water surface elevation was expressed as:

$$\eta(x,y) = \eta tide + \eta SLR \quad \text{(Eq.2)}$$

Where ηtide is the tidal water level and ηSLR is the incremental rise in mean sea level under future climate scenarios. Areas satisfying the condition $\eta(x,y) > z^*(x,y)$ were identified as inundated zones. Iterative raster calculations were applied within a GIS environment to capture the connectivity of water flow, using neighborhood functions to simulate lateral water spreading across adjacent cells.

The result of these geospatial operations was an inundation map (Ω_inund), representing the spatial extent of coastal flooding under each scenario. This inundation footprint was then overlaid with population distribution data, derived from census-based grids, to estimate the number of people exposed. The affected population was calculated as:

$$P_{aff} = \Sigma(x,y \in \Omega inund)\ p(x,y) \quad \text{(Eq. 3)}$$

where p(x,y) denotes the population count in grid cell (x,y). This enabled the quantification of the human dimension of risk, identifying communities most likely to experience displacement or loss of livelihood.

In parallel, the inundation map was superimposed with coastal land-use maps, which were derived from topographic data and high-resolution satellite imagery (e.g., Ikonos). This spatial overlay yielded the set of land-use categories directly affected by inundation (L_aff). Each land-use class was associated with an economic function and corresponding asset value per unit area (V_k). The proportion of affected land use was quantified as:

$$Ak\hat{\ }aff = \Sigma(x,y \in \Omega inund \cap \Omega\_k)\ a(x,y) \quad \text{(Eq. 4)}$$

Where a(x,y) is the cell area, and Ω_k is the footprint of land-use class k. To translate physical exposure into economic losses, depth–damage relationships were applied. For each land-use class k, the economic loss was estimated as:

$$Lk = Vk \cdot \delta k(dmax) \quad \text{(Eq. 5)}$$

Where dmax is the maximum inundation depth in the affected area, and δk(d) is a depth–damage function ranging from 0 (no damage) to 1 (total damage). The economic loss assessment built upon these hazard outputs by overlaying inundation maps with asset exposure data. A damage-based valuation framework was applied, in which losses were classified by asset categories: residential buildings, agricultural land, and public infrastructure. For each category, depth–damage functions were used to translate inundation depths into proportional damage rates, which were then multiplied by the replacement value of exposed assets. The total direct economic loss was estimated as the sum of damages across all affected assets, while particular attention was given to National Strategic Projects (Proyek Strategis Nasional, PSN), which were assigned higher weights due to their role in supporting regional and national economic functions.

In addition, the framework allows for the calculation of expected annual damage (EAD) when multiple tsunami scenarios with associated probabilities are considered. This probabilistic approach integrates hazard frequency with economic exposure to provide long-term risk estimates.

This study adopts the Total Economic Value (TEV) framework to estimate the potential economic consequences of a hypothetical tsunami event affecting Yogyakarta International Airport (YIA). The TEV framework provides a comprehensive structure by distinguishing three major categories of losses. Direct losses refer to the immediate physical damages sustained by critical infrastructure such as runways, aprons, and terminal facilities. Indirect losses capture the wider economic repercussions beyond the physical site, including disruption of airport operations, reduced tourism flows, and adverse impacts on small and medium enterprises (SMEs) that depend on airport connectivity. Finally, intangible losses encompass non-market values that are often overlooked but equally significant, such as the erosion of social cohesion, the loss of cultural heritage, and degradation of ecosystems that support coastal resilience. This study applies a structured approach to estimate the potential economic losses from a disaster event. The framework accounts for both human impacts and physical damages, using the following formulas (UN, 2013; Freeman et al., 2014; Gall, 2015; Mitchell-Wallace, 2017; Hirsch, 2017):

Table 1. Formula for valuation economic loss

No	Component	Formula
1	Fatalities	Ldeath = Ndeath × VSL where Ndeath is the number of fatalities and VSL is the value of a statistical life.
2	Injuries	Linjury = (Nminor × Cminor) + (Nsevere × Csevere) where Nminor is the number of minor injuries, Cminor is the unit cost of minor injury, Nsevere is the number of severe injuries, and Csevere is the unit cost of severe injury
3	Affected People	Laffected = Naffected × ER × PPD where N_affected is the total number of people affected (excluding deaths and injuries), ER is the employment rate in the affected area, and PPD is productivity per person per day.
4	Damage to Buildings	Lphysical = Σ (Hti × DUVi) + (Hti × HUPi) where Hti is the number of houses/buildings by type, DUVi is the unit damage value per building type, and HUPi is the replacement cost per unit of each building type
5	Total Economic Losses	Ltotal = Ldeath + Linjury + Laffected + Lphysical

Table 1 outlines the formulas used to estimate the economic losses resulting from disasters. The first component, fatalities, is valued using the Value of a Statistical Life (VSL), which monetizes the loss of human life based on the number of deaths (Ndeath) multiplied by VSL. The second component, injuries, accounts for both minor and severe cases. It is calculated by multiplying the number of minor injuries by the unit cost of minor injury (Cminor), and the number of severe injuries by the unit cost of severe injury (Csevere). The third component, affected people, represents the economic loss from disruption of livelihood and productivity among survivors who are not injured or killed. This is derived by multiplying the total affected population (Naffected) by the employment rate (ER) and average daily productivity per person (PPD).

The fourth component, damage to buildings, evaluates physical losses based on two perspectives: the unit damage value (DUVi) and the replacement cost (HUPi) for each building type, multiplied by the number of affected units (Hti). Finally, the total economic loss (Ltotal) is obtained by summing all components: fatalities, injuries, affected people, and physical damages. This structured approach ensures a comprehensive valuation that captures both human and material impacts of a disaster.

To operationalize this framework, the analysis integrates multiple datasets, including hazard maps derived from tsunami inundation modeling, spatially explicit economic profiles of exposed sectors, and infrastructure vulnerability assessments conducted through GIS-based tools. By overlaying physical hazard layers with socio-economic data, the study identifies which assets and communities are most at risk, while also quantifying the magnitude of exposure across different TEV dimensions. This spatially integrated approach allows the analysis to capture both measurable financial losses and harder-to-quantify social and environmental impacts, ensuring that the resulting estimates reflect the full spectrum of tsunami risk.

3. Results and Discussion

Indonesia is globally recognized as one of the most disaster-prone countries due to its geotectonic position at the confluence of the Indo-Australian, Eurasian, and Pacific tectonic plates. This unique geological setting makes the archipelago highly susceptible to seismic activity, volcanic eruptions, and tsunami hazards. Among the regions frequently affected is Yogyakarta, a cultural and economic hub located on the southern coast of Java. Historical and contemporary records demonstrate that this region has experienced repeated destructive earthquakes, with significant implications for human security, infrastructure resilience, and regional development. According to historical data from the Meteorology, Climatology, and Geophysics Agency (BMKG), a devastating earthquake struck Yogyakarta and its surrounding districts, Bantul, Klaten, Gunung Kidul, and Kulon Progo on May 27, 2006. The seismic event occurred at 05:53:58 local time, with an epicenter located at 8.04° South Latitude and 110.43° East Longitude, at a depth of 33 km, and a magnitude of 5.9 Mb. Despite its moderate magnitude compared to other megathrust events in Indonesia, the shallow depth and proximity to densely populated areas amplified its destructive impact. The disaster caused 5,857 fatalities, left 37,229 people with severe injuries, and thousands more with minor injuries. Furthermore, it resulted in massive infrastructure damage, with 135,451 buildings reported as heavily damaged and an additional 188,234 buildings suffering partial damage (Islam et al., 2022).

The 2006 Yogyakarta earthquake is not an isolated event. Historical records indicate that the region has been struck by at least four major destructive earthquakes: in 1867, 1943, 1981, and 2006. Each of these events registered maximum intensities ranging from VII to IX on the Modified Mercalli Intensity (MMI) scale, highlighting the persistent seismic risk in the area. The 1867 event, for example, devastated large parts of Yogyakarta city, while the 1943 earthquake caused widespread structural damage across central Java. The recurrence of such destructive events underscores the need for long-term seismic preparedness and urban planning that integrates disaster risk reduction strategies.

While the seismic hazard is well documented, Yogyakarta is also vulnerable to secondary hazards such as tsunamis, particularly given its location along the southern coast that directly faces the Indian Ocean. Tsunami scenarios modeled for the region suggest that waves could reach a maximum height of 14 meters. Such an event would have catastrophic implications for critical infrastructure, including airports that serve as vital hubs for both passenger mobility and cargo distribution. Simulation results indicate that a tsunami of this scale could inundate the entire runway, taxiway, and apron areas of the Yogyakarta International Airport (YIA). Inundation depths could reach up to 10 meters in these sections, rendering them inoperable for an extended period. The inability to use these facilities would not only disrupt aviation operations but also impede emergency response, humanitarian logistics, and economic activities dependent on regional connectivity.

Interestingly, the modeled scenario shows that the airport's terminal building would be relatively less affected. The flood depth in the terminal area is projected to be approximately 1 meter, which, although disruptive, is not as catastrophic as the conditions on the airside infrastructure. Moreover, the inundation does not extend significantly into the parking areas or further northward. This discrepancy in exposure suggests that mitigation and adaptation strategies could prioritize strengthening and elevating airside facilities, while simultaneously ensuring that landside facilities remain functional for emergency coordination and passenger management during post-disaster recovery.

The combination of earthquake and tsunami risks highlights the multi-hazard environment in which Yogyakarta is situated. Earthquakes of shallow depth near urban centers cause direct casualties and infrastructure losses, while secondary hazards such as tsunamis compound the disaster's socio-economic consequences. The 2006 earthquake serves as a critical reminder of the region's vulnerability, given that the majority of fatalities were attributed to building collapses rather than secondary hazards. This emphasizes the importance of resilient building codes, community preparedness, and retrofitting of existing structures. In contrast, the tsunami scenario underscores the need for coastal zone management, protective infrastructure, and the integration of airport resilience planning within broader disaster risk management frameworks.

From an economic perspective, the consequences of such hazards are profound. The destruction of housing, commercial facilities, and public infrastructure leads to direct economic losses, while the disruption of transportation networks, tourism, and small and medium enterprises generates significant indirect losses. In the context of Yogyakarta, which is both a major tourist destination and an educational center, the impacts of prolonged disruption could extend beyond the local economy to affect national growth. Moreover, airports like YIA serve as gateways not only for tourism but also for trade, medical evacuations, and emergency aid distribution, amplifying the cascading effects of their disruption.

In conclusion, the historical and potential future hazards in Yogyakarta underscore the urgency of integrating disaster risk reduction into urban development and infrastructure planning. The recurrent pattern of damaging earthquakes highlights the need for continuous public education, structural resilience measures, and preparedness programs. Meanwhile, the tsunami scenario demonstrates the vulnerability of critical infrastructure such as airports, where even limited inundation can halt operations with far-reaching consequences. By combining seismic risk assessment, tsunami modeling, and infrastructure vulnerability analysis, policymakers and planners can develop more comprehensive strategies to safeguard both human lives and economic assets. Such integrated approaches are essential for achieving sustainable development and resilience in one of Indonesia's most hazard-prone yet economically and culturally significant regions.

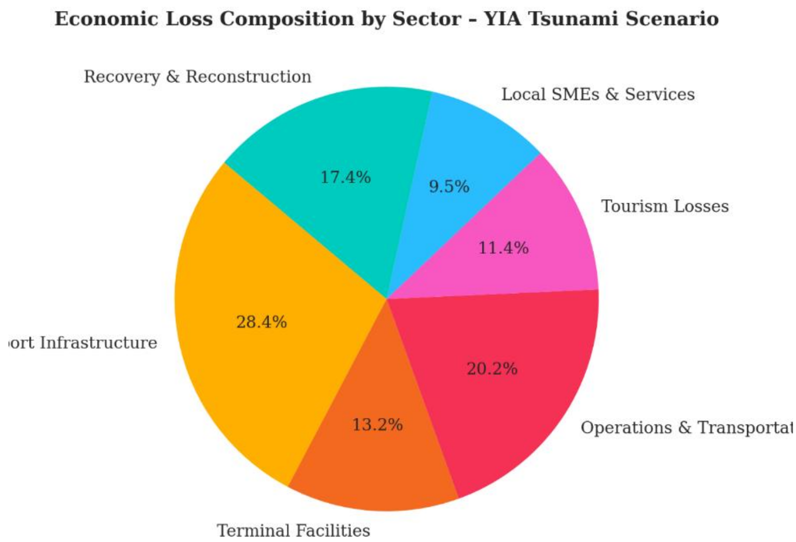

Fig. 3.Economic loss by sector

The analysis of economic loss composition under the YIA tsunami scenario demonstrates that airport infrastructure constitutes the largest share of potential losses, accounting for 28.4% of the total. This reflects the high vulnerability and replacement costs associated with critical physical assets such as runways, taxiways, and apron facilities, which are indispensable for sustaining aviation operations. Damage in this sector not only requires substantial reconstruction efforts but also triggers cascading effects on airport functionality. The second largest component is operations and transportation, contributing 20.2% of the total losses. This category captures the interruption of passenger mobility, cargo distribution, and associated transportation services such as taxis, airport trains, and shuttle buses. The interdependency between airport facilities and regional connectivity amplifies the scale of indirect losses. Recovery and reconstruction costs also represent a significant proportion, estimated at 17.4%, as post-disaster rehabilitation involves both immediate restoration and long-term resilience-building measures. Other important components include terminal facilities (13.2%), which face inundation risks that directly impact passenger and cargo processing activities, and tourism losses (11.4%), stemming from reduced visitor arrivals due to operational disruption. Meanwhile, local SMEs and service providers represent 9.5% of the losses, reflecting the economic fragility of businesses that depend on airport activity. Collectively, the composition underscores that while direct infrastructure damage is the dominant factor, indirect and induced economic impacts, particularly on operations, tourism, and local services are equally critical in shaping the overall magnitude of tsunami-related losses at YIA.

The findings emphasize that a single disaster event could severely impact regional mobility and economic stability, making it essential to incorporate disaster risk assessments in the planning phase of PSNs. The location of Yogyakarta International Airport (YIA) on the southern coast of Java inherently places it within a zone of high geological and hydrometeorological risk. To estimate potential economic losses, the study applies the Total Economic Value (TEV) framework in combination with scenario-based hazard modeling. Within this formulation, losses are categorized into direct and indirect impacts. Direct economic losses refer to immediate damages to airport infrastructure, including the runway, taxiway, apron, terminal, and support facilities, which manifest as both physical destruction and operational disruption. Indirect economic losses represent secondary effects stemming from the disruption of airport operations, such as reduced passenger flows, halted cargo logistics, diminished revenues in surrounding businesses—hotels, restaurants, and retail outlets—and broader declines in the tourism sector. These losses are further estimated under four tsunami hazard scenarios with a maximum wave height of 22 meters, selected based on hydrodynamic modeling outputs and regional geological assessments to reflect both moderate and extreme events.

The tsunami hazard modeling indicates that a maximum tsunami height of 22 meters would enable water to inundate the entirety of Yogyakarta International Airport (YIA). At the airport itself, tsunami waves could reach a height of approximately 12 meters, with an estimated travel time of 35 minutes from the source to the facility. Among the airport components, the apron and runway are identified as the most vulnerable areas to inundation, given their ground-level location and direct exposure to floodwaters. The spatial extent of inundation highlights the importance of considering not only physical exposure but also the cascading operational impacts that arise when critical airport functions are disrupted. Public areas and vital facilities of YIA were assessed for their disaster vulnerability, with priority given to assets essential for operational continuity. These include the passenger terminal, office spaces, cargo warehouses, and apron areas. Flooding of the apron and runway would render the airport unable to accommodate aircraft landings and take-offs, effectively halting passenger mobility and disrupting cargo distribution activities. Inundation of the cargo terminal, which is located at ground level, would further exacerbate economic losses through damage to stored goods and delays in supply chain operations. Such disruptions illustrate how direct physical damage translates into significant economic and logistical consequences for both the aviation sector and the wider regional economy.

Supporting infrastructure within the airport complex is also potentially at risk from tsunami inundation. Facilities such as the Air Traffic Control (ATC) tower, the airport railway station, firefighting units, fuel storage facilities, and parking areas represent key nodes of airport operations. Although the railway station, constructed at approximately 17 meters above sea level (Mdpl), is likely to remain outside the inundation zone, other ground-level facilities are more susceptible. Similarly, the ATC tower, located at around 20 Mdpl, would likely be protected from direct wave impact, with only its lower levels potentially affected. These variations in elevation underscore the differential vulnerability of airport subsystems, reinforcing the need for site-specific disaster preparedness measures tailored to both critical and supporting infrastructure.

Table 2. Total economic loss

No	Loss	Component	Formula	Value	Economic Loss
1	Direct economic loss	Runway, taxiway, and apron damage	Damage area (m^2)	243.750	243,750,000,000
			Unit price (IDR)	1,000,000	
			Percentage (%)	100%	
		YIA's income loss			
		Aero & Non-Aero	Passenggers (Peoples/day)	11,000	123,750,000,000
			Airport tax, rental, concessions, utilities, and parking (IDR)	125,000	
			Recovery period (days)	90	
		Cargo	Cargo revenue (IDR/day)	20,000,000	1,800,000,000
			Recovery period (day)	90	
2	Indirect economic loss	Loss of net revenue during the recovery period in several service sectors			
		1. Airport Transportation Sector			
		a. Train	Average revenue (IDR/Day)	34,000,000	3,060,000,000
		b. Taxi	Average revenue (IDR/Day)	64,000,000	5,760,000,000
		c. Special rental transport	Average revenue (IDR/Day)	51,000,000	4,590,000,000
		d. Satelku	Average revenue (IDR/Day)	26,000,000	2,340,000,000
		e. Damri	Average revenue (IDR/Day)	37,000,000	3,330,000,000
		f. Online taxi	Average revenue (IDR/Day)	30,000,000	2,700,000,000
		Recovery period (Days)		90	
		2. Retail otlet	Number of outlet (outlet)	10	7,200,000,000
			Average revenue (IDR/Day)	8,000,000	
			Recovery period (days)	90	
		3. Hotels	Number of hotels (units)	4	18,000,000,000
			Average revenue (IDR/Day)	50,000,000	
			Recovery period (days)	90	
		4. Restaurants	Number of restaurant (restaurant)	10	9,000,000,000
			Number of restaurants (units)	10,000,000	
			Total revenue (IDR/Day)	90	
		5. Income loss	Number of affected households (HH)	121	178,360,380
			Duration of unemployment (days)	90	

			Standard wage (IDR)	1,981,782	
		6. Decline in tourism revenue	Number of air travelers (persons/day)	128	288,000,000
			Recovery period (days)	90	
			Entrance ticket (IDR)	25,000	
3	Indirect Non-Economic Losses	Human casualties			
		Injured victim	Injured victims (persons)	4,000	4,000,000,000
			Cost of minor injuries (IDR)	500,000	
			Severe injuries (persons)	200	
			Cost of severe injuries (IDR)	10,000,000	
Total Economic Loss					429,746,360,380

This study employs a scenario-based disaster risk assessment combined with the Total Economic Value (TEV) framework to estimate potential losses at Yogyakarta International Airport (YIA) under extreme tsunami conditions. Primary hazard data were derived from the Meteorology, Climatology, and Geophysics Agency (BMKG) and supplemented with hydrodynamic tsunami modeling results specific to the southern coast of Java. Historical earthquake and tsunami records (1867, 1943, 1981, 2006) were also reviewed to contextualize the hazard scenarios. The extreme inundation scenario of a 22-meter tsunami was selected based on regional geological assessments and modeling outputs, representing a worst-case condition for YIA's location on the coastal plain.

The TEV approach was applied to capture both direct and indirect economic losses. Direct losses include physical damage to airport infrastructure such as runways, taxiways, aprons, terminals, and support facilities. Indirect losses account for revenue disruption in aviation operations, passenger mobility, cargo logistics, tourism, and surrounding service sectors such as hotels, restaurants, and retail outlets. Non-economic losses were also included, covering casualties and injury-related costs. The valuation formulas used in this study follow widely applied disaster economics methods (e.g., Ldeath = Ndeath × VSL; Linjury=(Nminor×Cminor)+(Nsevere×Csevere); Lphysical = Σ(Hti×DUVi) + (Hti×HUPi)), ensuring comparability with previous research.

Data inputs included passenger and cargo statistics from airport operations reports, revenue figures from transportation and service providers, and productivity metrics from regional economic surveys. The recovery period was conservatively estimated at 90 days, consistent with post-disaster operational benchmarks in comparable aviation disruptions. This structured methodology enables a comprehensive estimation of both tangible and intangible losses, thereby supporting a robust evaluation of YIA's vulnerability to tsunami hazards.

The 22 meter scenario represents an extreme, worst-case event. With wave heights exceeding 12 meters at the airport site and an arrival time of approximately 35 minutes, this tsunami would inundate nearly all facilities. The estimation of economic losses under the inundation scenario for Yogyakarta International Airport (YIA) reveals substantial sectoral variation in potential damages. The airport infrastructure category emerges as the most affected, with projected losses of approximately IDR 450 billion. This reflects the high replacement and repair costs associated with critical assets such as runways, taxiways, and aprons, which are directly exposed to flooding and essential for maintaining aviation operations.

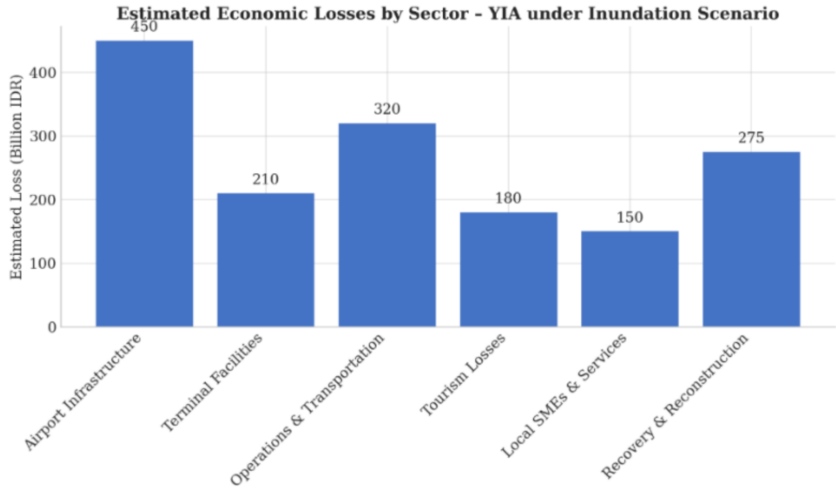

Fig. 4. Estimated economic losses

The second largest source of losses is operations and transportation, estimated at IDR 320 billion, followed by recovery and reconstruction efforts at IDR 275 billion. These figures emphasize the dual burden of both immediate operational disruption and the significant financial commitment required for post-disaster rehabilitation. Terminal facilities contribute an additional IDR 210 billion in losses, highlighting the vulnerability of passenger terminals, cargo warehouses, and related ground facilities that are typically located at or near ground level. Beyond direct infrastructure and operations, the broader economy also faces notable impacts. Tourism losses are projected at IDR 180 billion, reflecting reduced visitor arrivals and travel disruptions. Local SMEs and service providers, many of which rely heavily on airport activity, are estimated to incur losses of IDR 150 billion. Although smaller in magnitude compared to infrastructure-related costs, these categories represent the wider socio-economic consequences of tsunami inundation, particularly in terms of disrupted livelihoods and weakened regional economic activity. Collectively, the distribution of losses demonstrates that while physical infrastructure bears the heaviest burden, indirect and induced impacts across services, tourism, and reconstruction are equally critical in shaping the overall economic risk profile of YIA.

The findings of this study highlight the profound vulnerability of Yogyakarta International Airport (YIA) to tsunami hazards, with potential economic losses exceeding IDR 429 billion under the extreme scenario of a 22-meter wave. The dominance of direct infrastructure losses, particularly damage to runways, taxiways, and aprons, underscores the sensitivity of aviation infrastructure to coastal inundation. These components are indispensable for flight operations, and their damage not only incurs high replacement costs but also initiates cascading operational disruptions. This pattern is consistent with previous disaster studies, where infrastructure failure serves as the primary driver of economic paralysis in critical facilities.

Beyond infrastructure, the study demonstrates the magnitude of indirect and induced economic impacts. Losses in operations and transportation (20.2%) illustrate how quickly service disruptions propagate through interconnected systems, affecting airport trains, taxis, shuttle buses, and other transport modes that link the airport to the broader economy. Similarly, the decline in tourism (11.4%) and losses among SMEs and service providers (9.5%) reveal the fragility of economic activities that depend on airport connectivity. Such findings align with the concept of “ripple effects” in disaster economics, where damage to a central node such as an airport generates disproportionate impacts across multiple sectors, particularly in regions where tourism and service industries form a significant share of local livelihoods.

The analysis further emphasizes the financial burden of recovery and reconstruction, which accounts for 17.4% of losses. Post-disaster recovery not only involves immediate repair but also the integration of resilience-building measures to reduce future risk. This dual financial demand reflects the growing recognition that reconstruction is both a cost center and an opportunity to embed disaster risk reduction principles. The results suggest that future investments in YIA must prioritize not only structural mitigation measures, such as elevated facilities and reinforced critical infrastructure, but also non-structural strategies, including emergency planning, redundancy in operations, and business continuity management.

These findings have critical policy implications. As YIA is classified as a National Strategic Project (PSN), its functionality extends beyond local mobility to regional and national economic stability. The TEV-based assessment confirms that economic risk is not confined to direct damages but includes indirect and intangible components that must be factored into investment decisions. Integrating comprehensive disaster risk assessments into the planning and operation of PSNs is therefore essential to safeguard economic resilience. This is particularly urgent given YIA's geographical setting along the southern coast of Java, where the convergence of seismic, hydrometeorological, and climate-related hazards places the airport in a multi-hazard risk zone.

Finally, the differential vulnerability of airport subsystems—such as the relatively lower risk faced by elevated structures like the ATC tower and railway station compared to ground-level facilities—illustrates the importance of site-specific disaster preparedness. Tailoring mitigation strategies to varying levels of risk within the airport complex could substantially reduce total economic losses. Overall, the study underscores that resilience at YIA requires a multi-dimensional approach: strengthening physical infrastructure, safeguarding interconnected economic sectors, and institutionalizing risk-informed planning in airport and regional development strategies.

4. Conclusions

This study demonstrates that Yogyakarta International Airport (YIA), due to its geographical location on the southern coast of Java, is highly vulnerable to tsunami hazards. The hazard modeling scenario with a maximum wave height of 22 meters shows that nearly all airport facilities could be inundated, with wave heights reaching 12 meters at the airport site and an arrival time of approximately 35 minutes. Critical infrastructure, such as runways, taxiways, and aprons, are identified as the most vulnerable components, where inundation would immediately disrupt aviation operations and trigger cascading effects on passenger mobility and cargo distribution.

The application of the Total Economic Value (TEV) framework, supported by scenario-based hazard modeling, reveals a wide spectrum of losses that extend beyond physical damage. The largest share of estimated losses arises from airport infrastructure (IDR 450 billion), followed by operations and transportation (IDR 320 billion) and recovery and reconstruction (IDR 275 billion). Other components include terminal facilities (IDR 210 billion), tourism (IDR 180 billion), and local SMEs and services (IDR 150 billion). In total, the estimated economic loss under the extreme scenario amounts to approximately IDR 430 billion, reflecting both direct and indirect consequences. While direct infrastructure damage dominates, the study also underscores the significance of indirect and induced impacts, particularly in tourism, SMEs, and service sectors, which affect regional economic stability and livelihoods.

Overall, the findings highlight the urgent need to integrate disaster risk assessment into the planning and operation of National Strategic Projects (PSNs), particularly for critical infrastructure such as airports located in hazard-prone areas. Enhancing preparedness measures, strengthening physical resilience, and developing recovery strategies tailored to both critical and supporting infrastructure are essential to minimize economic disruption. By combining hazard modeling with an economic valuation framework, this study provides a comprehensive basis for evidence-based decision-making in disaster risk reduction and infrastructure investment, ensuring that YIA can remain operationally and economically resilient in the face of future tsunami events.Hazard exposure analysis demonstrates that YIA is acutely vulnerable to tsunamis, with minimal lead time, significant inundation depths, and widespread asset exposure. Estimated economic losses span airside and landside infrastructure, compounded by severe multiplier effects across tourism, logistics, and the regional economy. Scenario comparison confirms that investing in DRR yields disproportionately high benefits, both in avoided losses and accelerated recovery.

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Author Contribution

Conceptualization: W.B. and M.F.R.; Methodology: W.B. and M.F.R.; Data curation: W.B. and M.F.R.; Formal analysis: W.B.; Investigation: W.B. and M.F.R.; Resources: W.B. and M.F.R.; Writing, review & editing: W.B.

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The datasets supporting the findings of this study, including hazard modeling outputs and economic loss calculations, are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflict of interest.

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