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Review Article

Advancing Tsunami Vulnerability Modelling: A Systematic Review and Bibliometric Analysis of Remote Sensing and GIS Applications

  Nurhasanah Tika^{1,2✉},   Nagara Rakyan Paksi^{1,2} & Dimyati Muhammad¹

¹ Department of Geography, Faculty of Mathematics and Natural Sciences, Universitas Indonesia, Depok, Indonesia

² Geospatial Information Agency, Bogor, Indonesia

✉ Correspondence: tika.nurhasanah32@ui.ac.id

Abstract: This study conducts a systematic review and bibliometric analysis of tsunami vulnerability modelling using remote sensing and Geographic Information Systems (GIS) to assess research trends, methodologies, and challenges in disaster risk assessment. Sixty-six articles published between 2014 and 2024 were analyzed from the Scopus database, revealing an increasing reliance on geospatial technologies for tsunami hazard mapping, vulnerability assessment, and risk mitigation. The findings highlight the dominance of GIS-based spatial analysis and numerical modelling techniques, with remote sensing providing critical data for hazard simulations. The study also identifies a growing trend in integrating machine learning with GIS to enhance tsunami risk prediction and improve early warning systems. Despite technological advancements, challenges persist, particularly in ensuring data accessibility, standardizing vulnerability assessment frameworks, and addressing socio-economic disparities in disaster resilience. The review emphasizes the need for interdisciplinary collaboration to develop adaptive and inclusive approaches, particularly in regions with limited technical capacity. Furthermore, multi-hazard vulnerability frameworks are gaining prominence, incorporating tsunami risks alongside coastal hazards such as storm surges and sea-level rise. This study underscores the critical role of remote sensing and GIS in advancing tsunami vulnerability modelling while highlighting existing research gaps. Future research should improve model accuracy, integrate real-time environmental data, and develop innovative solutions to enhance community preparedness and coastal resilience. By synthesizing recent studies and analyzing emerging trends, this paper provides valuable insights for researchers, policymakers, and disaster management practitioners working to mitigate tsunami risks in vulnerable coastal areas.

Keywords: systematic literature review; bibliometric analysis; tsunami vulnerability; Geographic Information System (GIS); remote sensing; disaster risk assessment; machine learning

Highlights:

- Tsunamis cause significant damage to coastal regions, impacting lives and economies.
- Remote sensing and GIS are essential tools for assessing tsunami vulnerability.
- Geospatial technologies improve disaster preparedness and coastal resilience strategies.

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1. Introduction

Tsunamis are one of the most destructive natural disasters, causing damage in heavily populated and economically significant coastal areas (Benazir et al., 2024). This calamity may result in loss of life, property destruction, and long-term socioeconomic consequences (Rafliana et al., 2022). Climate change and geological movements have raised concerns about rising tsunami frequency and intensity, necessitating improvements in risk assessment (Krichen et al., 2024). Remote sensing and Geographic Information Systems (GIS) have become indispensable in this regard, providing tremendous capabilities for collecting, analyzing, and visualizing spatial data that are critical for assessing the vulnerability of coastal areas to tsunamis (Febrina et al., 2020; Muzani et al., 2024). Remote sensing and GIS technology help build detailed vulnerability assessments and maps, guiding preparedness activities and boosting coastal resilience.

In recent years, systematic reviews and bibliometric analyses have gained popularity in disaster research as approaches for synthesizing a significant amount of literature to identify trends in scientific studies (Oh et al., 2020; Yazdani et al., 2024). A systematic review thoroughly assesses existing research, whereas bibliometric analysis provides quantitative insights into publication trends, influential publications, and new research areas (Khan et al., 2023; Shi et al., 2024). These strategies are beneficial in fields such as tsunami vulnerability modelling, where interdisciplinary approaches using geospatial technologies are quickly expanding. For instance, recent studies in disaster risk research have highlighted a growing trend in integrating GIS-based hazard assessments with machine learning techniques to improve prediction accuracy (Liu et al., 2021; Makinoshima et al., 2021; Mulia et al., 2022; Cesario et al., 2024). Additionally, an increasing number of studies have focused on multi-hazard vulnerability

assessments, demonstrating the importance of integrating tsunami risk with other coastal hazards such as storm surges and sea-level rise (Deb et al., 2024; Lin and Singh, 2024; Setiawati et al., 2024; Zhang et al., 2024). These insights illustrate how systematic reviews and bibliometric analyses can uncover emerging research directions and highlight critical knowledge gaps that require further investigation.

The combination of GIS and remote sensing data has emerged as a powerful technique for mapping tsunami vulnerability and using advanced spatial analysis to improve disaster risk management (Eckert et al., 2012; Cankaya et al., 2016; Sambah et al., 2016; Koshimura et al., 2020; Hamouda et al., 2024). GIS enables the overlay of numerous environmental characteristics such as height, slope, land use, and coastline proximity, resulting in detailed vulnerability maps (Muzani et al., 2024; Biswas et al., 2024). These maps are useful for disaster risk management because they identify high-risk locations requiring targeted mitigation actions (Thomas et al., 2021; Ayuningtyas et al., 2021). Remote sensing improves this process by providing real-time data on land cover changes and other dynamic elements that affect tsunami risk (Jitt-Aer et al., 2022; Senjana et al., 2023; Ghadamode et al., 2024). These technologies work together to assist targeted mitigation techniques and proactive planning for effective tsunami risk reduction.

Despite significant developments in remote sensing and GIS-based tsunami modelling, considerable challenges remain, particularly in ensuring the accessibility and practical application of these technologies in vulnerable locations. This is especially true in developing nations, where insufficient technical expertise and resources can prevent efficient implementation (Febrina et al., 2023; Wibowo et al., 2023). A defined framework for conducting vulnerability assessments across different geographic contexts is necessary for consistency and comparability (Guntur et al., 2017). To overcome these limitations, multi-stakeholder collaboration is essential, with researchers, policymakers, and local communities working together to develop inclusive, adaptive, and resource-efficient solutions.

This review study aims to thoroughly analyze existing research on tsunami vulnerability modelling, focusing on integrating remote sensing and GIS technology. Furthermore, it will conduct a bibliometric analysis to identify significant trends in this subject over the past few years, emphasizing influential research and identifying gaps in existing knowledge (Paramesti, 2011; Shi et al., 2024). Using this dual approach, the paper seeks to provide a detailed understanding of how these methodologies have been employed in tsunami risk assessments while also proposing strategies and objectives for future research on this essential topic.

In conclusion, as climate change increases the risk of natural disasters, such as tsunamis, the need for advanced and precise modelling tools to estimate vulnerability at local and regional scales grows (Biswas et al., 2024). The combination of remote sensing and GIS offers a potent way to address these challenges, allowing for extensive spatial analysis and risk evaluations. However, additional innovation is required to improve the accessibility, usability, and adaptation of these technologies, particularly in low-income areas (Wibowo et al., 2023). This work aims to contribute to these efforts by thoroughly evaluating current research, highlighting significant gaps, and providing future directions for tsunami vulnerability modelling using geospatial technology. By synthesizing recent studies and analyzing research trends, this review will provide valuable insights into the evolving landscape of tsunami risk assessment. These advances will considerably boost disaster preparedness and resilience in vulnerable coastal areas while informing policymakers and practitioners on effective mitigation strategies.

2. Literature Review

2.1. Approach to quantifying tsunami hazard potential

A thorough interdisciplinary approach is required to quantify tsunami hazard potential, combining geological, geophysical, and advanced numerical modelling techniques (Grezio et al., 2017; Camargo et al., 2019). Historical tsunami event analysis, comprehensive paleotsunami research, and high-resolution geophysical surveys are essential for understanding fault mechanisms, seafloor topography, and potential tsunami sources (Løvholt et al., 2012; Pranantyo et al., 2021). Historical tsunami statistics offer an understanding of previous disasters by identifying high-risk areas and recurring patterns (Rubin et al., 2017; Daly et al., 2019; Yap et al., 2023). Paleotsunami research contributes to these records by uncovering evidence of ancient tsunami deposits, shedding light on occurrences before written history (Masuda et al., 2022). At the same time, geophysical studies such as seismic reflection and bathymetric mapping reveal fault activity and submerged structures that may cause future tsunamis (Hughes et al., 2024).

These various datasets provide input for sophisticated numerical models, which are crucial for simulating tsunami-generating systems, complex wave propagation patterns, and detailed inundation scenarios in coastal areas (Sugawara, 2021; Zanker et al., 2024; Scala et al., 2024). Numerical models use complex hydrodynamic equations to simulate how seismic energy enters water and travels over the ocean (Honarmand et al., 2020). High-resolution topography and bathymetric data improve the accuracy of these simulations by capturing tsunami waves' interactions with coastal landforms and infrastructure (Xhafaj et al., 2024). Recent advances in processing capacity have enabled the incorporation of real-time data from seismic sensors and ocean buoys, hence boosting early warning and forecasting capacities (Plevris, 2024). These models, which combine probabilistic and deterministic methodologies, may assess immediate consequences and long-term hazards, assisting in creating focused mitigation policies and resilient urban planning for coastal areas (Morasco et al., 2021).

2.2. Indicators to Assess Tsunami Regional Vulnerability

Assessing regional tsunami vulnerability is essential for identifying high-risk areas and developing effective disaster risk reduction strategies (Aguirre-Ayerbe et al., 2018; Benazir & Oktari, 2024). Such studies' geographic, socio-economic, and infrastructure characteristics are vital indicators (Botzen et al., 2019; Biswas and Nautiyal, 2023). Geographic indicators, such as coastline proximity, elevation, and slope, provide critical information about a region's physical vulnerability to tsunami inundation (Bukvic et al., 2020; Anfuso et al., 2021). Low-lying coastal areas and locations with steep underwater gradients are especially vulnerable due to the possibility of increased wave heights (Jevrejeva et al., 2024). Furthermore, historical records of tsunami episodes and the presence of tectonic fault lines can aid in estimating the possibility of future occurrences (Selva et al., 2021). Geographic considerations help identify high-risk locations and inform early warning systems and evacuation plans (Dickson et al., 2012; Trogrlić et al., 2022; UNDRR, 2023).

Furthermore, historical tsunami records and tectonic fault lines can be used to make predictions of future occurrences (Selva et al., 2021). Geographic considerations help identify high-risk locations and inform early warning systems and evacuation plans (Dickson et al., 2012; Trogrlić et al., 2022; UNDRR, 2023). Infrastructural factors such as building resilience, evacuation route availability, and access to emergency services all impact tsunami event outcomes (Cienfuegos et al., 2024; Dias et al., 2024). Insufficiently constructed housing and weak disaster response systems

are more likely to result in higher casualties and longer recovery times (Joseph et al., 2021; Hofmann, 2022). A comprehensive strategy that includes these indicators is critical for identifying susceptible areas and prioritizing resilience-building measures (Ma et al., 2023; Lv & Sarker, 2024; Rathnayaka et al., 2024).

2.3. Advantages of remote sensing and GIS in tsunami hazard and vulnerability modelling

GIS have become important tools in tsunami and vulnerability modelling because they provide extensive, accurate, timely spatial data (Daud et al., 2024). Remote sensing technologies, such as satellite images and LiDAR, allow for detailed mapping of coastal topography, land use, and bathymetry, which is necessary for understanding tsunami inundation patterns and detecting vulnerable locations (Cavalli et al., 2024). These systems can also track changes in coastal environments, such as coastline erosion and urban expansion, that enable dynamic risk assessments (Cavalli, 2024). The capacity to acquire high-resolution data over broad geographic areas assures that remote sensing provides a cost-effective strategy for detecting risk-prone regions, even in areas that are otherwise impossible to access (Shafian & Hu, 2024).

GIS improves the usability of remote sensing by allowing the integration and analysis of various datasets, including demographic, infrastructure, and environmental data (Rezvani et al., 2023). Complex vulnerability models can be created using GIS to simulate tsunami impacts, identify high-risk zones, and assess the exposure of individuals and infrastructure (Sambah and Miura, 2019). GIS can combine wave inundation models with population density maps to locate regions with the highest human exposure and guide emergency response planning (Behrens et al., 2021). Furthermore, GIS provides scenario-based analysis, allowing policymakers to evaluate the effectiveness of various mitigation techniques, such as creating sea barriers or establishing evacuation routes (Kumar et al., 2021). Remote sensing and GIS provide a rigorous framework for comprehensive tsunami risk and vulnerability modelling and support the design of proactive hazard management plans and strengthening community resilience (Daud et al., 2024; Durap & Balas, 2024).

2.4. Trends and Developments in Tsunami Modelling and Vulnerability Research

In recent decades, research on tsunami modelling and vulnerability has developed significantly, especially with the increasing use of geospatial technology and advanced computational methods. Physics-based numerical models, such as COMCOT and MOST, are increasingly used to simulate tsunami wave propagation and its impact on coastal areas (Marras and Mandli, 2020). In addition, integrating Geographic Information System (GIS) and remote sensing data has enabled more accurate spatial analysis in identifying high-risk areas. Recent trends also show the increasing use of artificial intelligence and machine learning in improving the accuracy of tsunami risk prediction and optimizing early warning systems (Linardos et al., 2022; Plevi, 2024). Nonetheless, challenges remain in ensuring that these models are adaptable to different geographical conditions and that adequate data is available in disaster-prone areas.

On the other hand, tsunami vulnerability research increasingly focuses on multidisciplinary approaches that incorporate environmental, social, and economic factors. Recent studies have developed community-based vulnerability indices considering demographics, infrastructure, and community preparedness in tsunamis (Rafliana et al., 2022). In addition, multi-hazard assessment is being applied to understand the interaction between tsunamis and other disasters, such as sea level rise and coastal storms (Reis et al., 2022; Stigler et al., 2023). Real-time data from ocean sensors and satellites has also accelerated information gathering for faster and more appropriate disaster response (Jongsoo et al., 2024). In the future, research in this field needs to focus more on improving the accessibility of technology for developing countries, as well as strengthening collaboration between researchers to create more adaptive and precise models to reduce tsunami impacts in various regions of the world.

2.5. Gaps and Proposed Future Research Directions

Despite significant advancements in disaster risk and vulnerability modelling, several critical gaps remain in improving disaster mitigation efforts. Challenges related to data accessibility and the interconnectivity of diverse datasets continue to hinder progress in disaster risk research (Li et al., 2019). While satellite-based remote sensing can provide global coverage, high-resolution satellite imagery remains limited, particularly in developing countries. Furthermore, developing complex disaster risk models incorporating diverse factors—geology, hydrology, meteorology, land use, social dynamics, economics, and public health—requires a multidisciplinary approach to ensure seamless integration and comprehensive analysis. This review identifies gaps and explores future advancements in tsunami risk modelling and vulnerability assessment research.

3. Materials and Methods

This research uses a Systematic Literature Review (SLR) method. Systematic Literature Review (SLR) is a research method that uses a systematic, transparent, and structured approach to identify, evaluate, and synthesize all scientific evidence related to a specific research question. SLR aims to minimize bias by following strict protocols, from planning to reporting results (Huelin et al., 2015). The first stage of this SLR is a systematic search. A systematic search was conducted on Elsevier's Scopus database using various keywords relevant to the study's research question. Scopus has an extensive database of journals with multiple integrated and global disciplines (Arimjaya and Dimiyati, 2022; Pradana and Dimiyati, 2024). Creating a systematic search strategy is challenging because there needs to be a balance between sensitivity and specificity (Bramer et al., 2018). This search combines keywords and index terms with boolean operators (AND, OR, NOT). For the review results, reporting requirements are as follows: The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method. In line with PRISMA, the bibliometric analysis method is famous for exploring and analyzing large volumes of scientific data. It is essential to understand that though bibliometric analysis is an effective method of summarizing and synthesizing literature, it is not without limitations (Donthu et al., 2021). Bibliometric analysis is limited by database biases, overreliance on quantitative metrics, incomplete coverage of non-English or grey literature, inability to capture contextual nuances, and temporal/geographical skews, necessitating complementary qualitative methods for robust synthesis (Romanelli et al., 2021).

3.1. Data source

This review used the Scopus database because of its credibility in providing a large amount of literature in various disciplines. The data used for the review were search results as of November 18, 2024, with the keywords TITLE-ABS-KEY ("Tsunami" "vulnerability"). The type of publications

used was limited to articles and conference papers. The search results identified 1524 articles and conference papers related to the keywords used. The data generated from the Scopus search was then downloaded in BibTeX format and used for bibliometric analysis.

3.2. Screening

The screening activity itself is carried out to limit the number of papers that we will review according to the keywords we choose so that they match the theme. Papers are limited to publication from 2014-2024, written in English, only for articles, subject area limited to Earth and Planetary Science, and Limited to all open-access. The final query format for this screening was as follows: TITLE-ABS-KEY("Tsunami" "vulnerability") TITLE-ABS-KEY("Tsunami" "modelling") AND PUBYEAR > 2013 AND PUBYEAR < 2026 AND (LIMIT-TO (OA, "all")) AND (LIMIT-TO (PUBSTAGE, "final")) AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "cp")) AND (LIMIT-TO (LANGUAGE, "English")).

3.3. Eligibility

The eligible papers for deep review consisted of 66 papers (Figure 1) with the following criteria: (1) relevant to the topic, (2) included tsunami, remote sensing and GIS, vulnerability and modelling, and (3) included modelling for both tsunami and vulnerability. These final selected articles were reviewed to represent an overview of data, methodologies, variables, and tsunami and vulnerability modelling findings. The in-depth review criteria emphasized megathrust-induced tsunamis. Vulnerabilities reviewed relate to vulnerabilities in coastal areas with various vulnerability weighting methods.

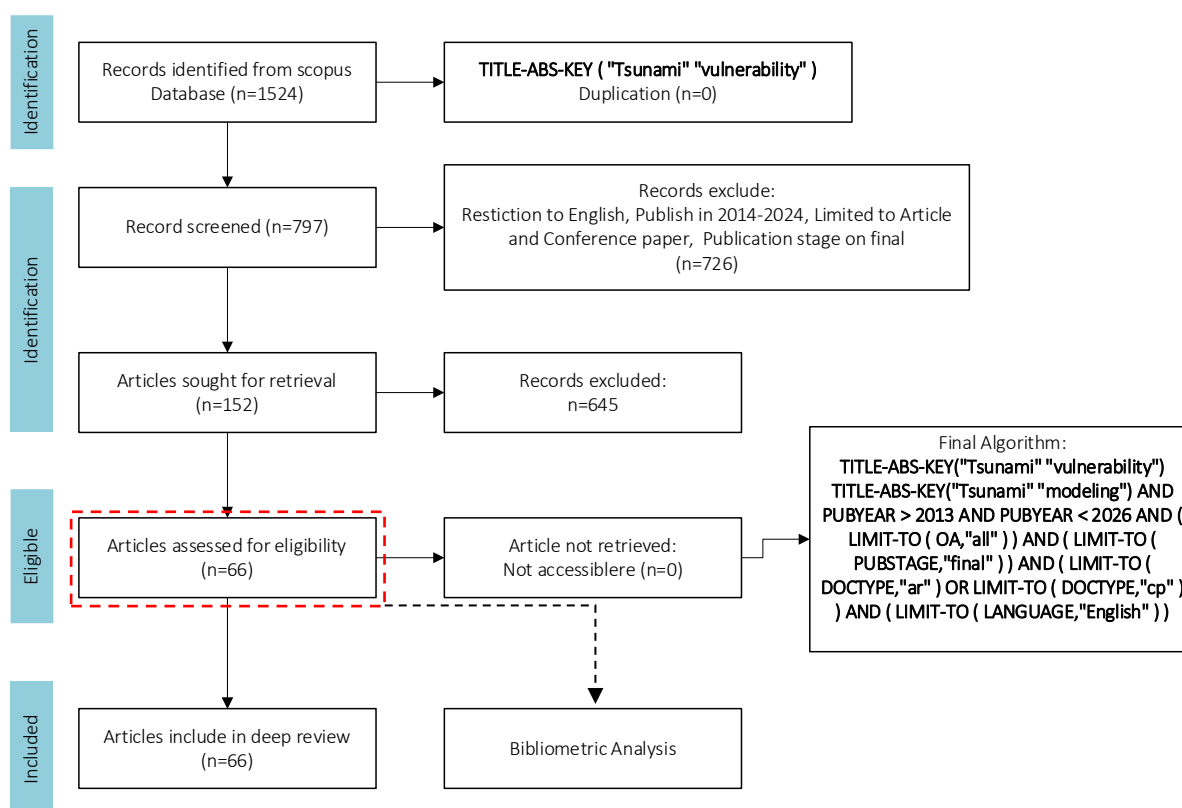


Figure 1. PRISMA flow diagram for systematic literature review and bibliometric analysis on tsunami vulnerability

The diagram above shows the systematic process of screening tsunami vulnerability-related literature using the Scopus database. Starting with 1,524 articles identified by the keywords “Tsunami” and “Vulnerability”, an initial screening was conducted, removing duplicates (0) and limiting to English-language articles, published between 2014-2024, and limited to articles and conference papers (726 articles were eliminated). Of the 797 articles screened, 152 were selected for more in-depth examinations. A further 645 articles were eliminated due to irrelevance, e.g., not covering tsunamis, remote sensing, GIS, or vulnerability modeling. After the eligibility stage, only 66 articles were analyzed in depth using bibliometric analysis, with zero inaccessible articles. Thus, a total of 66 papers were used for the bibliometric process.

4. Results

4.1. Findings

A detailed examination of 66 publications from the database was carried out, with particular emphasis on crucial aspects such as author information, publication year, usage of GIS and remote sensing data, participation in vulnerability analysis, relevant methodology, data kinds, and

primary findings. This systematic review sheds light on these study's methods and outcomes by emphasizing patterns in using geospatial data for tsunami hazard and vulnerability research. Table 1 lists the top ten most-cited works that combine vulnerability assessment, geographic information systems, and remote sensing. These highly referenced studies stress the relevance of spatial analysis in understanding and mitigating tsunami dangers and the significant contributions of GIS and remote sensing technologies in this sector. A widely used method for tsunami modelling is (Cornell Multi-grid Coupled Tsunami) COMCOT, while a comprehensive Post-Tsunami Vulnerability Assessment (PTVA-4) is used for vulnerability modelling. The data involved in tsunami hazard modelling are bathymetry, topography, and earthquake events from historical data to model wave heights under several scenarios. In the calculation of disaster risk, the data involved includes social aspects (population), infrastructure (buildings, roads, public facilities), and economic aspects (land use).

Table 1. Top 10 most cited works in 66 articles: A Summary of Methods, findings, and locations

References	Times cited	Remote Sensing & GIS	Vulnerability assessment	Methods	Data	Findings	Location
Anderson et al., 2018	65	Yes	Yes	- Passive Flooding Model - non-hydrostatic XBeach model - Erosion Model	Sea level scenarios based on IPCC¹ AR5 RCP8.5 projections	- The "bathtub" approach alone misses 35-54% of the total land area at risk - At 0.98m sea level rise: Additional 41.8 km² of land exposed across three islands, O'ahu: 20.1 km², Kaua'i: 15.4 km², Maui: 6.3 km²¹ - Exposure to hazards roughly triples on each island compared to present-day level - The rate of new land exposure approximately doubles from ~30 km²/m to ~60 km²/m as the sea level rises from 0.17m to 0.98m	O'ahu, Kaua'i, and Maui, Hawaii
Koshimura et al., 2014	63	Yes	Yes	- RTK-GPS² measurement - NDWI³ calculation 2-D projective transformation	- ALOS satellite imagery - Aerial photographs - ZENRIN building - Video footage from a helicopter - Survivor videos - Tsunami inundation limits - Flow depth - Structural damage	- Inundation extended up to 5 km - Maximum tsunami run-up 40m in Iwate Prefecture 30% of structures in Miyagi Prefecture's inundation zone were destroyed - Buildings were particularly vulnerable when flow depth exceeded 2m 6m flow depth caused total devastation - Tsunami front velocities reached approximately 8 m/s within 1 km of shoreline - Flow velocities decreased with distance inland	Tohoku region, Japan
Cardenas et al., 2015	59	Yes	Yes	- Flood level documentation and ground surveys - Water sampling from wells and piezometers. - Two-dimensional electrical resistivity surveys. - Groundwater modelling using coupled variable-density flow and solute transport	- Flood inundation levels and extent - Groundwater table elevations. - Water salinity measurements. - Electrical resistivity measurements. - Water samples from 34 wells.	- Storm surge reached 7 meters above sea level. Initial contamination: 90% of wells were non-potable with up to 17.6% seawater concentration - After 8 months: Wells freshened to 0.1-2% seawater concentration - Model predicts 1-2 years for the shallow aquifer to become potable again - Complete aquifer recovery is estimated to take 5-10 years. - Main contamination occurred through poorly sealed wells rather than surface infiltration	Samar, Philippines
Pitilakis et al., 2016	40	Yes	Yes	- MCS⁴ analyzing seismic events and ground motions - Probabilistic vulnerability and risk assessment - Road network and harbor infrastructure systems analysis	- Road network - Harbor - Annual cargo capacity - Seismic zones	- Interdependencies between systems highly influence transportation infrastructure performance - Building collapses significantly impact road network connectivity, especially at low annual rates - Harbor operations are critically dependent on crane functionality and electric power distribution. - Areas near the coast showed high vulnerability due to soil liquefaction risks	Thessaloniki, Greece

				Indicators used to measure system functionality			
Aravena Pelizari et al., 2021	35	Yes	Yes	- DCNNs⁵ analysis categorization workflow to structure street-level imagery 3Mixed research methods combining quantitative and qualitative approaches - Scenario-based seismic risk analysis comparing potential earthquake sources - High-resolution satellite imagery analysis	- SPOT - Pléiades - GSV⁶ imagery and metadata - GUF⁷ data - Census data from Chile's National Statistics Institute (2017) - DEM⁸ from satellite imagery - Building inventory data categorized by construction types	- Smaller magnitude earthquakes (M6-7.5) on local faults produce 9-17 times more damage compared to large offshore subduction zone earthquakes - Unreinforced masonry structures are most vulnerable to earthquake shaking - Most vulnerable districts identified: Ñuñoa, Santiago, and Providencia - DCNNs achieved accuracies beyond $\kappa=0.81$ for building classification tasks - The method demonstrates the potential for efficient large-scale building characterization for seismic risk assessment	Santiago, Chile
Mebarki et al., 2016	34	Yes	Yes	- Probabilistic model for tsunami wave height prediction and run-up calculations - Monte Carlo simulations to analyze tank failure risks - Five different tank sizes ranging from scenario - Multiple failure modes: uplift, sliding, buckling, and overturning	- GEBCO⁹ - Tanks with heights and diameters - Calibrated using real tsunami wave heights from the Akita Oki earthquake	- Sliding failure occurs before other failure modes in both small and large tanks - Small tanks can fail from tsunamis less than 3m high - With proper barriers and anchors, tanks can withstand tsunamis up to 10m and can resist tsunamis up to 15m - Model predictions showed 95% accuracy when compared to observed tsunami heights	Japan
Toma-Danila et al., 2020	23	Yes	Yes	The researchers developed a GIS-based toolbox called "Network-risk" that: - Creates transportation network models - Evaluates which segments could be damaged by natural hazards - Generates random damage scenarios - Analyzes connectivity loss and socioeconomic impacts	- OSM¹⁰ road network data - Building vulnerability data - Traffic data - Emergency facility locations - Historical earthquake data from past events (1940 and 1977)	- The city has 1.2 million registered vehicles for over 2 million inhabitants - Ranks as Europe's most congested capital city - Over 31,430 residential buildings built before 1946 are vulnerable to earthquakes - Poor road network maintenance and illegal parking further complicate emergency response - Even if only 1% of buildings collapse in an earthquake, it could lead to severe road blockages and hamper emergency response	
Bencheikroun et al., 2015	21	Yes	Yes	- High-res. inundation modelling using COMCOT¹¹-lx code - GIS multi-criteria approach for building vulnerability assessment - Nested grids for tsunami simulation	- GEBCO - Topographic maps - Marine maps 1m res. harbor depth data - Building classification - Coastal structure	- Over 4.5 km² of coastal area prone to tsunami flooding - Flow depths ranging from 0.5m to over 6m - Maximum horizontal inundation distances up to 2.7 km inland - Building vulnerability varied from "very high" for single-story structures to "low" for multi-story RC buildings - The harbor area is completely flooded with depths reaching 3m.	Tangier, Morocco
Cankaya et al., 2016	21	Yes	Yes	GIS¹²-based tsunami risk evaluation using MeTHuVA¹³: - High-res (1m) tsunami numerical modelling using the NAMI DANCE code. - MCDA¹⁴ - AHP¹⁵	- Bathymetry and topography - Vector dataset of Istanbul's metropolitan structures - DEM with 5m resolution from aerial photogrammetry	- The YAN tsunami source caused longer inundation distances and higher flow depths than the PIN source. - Maximum flow depth exceeded 6m near the shoreline east of Yenikapı Fishery Port. - Higher flow depths were observed in front of the historical city wall due to water accumulation.	Istanbul, Turkey

				▪ Historical tsunami records ▪ Earthquake scenario data for PIN and YAN fault sources	▪ Vulnerability assessment		
Nakanishi et al., 2020	21	Yes	Yes	▪ Developed an ABM¹⁶ evacuation simulation tool ▪ Combining storm surge simulation with evacuation behavior modelling ▪ Used questionnaire surveys and interviews to gather resident evacuation preferences ▪ underwater surveys ▪ workshops	▪ OSM for road network data ▪ Census data for household distribution ▪ Resident questionnaire survey results from June 2018 ▪ Historical data from 2004 typhoons that caused flooding ▪ Sea bottom topography measurements	▪ Storm surge simulation showed tidal height is consistent with the squared value of wind speed changes ▪ Model successfully predicted tidal height changes during peak periods with R-squared values of 0.76 for linear approximation and 0.96 for exponential approximation ▪ Previous major flooding in 2004 affected 15,645 houses and inundated 980 hectares ▪ Demonstrated that simulation can be effectively used for community evacuation planning	Takamatsu, Japan

¹ IPCC: Intergovernmental Panel on Climate Change

² RTK-GPS : Real-Time Kinematic Global Navigation Sattelite System

³ NDWI : Normalized Difference Water Index

⁴ MCS : Monte Carlo Simulation

⁵ DCNNs : Deep Convolutional Neural Networks

⁶ GSV : Google Street View

⁷ GUF : Global Urban Footprint

⁸ DEM : Digital Elevation Model

⁹ GEBCO : General Bathymetric Chart of the Oceans

¹⁰ OSM : OpenStreetMap

¹¹ COMCOT : Cornell Multi-grid Coupled Tsunami

¹² GIS : Geographic Information System

¹³ MeThuVA: METU Tsunami Human Vulnerability Assessment

¹⁴ MCDA: Multi-Criteria Decision Analysis

¹⁵ AHP: Analytical Hierarchical Process

¹⁶ ABM: Agent-based Model

4.2. The Distribution of Research and Collaboration Based on Countries

The bibliometric analysis of the worldwide scientific production map (Figure 2), which uses data from the Scopus database, indicates significant differences in research output between areas. Countries are tinted in different shades of blue, with darker colors reflecting higher levels of scientific output. In particular, Indonesia (47) is a key contributor, highlighted in dark blue, showing its importance in worldwide scientific publications. In the Americas, the United States (19), Chile (11), and Canada (2) make significant contributions. Similarly, Europe sees considerable contributions from Germany (16), the United Kingdom (11) and Turkey (8). Asia is the most prolific region, with Japan (22) leading the way, followed by China (16), the Philippines (6) and India (5). New Zealand (5) and Australia (2) have significant scientific output. In contrast, many African, Central Asian, and South American countries remain lightly tinted or unshaded, indicating low levels of research effort. This distribution implies that scientific production is concentrated in locations prone to natural disasters such as tsunamis and areas with geological dangers such as sea-floor fault lines, volcanoes, and probable undersea landslides.

The country cooperation map displays the worldwide scientific collaboration network, with lines connecting countries in blue-shaded sections of the planet. The connecting lines between countries denote collaborative links, with thicker lines indicating more significant or frequent partnerships. North America, Europe, and Asia are especially intertwined as substantial sites for international scientific collaboration. There are strong ties between North America, Europe, and Asia. Southeast Asia, particularly Indonesia, has various linkages to surrounding countries and distant allies such as Australia and Europe. This emphasizes Indonesia's vital role in developing regional research networks while engaging with the global scientific community. Emerging links between countries in Africa, South America, and other regions point to a growing trend of inclusivity in global research endeavors. However, some locations still need to be connected within these networks, as evidenced by lighter coloration or fewer collaboration lines.



Figure 2. Bibliometric result for country scientific production and collaboration distribution map

on the globally available General Bathymetric Chart of the Oceans (GEBCO) with a resolution of 500 m. In contrast, topographic data utilize the Shuttle Radar Topography Mission (SRTM) dataset globally at a resolution of 30–90 m. The level of detail in bathymetric data significantly affects the accuracy of tsunami wave propagation simulations. Upon reaching the coastline, tsunami wave interactions with coastal and inland topography determine the extent of inland inundation. Comparisons of different data resolutions reveal that higher-resolution datasets, such as high-resolution multibeam bathymetry, produce more precise run-up estimates (Orphin et al., 2016). Therefore, the bathymetric and topographic data resolution selection depends on the study scale—GEBCO and SRTM data are sufficient for global analyses. In contrast, higher-resolution data are required for local-scale studies to achieve more accurate inundation estimations.

Historical tsunami records provide valuable insights into past event patterns (Salmanidou et al., 2021; León et al., 2022; Durap & Balas, 2024; Shi et al., 2024). Additionally, these records are used to calibrate predictive models (Lynett et al., 2014; El Moussaoui et al., 2017). A total of 25 studies have incorporated historical tsunami records into hazard simulations. Earthquake parameters such as magnitude, depth, and fault mechanisms are critical in determining tsunami generation potential. The magnitude and depth of an earthquake influence wave height and the extent of the affected area (Bencheikroun et al., 2013; Sambah et al., 2024; Shi et al., 2024). Thrust faults in subduction zones generate more significant tsunami potential than strike-slip faults (Re et al., 2022; Haider et al., 2024). A total of 11 studies have incorporated earthquake parameter data into tsunami hazard simulations. Additionally, tide gauge data validate tsunami wave height and arrival time predictions (Lynett et al., 2014; El Moussaoui et al., 2017). Tide gauges play a crucial role in evaluating and calibrating tsunami models to ensure simulation accuracy, though only two studies have used them. Meanwhile, remote sensing imagery aids in impact mapping and numerical model validation (Koshimura et al., 2014; Oerphion et al., 2016; Damanik et al., 2018; Pelizari et al., 2021; Bamouda et al., 2024). The frequency of data usage depends on study objectives—bathymetry and topography data are almost universally used; historical data are shared in statistical analyses; earthquake and tide gauge data are essential for studies focused on actual tsunami events; and remote sensing imagery is predominantly applied in impact studies and post-tsunami mapping.

Table 2. Data for quantifying tsunami hazards and assessing tsunami vulnerability

Quantifying Tsunami Hazard	Assessing Tsunami Vulnerability
Bathymetry and topography	Socio-economics
Historical record of the tsunami	Building characteristics
Earthquake parameters	Infrastructure
Tide gauge	Environment

Assessing coastal vulnerability to tsunamis encompasses land use, socio-economic factors, building characteristics, and infrastructure (Table 2). Socio-economic data are the most frequently utilized in 19 studies (Figure 4.b). Key socio-economic parameters influencing regional vulnerability include population density, demographic distribution, education and income levels, and access to early warning systems. Population density is used to quantify residents per unit area, particularly in tsunami-prone zones (Hong & Tsai, 2020; Nakai et al., 2021; Hamouda et al., 2024). Demographic distribution categorizes populations by age, gender, and vulnerable groups (e.g., elderly and disabled individuals) with differing responses to warnings and evacuation systems (Wood et al., 2019; Ward et al., 2020). Education levels reflect a community's ability to comprehend tsunami risks and respond effectively to warnings (Loichinger et al., 2015). Income and poverty levels help measure household economic capacity for adaptation and recovery (Ward et al., 2020). Access to early warning systems evaluates infrastructure availability and public awareness of warning mechanisms (Riancho et al., 2015; Pitilakasi et al., 2016; Cels et al., 2023). Building characteristics represent the second most common data type in tsunami vulnerability assessments, utilized in 18 studies. Relevant parameters include construction materials (e.g., concrete, brick, wood), building height and number of floors, and distance from the coastline (Bencheikroun et al., 2013; El Moussaoui et al., 2017; Fajri et al., 2021; Nurmaya et al., 2023; Scorzini et al., 2024). These structural attributes influence building resilience against tsunami impacts.

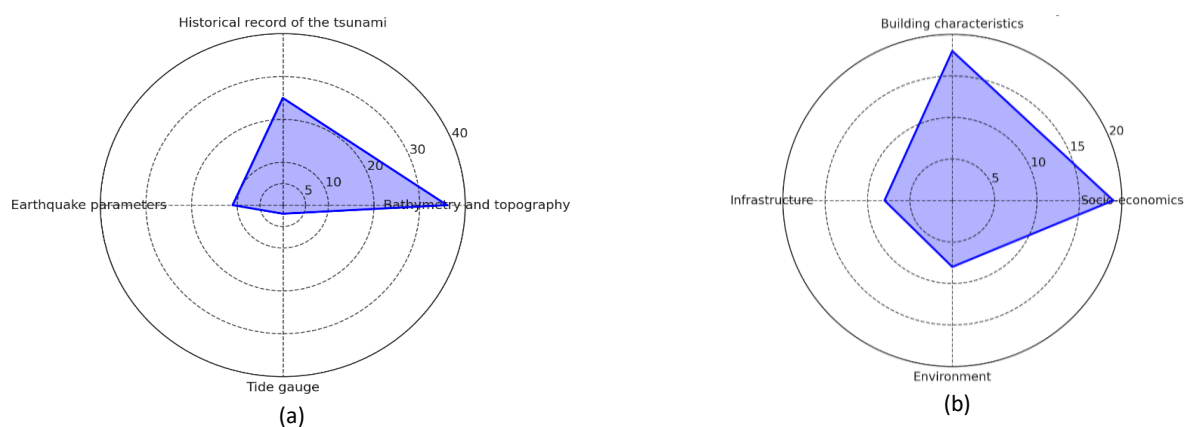


Figure 4. Data used in research (a) Data for quantifying tsunami hazard (b) Data for Quantifying Tsunami Vulnerability

Infrastructure data, which assesses physical assets affecting mitigation capacity, emergency response, and post-disaster recovery, have been used in eight studies. These include transportation networks, evacuation facilities, early warning systems, and public utilities. Transportation network parameters such as road density and width, bridge locations and conditions, and access to ports or airports are critical in vulnerability assessments. Research indicates that narrow and damaged roads can slow evacuations by up to 40% (Ulza et al., 2023). Road networks, ports, and airports also influence the speed of logistical aid distribution following a disaster. Evacuation facilities—including shelter availability (multi-story buildings or artificial hills), shelter capacity, and proximity to shelters—are key factors in tsunami vulnerability assessments (Honesti et al., 2015; León et al., 2022; Batsaris 2025). Early warning system parameters, such as sensor coverage, siren distribution, and communication channel availability, are crucial in emergency response (Riancho et al., 2015; Marfai et al., 2018; Hong & Tsai, 2020; Toma-Danila et al., 2020; Choi et al., 2024). Public utilities, such as water supply networks and drainage systems, are also essential for tsunami disaster mitigation (Harbitz et al., 2016). Environmental data, which include natural parameters influencing tsunami impacts and ecosystem adaptability, have been utilized in eight studies. Coastal vegetation, such as mangroves functioning as natural breakwaters, can reduce wave height by 30–50% and wave speed by 40–60% (Loichinger et al., 2015; Ulza et al., 2023).

4.5. Method for quantifying tsunami hazards and assessing tsunami vulnerability

A review of articles showed several methods used in tsunami research (Table 3). Numerical modelling methods are the most commonly used as they can reproduce tsunami propagation and impacts with a high degree of accuracy (Patel et al., 2016; El Moussaoui et al., 2017; Destrayanti et al., 2023; Shi et al., 2024; Haider et al., 2024; Sambah et al., 2024). The model uses physical equations to simulate tsunami waves based on earthquake parameters and seabed topography. The GIS-based analysis method enables mapping hazard zones and vulnerable areas by considering various geospatial parameters and incorporating weighting techniques (Sugandhi et al., 2024). Empirical formula methods are also often applied for quick estimation, although they are less accurate than numerical models. (Honesti et al., 2015; Scorzini et al., 2024). An empirical formula was also used to estimate building vulnerability (Honesti et al., 2015; Ulza et al., 2024). Statistical approaches are used to extrapolate the probability of tsunami occurrence based on historical data, often used in long-term analysis, as well as damage analysis of coastal areas (Rehman & Cho, 2016; Macabuag et al., 2018; Ogawa et al., 2021; Wang & Sebastian, 2022; Kajitani et al., 2023). Machine learning methods are gaining popularity due to their ability to process large data and identify patterns that are not detected by conventional methods (Mebarki et al., 2016; Prasetyo et al., 2021; Hamouda et al., 2024; Scorzini et al., 2024; Wu & Garlock, 2024). However, the application of machine learning is still limited to exploratory studies and has not been widely used in early warning.

Thirteen numerical models for quantifying tsunami hazards were identified in the research database, including MIKE-21, Cornell Multi-grid Coupled Tsunami (COMCOT), Method of Splitting Tsunami (MOST), Delft3D, Smoothed Particle Hydrodynamics (SPH), NAMI DANCE, Boussinesq Model, NEOWAVE, Gerris Flow Solver, TURMINA, Xbeach, Storm Surge and Tsunami Simulator (STOC), N-WAVE, TsunAWI, and COULWAVE, which were utilised in 22 studies (Figure 4.a). Additionally, seven other studies employed numerical modelling without specifying the model used. COMCOT was the most frequently applied model for tsunami disaster simulations, appearing in six studies conducted in Indonesia, China, Morocco, and Iran (Bencheikroun et al., 2013; El Moussaoui et al., 2017; Mohammadi et al., 2017; Destrayanti et al., 2023; Sambah et al., 2024; Shi et al., 2024). NAMI DANCE and NEOWAVE were also widely used, each in two studies—NAMI DANCE in Turkey and Pakistan and NEOWAVE in Samoa and Chile (Cankaya et al., 2016; Patel et al., 2016; Martínez et al., 2017). Other models were only found in a single study: MIKE-21 in China, MOST, SPH, and COULWAVE in the United States, Delft3D in Pakistan, Boussinesq Model in South Korea, Gerris Flow Solver in Tokelau, TURMINA in Indonesia, Xbeach in Hawaii, STOC in Chile, N-WAVE in China, and TsunAWI in Peru. Numerical modelling requires accurate input data, including earthquake parameters such as magnitude, depth, and fault mechanisms and environmental data such as bathymetry and topography. One of its key advantages is the ability to test various tsunami scenarios to support early warning systems and disaster mitigation efforts (Fajri et al., 2021; Salmanidou et al., 2021; Destrayanti et al., 2023; Hamouda et al., 2024). However, this method has limitations, such as high computational demands and long processing times, particularly for high-resolution simulations (Mohammadi et al., 2017; Gao et al., 2020). Consequently, numerical models are often integrated with other approaches, such as statistical or machine learning, to enhance prediction efficiency and accuracy. Extensive research has demonstrated the effectiveness of numerical modelling, making it the most commonly used tool in tsunami studies.

Table 3. Method distribution and usage

Methods	Number of Researches	Primary Uses
Numerical Modelling	29	Wave propagation and inundation simulations
GIS-based Analysis	23	Risk mapping and hazard zoning, evacuation analysis, and multi-layer data integration
Empirical Formula	9	Wave power estimation, current velocity, and structure impact
Statistical Approach	16	Development of fragility curves, risk probabilistic analysis, and model validation
Artificial Intelligent	5	Automatic object classification, damage prediction, and evacuation route optimization

Each numerical model is designed with a specific purpose, calculation focus, and set of variables, which can be categorized based on temporal resolution, scale, physical complexity, and computational cost (Table 4). Some models simulate wave propagation over different time scales, ranging from minutes (e.g., COMCOT, MOST), seconds (e.g., MIKE-21, Delft3D, NAMI DANCE, Boussinesq Model, NEOWAVE, TURMINA, STOC, N-WAVE, TsunAWI), to milliseconds (e.g., SPH, Gerris Flow Solver, Xbeach, COULWAVE) (Orphin et al., 2016; Patel et al., 2016; Destrayanti et al., 2023; Shi et al., 2024). The spatial scale of these models also varies, with some applicable at global scales (e.g., COMCOT, MOST), regional scales (e.g., MIKE-21, NAMI DANCE, N-WAVE), local scales (e.g., Delft3D, Boussinesq Model, NEOWAVE, Gerris Flow Solver, TURMINA, STOC, TsunAWI), and micro scales focused on specific coastal areas (e.g., SPH, Xbeach, COULWAVE) (Lynett et al., 2014; Orphin et al., 2016; Patel et al., 2016; Mohammadi et al., 2017; El Moussaoui et al., 2017; Martínez et al., 2017; Shi et al., 2024). The complexity of the physical processes modelled varies as well. Some models incorporate a moderate number of variables and calculation steps (e.g., MIKE-21, MOST, NAMI DANCE, TURMINA, N-WAVE), while others

account for more detailed physics (e.g., COMCOT, Delft3D, Boussinesq Model, NEOWAVE, Gerris Flow Solver, STOC, TsunAWI). The most computationally demanding models feature highly complex physics calculations (e.g., SPH, Xbeach, COULWAVE). The computational cost determines the interplay between temporal resolution, spatial scale, and physical complexity. Higher temporal resolution, finer spatial detail, and more complex physics calculations generally increase computational demands. Therefore, selecting an appropriate numerical model must align with the specific requirements of tsunami wave simulations to accurately assess inundation areas.

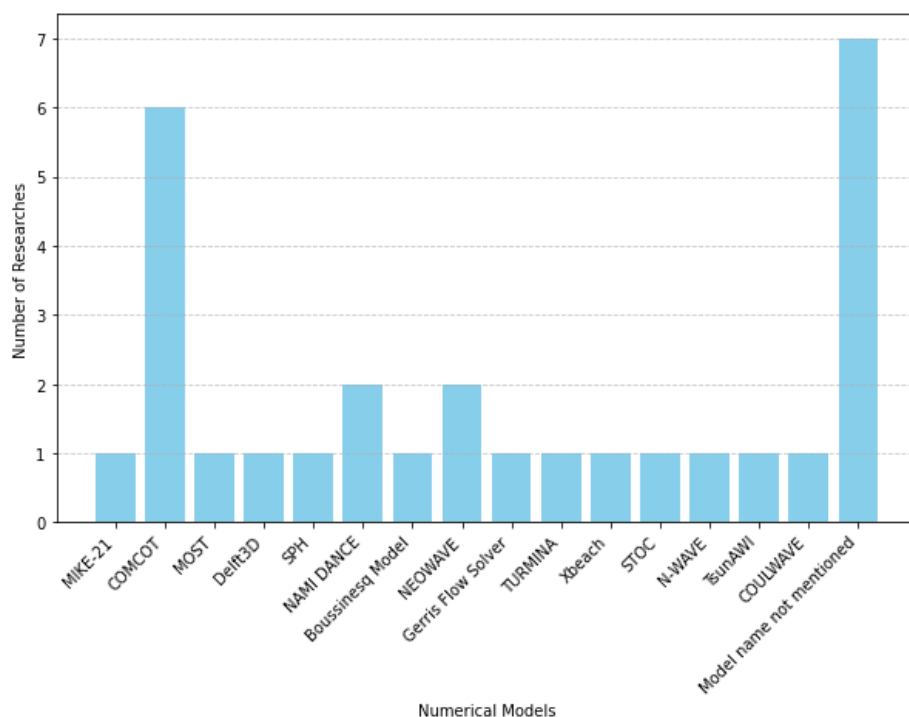


Figure 5. The various numerical models that appear in research databases for quantifying tsunami hazards

Tsunami simulation technologies also play an essential role in this research, providing a predictive dimension that improves the reliability and accuracy of hazard estimates. When paired with simulation software, Digital Elevation Model National (DEMNAS) data provides crucial topographic changes that enable precise modelling of tsunami wave propagation across landscapes. Destrayanti et al. (2023) use DEMNAS data and COMCOT simulation software to predict wave arrival timings, heights, and inland penetration distances in Cilacap, Indonesia, revealing essential details on the spatial scope of potential impacts. These thorough models assist disaster management teams in determining potential impact zones and designing evacuation routes considering the timing and magnitude of wave arrival. Combining DEMNAS data and simulation models considerably enhances prediction accuracy, providing a solid foundation for disaster response planning.

Tsunami vulnerability assessment can be approached through various methods, including vulnerability modelling, spatial analysis, socio-economic evaluation, and the application of artificial intelligence technology to predict the extent of damage in affected areas. Several models have been developed in previous studies to assess tsunami vulnerability, including the Papathoma Tsunami Vulnerability Assessment (PTVA), Fragility Curves, Oasis Loss, Bayesian Network, and METU Tsunami Human Vulnerability Assessment (MeThuVA). The PTVA model is widely utilized due to its structured framework for evaluating resilience at a local scale (Tavares et al., 2016; Wood et al., 2019; Re et al., 2022; Nurmaya et al., 2023; Purbani et al., 2023). This model considers multiple factors, such as structural characteristics, material quality, and proximity to shorelines, to estimate the risk of tsunami damage. For instance, Nurmaya et al. (2023) analysed 229 buildings, categorising them based on vulnerability levels and providing data-driven insights to aid urban planners and policymakers in enhancing structural resilience in tsunami-prone areas. The PTVA model offers actionable recommendations for targeted infrastructure improvements by classifying buildings according to their physical attributes and relative risk. Its extensive use in studies highlights its reliability as a standardized vulnerability assessment tool, facilitating comparative evaluations across different regions.

Fragility curves, on the other hand, assess the probability of building damage at varying tsunami intensity levels, with key parameters including construction materials and wave height (Honesti et al., 2015; Rehman & Cho, 2016; Macabuag et al., 2018; Ulza et al., 2023). While both PTVA and fragility curves are used for tsunami vulnerability assessment, they serve distinct purposes: PTVA focuses on evaluating the vulnerability of buildings and tsunami risk in a given area, whereas fragility curves specifically measure the likelihood of structural damage under different tsunami intensities. Oasis Loss is an open-source model designed for comprehensive disaster risk assessment, integrating climate, hazard, vulnerability, and exposure data to predict economic and financial losses caused by natural disasters, including tsunamis (Salmanidou et al., 2021). Meanwhile, the Bayesian Network is a probabilistic model that estimates tsunami threats based on seismic parameters while quantifying uncertainties in input data (Durap & Balas, 2024). MeThuVA offers a holistic framework for assessing tsunami risk in urban coastal areas by combining numerical tsunami modelling with GIS-based vulnerability analysis and Multi-Criteria Decision Analysis (MCDA) (Cankaya et al., 2016). This model evaluates key factors such as spatial vulnerability—including metropolitan land use, geology, elevation, and distance from the coastline—and evacuation resilience, considering land slope, distance to flat areas, proximity to buildings, and accessibility to road networks. By integrating these various models and approaches, tsunami vulnerability assessment can provide valuable insights to enhance disaster preparedness and resilience in coastal communities.

Table 4. Comparison of numerical models for tsunami hazards quantification

Models	Parameters			
	Temporal Resolution	Scale	Physics Complexity	Computation Cost
MIKE-21	Seconds	Regional	Moderate	High
COMCOT	Minutes	Global	High	High
MOST	Minutes	Global	Moderate	Moderate
Delft3D	Seconds	Local	High	Very high
SPH	Milliseconds	Micro	Very high	Extreme
NAMI DANCE	Seconds	Regional	Moderate	Moderate
Boussinesq Model	Seconds	Local	High	Very high
NEOWAVE	Seconds	Local	High	High
Gerris Flow Solver	Milliseconds	Local	High	Extreme
TURMINA	Seconds	Local	Moderate	Moderate
Xbeach	Milliseconds	Micro	Very high	Extreme
STOC	Seconds	Local	High	High
N-WAVE	Seconds	Regional	Moderate	Moderate
TsunAWI	Seconds	Local	High	High
COULWAVE	Milliseconds	Micro	Very high	Extreme

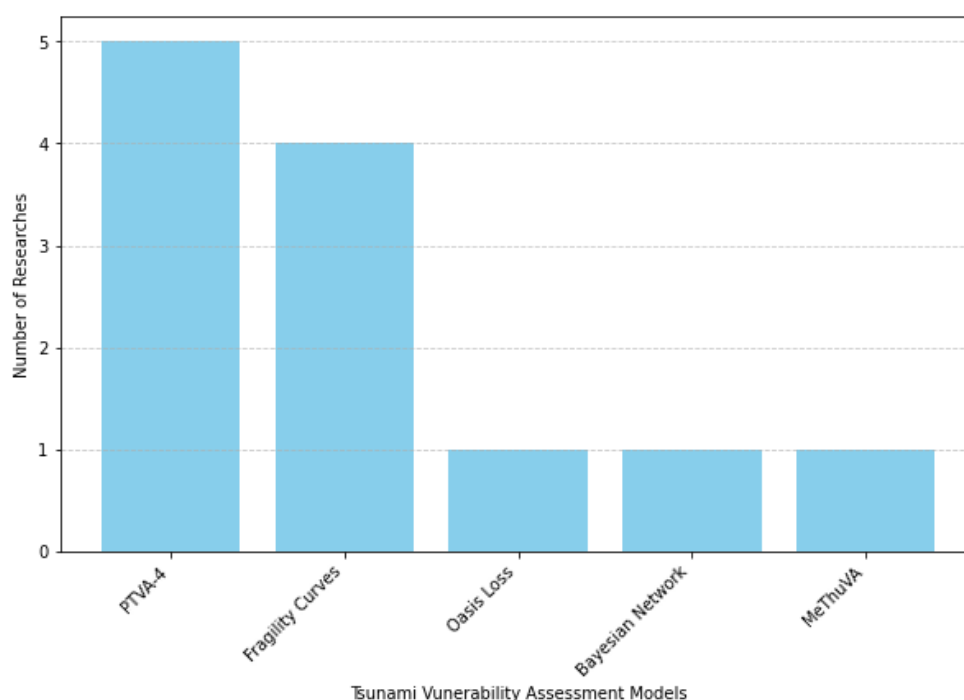


Figure 6. The various models that appear in research databases for assessing tsunami vulnerability

The spatial analysis approach in tsunami vulnerability assessment utilizes GIS to map tsunami-prone areas by integrating socio-economic data, building characteristics, infrastructure, and environmental conditions. This method is often combined with weighting techniques such as the Analytical Hierarchy Process (AHP), which provides a structured and measurable approach to assigning weights to various tsunami vulnerability factors. Socio-economic evaluation is conducted through field surveys to assess community perceptions of tsunami preparedness. This evaluation can incorporate quantitative and qualitative approaches, offering a comprehensive understanding of social resilience in disaster-prone areas. The use of artificial intelligence in tsunami vulnerability assessment is increasingly advancing, enhancing the analysis's accuracy and efficiency. Machine learning-based statistical modelling, such as Maximum Likelihood Estimation and Least Squares Regression, has been used to develop fragility curves for predicting building damage (Ulza et al., 2023). The Extra Trees model demonstrated an 88.9% accuracy in predicting tsunami damage

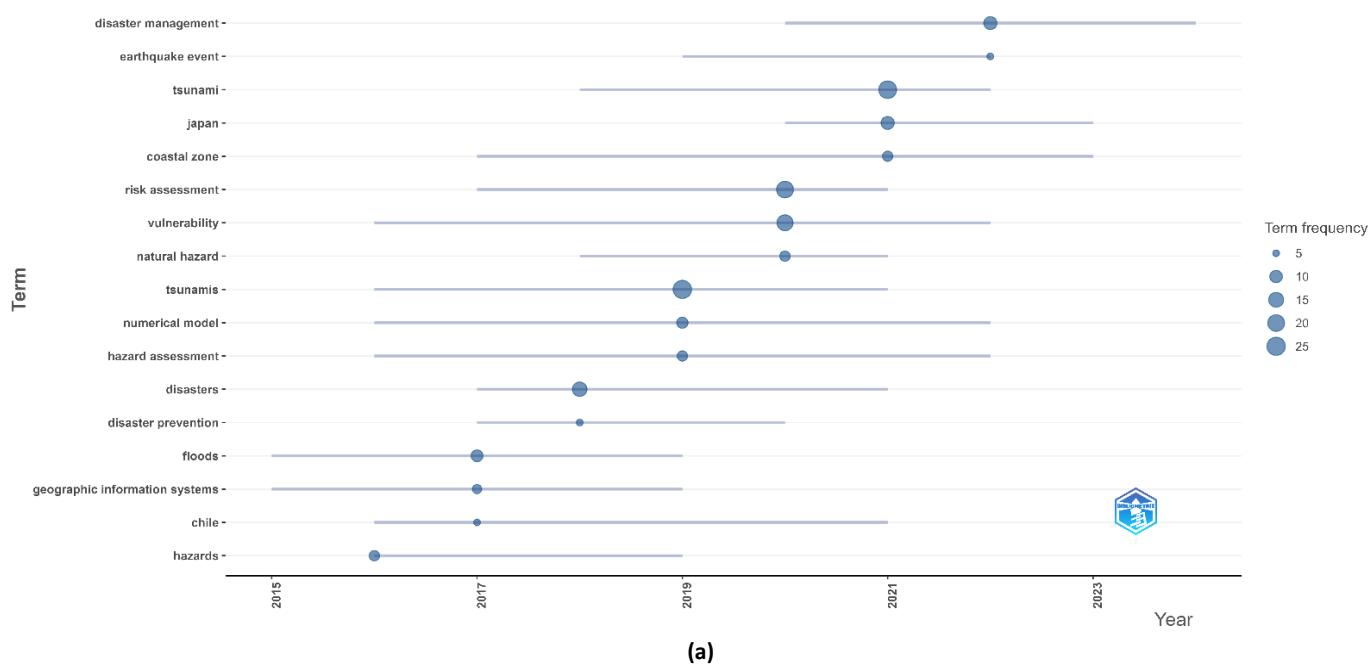
by integrating hydrodynamic variables, shoreline distance, building protection, and debris impact (Scorzini et al., 2024). Additionally, the Random Forest and K-nearest Neighbors algorithms have been applied for vegetation change prediction, tsunami vulnerability classification, and spatial data optimization for identifying vulnerability patterns, achieving MSE values of 0.002–0.003 and RMSE values of 0.045–0.055 (Prasetyo et al., 2021). Deep Convolutional Neural Networks (DCNNs) have also been employed to analyze Google Street View images, classifying building construction types with an accuracy of 0.81 (Aravena Pelizari et al., 2021). AI technology has proven to be a valuable tool in tsunami vulnerability assessment, capable of processing vast amounts of data—including remote sensing and GIS—while offering scalability from extended processing times to real-time applications.

The overall findings of this research reflect an increasing trend of combining quantitative and spatial data to create localized, data-rich danger maps that aid in disaster preparedness and response tactics. For example, Sugandhi et al. (2023) identify low-hazard areas that span more than 61% of Ambon, which is critical for developing safe evacuation routes and infrastructure development. This technique not only reveals high-vulnerability locations but also safer zones that are crucial for strategic planning in heavily inhabited or infrastructure-heavy areas. These studies contribute to a more nuanced knowledge of tsunami risk by creating precise hazard maps that reflect localized risk variations, providing decision-makers with critical information for optimizing resource allocation and evacuation protocols. The research from Destrayanti et al. (2023) underlines the need to precisely simulate wave arrival times and inundation paths, which are crucial for prompt evacuation and response measures. Precise estimates of wave arrival timings, particularly in highly populated coastal locations, allow for more coordinated evacuations and reduce hazards to human life. These studies demonstrate that an integrated strategy that includes geospatial research, simulation tools, and vulnerability assessment models provides a comprehensive framework for understanding and minimizing tsunami threats. This holistic approach reflects a methodological change toward highly localized, data-driven tsunami hazard assessments to increase infrastructure resilience and community preparation.

The effectiveness of these methods largely depends on the availability and quality of the data used. Numerical models require precise bathymetric and topographic data to generate reliable predictions. Historical records and earthquake parameters are crucial in producing more accurate estimates in statistical and machine-learning approaches. The use of tide gauges and remote sensing imagery further aids in validating model outputs and analyzing tsunami impacts. To enhance the accuracy and reliability of predictions, tsunami hazard studies often integrate multiple methods and diverse data sources. Socio-economic factors, building characteristics, infrastructure details, and land use information—typically available in geospatial data formats—are widely utilized for comprehensive tsunami vulnerability assessments across various scales. As technology advances and the volume of available data grows, these methods are expected to evolve, enabling more precise and effective tsunami hazard estimation.

4.6. Trends and Future Research Potential

The "Trend Topics" chart (Figure 7. a) summarizes the evolution of tsunami research from 2014 to 2024, highlighting important areas of interest and their frequency over time. Terms such as "disaster management," "earthquake event," and "tsunami" have remained significant, with a large increase in research activity following 2019. This reflects an increasing emphasis on understanding and mitigating the effects of tsunamis, particularly in disaster management and earthquake research. The term "vulnerability" has also gained use in recent years, indicating a growing emphasis on assessing the vulnerability of communities and infrastructure to tsunami damage. This move reflects the more significant trend of combining hazard modelling and vulnerability assessments to construct more comprehensive disaster preparedness plans.



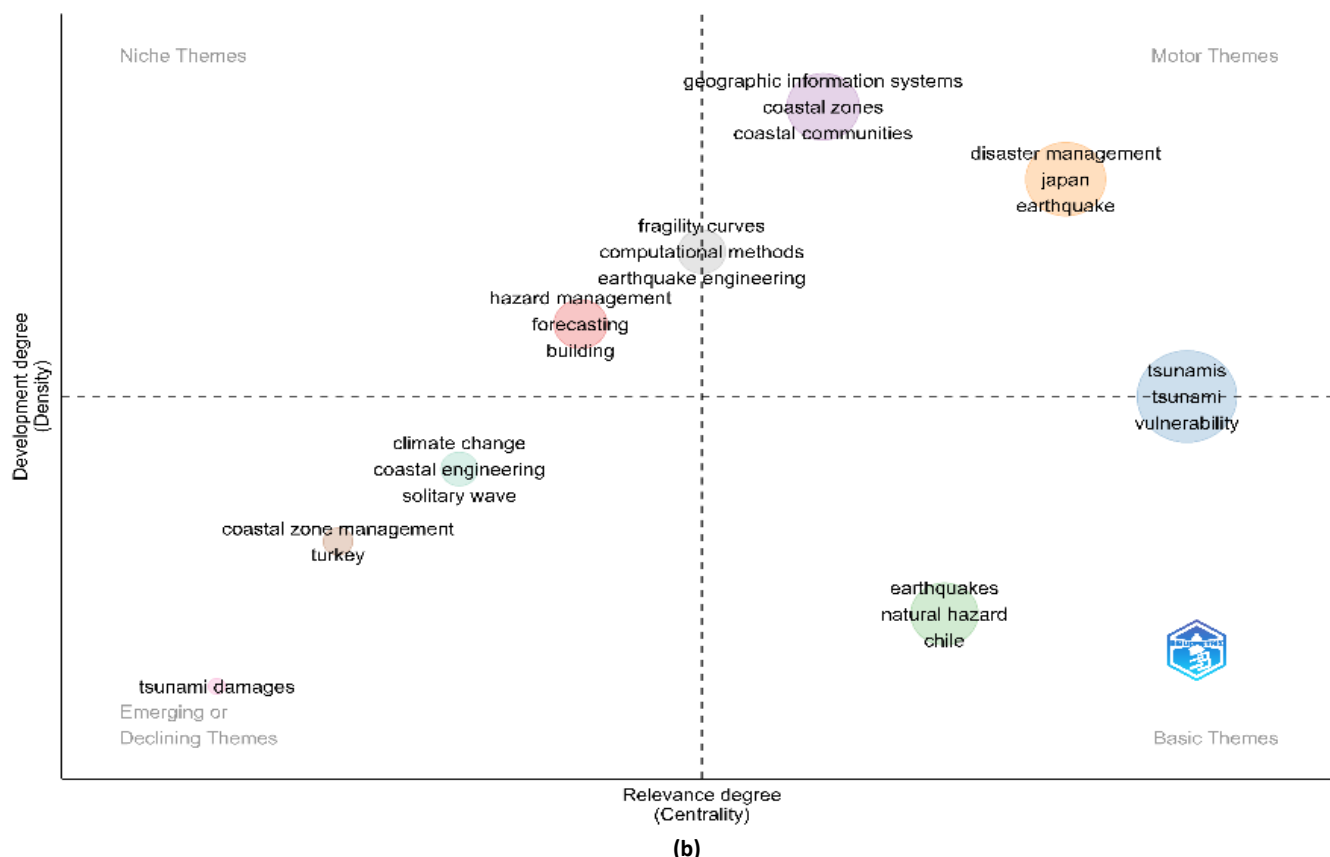


Figure 7. Bibliometric result for: (a) Trend topics; (b) Thematic map

The thematic map (Figure 7. b) organizes these subjects by importance (centrality) and development (density), providing additional insight into the current state of tsunami research. In the "Motor Themes" quadrant, themes such as "disaster management," "Japan," "earthquake," "Geographic Information System (GIS)," "coastal zones," and "coastal communities" are well-developed and fundamental to the area, driving much of current research. These themes are expected to remain central to future research because they are crucial in understanding and responding to tsunami events. For example, GIS has proven to be a handy tool for spatial analysis and risk assessment in tsunami-prone locations. Nurmay et al. (2023) and Destrayanti et al. (2023) conducted research in Indonesia that used GIS for vulnerability mapping and evacuation route optimization, indicating its utility for hazard assessment and disaster response. Meanwhile, subjects like "vulnerability" and "tsunamis" appear in the "Basic Themes" quadrant, indicating that, while foundational, there is still an opportunity for additional growth. This implies that future studies may focus on increasing our understanding of these areas, mainly how risks can be addressed through improved disaster management methods.

In contrast, topics such as "hazard management," "forecasting," and "building" are shown in the "Niche Themes" quadrant. These topics have a low level of relevance because they are on the left side. Such research in the context of tsunamis tends to focus on local or geographically specific applications, with limited connectivity to other, more global fields. Despite their importance, these topics are technical and often separated from fundamental research, such as wave and inundation modelling and tectonic mechanisms.

However, topics like "climate change" and "coastal engineering" are shown in the "Emerging or Declining Themes" quadrant, indicating either increased interest or a shift in focus in tsunami research. Given the expanding effects of climate change on coastal areas, this could be an essential topic for future research. Research on how rising sea levels and shifting weather patterns affect tsunami threats could yield valuable insights for coastal zone management and disaster mitigation efforts. Furthermore, climate change estimates in existing tsunami models could aid in long-term risk assessments for vulnerable coastal areas.

Tsunami research is moving toward a more comprehensive strategy that includes hazard modelling and vulnerability assessment. The increased emphasis on disaster management and vulnerability reflects a continuous attempt to strengthen community resilience to tsunamis. Future research opportunities include expanding on these themes and investigating emerging areas such as climate change's impact on coastal disasters. Researchers such as Sugandhi et al. (2023) and Kajitani et al. (2023) are already adding to the corpus of knowledge by focusing on spatial modelling and infrastructure resilience. These discoveries indicate that future research will rely on modern technologies, including GIS and numerical models, to better our understanding of tsunami dangers and build more effective mitigation techniques.

5. Discussion

The results of this study show that GIS-based approaches, remote sensing and numerical modeling play an important role in identifying tsunami risks in Europe. A study conducted in Istanbul, Turkey (Cankaya et al., 2016) used the MeTHuVA approach that combines bathymetry, topography and urban infrastructure data to assess tsunami risk. Findings showed that tsunami sources from the YAN zone generated greater inundation depths compared to PIN sources, highlighting the importance of spatial mapping in disaster mitigation. The YAN and PIN zones are two

tsunami source scenarios originating from the Marmara Sea subduction zone, with the YAN zone generating higher waves and a wider inundation extent than the PIN zone which has a more localized impact.

In Thessaloniki, Greece (Pitilakis et al., 2016), research shows that transportation infrastructure is highly vulnerable to tsunami impacts. The probabilistic analysis conducted showed that disruptions to road networks and ports can hamper emergency response, especially in areas with a high risk of soil liquefaction. These results indicate the need for strategic planning to improve the resilience of transportation infrastructure in coastal areas. In Italy, a study by Re et al. (2022) used an improved PTVA model to incorporate social and structural variables to assess tsunami risk in Sicily. Findings showed that zone A1 had the highest level of vulnerability, with buildings more susceptible to damage from high waves. Another study in L'Aquila (Parisi & Acconcia, 2021) also confirmed that low-rise buildings are more at risk of structural damage, despite having retrofitting systems. In Germany, research by Maiwald & Schwarz (2022) showed that methods based on historical data from floods and earthquakes can improve the accuracy of tsunami impact predictions. Analysis of data from previous disasters, including the 2002 floods in Germany and the 2011 earthquake in Japan, enables more precise risk modeling for coastal areas.

The role of remote sensing in this study is also very significant, especially in tsunami impact mapping and land change analysis in coastal areas. The study by Durap & Balas (2024) in Antalya, Turkey, showed that combining buoy measurement data with 3D hydrodynamic models can improve the understanding of tsunami wave behavior. Meanwhile, the use of high-resolution satellite imagery in Istanbul and Saxony studies helped to assess infrastructure damage and supported the process of mapping hazard zones more accurately. This study confirms that remote sensing technology is essential in collecting real-time data and improving the accuracy of tsunami prediction models.

Overall, these studies highlight the importance of integrating geospatial data, remote sensing and numerical modeling methods in understanding tsunami risk in Europe. These studies also show that GIS-based approaches can provide more comprehensive insights into infrastructure, social and economic risks in coastal areas.

5.1. Limitation

While this study offers valuable insights into tsunami vulnerability modelling, several limitations must be acknowledged. First, the literature search was confined to the Scopus database, potentially omitting significant studies indexed in other sources such as the Cochrane Library, Dimensions, Lens.org, OpenAlex, PubMed, Google Scholar, and Web of Science. This restriction may have narrowed the breadth of the findings. Second, the review was limited to studies published between 2014 and 2024 to examine technological advancements in tsunami hazard and vulnerability research over the past decade. Furthermore, only openly accessible papers were considered, which may have excluded earlier studies, including those behind paywalls, that could provide valuable insights. Third, the selection of keywords—such as "tsunami," "vulnerability," and "modelling"—may not comprehensively capture all relevant studies, particularly those employing alternative terminology or addressing a broader disaster context. Consequently, the review may underrepresent region-specific methodologies or challenges in under-researched areas, potentially limiting the findings' generalizability across diverse geographic and socio-economic contexts.

5.2. Future research recommendation

Future research should focus on improving tsunami susceptibility models by including new variables such as climate change projections, socioeconomic characteristics, and real-time environmental data. Several studies, notably those by Kajitani et al. (2023), have underlined the importance of understanding how increasing sea levels and changing weather patterns influence tsunami hazards for improving long-term risk estimates. Integrating machine learning methodologies with remote sensing and GIS can improve the accuracy and agility of vulnerability assessments, allowing for dynamic changes in response to unanticipated conditions. These developments will be critical in constructing more resilient coastal areas in the face of rising natural hazards, ensuring that disaster prevention policies remain adaptive and forward-thinking.

6. Conclusions

Based on the results of this study, it can be concluded that geospatial approaches, including the use of GIS, remote sensing and numerical models, have a crucial role to play in improving the understanding and mitigation of tsunami risks in Europe. Studies in Turkey and Greece show that transportation infrastructure and road networks should be a key focus in tsunami preparedness strategies. In Italy, the PTVA model provides important insights in assessing the vulnerability of buildings based on structural and social factors. Meanwhile, research in Germany showed that analyzing historical data can improve the accuracy of tsunami prediction models.

Remote sensing technology also contributes significantly to tsunami risk analysis. The use of high-resolution satellite imagery and buoy measurements has been shown to improve hazard zone mapping and accelerate emergency response. With these technologies, tsunami prediction models can be updated in real-time, providing more accurate warnings for vulnerable coastal areas. In the context of disaster mitigation, GIS and remote sensing-based approaches enable the identification of high-risk zones and support more effective emergency response planning. These studies also emphasize the need to develop more integrated data-driven strategies to improve the resilience of coastal areas to tsunamis.

Going forward, further research is needed to develop more sophisticated prediction models by integrating artificial intelligence and real-time data. In addition, a multidisciplinary approach combining social, economic and environmental aspects could provide a deeper understanding of tsunami impacts in different regions in Europe.

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<https://www.ine.es/en/index.htm>. Supply and demand data of metropolitan public transport (Metropolitan Mobility Observatory): <https://observatoriomovilidad.es/informes/>.

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