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Comparative Study of Tsunami Inundation Maps in Padang, Indonesia

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Abstract Historical tsunami database records that tsunamis hit Padang city in 1797 and 1833. Even though the Padang city government had released a tsunami evacuation map for the city, it has not provided complete information for the estimated tsunami inundation areas and the inundation depths. Additional analysis is needed to improve the information on the city tsunami zones in tsunami inundation maps. The inundation maps in this study are divided into three maps based on the numerical simulations of the tsunami from the sources of Pagai and Sipora blocks (2 maps), and topographic data (1 map). Due to these, each tsunami event was simulated in four areas, namely: 1) Ulak Karang; 2) Air Tawar; 3) Parupuk Tabing, and 4) Pasir Jambak sub-districts. Based on the results of this study, it is found that the coastal areas of Ulak Karang and Air Tawar are lower-lying areas than the coastal areas of Parupuk Tabing and Pasir Jambak. The directions of the inundation distribution and run-up in the simulations are influenced by the direction of the tsunami waves generated by the tsunami sources. The tsunamis on land will be further in a low-lying area, then propagate before finally stopping at high relief. Although overall tsunami inundation based on topographic data inundates a wider area, there are many shortcomings of the simulations, such as the direction of the tsunami inundation on the mainland, soil roughness factors, and building barriers, which are not considered parameters.

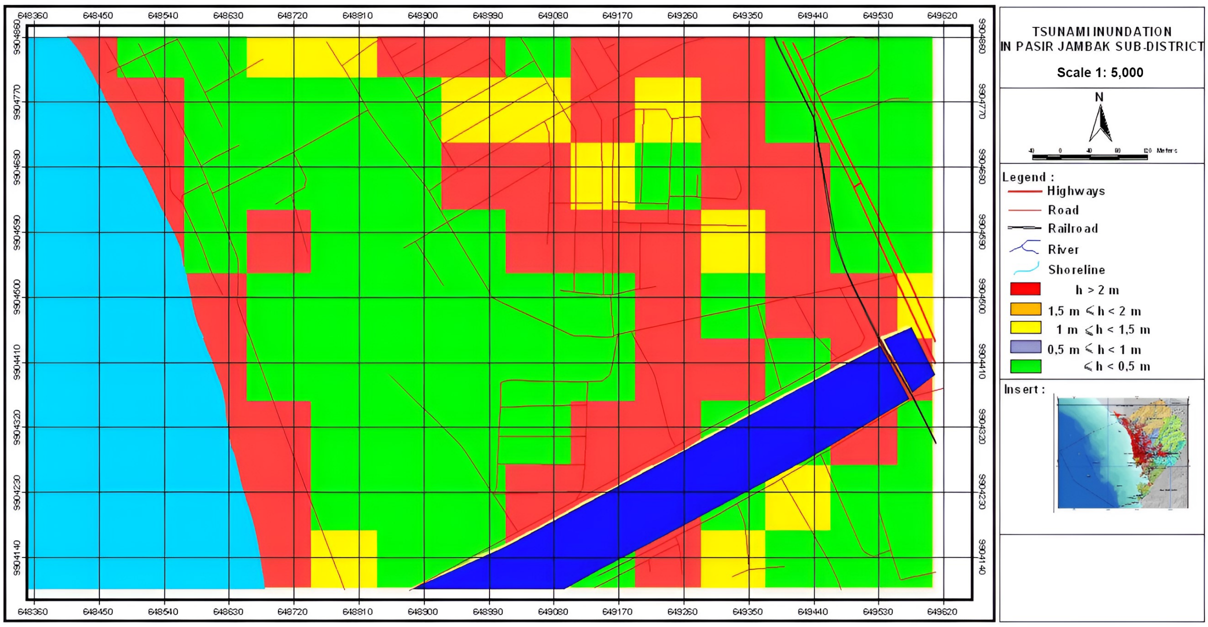
Keywords Padang, Tsunami, Inundation, Topography

1. Introduction

The west coast of Sumatra is an earthquake-vulnerable area due to its tectonic location close to the subduction zones, and they are where the Indo-Australian plate boundary is slowly descending beneath the Eurasian plate, due to the density of the Eurasian plate is lower than the density of the Indo-Australian plate with a movement of about 6-7 centimetres/year [1]. When these plates slide past each other, they can induce an earthquake followed by tsunamis. Indonesia received more attention after an earthquake followed by a tsunami in Aceh on December 26, 2004, with a Moment magnitude (Mw) of 9.0-9.3. The next series is the Nias earthquake on March 28, 2005 (Mw 8.7 event) and the West Sumatra earthquake on 30 September 2009 (Mw 7.9 event). Interseismic deformation above megathrust is recorded in microatolls in the Mentawai islands, and it is stated that a repeat of large earthquakes followed by tsunamis occurs every 200 years [2]. On the other hand, not all large earthquakes cause tsunamis, like the 2005 Nias and the 2009 West Sumatra earthquakes. This is caused by the earthquake epicentre which is not in the megathrust area and the parameters required for the occurrence of a tsunami are not met [3].

(b) Air Tawar

(c) Parupuk Tabing



(d) Pasir Jambak

Figure 4. Tsunami Inundation Map based on Topographic Data

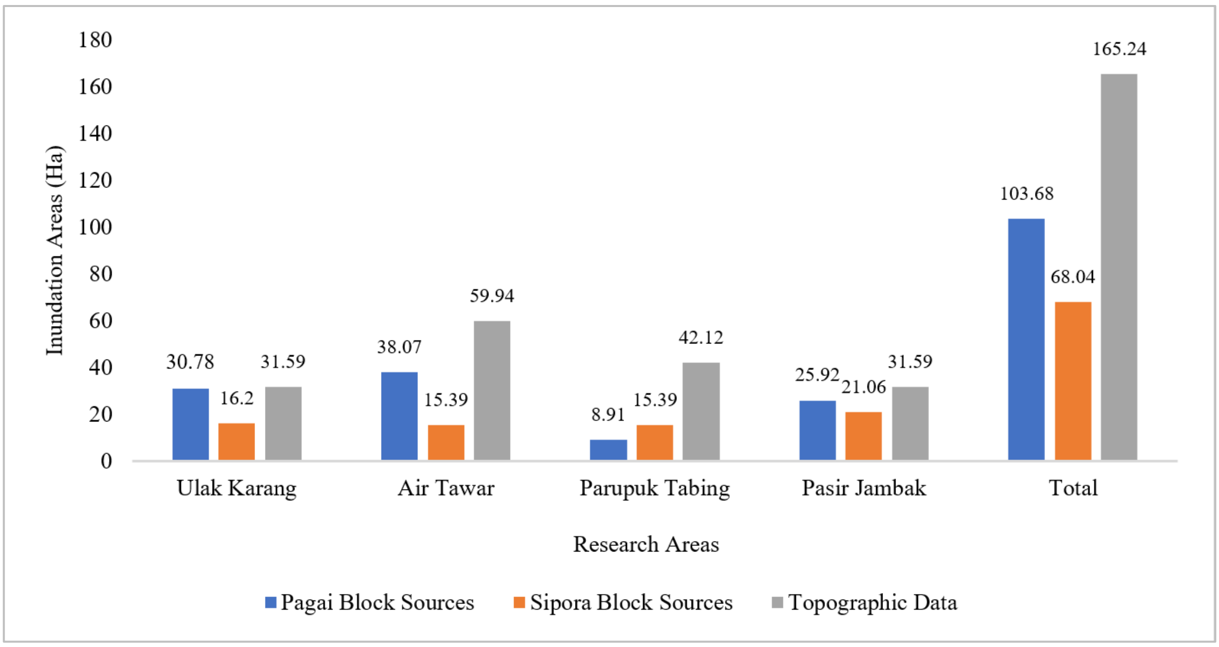


Figure 5. Tsunami Inundation

Figure 5 is a graph of the inundation of each study area. For the tsunami sourced from the Pagai block, the largest inundation occurs in the Air Tawar which reaches 38.07 hectares. Meanwhile, in the sources of the Sipora block tsunami, the largest inundation occurs in Pasir Jambak (reaching 31.59 hectares). Here, the tsunami inundation area is closely related to the tsunami height and the topographic profile of a coastal zone. In this study, it can be seen that the flat zones tend to have extensive inundation, while in higher zones, tsunami inundation only occurs around the coasts. The direction of inundation tsunami distribution is also related to the direction of a tsunami wave from the ocean. On the other hand, the results of the tsunami wave based on topographic data, the widest inundation area is in Air Tawar, reaching 59.94 hectares. Here, the assumptions used are only based on the difference between the topographic data and the tsunami height. Although overall the tsunami inundation based on topographic data results in a larger affected area, there are many shortcomings, such as the direction of the tsunami inundation on the mainland, the factors of soil roughness and building barriers that are not considered.

The results of the inundation in the 2 (two) models are not much different from the historical data of earthquake events followed by tsunamis recorded in 1797 and 1883 in the city of Padang [2,5,6]. The model results are quite reliable even though the accuracy of the inundation area is not known with certainty in each district. It is a fact that, the tsunami on the west coast of Padang has a return period of 200 years. At this moment in time, the tsunami has entered its return period in this city.

3.1.2. Comparison of Inundation Maps: Historical versus Modern Approaches

Comparing historical and modern tsunami inundation maps reveals significant advancements in mapping accuracy and detail. Early inundation maps in Padang, created primarily using empirical methods, often lacked precision due to limited data availability and simplistic modeling techniques. These maps provided a basic overview of potential inundation zones but were not sufficiently detailed for effective emergency planning and response. In contrast, modern inundation maps benefit from high-resolution topographic and bathymetric data, advanced numerical models, and comprehensive validation processes [26].

Modern inundation maps in Padang have incorporated data from recent technological advancements, such as satellite imagery and LiDAR, to enhance topographic accuracy. These data sources enable the creation of detailed digital elevation models (DEMs) that are crucial for accurate hydrodynamic modeling [27]. Furthermore, the use of sophisticated numerical models, such as the nonlinear shallow water equations and finite element methods, has improved the precision of wave propagation and inundation predictions. The integration of real-time monitoring systems and scenario-based simulations has also enhanced the predictive capabilities of modern inundation maps.

A significant difference between historical and modern inundation maps is the inclusion of uncertainty analysis in contemporary approaches. Modern maps often provide probabilistic inundation zones, which account for uncertainties in tsunami source parameters and model inputs. This probabilistic approach allows for better risk communication and more informed decision-making in disaster management. Consequently, modern inundation maps offer a more comprehensive and reliable tool for tsunami risk assessment and mitigation in Padang.

3.1.3. Challenges in Tsunami Inundation Mapping in Padang

Despite significant advancements, tsunami inundation mapping in Padang faces several challenges. One primary challenge is the accurate representation of coastal topography and bathymetry [28]. High-resolution data are essential for precise modeling, but obtaining such data can be difficult due to logistical and financial constraints. Additionally, rapid urban development and coastal changes can quickly render existing topographic data obsolete, necessitating frequent updates to maintain map accuracy.

Another challenge is the inherent uncertainty in tsunami source parameters. Earthquake-induced tsunamis depend on various factors, such as fault slip, rupture length, and seafloor displacement, which are difficult to predict accurately. This uncertainty can lead to significant variations in predicted inundation extents, complicating risk assessments and emergency planning. To address this, modern approaches often use a range of plausible scenarios to provide a spectrum of potential outcomes [29].

The integration of community and stakeholder input into the mapping process is another critical challenge. Effective disaster preparedness requires that inundation maps are not only scientifically accurate but also understandable and actionable for local communities [30]. This necessitates ongoing education and engagement efforts to ensure that the maps are used effectively in emergency planning and response. Additionally, cultural and socio-economic factors can influence how communities perceive and respond to tsunami risks, necessitating tailored communication strategies.

Finally, the development and maintenance of real-time monitoring and early warning systems are crucial for effective tsunami risk management. These systems rely on timely and accurate data to provide warnings and guide evacuations, but they require significant investment in infrastructure and technology [31]. Ensuring the reliability and accessibility of these systems is essential for protecting lives and property in tsunami-prone areas like Padang.

3.1.4. Implications for Disaster Preparedness and Risk Reduction

Tsunami inundation maps play a vital role in disaster preparedness and risk reduction in coastal regions. In Padang, these maps are used to inform land use planning, infrastructure development, and emergency response strategies [32]. By identifying high-risk areas, authorities can implement zoning regulations that restrict development in vulnerable zones and promote the construction of tsunami-resistant structures. Additionally, inundation maps guide the design and placement of critical infrastructure, such as evacuation routes and shelters, ensuring that these facilities are accessible and effective during a tsunami event [33].

The use of inundation maps in public education and community preparedness programs is another critical application. These maps help to raise awareness about tsunami risks and promote preparedness measures, such as evacuation planning and emergency drills [34]. By visualizing the potential impacts of a tsunami, communities can better understand their vulnerabilities and take proactive steps to reduce risk. Effective communication of inundation maps requires clear and accessible formats that are tailored to the needs and preferences of different audiences.

In addition to guiding local preparedness efforts, tsunami inundation maps are essential for regional and national disaster management strategies. These maps provide a basis for coordinating response efforts across multiple jurisdictions and agencies, ensuring a comprehensive and unified approach to tsunami risk reduction [35]. They also support the development of early warning systems and evacuation protocols, which are critical for minimizing casualties and damage during a tsunami event.

Overall, the continued improvement and application of tsunami inundation maps are crucial for enhancing resilience in coastal communities like Padang. By integrating advanced modeling techniques, high-resolution data, and community engagement, these maps can provide a powerful tool for reducing the impacts of future tsunamis and protecting lives and property.

3.2. Discussion

The comparative study of tsunami inundation maps in Padang, Indonesia, reveals significant insights into the evolution of tsunami risk assessment methodologies and their implications for disaster preparedness. The early tsunami inundation maps primarily relied on empirical data and historical tsunami events, which provided a basic understanding of potential inundation zones. However, these early maps were often limited in accuracy and detail due to the lack of high-resolution topographic and bathymetric data. As a result, they could not effectively guide detailed emergency planning and infrastructure development in tsunami-prone areas [30].

Modern tsunami inundation maps have significantly improved due to advancements in technology and modeling techniques. High-resolution digital elevation models (DEMs) derived from LiDAR and satellite imagery have enhanced the accuracy of coastal topography representation, which is crucial for precise hydrodynamic modeling [22]. Additionally, sophisticated numerical models, such as those incorporating nonlinear shallow water equations, have provided more accurate predictions of wave propagation and inundation extents [7]. The integration of these advanced techniques has resulted in more reliable and detailed inundation maps, which are essential for effective disaster risk management.

Despite these advancements, several challenges remain in creating accurate tsunami inundation maps for Padang. One major challenge is the dynamic nature of coastal environments, which requires frequent updates to topographic and bathymetric data to maintain map accuracy. Rapid urban development and natural coastal changes can quickly render existing data obsolete, necessitating ongoing monitoring and data acquisition efforts. Furthermore, uncertainties in tsunami source parameters, such as fault slip and rupture length, can lead to significant variations in predicted inundation extents, complicating risk assessments.

The role of community engagement and stakeholder involvement in the mapping process is also critical. Effective tsunami risk management requires that inundation maps are not only scientifically accurate but also understandable and actionable for local communities [27]. This necessitates ongoing education and engagement efforts to ensure that the maps are used effectively in emergency planning and response. Tailored communication strategies that consider cultural and socio-economic factors are essential to enhance community preparedness and resilience. It is essential that scientific findings are effectively operationalized through collaboration with policy makers resulting in the development of practical tools such as evacuation planning maps, land use regulations and early warning systems. Scientifically generated models can improve institutional resilience and response capabilities.

4. Conclusions

The tsunami heights due to the earthquake from the Sipora block are lower than the simulation results from the Pagai block. This is because 80% of the initial tsunami waves have been hampered by the Mentawai islands, while some others crawl through the gaps between the islands. The reduction of tsunami energy is generally beneficial for the observation areas, but it will still be so dangerous for the areas which are directly stricken by the waves. The Pagai and Sipora block source tsunami models produce different arrival times and tsunami heights at every research location even though the location is the same distance from the shorelines. This is due to the different coastal profiles. The coastal profiles of Ulak Karang and Air Tawar sub-districts are more sloping than Parupuk Tabing and Pasir Jambak sub-districts. The inundation and run-up directions in the simulations are influenced by the arrival wave directions from the ocean. Tsunami inundation usually starts from the lowest topography, propagates and stops in areas with higher topography. Although overall the tsunami inundation based on topography data results in a larger affected area, the simulation lacks the direction of the tsunami inundation on the mainland and the soil roughness factor. Here, all buildings along the coasts are also considered in the simulations.

In conclusion, the comparative study of tsunami inundation maps in Padang highlights the significant progress that has been made in tsunami risk assessment methodology. The transition from empirical models to advanced numerical models has improved the accuracy and reliability of inundation predictions. However, ongoing challenges, such as data acquisition, model uncertainty, and community engagement, must be addressed to further enhance the effectiveness of these maps in disaster preparedness and risk reduction. The continued development and application of high-resolution data and sophisticated modeling techniques, coupled with effective community engagement, are critical to enhancing coastal communities' resilience to tsunami hazards.

The findings underscore the importance of incorporating multi-scenario hazard assessments into urban spatial planning and disaster risk management. To reduce the adverse impacts of tsunami inundation, tsunami mitigation activities need to be undertaken, in the form of green belt construction, spatial planning, evacuation route construction, and tsunami early warning systems in the study areas. Emphasis is placed on integrating scientifically based risk information into policy frameworks and community-based preparedness initiatives to strengthen resilience to future tsunami events.

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