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How Can Local Knowledge and Infrastructure Engineering be Bridged for Tsunami Resilience? A Systematic Scoping Review of Socio-Technical Mitigation Framework

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ABSTRACT

Tsunami resilience research has advanced significantly in both indigenous knowledge and engineering-based mitigation. However, these domains are often treated in isolation, which limits the development of integrated socio-technical catastrophe risk reduction solutions. This review examines how recent literature conceptualizes the relationship between local knowledge and tsunami mitigation engineering and operational planning, identifies mitigation functions that bridge these domains, and highlights existing knowledge gaps in socio-technical tsunami resilience. A systematic scoping study was undertaken utilizing the PRISMA framework and peer-reviewed literature published from 2020 to early 2026. Scopus and Web of Science search algorithms were used, supplemented by manual searches, to conduct the searches. The review used narrative analysis to synthesize twenty papers that met inclusion criteria. For each study, we categorized how indigenous knowledge was handled, what engineering could be put into action, and the socio-technical integration. The results show that indigenous knowledge is closely linked to how people perceive risks, understand warning messages, and evacuate. In contrast, engineering studies mostly focus on hazard assessment, early warning systems, evacuation modeling, and infrastructure development. In fields like warning architecture, evacuation route planning, and shelter location, research has rarely incorporated culturally grounded knowledge directly. Japanese Bosai and Indonesian Smong practices exemplify socio-technical integration; in both cases, engineering systems incorporate collective memory, trustworthy communication, and institutional support. A growing disparity exists between what communities know and what engineers do in the field. The study concluded that indigenous knowledge should be integrated into engineering designs, warning systems, evacuation strategies, and infrastructure development to make communities more resilient to tsunamis. Consideration of co-designed socio-technical frameworks, comparison of their application in various tsunami-prone areas, and development of equity-sensitive indicators are all avenues for future study that can contribute to disaster risk reduction efforts that are more community-centered and inclusive.

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■ INTRODUCTION

Tsunamis pose a unique threat to coastal fishing communities already plagued by climate change, natural disasters, and human interference (Yonvitner et al., 2021, 2020). Resilience to tsunamis is a socio-technical issue because accurate risk assessment must be translated into clear warnings, clear evacuation routes, accessible shelters, and trustworthy decision-making. Unlike near-field tsunamis, which provide only minutes for evacuation, long recurrence intervals erase community memory. For preparedness to work, infrastructure and institutions must work together (Benazir & Oktari, 2024; Carvajal et al., 2019; Daly et al., 2019; Rubin et al., 2017). Understanding

how communities respond to danger, alongside hazard modeling and physical infrastructure, is essential to reduce tsunami risk. Because it enhances the capacity to recognize dangers and comprehend warnings, local knowledge, a kind of indigenous knowledge, is vital for tsunami readiness. The Smong tradition of Simeulue, which includes storytelling, music, and effective evacuation techniques, can be passed down through generations (Rahman et al., 2024; Sutton et al., 2021). Research in other tsunami-prone regions suggests that local knowledge may encompass a variety of sources, including environmental indicators, oral histories,

cultural practices, and socially embedded mechanisms for identifying and responding to hazards (Mikulecký et al., 2023). However, treating local knowledge as a replacement for scientific information would be a mistake. Studies on disaster preparedness increasingly view local and scientific knowledge as two sides of the same coin, with the potential to form a hybrid system that can aid risk assessment, early warning, adaptation, and preparation (Hadlos et al., 2022; Hermans et al., 2022). At the same time, engineering advances have improved probabilistic tsunami hazard estimation, early warning systems, evacuation simulation, infrastructure design, and ETA modeling (Park & Cox, 2016; Hui et al., 2022; Mulia et al., 2020; Mori et al., 2022). These developments have improved our capacity to predict the severity of danger, pinpoint vulnerable areas, determine the need for evacuation plans, and plan mitigation infrastructure. Recent research also emphasizes that early-warning systems must connect risk knowledge, monitoring and forecasting, warning communication, and preparedness and response as an integrated process rather than as independent technical components (Hermans et al., 2022).

Previous reviews provide important comparative evidence for assessing this research gap. In their systematic literature review of local and Indigenous knowledge in disaster risk reduction, Hadlos et al. (2022) examined the field's evolution and its relationship to disaster risk reduction priorities. Their review shows that local knowledge has gained greater recognition in disaster preparedness and risk reduction, while also highlighting the need to strengthen the link between knowledge-based practices and broader disaster risk reduction agendas. Similarly, Hermans et al. (2022) reviewed the integration of local and scientific knowledge in early warning systems and found that integration takes different forms, including participatory mapping and knowledge triangulation. However, their findings also highlight persistent challenges associated with power relations, social interaction, and the contextual application of different knowledge systems. These reviews establish that knowledge integration is already an important area of disaster risk reduction research. Nevertheless, they also indicate the need to examine not only whether different knowledge systems are acknowledged or combined, but also how their integration is translated into specific mitigation functions and operational decisions.

However, the connections between knowledge incorporation and technology implementation in these advancements remain underexplored. Memory, culture, risk perception, trust, and local preparedness are typical foci of community-based research, in contrast to the sensing, modeling, evacuation time, route optimization, and infrastructure design typical of engineering studies. Reviews of indigenous and local knowledge increasingly emphasize integration. However, most of the literature still focuses on recording knowledge, participatory mapping, communication, or early warning systems, rather than using this information to inform planning and design decisions (Hermans et al., 2022; Hadlos et al., 2022). Through community engagement, vulnerability assessment, identification of local and scientific initiatives, and the design of an integrated strategy, this paper proposes a framework for integrating indigenous and scientific knowledge. Later assessments still raise questions about how to combine diverse knowledge systems, where integration happens, and how to operationalize it in practice. This is particularly relevant to tsunami mitigation, since the value of local knowledge is ultimately measured by its ability to inform decision-making under severe time constraints. Signs with cultural significance may help people see danger sooner, but whether they prompt an evacuation is dependent on how easily people can reach safe havens and routes. Similarly, ETA modeling can predict how much time remains for evacuation, but its real-world effectiveness depends on how well people understand, believe, and act on warnings. Consequently, the main challenge is not just combining two bodies of information but also creating a workable link between deeply ingrained cultural perceptions of risk and how people interpret warnings, behave in evacuations, and plan infrastructure. Aceh and Simeulue highlight how local knowledge and disaster management institutional frameworks evolved in tandem. Benazir et al. (2023) showcase tsunami modeling integrated with community preparedness and local viewpoints, and how ETA and inundation modeling can enhance evacuation planning (Benazir & Oktari, 2024). According to Pastrana-Huguet et al. (2022), another example

of the dynamic between cultural memory, catastrophe preparation, and institutions is the Japanese Bosai culture. However, nothing in this should be construed as meaning there is no transferable integration model. Its significance lies in revealing the likely sites of convergence among cultural knowledge, institutional forms, and technical systems. There is increasing recognition in research that infrastructure performance differs across socioeconomic classes. People interpret and respond to warnings differently and seek safety differently, based on age, mobility, access to communication, household characteristics, and trust in institutions (Chen et al., 2022; Ito et al., 2021; Nakasu, 2026). Therefore, physical capacity and technological performance are not sufficient criteria for evaluating infrastructure lifespan. We also need to consider different populations' ability to access and use evacuation routes, shelters, warning systems, and communications infrastructure. This concept expands infrastructure engineering beyond physical provision to decision-ready, community-centric mitigation.

Evidence from tsunami-specific studies further demonstrates that the relationship between community knowledge and engineering is not absent. For example, Kubisch et al. (2020) examined tsunami evacuation planning in Talcahuano, Chile, by combining questionnaires on evacuation behavior with GIS-based evacuation simulation. Their study shows how evidence on people's evacuation decisions, travel modes, and movement constraints can complement spatial modeling and inform evacuation planning. Likewise, studies on Smong in Simeulue and the integration of COMCOT modeling with community surveys and interviews in Aceh show different ways cultural memory, community experience, and technical analysis can inform tsunami preparedness. These examples qualify the assumption that local knowledge and engineering have always been studied independently. However, mixed-method approaches, or community-informed planning, do not automatically show that culturally grounded knowledge has been systematically incorporated into infrastructure design criteria, shelter-location decisions, evacuation-route specifications, or engineering priorities. This distinction provides a basis for examining the degree of integration achieved in the reviewed literature rather than treating integration as either wholly absent or fully established.

So, three changes are visible in modern writing. First, using indigenous and local knowledge has been shown to benefit risk recognition, preparedness, understanding warnings, and community response (Hadlos et al., 2022; Mikulecký et al., 2023). Second, engineering research has developed increasingly sophisticated methods for threat assessment, ETA calculation, early warning, evacuation modeling, and infrastructure design (Hui et al., 2022; Mori et al., 2022; Mulia et al., 2020). Third, more research suggests merging local and scientific knowledge, particularly in people-centered early warning systems (Hermans et al., 2022). However, these improvements have not adequately provided a solid foundation for directly incorporating local knowledge into engineering and operational decisions. The current literature acknowledges integration as a promising trend. However, it also shows that, rather than occurring during engineering prioritization and infrastructure design, integration is more commonly seen in participatory mapping, risk assessment, communication, and preparedness (Hadlos et al., 2022; Hermans et al., 2022). This is not the case. It is one thing to recognize that local knowledge is vital; it is quite another to explain how that information should influence decisions about where to evacuate, where to position shelters, how to design warnings, where to deploy sensors, or how much to invest in infrastructure. Local and indigenous knowledge is being acknowledged more in disaster risk reduction, and engineering systems are improving at producing hazard and evacuation information ready for decision-making. However, research that specifically addresses how these two domains can be integrated into a cohesive socio-technical mitigation process remains scarce.

Taken together, the comparative literature suggests that the principal research gap is not the complete absence of studies connecting local knowledge with scientific or technical approaches. Rather, the gap concerns how explicitly these connections are operationalized and evaluated in tsunami mitigation. Previous reviews have examined knowledge integration across disaster risk reduction and early warning systems. Meanwhile, tsunami-specific studies have shown the value of combining community perspectives with evacuation analysis and hazard modeling. However, these contributions do not necessarily provide a consistent basis for determining how local knowledge influences identifiable engineering and policy decisions across different mitigation functions. It remains necessary to distinguish between acknowledging local knowledge as contextual information, using it to support warning interpretation or evacuation planning, and incorporating it as an explicit input into infrastructure-related decisions. This review addresses that analytical need by examining how studies treat local knowledge, the actionability of engineering outputs, and the degree of socio-

technical linkage reported across the included studies.

Literary works tend to emphasize the significance of indigenous knowledge systems like the Smong in Simeulue and the Bosai in Japan, even if traditional wisdom is depicted as solitary stories of preparation. This work's main contribution is not to re-interest these well-documented cultural practices but to use them as functional components in engineering frameworks. This review shows how qualitative socio-cultural parameters such as community-defined safe zones, trusted warning communication channels, and local risk perception thresholds can be systematically translated into quantitative variables for numerical tsunami modeling, agent-based evacuation simulations, and infrastructure decision support. The lag time between knowing and acting is so small that this gap is critical to tsunami resilience. This evaluation provides answers to three questions based on the provided background summary: 1) How has recent literature conceptualized the relationship between local knowledge and infrastructure engineering in tsunami resilience? 2) Which mitigation functions are most clearly reported as bridging local knowledge and engineering? 3) Where does culturally grounded knowledge remain disconnected from engineering and policy decisions? In this assessment, bridging means integrating indigenous or local knowledge into engineering and operational procedures, for example, in warning dissemination, interpreting estimated time of arrival (ETA), placing shelters, routing evacuations, communication systems, and infrastructure priorities. This criterion distinguishes between research that engages with local knowledge and engineering and real socio-technical integration in the same crisis scenario. With this approach, we can generate new data to identify where knowledge integration is happening, where it is lacking, and which mitigation functions are most likely to enable it. Therefore, the analysis provides a socio-technical perspective on tsunami resilience, linking culturally entrenched knowledge with engineering-based mitigation and providing a platform for more community-oriented, context-aware, and operationally meaningful frameworks for tsunami risk reduction.

■ METHOD

Research Design

The study is designed as a systematic scoping review in journal form, based on PRISMA logic. Contemporary research includes qualitative studies, hazard models, evacuation simulations, policy analyses, and review papers. Therefore, we intentionally framed the review as a socio-technical synthesis challenge rather than a limited intervention-effect problem. The new publication stratifies the evidence for the primary outcomes into a core set and a validated bibliography to promote contextualization and comparative understanding. This evaluation was not registered using a formal protocol.

Search strategy

The literature search was performed on Scopus and Web of Science in May–June 2026, using pre-defined combinations of the following terms: tsunami, indigenous, local knowledge, engineering, early warning, evacuation, and resilience. The retrieved records were reviewed against the pre-determined eligibility criteria. Relevant citation information was checked a second time to guarantee accuracy in the screening and data-extraction processes. Engineering, ecology, and social science are the only acceptable majors. From 2020 through early 2026, publications will be included to build a substantial evidence base. The search string is: ("tsunami" OR "tsunami risk" OR "tsunami resilience" OR "tsunami preparedness" OR "tsunami evacuation" OR "tsunami early warning") AND (indigenous OR "local knowledge" OR "traditional knowledge" OR oral OR narrative OR song OR culture OR *Smong* OR Bosai OR infrastructure OR engineering OR "probabilistic hazard" OR sensor* OR shelter* OR route* OR "decision support") AND (resilience* OR mitigation* OR prepared* OR warning OR evacuation OR planning OR governance). In the first search, all quartiles were considered.

Inclusion and Exclusion Criteria

The eligibility (inclusion and exclusion) criteria were classified into three categories: thematic distribution, geography, and technique, as presented in Table 1.

Data Analysis

Data analysis began with a systematic extraction sheet designed to collect, for each study, the year of publication, setting, study design and data, socio-technical focus, key contribution, and evidence robustness grade. In addition to the conventional methodologies of rigorous literature categorization and thematic synthesis in research on disaster risk reduction (Hadlos et al., 2022; Vasileiou et al., 2022), engineering actionability was coded on a three-point ordinal scale: 0 = none, indicating no identifiable engineering or operational implication; 1 = indirect, indicating a general or contextual implication that was not translated into a specific technical or operational decision; and 2 = decision-ready, indicating that the

Table 1. Inclusion and Exclusion Criteria

Criteria Category	Inclusion Criteria	Exclusion Criteria
Thematic distribution	Concerned with tsunami hazard, preparedness, early warning, evacuation, mitigation	Focused on earthquakes without substantive tsunami relevance, purely geophysical without mitigation implications, or not a natural disaster e.g., climate change, man-made hazard
Geographic	Studies addressing tsunami-prone coastal communities, regions, or systems, regardless of country, provided that the findings were relevant to tsunami mitigation, preparedness, evacuation, warning, or infrastructure planning.	Non-coastal area, area with no tsunami hazard
Methodology	Peer-reviewed journal articles employing empirical, modeling, simulation, review, conceptual, policy, institutional, or mixed-method approaches, provided that the study addressed tsunami mitigation, preparedness, warning, evacuation, risk reduction, or infrastructure-related decision-making.	Book, report, news items, opinion article, dissertation, insufficient methodology

study provided an identifiable output or recommendation that could inform a mitigation decision, such as evacuation planning, warning-system operation, route accessibility, shelter planning, or infrastructure design. These scores were distinguished from mitigation-function categories, which describe the substantive domain a study addresses rather than the degree to which its findings support engineering action. Local-knowledge treatment was coded separately as 0 = absent, 1 = implicit-contextual, and 2 = explicit-analytic. The evidence map cross-tabulated local-knowledge treatment against engineering actionability to examine whether the explicit treatment of local knowledge coincided with more actionable engineering or operational outputs. Mitigation functions, including behavior/warning, operational planning, and infrastructure design, were retained as descriptive categories to characterize the substantive focus of the included studies rather than as substitutes for the engineering-actionability scale.

Because the studies differed substantially in methodology, units of analysis, research designs, and reported results, we did not conduct a meta-analysis. The evidence base included studies that evaluated policies and institutions, investigated risk communication, conducted interviews with community members, utilized numerical tsunami models, conducted probabilistic tsunami hazard assessments, simulated evacuations, examined transport and routes, conducted conceptual or system-level studies, and studied narrative and cultural memory. Reported consequences included infrastructure development, cultural memory, warning interpretation, cultural ramifications, tsunami arrival time, flooding, evacuation time, route capacity, hazard potential, communication, and cultural repercussions. These studies did not share an intervention-outcome structure, effect measure, or similar endpoint, so researchers could not combine their findings meaningfully. The following themes guided the analysis and organization of the evidence: indigenous knowledge and cultural memory; analytics for evacuations; probabilistic risk assessment and engineering design; and socio-technical integration of local knowledge with infrastructure engineering. The synthesis also considered communication and warning systems. The synthesis did not aim to evaluate the combined intervention effect; rather, it sought commonalities, methods of information translation, and examples of strong or weak ties between engineering and indigenous knowledge.

Records identified from Scopus (n=91) and Web of Science (n=77), for a total of 168 records. After removing duplicates (n=39), we reviewed 129 records by title and abstract; 82

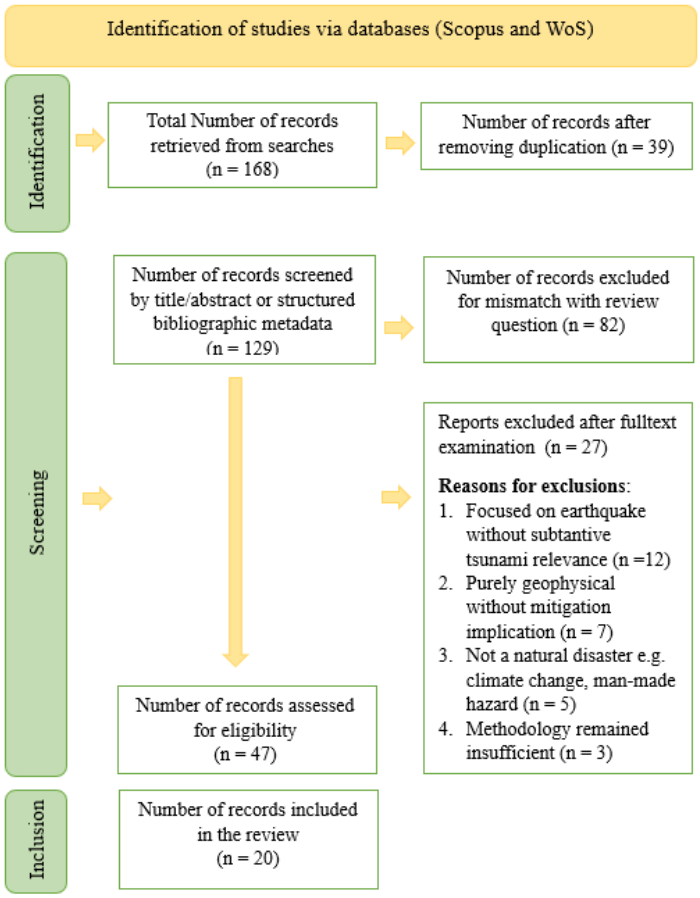


Figure 1. PRISMA-style workflow used to assemble the conservative evidence set for this review

were excluded because they did not meet the review question criteria. We excluded 27 records for specified reasons out of 47 that were assessed for eligibility based on full text. The twelve studies were excluded because they discussed earthquakes; about seven studies focused on non-mitigation geophysical studies, and five studies did not talk about natural disasters. Therefore, the remaining 23 articles were not included in the review. Three articles were excluded because their methodology was insufficient, as they did not clearly explain the inclusion and exclusion criteria. Finally, the twenty studies reviewed consist of seventeen studies indexed in Q1, two articles from Q2, and one article from a Q3 journal.

■ RESULT AND DISCUSSION

How has recent literature conceptualized the relationship between Local Knowledge and Infrastructure Engineering in Tsunami Resilience

Figure 2 illustrates the dispersion of the research by time and topic. Most studies focused on hazard assessment, early warning systems, evacuation planning, and decision support; publications increased after 2020. However, few studies explicitly merged indigenous wisdom with engineering. This suggests that local knowledge was not sufficiently considered in the design of evacuation routes, shelter seating arrangements, warning systems, and tsunami-resilient infrastructure. Studies in the region focused on indigenous knowledge and community readiness in Aceh and Simeulue, Indonesia; engineering and hazard assessment in China and Japan; and evacuation planning in Chile. Across time, the research landscape is scattered yet growing. Research from 2020 to 2022 examined indigenous and cultural knowledge, risk and hazard systems, warning and governance, evacuation and planning, and many other areas. Results suggest that social and technical methods are being improved simultaneously. In 2023, efforts to link local knowledge to operational or technological activity increased, with half of the studies reviewed being bridge cases or indigenous/cultural studies. This means a shift in emphasis. When indigenous/cultural and evacuation/planning research were represented at similar levels in 2024, it highlighted the growing need

for culturally based information in evacuation practice. However, using a bridge is still unusual. The 2026 distribution should raise red flags because it relies on a single study. Overall, the pattern indicates that the field has not yet achieved substantial integration. Knowledge, evacuation, warning, and engineering all appear to be progressing in separate directions, with only a tiny fraction of the total integrating these areas.

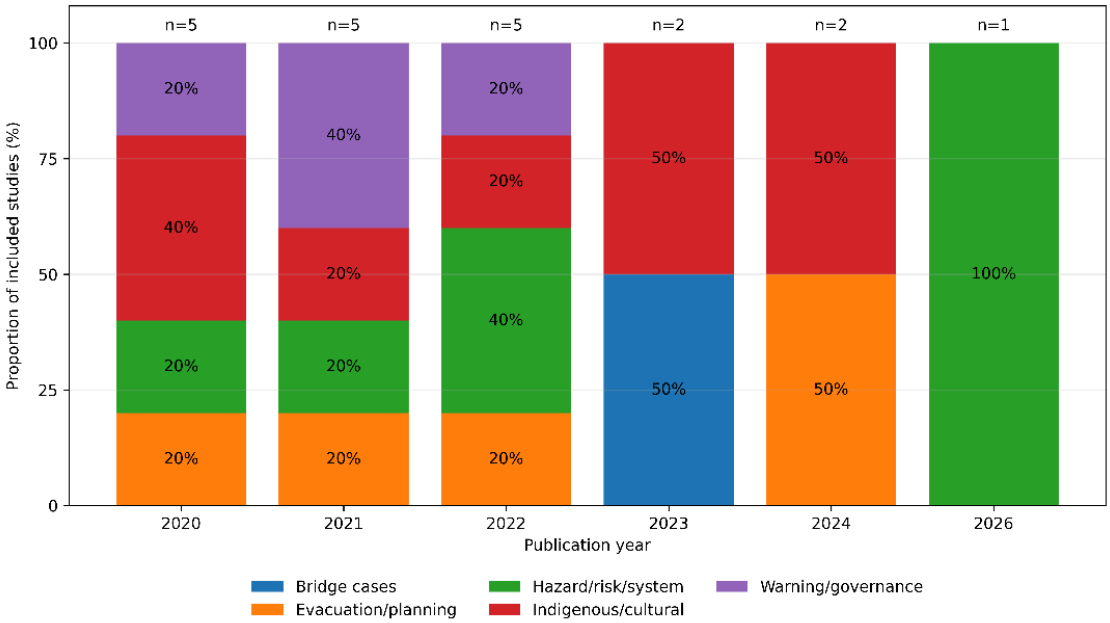


Figure 2. Proportional distribution of included studies by year and primary domain

Table 2 summarizes all twenty of these investigations. Studies 1-10 focused on communication, community participation, preparedness, cultural sensitivity, sociocultural studies, and people's perceptions and sense-making of potential risks. Specifically, studies 11–20 concentrate on engineering, modeling, evacuation analytics, operational planning, and system function recognition. The review's claims are supported by a growing number of citations, suggesting the focus is not limited to this study but reflects the field. Sumatran and Acehnese studies are more common, where field surveys of paleorecords and community narratives may be merged (Martin et al., 2019). In contrast, the eastern Pacific, Chile, Japan, and Hawai'i have more established literature on evacuation, near-field modeling, route optimization, agent-based simulation, and fast warning design (Wood et al., 2018). Again, consistent with this pattern, the manuscript claims a paucity of studies examining the relationship between the two domains, not a lack of data in either one individually.

Table 2. The summary of twenty studies reviewed

No	Study	Setting	Design/data	Socio-technical focus	Principal contribution
1.	Sufri et al. (2020b).	Aceh, Indonesia	Policy/ institutional assessment	Warning governance	Shows institutional coordination remains decisive for warning performance.
2.	Sutton et al. (2020a)	Simeulue, Indonesia	Risk-communication analysis of *Smong*	Indigenous warning memory	Explain how the name *Smong* itself sustains recognition and response.

No	Study	Setting	Design/data	Socio-technical focus	Principal contribution
3.	Sutton et al. (2020b)	Simeulue, Indonesia	Community-based transmission analysis	Intergenerational knowledge	Shows grandmother-led storytelling preserved evacuation memory.
4.	Rayawan et al. (2021)	Aceh, Indonesia	Preparedness/ miti-gation case analysis	Governance and preparedness	Links mitigation organization to preparedness outcomes.
5.	Sutton et al. (2021)	Simeulue, Indonesia	Communication and music in DRR	Cultural communication	Shows songs and lullabies function as durable warning media.
6.	Adityawan et al. (2023)	Indonesia	Technical concept paper	Last-mile warning	Proposes maritime wireless channels to accelerate warning delivery.
7.	Pastrana-Huguet et al. (2022)	Japan	Bosai policy-culture analysis	Culture-system integration	Shows cultural heritage and advanced DRM can reinforce each other.
8.	Benazir and Oktari (2023)	Aceh, Indonesia	COMCOT and survey/ interviews	Community knowledge and modeling	Bridges scenario modeling with community risk perception.
9.	Mikulecký et al. (2023)	Comparative/ conceptual	Conceptual synthesis	Indigenous knowledge integration	Treats indigenous knowledge as a usable tsunami-risk resource.
10.	Rahman et al. (2024)	Simeulue/ Aceh	37 interviews, 2022–2023	Narrative transmission	*Smong* narratives evolve across generations.
11.	Kubisch et al. (2020)	Chile	Multi-perspective evacuation planning	Evacuation planning	Demonstrates evacuation analysis can improve Chilean planning.
12.	Mulia et al. (2020)	Sea of Japan coast	Regional PTHA using Monte Carlo logic trees	Hazard modelling	Shows return-period hazard varies by source

No	Study	Setting	Design/data	Socio-technical focus	Principal contribution
					type and location.
13.	Ito et al. (2021)	Evacuation planning context	Simulation and numerical analysis	Evacuation analytics	Identifies difficult-to-evacuate areas for planning.
14.	Srinivasa Kumar and Manneela (2021)	Global / review	Review of TEWS progress	System review	Synthesize strengths and persistent gaps in tsunami warning systems.
15.	Liu et al. (2021)	Southeast China	PTHA with regional and local sources	Hazard modelling	Shows hazard dominance differs across coastal segments.
16.	Chen et al. (2022)	Planning contexts	Transport and evacuation analysis	Evacuation time/ logistics	Shows route capacity and timing strongly shape outcomes.
17.	Hui et al. (2022)	Chinese coast	Integrated hazard-exposure-vulnerability analysis	Risk integration	Moves from hazard only to fuller risk characterization.
18.	Mori et al. (2022)	Global	State-of-the-art review	Socio-technical systems	Argues hardware and software countermeasures should be integrated.
19.	Benazir and Oktari (2024)	Aceh coast, Indonesia	ETA and inundation modelling	ETA mapping / planning	Links ETA windows to shelter siting and route priorities.
20.	Nakasu (2026)	Aging-society policy	Vulnerability index and projection	Demography and evacuation equity	Shows aging alone can raise mortality risk despite constant hazard.

The assessment found that engineering-based tsunami studies and those that prioritize indigenous knowledge differed significantly. Figure 3 is a proof map showing how much indigenous and local knowledge has been used in engineering for tsunami protection and how much of it the included studies incorporated. Because of the limited sample size (n = 20) and the concentration of indigenous and local knowledge discussions in this research, interpret the evidence map with care. Local knowledge was specifically addressed in seven studies. There were two studies pertaining to operational planning and five to behavior and warning. In

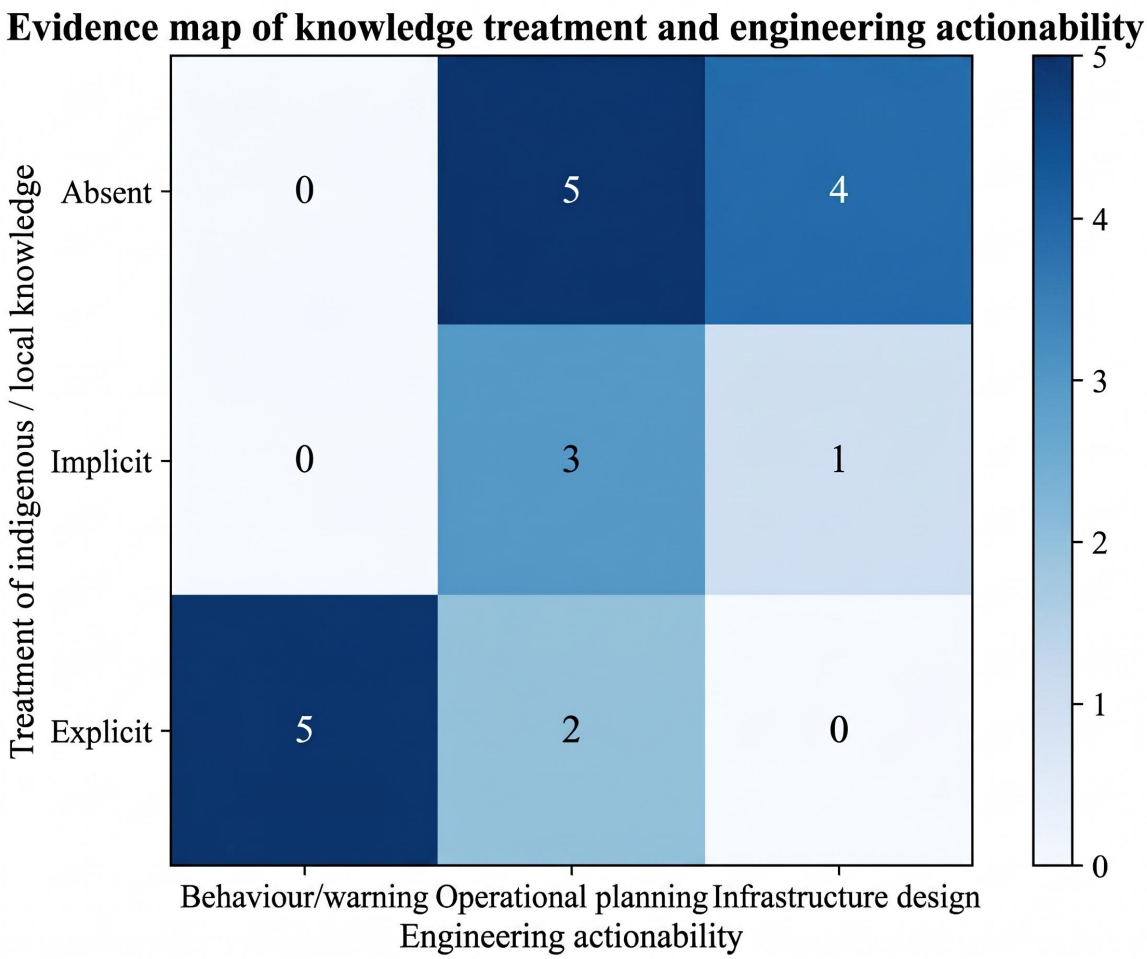


Figure 3. Evidence map of indigenous/local knowledge treatment and engineering actionability

infrastructure design research, local wisdom was completely ignored. The diffusion of technical literature varies by place and region, but that does not mean such writing does not integrate local knowledge. In fact, this analysis shows that local knowledge was more often leveraged to shape threat assessment, warning interpretation, and evacuation behavior than to be explicitly embedded in infrastructure design. We do know that reporting processes, disciplinary boundaries, and language influenced the classification. However, the small sample size means we cannot determine definitively how pervasive this tendency is. Our results do not rule out engineers' use of local knowledge; rather, they point to a gap in the literature on knowledge translation.

Which mitigation functions are most clearly reported as bridging local knowledge and engineering?

More information about this bridge function is given in Table 2. The Smong trials show that those who emphasize locally transmitted warning memory, storytelling, music, and intergenerational communication are better able to perceive danger and respond to evacuations. Bosai study concentrates on cultural legacy and modern approaches to disaster management. The Aceh study is another example of interpreting technological models through community experience, combining COMCOT modeling with surveys and interviews. More evidence suggests that operational planning plays a bridging role. This includes research on tsunami arrival times, coastal segmentation for route prioritization, shelter locations, and varied evacuation plans. Conversely, more engineering-oriented studies tend to emphasize metrics like journey time, route capacity, logistics, hazard likelihood, and model findings, and less on culturally grounded data. The cross-study indicated that the bridge is most stable at locations where engineering data processing is necessary for warning and evacuation decision-making. As we move into more structured technological applications, the relationship deteriorates. This distinction matters because research shows that engineering and

local knowledge co-exist and mostly interact for interpretation, communication, preparedness, and evacuation decision-making.

Table 2 adds evidence that smong are more resilient to tsunamis than others because they use storytelling, singing, and passing information from one generation to the next. While nandong smong and tsunami lullabies promote risk communication and readiness, the smong tradition teaches people to recognize danger and evacuate when a tsunami comes (Sutton et al., 2020a; Sutton et al., 2021). Rahman et al. (2024) further show that gender, education, and contemporary media all contribute to knowledge as an evolving system. Similarly, Benazir et al. (2023) illustrate the interplay between evacuation circumstances, land use, local knowledge, and settlement patterns in determining the necessary level of preparation. One example of how cultural heritage might improve disaster management is the Bosai custom in Japan, while Mikulecký et al. (2023) maintain that traditional wisdom should not be treated as historical proof but as a practical asset. Overall, these results suggest that culturally grounded warning systems are effective because of their reliability, social integration, and frequent rehearsal. However, as observed in Figure 3, only a handful of studies translate indigenous knowledge to engineering applications such as siting shelters, designing evacuation routes, or placing sensors. This points to the need for a stronger integration between indigenous knowledge and infrastructure engineering to help support socio-technical tsunami resilience.

These studies show that the main obstacle to coordination is not the availability of technical knowledge, but translating technical outputs into operational roles and locally grounded response mechanisms. ETA observation stations and coastline segmentation offer actionable information for route priority, shelter siting, and differential evacuation planning. However, evidence from Aceh shows that improvements in early-warning capacity do not automatically resolve institutional coordination and role clarity. Overall, our results show that technology gains are operationally relevant only when hazard information can be transformed into explicitly allocated roles and coordinated evacuation decisions. The remaining challenge, thus, is coordinating technical knowledge, institutional duties, and community-facing responsiveness, rather than a lack of technical capacity per se (Benazir & Oktari, 2024; Sufri et al., 2020b; Rayawan et al., 2021). Benazir et al. (2023) provide one of the most explicit examples of socio-technical integration, combining COMCOT modeling with questionnaires and interviews and showing that engineering models are more valuable when reviewed alongside local knowledge and community experience.

Engineering applications are most evident in evacuation analytics (Table 2, Studies 11–20). Ito et al. (2021), Chen et al. (2022), and Kubisch et al. (2020) illustrate that evacuation efficiency, route capacity, infrastructure, and logistical restrictions all have a role. These studies are useful for decision-making, but they rarely consider indigenous wisdom. So, evacuation modeling has progressed, but it still disconnects from culturally based risk assessment and effective local communication. Studies by Hui et al. (2022), Liu et al. (2021), and Mulia et al. (2020) show how probability-based risk assessment supports infrastructure design and land-use planning. Likewise, Srinivasa Kumar & Manneela (2021) and Mori et al. (2022) highlight developments in early warning systems and tsunami monitoring. Figure 2 shows that engineering-oriented studies are gaining prominence because they deliver scalable, decision-ready solutions. However, they rarely account for indigenous knowledge or community perspectives. Carvajal et al. (2019) further show that near-field tsunamis only allow minutes for evacuation, making evacuation pathways and vertical shelters as important as detection systems. In general, engineering studies rarely incorporate local knowledge when designing infrastructure. This highlights the importance of combining engineering with communication and planning grounded in culture.

Where does culturally grounded knowledge remain disconnected from engineering and policy decisions?

Based on the evidence, infrastructure design stands out as the most evident point of disconnect. Figure 3 shows no research linking infrastructure design to explicit local-knowledge treatment. One study falls into the implicit category, and four fall into the absent-local-knowledge category. In contrast, two operational-planning instances and five behavior/warning scenarios demonstrate explicit local-knowledge treatment. This matches Table 2. Examples of engineering-focused studies include hazard modeling, transportation and route analyses; ETA mapping, risk integration, and demographic or evacuation-equity analyses. Key technical products include risk assessments, evacuation plans, anticipated travel times, capacity estimates, shelter placement, and route priority. Research comparisons show a divide not only between "local knowledge" and "engineering" per se. This gap becomes especially clear when formal engineering judgments require locally grounded

knowledge. The data under investigation show local competency in warning detection, communication, preparedness, and evacuation behavior, while engineering studies increasingly provide decision-ready representations of hazard, time, routes, and infrastructure. We know less about how the latter becomes direct engineering input.

This flaw is clear in the specific infrastructure examples the articles described. There was minimal evidence of direct involvement of indigenous peoples in the formulation of evacuation plans, sensors, or technical standards; however, one study had an indirect tie to local knowledge, and four studies focused on engineering in this area. All signs point to a disconnect between locally relevant operational data and formal engineering decisions on infrastructure. This finding should be regarded with caution, given the lack of studies directly addressing local knowledge across the broader body of evidence. While this finding highlights a gap in the literature under consideration, it does not establish that this tendency is ubiquitous in the tsunami engineering industry.

The research reviewed points to the difficulty of coordinating different types of knowledge, institutional responsibilities, and operational roles as the fundamental hurdle to tsunami-risk management, not the absence of information or technology per se. The findings show that, overall, demographic risk, hazard modeling, indigenous knowledge, warning governance, and evacuation preparedness are often handled separately. This fragmentation creates coordination gaps among players who provide hazard information, organizations responsible for warning dissemination, communities that interpret warnings, and agencies responsible for evacuation routes and shelters. Thus, the data indicate that tsunami resilience depends not only on the quality of individual components but also on how well they connect.

Both governance-oriented and technical warning research show that technological warning capability does not necessarily translate into effective community action. This shows a shared institutional coordination issue. Warning performance is dependent on interagency cooperation and organizational processes that disseminate technical knowledge to communities, according to studies of tsunami early-warning systems and the Aceh institutional evaluation. This also aligns with findings from the Smong studies, which show that different communities identify and communicate tsunami danger in different ways. Overall, these studies suggest that society may not always understand institutional warnings. Aspects of the coordination problem include, but are not limited to, the need for faster warning dissemination and the establishment of trust, interpretation, and response channels between official warning systems and local communities.

The second barrier is transferring data between disciplines. Local knowledge is mainly framed by risk perception, memory, and warning and evacuation behavior in studies on Smong, cultural communication, and indigenous knowledge, while hazard-modeling and infrastructure-oriented studies mainly produce numerical data on flooding, likelihood, arrival time, routes, and system performance. The cross-study pattern shows that these two knowledge systems often work in tandem rather than as shared decision variables. For example, there is little knowledge about how multiple types of information are integrated to make decisions such as placement of shelters, prioritizing of evacuation routes, warning thresholds, or placement of infrastructure. Engineering models can advise us when and where to evacuate. Community knowledge can tell us whether signals are reliable.

The same incoherence becomes much more apparent when moving from operational planning to infrastructure design. Research on evacuations shows that factors such as route capacity, travel time, inaccessible areas, and shelter priorities are crucial. Research on population dynamics and mobility restrictions has shown that evacuation requirements vary. However, these findings are inconsistently connected to knowledge embedded in culture or institutional decision-making. Thus, while technological models may suggest spatial or temporal priorities, little evidence shows how community knowledge, social inequalities, and institutional duties should modify those priorities before translating them into infrastructure decisions. So, the research has limited applicability across different time frames. Local knowledge usually draws on direct experience, stories, traditions, and social transmission, unlike hazard models, which rely on hypothetical or probabilistic predictions of future events. Warning systems have short decision windows. Infrastructure planning and governance have far longer institutional cycles. Living with these distinct temporal logics is a socio-technical co-ordination problem: decisions that work in the minutes available during a near-field tsunami need long-term cultural memory and preparation. The results show that preparedness systems must combine future-oriented information storage and strategic planning with the ability to make rapid judgments for daily operations.

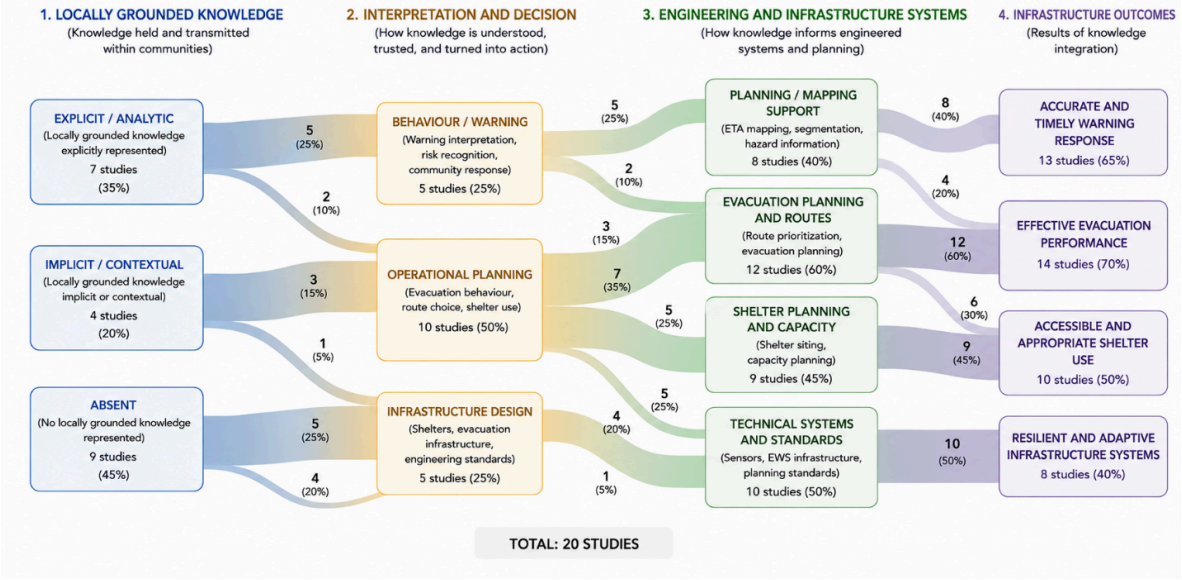


Figure 4. Conceptual bridge showing how indigenous knowledge, warning interpretation, evacuation behavior, and engineering systems interact in socio-technical tsunami resilience.

Figure 4 summarizes the main finding of this review: tsunami resilience depends on integrating indigenous knowledge, warning interpretation, evacuation behavior, and engineering systems rather than treating them as distinct components. Few studies directly connect these topics. Benazir et al. (2023) integrate numerical modeling with local knowledge, while Pastrana-Huguet et al. (2022) show how Japan's Bosai culture employs a similar systems approach. In contrast, studies by Rahman et al. (2024) and Mikulecký et al. (2023) prioritize understanding different cultures while avoiding technical problems, whereas Benazir and Oktari (2024), Chen et al. (2022), and Ito et al. (2021) devise technological solutions while placing less importance on regional knowledge. Nakasu (2026) notes that, however, even with accurate risk information, mortality rates may still rise given shifting demography and mobility constraints. Warning response and infrastructure use are influenced by psychosocial factors, including trust, risk perceptions, religiosity, coping capacities, and economic conditions, and consequently, socio-technical resilience (Rachman et al., 2023; Siroj et al., 2024). Thus, infrastructure should be seen not only as safe havens but also as the social frameworks that enable individuals to deploy these assets effectively.

As shown in Figure 4, culturally informed danger perception translates into warning interpretation, evacuation behavior, and functional infrastructure. This review indicates that tsunami research has independently confirmed the importance of indigenous knowledge and engineering but has not integrated them. Indigenous knowledge is used as an operational resource. Engineering studies show the importance of ETA modeling, hazard assessment, and evacuation simulation for planning (Benazir & Oktari, 2024; Liu et al., 2021). However, trust in government, collaboration, and warning efficacy are also crucial (Benazir et al., 2023; Sufri et al., 2020a). Because of methodological and assessment differences, co-design has not yet gained traction in engineering and socio-cultural studies. Sociocultural studies focus on trust, memory, and information transmission, whereas engineering focuses on optimizing infrastructure and predicting hazards (Wang et al., 2016). Success stories from Japan, Simeulue, and Banda Aceh show the value of institutionalizing indigenous knowledge for resilience, but how much this knowledge can be transferred depends on the specific setting (Ismail et al., 2018).

However, proof of interrelated socio-technical contexts is lacking. Culturally tailored warning communications can improve evacuation performance, but little is known about the potential advantages of incorporating indigenous knowledge into engineering design. Still, future evacuation and infrastructure models can benefit from the myriad locally embedded components that this research explores. Locally understood signals and established communication channels can, for instance, support warning recognition and response processes. Knowledge of place-based markers can inform assumptions about route choice and evacuation behavior. Perceived safe sites

can inform assumptions about the location and accessibility of potential shelters. Documented patterns of community migration can inform assumptions about evacuation behavior and route use. It is critical to consider social vulnerability and community interests when deciding who has access to the shelter and which routes are most advantageous. Here, we should not think of these variables as hard-coded technical specifications, but as potential model parameters that still need real-world testing.

This operationalization reveals four areas for further research. First, how to incorporate hazard information into trusted local communication systems. Second, how to incorporate locally based evacuation behavior and social vulnerability into evacuation plans. Third, how to incorporate locally identified routes, landmarks, and perceived safe locations into infrastructure and shelter plans from the outset. Last, how to sustain preparedness through technical systems and ongoing cultural transmission. Future studies could ideally combine ETA with evacuation simulations, openly record and parameterize these locally grounded elements, and compare results with real-life evacuation data. Comparative research across coastal settings would help determine whether the relevance and predictive potential of equity-sensitive indicators vary by cultural and geographic location. Such indicators should measure how well the infrastructure performs, and who receives, trusts, and acts on alerts. The diversity and spatial distribution of the data collection are rather successful in consistently identifying the major components of socio-technical tsunami resistance. The second domain of inquiry relates to translating these locally based features into testable technical and operational parameters. Next, we need to see whether including them improves infrastructure decisions, evacuation plans, and alerts.

■ CONCLUSION

This comprehensive scoping assessment shows substantial evidence on both indigenous knowledge and engineering-based mitigation in tsunami research, but little effort has been made to integrate the two. Indigenous knowledge enhances the ability to perceive danger, understand warnings, and evacuate safely. Engineering studies often focus on infrastructure design, evacuation simulations, early warning systems, and hazard assessments. Culturally grounded knowledge influences engineering decisions on evacuation routes, shelter seating, warning systems, and infrastructure development, but few studies directly incorporate it. The article highlights a knowledge-translation gap: engineering techniques seldom use acknowledged local expertise. Community recollection, reliable communication, and institutional backing may strengthen disaster readiness and complement engineering approaches, as shown in both the Japanese Bosai tradition and the Smong tradition of Simeulue. This analysis highlights the connection between tsunami and local knowledge, which is complementary but poorly integrated. Warning interpretation, communication, and evacuation behavior are most closely correlated with local knowledge. Engineering research focuses primarily on time, routes, hazards, and operational planning. Only in evacuation and warning systems are linkages clearly defined, and local knowledge is not evidently integrated into infrastructure design. Consequently, the main issue is the inefficient transition of information from informal to formal engineering and operational decision-making. Future research should focus on tsunami-prone areas where evacuation and early warning system (ETA) plans have been co-designed and evaluated to support knowledge-engineering integration. Ultimately, this research moves away from preserving indigenous knowledge systems (like the Bosai and Smong) and toward developing quantitative engineering characteristics grounded in qualitative socio-cultural indicators. Incorporating community-based behavioral logic, spatial memory, and trust dynamics, this research updates evacuation models and algorithms for infrastructure planning, providing a concrete socio-technical framework. Future studies should empirically validate these translated aspects in co-designed tsunami evacuation models to ensure the mitigation measures are both technically strong and culturally appropriate.

■ DECLARATION OF GENERATIVE AI USAGE IN THE WRITING PROCESS

The authors used Scopus AI and DeepL to create this paper, assisting with drafting, language editing, grammatical correction, and improving clarity and readability. The writers took responsibility for the final content of the article, reviewing and modifying it as needed after using these tools.

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