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A Study on Ethical Dilemmas in Tsunami Evacuation Using a Margin Time Approach

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Abstract Stopover behavior, such as checking on family members, assisting neighbors, or gathering information, frequently delayed tsunami evacuation and increased fatality risk during the 2011 Great East Japan Earthquake. Rooted in relational responsibility and cultural norms, such behavior creates an ethical dilemma under severe time constraints, yet existing research lacks a rigorous framework for identifying where and to what extent these delays become life-threatening.

Focusing on the Taro district of Miyako City and Rikuzentakata City in Iwate Prefecture, this study builds pedestrian evacuation networks from publicly available geospatial data, including maximum-class tsunami inundation scenarios, minimum tsunami arrival times, coastlines, road networks, and a 1-meter-mesh digital elevation model. We define the evacuation time margin as Margin = $T_{Arrival} - (T_{Walk} + T_{Stopover})$ and classify each location as Red (evacuation infeasible), Yellow (feasible only without delay), or Green (sufficient margin), with unroutable points treated as Gray. The Yellow zone, termed the Ethical Dilemma Band (EDB), marks where brief hesitation can determine survival. Walking-speed and slope-dependent sensitivity analyses further test how EDBs expand across stopover durations.

In Taro, the area is almost entirely safe under immediate evacuation, with the Yellow zone negligible at a 5-minute stopover but expanding non-linearly from about 10 minutes onward. Rikuzentakata shows persistent coastal Red zones and a wide Yellow expansion beginning as early as 5 minutes. Slower walking enlarges the Yellow zone in both regions, while slope correction additionally produces new Red cells in steep Taro and expands the existing Red zone in Rikuzentakata. Ethical dilemmas thus arise from temporal structures shaped by topography and road networks.

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The study introduces ethics as spatial structure, places time-creating (+Margin) and delay-reducing (−Stopover) measures on a shared temporal scale, and shows that EDB expansion is region-specific, supporting evacuation planning tailored to local conditions.

Keywords: tsunami evacuation, ethical dilemma, tsunami tendenko

1. INTRODUCTION

1.1 Tsunami Evacuation Behavior and Ethical Dimensions

During the 2011 Great East Japan Earthquake, many residents engaged in stopover behavior that delayed the start of evacuation. In this study, stopover behavior refers to intentional actions that delay the start of evacuation, such as checking on family members, picking up children, returning home briefly, or assisting neighbors. These actions arise from relational responsibilities and everyday social roles. Although tsunami evacuation principles emphasize "evacuating immediately, to higher ground, and inland," even small delays can become life-threatening. Yet stopover behaviors are not necessarily irrational. They often reflect relational responsibilities toward family and community, and a desire to maintain everyday continuity. In tsunami evacuation, individuals often face a tension between protecting their own lives and caring for others, creating ethical dilemmas under severe time constraints.

Cultural norms in coastal regions highlight the importance of simple and rapid decision-making. In the Sanriku region of Iwate Prefecture, the principle of *tsunami tendenko* has been widely discussed. It is a locally rooted principle that encourages immediate and independent evacuation at the moment of an earthquake. On Simeulue Island in Indonesia, the traditional knowledge of *Smong* plays a similar role. *Smong* tells people to run to higher ground when they feel strong shaking or notice the sea receding. This knowledge saved many lives during the 2004 Indian Ocean tsunami. These cultural teachings simplify initial decisions, reduce hesitation, and speed up evacuation. Even so, actual evacuation behavior is shaped by many factors, including family structure, mutual aid practices, road networks, topography, and information flow. These factors can make evacuating without hesitation difficult in practice.

This study approaches these challenges not as individual failures to evacuate immediately, but as structural issues arising from the intersection of temporal constraints (time remaining before tsunami arrival) and relational responsibilities (concern for others). Ethical dilemmas are therefore framed not merely as matters of personal moral judgment but as outcomes produced through interactions among time, space, and information. By integrating minimum tsunami arrival time, walking evacuation time, and stopover delays on a common temporal axis, this study aims to quantify the remaining evacuation margin and identify spatial thresholds where ethical dilemmas most likely emerge. In this paper, we use the word "ethical" to refer to a dilemma that arises when two valid concerns are in conflict, namely protecting one's own life and caring for others. We do not use the word "ethical" to judge individual moral conduct. The 2011 Great East Japan Earthquake provides the behavioral motivation and disaster context

for this study, while the analysis itself is a forward-looking planning evaluation under present day conditions. It uses the post-2011 reorganized road network and the latest maximum-class (L2) tsunami hazard scenarios published by Iwate Prefecture. We also note here that, throughout this paper, $T_{Stopover}$ denotes the total pre-departure equivalent time loss attributable to stopover-related responsibilities such as locating family members, assisting vulnerable neighbors, or coordinating departure. It is modeled as a uniform departure delay added before the evacuee leaves the starting point, rather than as an in-transit stop along the route.

1.2 Conceptual Framework and Indicators

This study analyzes temporal and spatial factors jointly. It provides a foundation for designing evacuation plans suited to regional characteristics. The study focuses on two contrasting areas in Iwate Prefecture, the Taro district of Miyako City and Rikuzentakata City. It conducts quantitative analyses using publicly available geospatial data and high-resolution digital elevation data.

Evacuation time margin (Margin) is defined as:

$$\text{Margin} = T_{Arrival} - (T_{Walk} + T_{Stopover}) \quad (1)$$

Where $T_{Arrival}$ is the tsunami arrival time at each location, T_{Walk} is the shortest walking time along the road network, and $T_{Stopover}$ represents delays caused by stopover behaviors. Based on the sign and magnitude of the Margin, each location is classified into three categories: Red (evacuation infeasible), Yellow (infeasible or practically critical under the assumed delay), and Green (sufficient time margin). The Yellow zone is defined as the Ethical Dilemma Band (EDB), representing areas where stopover behavior renders evacuation infeasible or leaves only a practically critical residual margin.

2. LITERATURE REVIEW

Research on tsunami evacuation spans multiple disciplines—including engineering, geographic information science, social psychology, ethics, and urban planning—and has examined a wide range of topics such as evacuation decision-making, delay factors, route choice, and the allocation of evacuation facilities (Makinoshima et al., 2020). This study aims to visualize the spatio-temporal structure of tsunami evacuation as an ethical dilemma in which two motivations—protecting one's own life and caring for others—come into conflict under severe time constraints. The following sections review existing literature on evacuation behavior, ethical foundations, cultural norms, and spatio-temporal constraints to clarify the position of this research.

2.1 Actual Evacuation Behavior and Stopover Behavior

Studies on the 2011 Great East Japan Earthquake have consistently shown that delays in the start of evacuation are a major factor that increases mortality risk (Yun & Hamada, 2012; Schmöcker et al., 2023). Research on immediate post-shaking behavior ("milling") suggests that such delays may expand in a non-linear manner (Makinoshima & Imamura, 2024). Stopover behavior, including picking up family members, returning home, or assisting neighbors, has also been reported to substantially prolong evacuation time (Goto, 2016).

The phenomenon known as the "evacuation cascade," where evacuation decisions propagate through social interactions, has been documented for the 2011 tsunami (Makinoshima et al., 2022). Meanwhile, the behavior of surrounding residents and the location of family members have been identified as factors that affect evacuation decisions (Schmöcker et al., 2023).

In this study, stopover behavior is not treated as an "inappropriate action," but rather as an expression of relational rationality rooted in care for family and community. Milling behavior is treated separately, as a broader delay process associated with uncertainty, information seeking, or consultation with others. The analysis focuses on where these behaviors cause critical delays under specified stopover scenarios, using a spatio-temporal perspective.

2.2 Theoretical Foundations of Ethical Dilemmas

During disasters, ethical motivations such as "wanting to help family members" or "not wanting to abandon neighbors" often conflict with the survival principle of "protecting one's own life first." Kodama (2015) analyzed the normative values embedded in *tsunami tendenko* and highlighted the ethical tensions inherent in evacuation behavior. Matsuda (2025) conceptualized evacuation as a practice of care, showing how concern for others and self-preservation compete under tight time constraints.

Studies on decision-making suggest that situational perception, social conformity, and experience-based judgments affect whether emergency protocols are followed in crisis response (Kirschenbaum et al., 2023). Family decision-making adds further complexity, often resulting in rescue attempts or pick-up behaviors that significantly prolong evacuation (Goto, 2016; Savitt & Ge, 2019). A survey in Okitsu, Kochi Prefecture found that more than 40% of residents would first pick up their children from school during a major earthquake, demonstrating persistent resistance to the *tsunami tendenko* principle (Sun et al., 2013).

This study therefore seeks to quantify how ethical dilemmas—shaped by social relationships and responsibilities—manifest as delays at specific locations, understood through the interaction between time and space.

2.3 Cultural Evacuation Norms and Traditional Knowledge

Traditional knowledge embedded in local culture plays an important role in disaster risk reduction (DRR) (Pastrana-Huguet et al., 2025). In the Sanriku region, *tsunami tendenko* has

historically functioned as a cultural mechanism instructing individuals to evacuate independently rather than gathering as a family (Kodama, 2015; Suppasri et al., 2013). By contrast, the Indonesian concept of Smong emphasizes timing: evacuating immediately to higher ground upon sensing strong shaking or sea recession. A study in Padang, Indonesia compared community resilience to floods and tsunamis (Mulia & Handayani, 2024).

These norms share a common function: reducing stopover behavior. In other words, Smong defines when to evacuate, while tendenko defines with whom to evacuate. Although this study does not conduct a direct cultural comparison, it incorporates the perspective that such norms contribute to reducing delays and increasing available evacuation time (Margin).

The role of tendenko has been debated across several disciplines. Yamashita (2005, 2008) traces tendenko to a tradition pre-dating the 1896 Meiji-Sanriku earthquake and tsunami and documents the historical depth of this practice along the Sanriku coast. Building on this work, Yamori (2014) argues that tendenko should not be understood as a single injunction. Rather, it is a multi-layered concept. Its meanings extend beyond individual self-evacuation, and include the encouragement of evacuation by others, the prior building of mutual trust within communities, and the easing of survivor self-reproach.

From a philosophical perspective, Kodama (2015) has defended tendenko as a rule whose general practice would save the most lives. Oakley (2015) has asked whether self-preservation in disaster situations can be virtuous, noting the moral weight of abandoning loved ones in danger. From a sociological perspective, Goltz (2017) has challenged the assumption that role-based social obligations dissolve in emergencies, arguing that disaster research instead shows such obligations remain, and may even become stronger, in crises. He also notes that demographic realities limit the practical reach of tendenko. Older adults, people with disabilities, young children, and the caregivers and emergency responders who attend to them form a large and growing share of the population in tsunami-prone regions of Japan.

The present study does not settle this debate but draws on these perspectives in two ways. First, it treats cultural norms as one component of evacuation planning rather than the sole solution. Second, it takes the persistence of role-based behavior into account when it interprets regional differences. This persistence is emphasized by both Yamori's multi-layered reading and Goltz's sociological critique.

2.4 Spatio-Temporal Constraints and the Margin Concept (GIS Visualization and Facility Allocation)

GIS-based tsunami evacuation research has developed frameworks for evaluating evacuation feasibility based on physical constraints such as tsunami arrival time, elevation, topography, and road networks. For example, the Tsunami Vertical Evacuation (TVE) planning on the U.S. Pacific Northwest coast has been formulated as a GIS-based multi-criteria decision analysis (MCDA) problem for optimizing shelter placement (Wood et al., 2014). On Stromboli Island in Italy, GIS-based approaches have identified evacuation times and routes to safe zones

(Bonilauri et al., 2021). In Cilacap, Indonesia, a GIS-based evacuation model was used to determine suitable locations for Evacuation Shelter Buildings (ESBs) (Dewi, 2012).

In Rikuzentakata City, post-2011 analyses have examined the feasibility of evacuating first beyond the inundation boundary before moving to the nearest designated shelter, rather than using the direct path to the shelter (Sato et al., 2017). A study aimed at improving tsunami evacuation planning in Chile employed a multi-perspective research design combining standardized questionnaires and GIS-based simulations (Kubisch et al., 2020). Agent-based modeling (ABM) research has also incorporated transportation modes to clarify how delays affect survival rates (Mas et al., 2012).

However, few studies have spatially identified where stopover or milling behavior transitions into fatal delay.

In this study, Margin is defined as the remaining time after subtracting walking time and stopover time from the minimum tsunami arrival time. Locations where Margin is near zero or negative are visualized as the Ethical Dilemma Band (EDB). This visualization provides a perspective for understanding evacuation dilemmas not merely as individual decision-making issues, but as structural dilemmas arising from interactions among urban form, temporal constraints, and social behavior.

2.5 Research Objectives

Based on the gaps identified above, particularly the limited spatial integration of relational responsibilities with tsunami arrival constraints, and limited treatment of stopover behavior as a normal feature of evacuation, this study has three main focuses. First, it examines whether the expansion of EDBs with increased stopover time is non-linear rather than gradual. Second, it compares Taro and Rikuzentakata—two areas with distinct topographic and network characteristics—to explore how regional structures influence the behavior of EDBs. Third, based on the visualized EDBs, it organizes a two-axis perspective for evacuation planning: creating additional time (+Margin) and reducing delays (−Stopover), and discusses how these strategies should differ depending on regional conditions.

Furthermore, sensitivity analyses of Margin and EDBs were carried out across walking speed and stopover duration scenarios, giving quantitative comparisons of the robustness and spatial expansion of the EDB. Through this approach, ethical dilemmas are redefined not only as psychological or cultural issues but as phenomena arising from the interaction of urban structure and temporal constraints. Ultimately, this study aims to contribute to the design principle of “evacuation without hesitation.” It shows that EDB visualization can help identify gaps between planned evacuation procedures and actual behavior, thereby supporting more effective policy design.

3. METHODS

3.1 Study Areas

This study focuses on two coastal areas in Iwate Prefecture. They are the Taro district of Miyako City and Rikuzentakata City. Both areas suffered extensive damage during the 2011 Great East Japan Earthquake and Tsunami. Although land use, road networks, and evacuation facilities were reorganized after the disaster, important differences remain in topography, urban layout, and the spatial relationship between the coastline and inland areas. These contrasts in urban form and network structure make the two regions well suited for comparing spatial patterns of evacuation time margins and the emergence of ethical dilemmas.

The analysis extent was defined using the maximum-class tsunami inundation scenarios published by Iwate Prefecture, with an additional buffer added outside the inundation boundary to ensure comprehensive coverage. This scenario corresponds to the maximum-class (L2) tsunami envelope defined by Iwate Prefecture for evacuation planning. It combines the largest possible tsunami events, including the 2011 Tohoku tsunami and major historical tsunamis recorded along the Sanriku coast.

3.2 Data and Analytical Conditions

This study uses five primary datasets (Table 1): (1) maximum-class tsunami inundation zones (Iwate Prefecture, 2022), (2) minimum tsunami arrival time data (Iwate Prefecture, 2024), (3) coastline data (Geospatial Information Authority of Japan [GSI], 2025a), (4) road networks (OpenStreetMap contributors, 2025), and (5) 1-meter-mesh digital elevation model (GSI, 2025b). All datasets were converted into formats suitable for spatial analysis, and coordinate systems were unified to JGD2011 / Japan Plane Rectangular Coordinate System Zone X (EPSG:6678). As preprocessing, coordinate references were standardized across layers, and topological inconsistencies in the road network were corrected.

Road data obtained from OpenStreetMap (2025) were refined using ArcGIS Pro. Missing connections at intersections, broken centerlines, and incorrect node linkages were manually corrected. For short missing links between major roads, supplementary links were added with reference to aerial imagery and administrative maps. These edits ensured a connected pedestrian network that reflects actual walking conditions.

Starting points were generated by dividing the tsunami inundation zone (Iwate Prefecture, 2022) into a 50-m grid and extracting the centroid of each cell. Each centroid was snapped to the nearest road node within 100 m and treated as an origin on the road network. Evacuation completion was defined as the point where a pedestrian first crosses the outer boundary of the inundation zone while following the road network. The boundary line was extracted from the inundation polygon and intersected with the road network to identify potential destination nodes.

Tsunami arrival time $T_{Arrival}$ was estimated using the minimum distance D_{Coast} from each starting point to the coastline (GSI, 2025a) and the inland tsunami propagation speed V:

$$T_{\text{Arrival}} = T_{\text{Coast}} + \frac{D_{\text{Coast}}}{V} \quad (2)$$

Here, T_{Coast} is the predicted arrival time at the coastline (Iwate Prefecture, 2024), D_{Coast} is the distance from each starting point to the nearest point on the coastline (GSI, 2025a), and V is the inland propagation speed, set to 4.0 m/s. Video analysis of the 2011 Tohoku tsunami measured tsunami front speeds of about 8 m/s within 1 km of the shoreline, decreasing as the flow penetrated further inland (Hayashi & Koshimura, 2013). Evacuation-route studies for the Nankai Trough adopted run-up speeds of about 2 to 7 m/s, within an overall observed range of roughly 1 to 10 m/s (Kitamura et al., 2018, 2019). We adopted a single representative speed of 4.0 m/s, which reflects this inland deceleration in a simplified form. For each origin point i, $T_{Coast}(i)$ was taken from the nearest coastline segment and $D_{Coast}(i)$ was the straight-line distance to it. Because the Iwate Prefecture (2024) dataset provides a single representative T_{Coast} per study area, spatial variation in $T_{Arrival}$ arises through $D_{Coast}(i)$. Note that $T_{Arrival}$ is the modeled arrival time at the starting point i, not along the route. Evacuation is judged feasible when $T_{Walk}(i) + T_{Stopover} < T_{Arrival}(i)$. This criterion assumes evacuation proceeds monotonically inland toward the inundation boundary. It is not guaranteed for routes involving local detours or complex route-stage propagation, which lie outside this model.

Walking speed was set to v = 0.622 m/s, reflecting realistic conditions including older adults and people requiring assistance, based on guidelines from the Ministry of Land, Infrastructure, Transport and Tourism (2013). Uncertainty in this walking speed is examined in Section 4.5 through sensitivity scenarios of 0.498 and 0.744 m/s. Stopover behavior was modeled as departure delays of 0, 5, 10, 15, 20, and 25 minutes (Table 2), added uniformly to all starting points. Other parameters (road network, walking speed, coastline distance) were kept constant across the stopover-time scenarios. Starting points without a valid route to the boundary—due to isolated nodes or disconnected links—were classified as unreachable and displayed in gray on maps.

Table 1. Datasets used in the analysis

Data Type	Purpose
Maximum-class tsunami inundation zones (Iwate Prefecture, 2022)	Defining analysis extent; identifying evacuation completion boundary
Minimum tsunami arrival time (Iwate Prefecture, 2024)	Calculation of $T_{Arrival}$
Road network (OpenStreetMap contributors, 2025)	Calculation of T_{Walk} (shortest-path analysis)
Coastline data (GSI, 2025a)	Calculation of D_{Coast} (distance to the coastline)
Digital elevation model, 1-meter mesh (GSI, 2025b)	Computing road segment slope for the slope dependent sensitivity analysis

Note: Sources: Iwate Prefecture (2022, 2024); OpenStreetMap contributors (2025); Geospatial Information Authority of Japan (2025a, 2025b)

Table 2. Stopover time scenarios and representative role-based situations

Stopover Time	Representative Situations
0 minute	Immediate departure with no preparation or coordination
5 minutes	Brief check on family members at home; quick personal preparation
10 minutes	Single assistance to a nearby vulnerable neighbor
15 minutes	Multiple coordination tasks
20 minutes	Significant assistance involving a mobility impaired person or evacuation of a small group
25 minutes	Multi person assistance, extended coordination, or sequential pickups across locations

Note: These situations are illustrative thresholds used to interpret delay durations, not empirically estimated average behavior-specific times. They are represented analytically as equivalent pre-departure delays, and the spatial trajectories of stopover activities are not explicitly simulated.

3.3 GIS Analysis and Zoning Method

The core indicator used in this study is the evacuation time margin (Margin), defined for each starting point *i* as:

$$\text{Margin}(i) = T_{\text{Arrival}}(i) - (T_{\text{Walk}}(i) + T_{\text{Stopover}}) \quad (3)$$

Here, T_{Walk} is calculated from the shortest-path distance from each starting point to the nearest evacuation completion point, using:

$$T_{\text{Walk}}(i) = \frac{L(i)}{v} \quad (4)$$

Within this screening model, a positive Margin indicates that the evacuee is estimated to cross the inundation boundary before the tsunami arrival time at the origin point. A negative Margin indicates that the same sum exceeds $T_{\text{Arrival}}(i)$, so the model classifies the location as infeasible. This classification should not be interpreted as proof of actual safe evacuation, because the model does not simulate route-stage interactions between tsunami propagation and evacuee movement.

Margin was calculated under two conditions: **immediate evacuation** ($T_{\text{Stopover}} = 0$) and **stopover evacuation** ($T_{\text{Stopover}} = x$). Based on the difference between these two scenarios, we assigned each cell to one of three zones:

Zoning Criteria

$$\text{Margin}_0 \leq 0 \quad (5)$$

Red (Evacuation-Infeasible Zone): → Areas where evacuation cannot be completed before tsunami arrival even with immediate departure.

$$\text{Margin}_0 > 0 \text{ and } \text{Margin}_x \leq 0 \quad (6)$$

Yellow (Ethical Dilemma Band, EDB): → Areas where immediate evacuation is feasible but any stopover of x minutes or more results in failure to evacuate in time.

$$\text{Margin}_x > \text{tol} \tag{7}$$

Green (Sufficient-Margin Zone): → Areas where evacuation remains feasible with adequate time margin even when stopover behavior occurs.

Incorporation of Tolerance

To handle boundary conditions in time comparisons, a tolerance parameter (tol = 1 minute) was introduced. Accordingly, the Yellow zone (EDB) includes two types of cells:

1. Cells safe under immediate evacuation but unsafe when stopover is introduced
$$\text{Margin}_0 > 0,\ \text{Margin}_x \leq 0 \tag{8}$$

2. Cells that remain feasible under the assumed stopover but retain only a practically critical residual margin
$$0 < \text{Margin}_x \leq \text{tol},\ \text{Margin}_0 > 0 \tag{9}$$

The second category accounts for uncertainties in tsunami simulation and variability in walking speeds. Cells with small positive margins are treated as “practically critical,” and are conservatively included in the EDB, recognizing that even slight hesitation may create fatal risk. The tolerance is applied only to stopover comparisons where x is above 0. Under immediate evacuation (x = 0), the strict zero threshold is used. For this reason, the Yellow zone is empty at x = 0 by definition.

Slope-Dependent Walking-speed Sensitivity Analysis

The baseline analysis uses a constant walking speed of v = 0.622 m/s. However, real walking speed is also affected by terrain, especially when evacuees move uphill. To check how the terrain affects our zoning results, we conducted a sensitivity analysis. This analysis used a slope-dependent walking speed for each road segment, following the road-segment method of Parajuli et al. (2023).

Elevation data were obtained from the 1-meter-mesh digital elevation model of the GSI. Because the DEM tiles were distributed in geographic coordinates (JGD2024 for both Taro and Rikuzentakata), they were mosaicked and reprojected to JGD2011 / Japan Plane Rectangular Coordinate System Zone X (EPSG:6678) using the official NTv2 datum transformation, ensuring metric units for both elevation and planar distance. The reprojected DEM was smoothed with a 3 × 3 mean filter to suppress high-frequency noise, and slope was computed as percent rise. For each road segment, the mean slope was sampled along the segment from the slope raster, and a speed reduction factor was assigned according to its slope class, following the classification of Parajuli et al. (2023). The absolute segment slope was used as a conservative terrain penalty applied irrespective of travel direction, rather than a signed slope along the direction of evacuation. The factor is 1.00 for slopes of 0-3% and decreases stepwise

to 0.85 (3-6%), 0.70 (6-9%), 0.55 (9-12%), 0.45 (12-15%), 0.40 (15-18%), and 0.35 for slopes of 18% or greater. Formally, the slope-dependent walking time from starting point *i* is defined as:

$$\mathrm{T}_{Walk}(i) = \min_{P \in \mathcal{P}(i)} \sum_{e \in P} \frac{\ell_e}{v \cdot f(s_e)} \tag{10}$$

Where $\mathcal{P}(i)$ is the set of paths on the road network from starting point *i* to the evacuation completion points, ℓ_e is the length of road segment e, s_e is the absolute mean slope of segment e, v = 0.622 m/s is the baseline walking speed, and f is the stepwise speed reduction factor given above. The segment-specific walking time, computed as length / (0.622 × factor), was used as the impedance in the Closest Facility solver of the Network Analyst extension, so that routes were optimized for travel time under the slope-adjusted speeds. The constant-speed model in Eq. (4) is the special case in which $f = 1$ on every segment. Because these coefficients were used for flood evacuation (Parajuli et al., 2023) rather than validated for tsunami evacuation in Japan, they are used as a sensitivity scenario for the effect of terrain, not as definitive local parameters. The constant-speed baseline (v = 0.622 m/s) was retained unchanged, and the slope model was solved on the same network with identical origins, destinations, and network locations, so that the segment impedance was the only difference between the two.

This slope-dependent model was compared with the constant-speed baseline (v = 0.622 m/s) over the same road network and the same set of analysis points. The resulting sensitivity analysis is presented in Section 4.5, allowing assessment of (i) whether the qualitative patterns of EDB expansion observed under the constant-speed assumption persist when terrain effects are explicitly modeled, and (ii) the direction and magnitude of any bias introduced by the constant-speed assumption.

The zoning definition above enables us not only to identify static safe–danger boundaries, but also to extract areas that newly become hazardous due to stopover behavior. The Yellow zone represents the spatial region where minor hesitation—checking on others or delaying departure—can shift an otherwise survivable situation into fatal risk, making it the primary zone where ethical dilemmas manifest.

GIS Analysis Workflow

The GIS-based analysis followed these steps (Figure 1):

1. Data preprocessing, including unifying the coordinate systems to JGD2011 / Japan Plane Rectangular Coordinate System Zone X (EPSG:6678), repairing the road network topology, and calculating coastline distances.
2. Generating starting points as 50-meter grid centroids over the buffered extent, filtering them within the inundation polygon, and snapping them to the nearest road node within 100 meters.
3. Computing walking time under the constant baseline speed (v = 0.622 m/s) with the Closest Facility solver, together with a parallel slope-corrected variant (Step 3b) that

derives the mean slope of each road segment from the 1-meter DEM and applies a Parajuli et al. (2023) reduction factor to the segment speed.

4. Calculating tsunami arrival time ($T_{Arrival}$) at each starting point from the coastline arrival time and the inland propagation speed.
5. Calculating Margin for each scenario, with $T_{Stopover}$ taking values of 0, 5, 10, 15, 20, and 25 minutes.
6. Classifying each cell into Red, Yellow, Green, or Gray zones.
7. Visualizing the zoning results as maps of the spatial distribution of the four zones (Figures 2 and 3).
8. Aggregating zone-specific cell counts and areas (Tables 3 to 8) and conducting the walking-speed and slope-corrected sensitivity analyses, including the resulting Yellow-zone expansion (Figures 4 and 5).

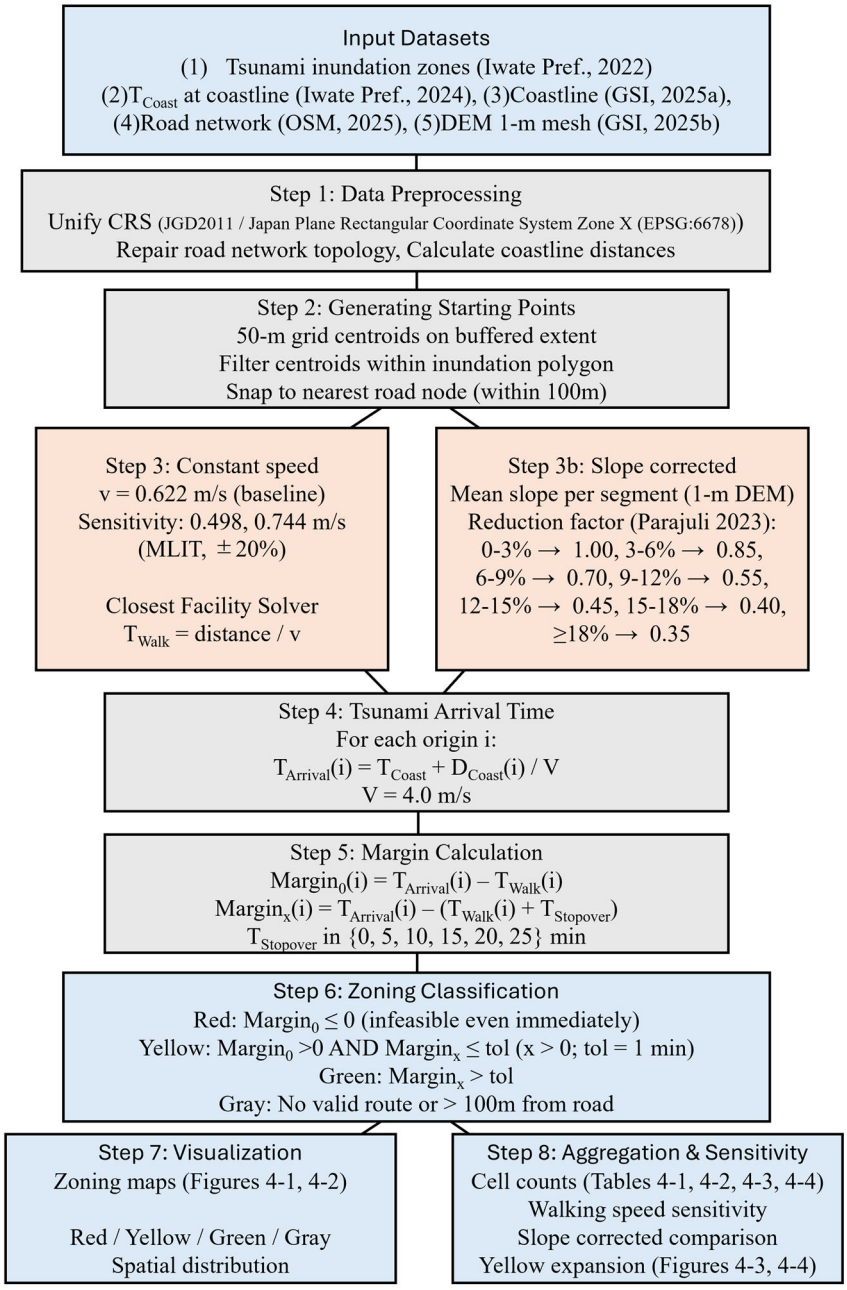


Figure 1. GIS analysis workflow from input datasets to zoning output for the EDB analysis

An overview of the GIS analysis pipeline, from input data to zoning output, is shown in Figure 1.

These procedures were applied consistently to both Taro and Rikuzentakata, allowing for a comparative assessment of EDB expansion patterns according to regional characteristics.

4. RESULTS

4.1 Overview of Zoning Outcomes

This section presents the calculated evacuation time margins (Margin) and the spatial distribution of zoning categories for the Taro district (Miyako City) and Rikuzentakata City, based on the methods described in Section 3. For both regions, the baseline walking speed was set to v = 0.622 m/s, and six stopover scenarios were examined, ranging from 0 to 25 minutes in 5-minute increments. In addition, sensitivity analyses were conducted using walking speeds of v = 0.498 m/s and v = 0.744 m/s, and a slope-dependent walking speed model based on road network segmentation. Results are summarized as the number of grid cells classified into each zone: Green (sufficient margin), Yellow (Ethical Dilemma Band), Red (evacuation infeasible), and Gray (no valid path).

4.2 Results for the Taro District

Within the inundation zone of the Taro District, 713 starting points were identified, of which 674 were analyzable. The remaining 39 points lay more than 100 meters from the road network and were classified as Gray. As shown in Table 3, all 674 analyzable points remained in the Green zone under immediate evacuation ($T_{Stopover} = 0$), and only 6 cells (about 0.9%) entered the Yellow zone under a 5-minute delay. When stopover time reached 10 minutes, 64 cells (about 9.5% of analyzable points) shifted to the Yellow zone (Figure 2). This number increased to 166 cells (24.6%) at 15 minutes, 329 cells (48.8%) at 20 minutes, and 539 cells (80.0%) at 25 minutes.

These patterns reflect the geographical characteristics of Taro. Although the surrounding terrain is steep, many residential areas are situated at relatively higher elevations, and the potential evacuation area is concentrated along the narrow ria coastline. As a result, immediate evacuation allows nearly the entire area to reach safety before tsunami arrival. However, even modest stopover delays rapidly reduce available time margins, causing large portions of the district to transition into the Yellow zone. The particularly sharp expansion of Yellow between 10 and 25 minutes suggests a non-linear, threshold-type growth of the Ethical Dilemma Band (EDB). The Yellow zone is negligible at a 5-minute stopover (6 cells) and then accelerates rapidly, with successive 5-minute increments adding roughly 58, 102, 163, and 210 cells.

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Table 3. Number of cells in each zone, Taro District (constant speed model, v = 0.622 m/s)

Stopover (min)	Green	Yellow	Red	Gray
0	674	0	0	39
5	668	6	0	39
10	610	64	0	39
15	508	166	0	39
20	345	329	0	39
25	135	539	0	39

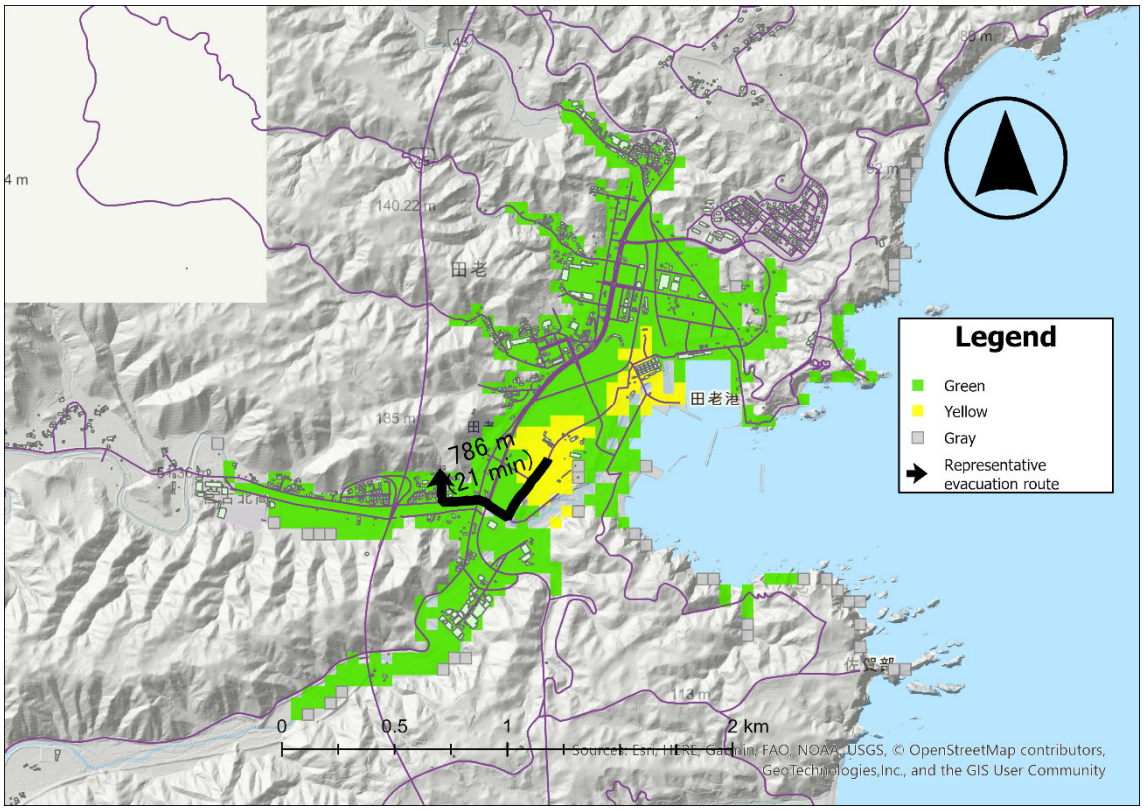


Figure 2. Zoning results for the Taro District (stopover = 10 minutes)

4.3 Results for Rikuzentakata City

In Rikuzentakata City, 7,509 starting points were identified, of which 6,553 were within the inundation zone analyzed in this study (the remainder lay in the buffer outside the inundation polygon), and 976 were classified as Gray due to limitations in road network connectivity, leaving 5,577 analyzable points. Because these Gray points are excluded from the feasibility calculation, the reported zone counts may understate the Ethical Dilemma Band in areas where road connectivity is poor. The number of Red-zone cells ($\text{Margin}_0 \leq 0$) remained constant at 149 across all stopover scenarios under the constant speed model and was concentrated in low-lying coastal areas. In contrast, the expansion of the Yellow zone was substantial. No Yellow cells appeared under the 0-minute stopover scenario, but the number increased to 180 cells at 5 minutes, 415 at 10 minutes, 716 at 15 minutes, 1,223 at 20 minutes, and 2,080 at 25 minutes (Table 4; Figure 3).

The Green zone covered about 97.3% of all analyzable points at 0 minutes (5,428 cells). It decreased to about 60.0% (3,348 cells) under the 25-minute stopover scenario. This shows a transition from Green to Yellow. The transition begins at the 5-minute scenario and accelerates with longer stopover. The successive 5-minute increments add about 180, 235, 301, 507, and 857 Yellow cells. The increments grow with stopover time. This indicates that the Rikuzentakata EDB also expands non-linearly. However, the onset of Yellow occurs at a much shorter stopover time than in Taro.

Compared with Taro, Rikuzentakata has gentler topography and a wide distribution of residential areas in low-lying plains. As a result, many starting points have shorter time margins before tsunami arrival, and the impact of stopover delays becomes more pronounced. In particular, when stopover time exceeds 20 minutes, large portions of the plains shift into the Yellow zone, demonstrating that even similar levels of delay can lead to a rapid increase in risk in flat terrain.

Table 4. Number of cells in each zone, Rikuzentakata City (constant speed model, v = 0.622 m/s)

Stopover (min)	Green	Yellow	Red	Gray
0	5,428	0	149	976
5	5,248	180	149	976
10	5,013	415	149	976
15	4,712	716	149	976
20	4,205	1,223	149	976
25	3,348	2,080	149	976

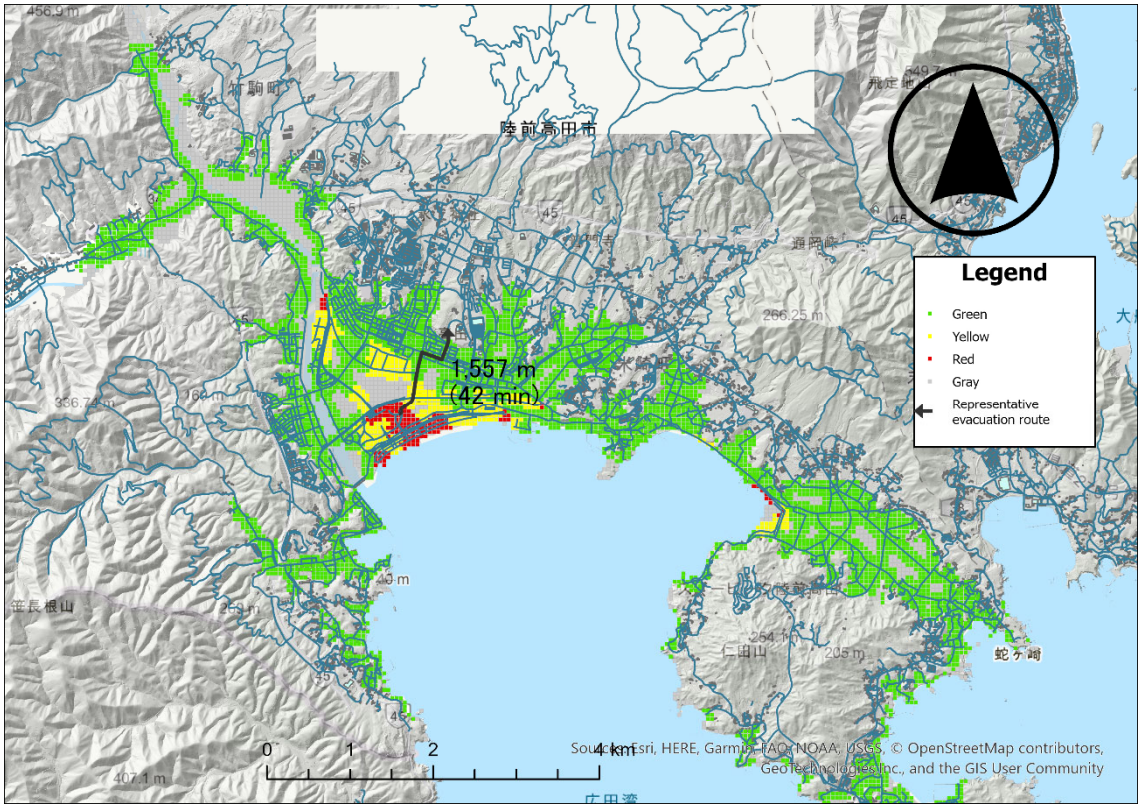


Figure 3. Zoning results for Rikuzentakata City (stopover = 10 minutes)

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4.4 Regional Comparison and Patterns of EDB Expansion

A comparison of the two regions shows clear differences. In Taro, no Red-zone cells appeared under the constant-speed (v = 0.622 m/s) model (0 out of 674 analyzable points). The onset of Yellow occurs sharply from 10 minutes of stopover onward. This shows a distinct threshold and a rapid transition. By contrast, Rikuzentakata shows persistent Red zones (149 cells out of 5,577 analyzable points). It also shows an earlier onset of Yellow expansion. Yellow cells already appear at a 5-minute stopover. They expand widely across the inundation footprint as stopover time increases (Figure 4). As shown in Sections 4.2 and 4.3, the per-5-minute increment in Yellow cells grows with stopover duration in both regions. Thus, the EDB expansion is non-linear in both. The regions differ in onset threshold and in geographic extent, not in linear versus non-linear character.

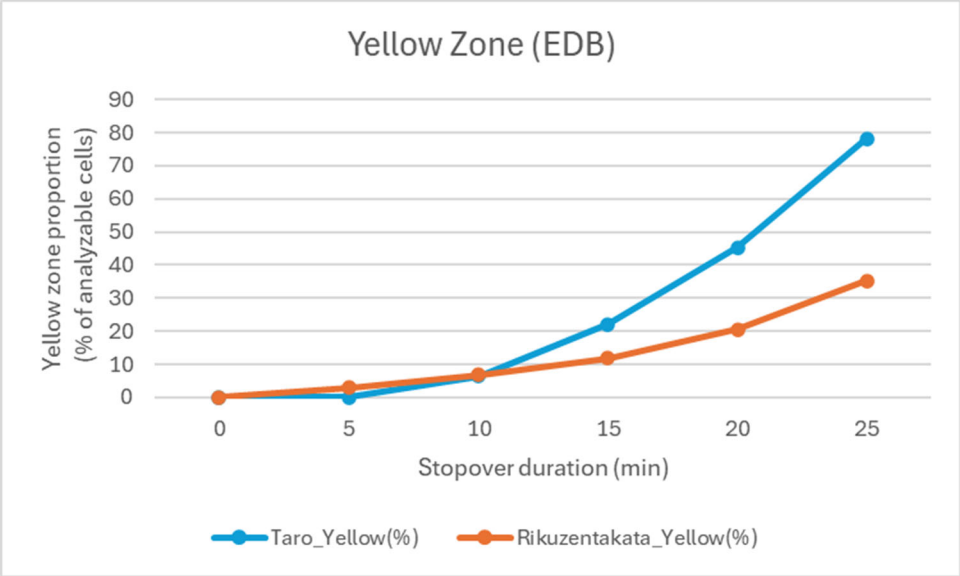


Figure 4. Changes in the Yellow Zone with increasing stopover time

Under a 25-minute stopover scenario, Yellow cells reach 80.0% of analyzable points in Taro (539 of 674), but only 37.3% in Rikuzentakata (2,080 of 5,577). In Taro, the analyzable area is compact, and the evacuation boundary is close, so most points cross the threshold at long stopover times. In Rikuzentakata, time margins vary more gradually across the wider plains, so fewer points cross the threshold even at 25 minutes. Thus, the spatial response of the EDB to stopover depends both on the length of delay and on how time margins are distributed in the area.

These differences stem from variations in topography and the structure of evacuation routes. Because the baseline analysis uses a constant walking speed, topography affects the results through the extent of the inundation footprint and resulting evacuation distance L(i). In steep regions like Taro, high ground lies close to the shoreline, so evacuation distances are short and immediate departure is highly effective, but even a few minutes of delay can become critical. In flat areas like Rikuzentakata, the inundation footprint extends far inland, so residents begin with small time margins, and delays spread their effects across a broader geographic area. The effect of slope on walking speed is examined in the sensitivity analysis in Section 4.5.

These results demonstrate that expansion of the Ethical Dilemma Band (EDB) is not determined solely by stopover duration. Instead, it is shaped by the interaction of three factors: topographic structure, urban network configuration, and behavioral delay. This interaction governs how and where evacuation becomes ethically and physically critical.

4.5 Sensitivity Analysis

In addition to the baseline v = 0.622 m/s, two other walking speeds were tested, v = 0.498 m/s (about 20% slower than the baseline) and v = 0.744 m/s (about 20% faster than the baseline). The slower speed represents walkers with greater mobility constraints, such as elderly people or those walking with small children. The faster speed represents able-bodied adults walking quickly. These three values cover a realistic range of pedestrian evacuation speeds.

The walking-speed sensitivity analysis showed how speed assumptions shift the extent of the EDB in each region. When walking speed decreased to v = 0.498 m/s, the Yellow zone expanded in both regions, and the Red zone increased substantially only in Rikuzentakata. At v = 0.744 m/s, the Yellow zone contracted in both regions, and the Red zone shrank substantially in Rikuzentakata (Figure 5).

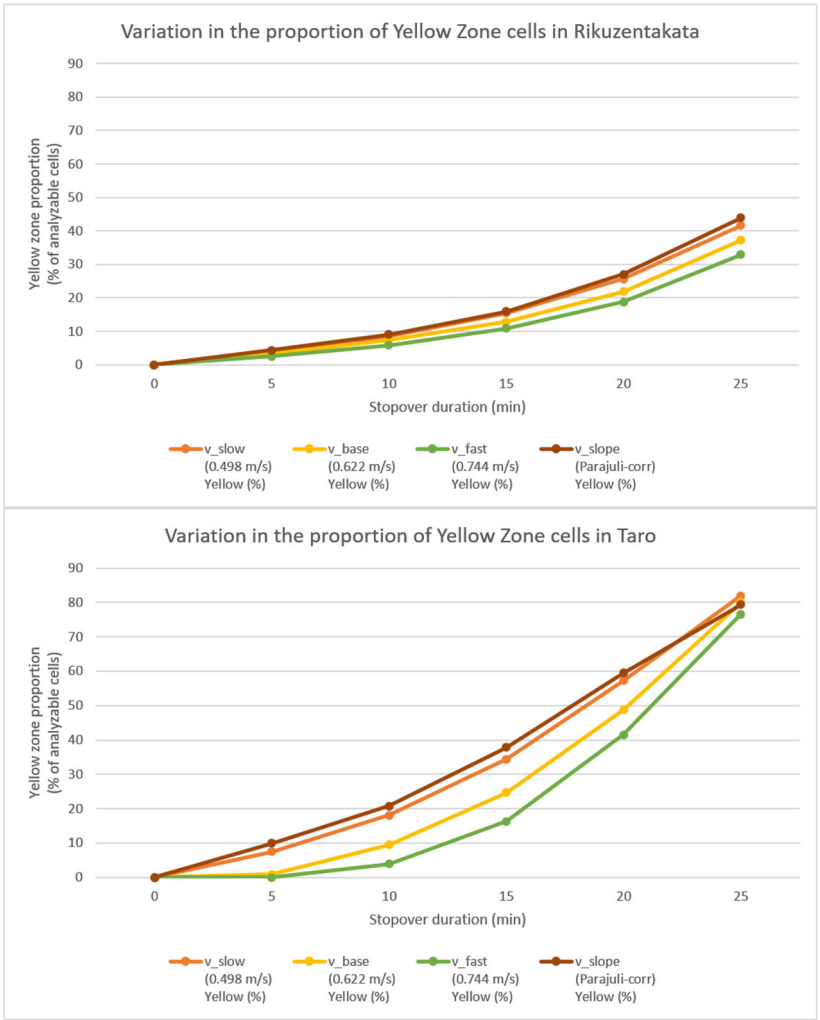


Figure 5. Variation in the proportion of Ethical Dilemma Zones (Yellow) (top) Rikuzentakata, (bottom) Taro

These results indicate that securing sufficient evacuation time margins requires both improvements in physical movement speed (e.g., mobility support, road environment enhancement) and faster initiation of evacuation (earlier decision-making). The model results also indicate that in flat areas, even a few minutes of stopover can result in substantial increases in risk.

Slope-Dependent Walking Speed: Road-Network-Segment Sensitivity

To assess the bias introduced by the constant-speed assumption, the road-network-segment sensitivity analysis from Section 3.3 was applied to both study areas (5,577 analyzable points in Rikuzentakata and 674 in Taro, with Gray points common to both models). In Rikuzentakata, slope correction substantially expanded the Red zone (from 149 to 357 cells, roughly 2.4-fold) and enlarged the Yellow zone at every non-zero stopover duration (Tables 5 and 6).

Table 5. Red and Gray Zone counts by walking-speed scenario, Rikuzentakata City (Red is independent of $T_{Stopover}$ by definition. n = 5,577, Gray = 976)

Scenario	Red	Gray	Analyzable
v = 0.498 (slow)	380	976	5,577
v = 0.622 (base)	149	976	5,577
v = 0.744 (fast)	15	976	5,577
Slope-corrected	357	976	5,577

Table 6. Yellow Zone (EDB) cell counts by stopover duration and walking-speed scenario, Rikuzentakata City

Stopover (min)	v = 0.498	v = 0.622	v = 0.744	slope-corrected
0	0	0	0	0
5	223	180	142	244
10	481	415	324	503
15	861	716	609	887
20	1,431	1,223	1,048	1,510
25	2,321	2,080	1,835	2,445

In Taro, slope correction produced more decisive effects. The constant-speed scenarios produced at most 2 Red cells, under the slowest case (v = 0.498 m/s). The slope-corrected model produced 60 Red cells. The Yellow zone also expanded markedly already at a 5-minute stopover. It reached 67 cells under the slope model, against 6 under the baseline constant-speed scenario. This shows that steep gradients can push otherwise feasible locations beyond the threshold of immediate evacuation feasibility (Tables 7 and 8). The Yellow zone also grew at every non-zero stopover duration up to 20 minutes, while at 25 minutes the count fell slightly below the constant speed baseline (535 against 539) because 60 cells had shifted to Red. Its saturation at long stopover durations reflects Taro's steep topography rather than the slope adjustment itself.

Table 7. Red and Gray Zone Counts by walking speed scenario, Taro District (Red is independent of $T_{Stopover}$ by definition. n = 674, Gray = 39)

Scenario	Red	Gray	Analyzable
v = 0.498 (slow)	2	39	674
v = 0.622 (base)	0	39	674
v = 0.744 (fast)	0	39	674
Slope-corrected	60	39	674

Table 8. Yellow Zone (EDB) Cell Counts by stopover duration and walking speed scenario, Taro District

Stopover (min)	v = 0.498	v = 0.622	v = 0.744	slope-corrected
0	0	0	0	0
5	50	6	0	67
10	122	64	26	140
15	232	166	110	255
20	386	329	280	401
25	552	539	516	535

Two findings are central. First, the qualitative patterns in Sections 4.2 and 4.3, the steady expansion of the Yellow zone with stopover duration, hold under slope-corrected walking speeds in both districts. Slope correction preserves the general tendency for EDB extent to increase with longer stopover durations, but it materially alters the onset threshold and immediate-evacuation feasibility in steep terrain such as Taro, where Yellow cells appear already at a 5-minute delay and Red cells newly emerge. Second, the slope-corrected model produces larger Red zones in both districts and larger Yellow zones at nearly all stopover durations, and the slope effect manifests differently between the two districts. In Taro it produces 60 Red cells, against at most 2 under the constant-speed scenarios, and shifts the onset of Yellow to a 5-minute stopover, while in Rikuzentakata it substantially enlarges the existing Red zone and uniformly increases the Yellow zone across all stopover durations.

The constant speed model is kept as the main analysis. The study aims to provide a simple and readily usable EDB. It is based on widely available walking speed guidelines, such as those of the Ministry of Land, Infrastructure, Transport and Tourism (2013). The aim is not to maximize precision through site specific terrain processing. The slope-corrected model serves as a conservative terrain-penalty sensitivity scenario. In this scenario, an absolute and direction-independent gradient penalty is applied to every segment, so no speed gain is credited on descents. By design, this enlarges the Red and Yellow zones in both districts. So the difference between the two scenarios should be read as a sensitivity range. It should not be read as a measured underestimate of the constant-speed result. Even so, planning based on the constant-speed EDB should include a safety margin. This is most important in steep terrain such as Taro, where the gap between the two scenarios is largest.

4.6 Summary of Results

This section presented the spatial distribution of evacuation time margins (Margin) and the resulting zoning classifications derived from the GIS analysis. The findings demonstrated that stopover behavior has a strong influence on the expansion of the Ethical Dilemma Band (EDB): both regions exhibit non-linear expansion, but the onset and spatial pattern differ. In Taro, Yellow is negligible until a 5-minute stopover (only 6 cells), and then expands sharply, concentrating in a relatively compact area, whereas in Rikuzentakata, Yellow appears already at 5 minutes and spreads widely across the low-lying plain. The slope-dependent and walking-speed sensitivity analyses supported these qualitative patterns. A conservative terrain-penalty scenario produced larger Red zones and generally larger Yellow zones than the constant-speed model in both districts, with the gap larger in steep terrain such as Taro.

These results indicate that ethical dilemmas in tsunami evacuation are not driven solely by psychological factors; rather, they emerge from the interaction between region-specific spatial structures and temporal constraints.

The next section discusses planning strategies for reducing the EDB and proposes directions for designing evacuation behavior suited to regional characteristics.

5. DISCUSSION

5.1 The Ethical Dilemma Band as a Spatial Structure

The results presented in Section 4 indicate that the Ethical Dilemma Band (EDB) is not merely an indicator of differences in evacuation time, but a spatial phenomenon shaped by topographic structure and the connectivity of road networks. The expansion of the EDB with increasing stopover time did not follow a simple, uniform pattern. Instead, certain localized areas experienced abrupt changes. Visual inspection suggests that abrupt local changes tend to appear where road networks are narrow and routes converge. Quantifying the contribution of road width and network bottlenecks is left for future work.

Topographic structure shapes both the spatial extent of the EDB and how robust the EDB estimate is to modeling assumptions. As the slope-dependent sensitivity analysis (Section 4.5) shows, the geometry of a region governs both the location of dilemma-prone areas and the magnitude of uncertainty in their delineation. Steeper terrains give EDB estimates that are more sensitive to the walking-speed value, and therefore need a larger safety margin when planning is based on constant-speed models.

This suggests that the EDB is not simply a binary division between “evacuation feasible” and “evacuation infeasible,” but a critical band where planned evacuation assumptions diverge from the realities of ethical decision-making. When stopover behavior is assumed to occur, it becomes possible to spatially identify where and to what degree delays become fatal. From this perspective, the EDB (shown in yellow) should not be understood merely as an area with

insufficient evacuation time, but as a boundary zone where discrepancies between planning rationality and ethical realities become visible.

The EDB defined here does not directly measure individual ethical decisions. It identifies structural zones where such decisions are likely to carry fatal consequences under strict time constraints. The EDB is therefore not a predictive model of individual behavior but an approximation of where potential ethical dilemmas are likely to surface.

The conceptual contribution of the EDB lies in its treatment of evacuation time. Conventional tsunami arrival-time and clearance-time maps, including those released for hazards such as the Nankai Trough earthquake (e.g., Kochi Prefecture, 2025), indicate the temporal progression of the hazard but do not represent the time consumed by relationally motivated stopover behaviors.

The EDB asks a different question. Stopover behaviors, such as locating family members, assisting vulnerable neighbors, or coordinating departure with school or workplace, use up some of the available time. The question is where in the inundation zone this loss of time makes evacuation infeasible. The EDB and existing time-based maps complement rather than replace each other. The EDB shows where ethical dilemmas are likely to occur, while existing maps show where time is most constrained.

5.2 *Tsunami Tendenko* and the Realities of Implementation

The principle of *tsunami tendenko* encourages each person to evacuate immediately and without hesitation after an earthquake and is intended to increase overall survival rates. However, in real evacuation situations, relational responsibilities—such as concern for family members or neighbors—often create delays. The EDB mapped in Section 4 highlights areas where the two ethical imperatives—immediate self-evacuation and responsibility toward others—are most likely to come into conflict.

The central issue is not determining which choice is "correct," but rather designing environments in which such conflicts are less likely to arise. Using the Margin indicator as a common axis, this study enables integrated consideration of both spatial improvements (+Margin) and behavioral improvements (–Stopover). Reducing the EDB is not simply about speeding up evacuation; it is about creating the conditions for "evacuation without hesitation," thereby reducing ethical burdens and enhancing the feasibility of evacuation behavior itself.

5.3 Cultural Norms and Regional Characteristics

Cultural norms and local traditions, such as *tsunami tendenko* and *Smong*, help reduce hesitation by sharing common triggers and action rules for evacuation. They speed up decision-making and predefine role-sharing and communication, including who evacuates with whom and under what signal to act. In this way they systematically shorten stopover delay. Such culturally rooted norms, however, cannot replace underlying spatial constraints.

As shown in Section 4, the manifestation of the EDB differs depending on urban form and evacuation routes. Therefore, effective planning must be based on the complementary relationship between cultural measures that reduce delay (–Stopover) and spatial measures that increase available time (+Margin). By aligning evacuation norms, training, and community-level agreements with each region's unique ethical dilemma zones, it becomes possible to develop more effective and context-specific "ethical disaster management plans."

The multi-layered view of cultural norms by Yamori (2014) and the sociological critique by Goltz (2017) help interpret these regional differences. Yamori (2014) notes that such norms both prompt immediate departure and predefine roles, reducing the time cost of relational responsibilities. Goltz (2017) argues that these responsibilities cannot be removed by exhortation alone, but remain structural features of behavior that planning must accommodate. More broadly, disaster research often finds that role-based obligations toward family, dependents, and community members do not weaken in a life-threatening emergency but tend to become stronger. Evacuation planning should therefore treat these norms as structural conditions of behavior, not as obstacles to be removed.

Read together, these perspectives suggest that cultural norms are one component of evacuation planning, not its sole solution. In steep regions like Taro, where immediate departure is highly effective, norms that reduce hesitation remain critical. In flat regions like Rikuzentakata, where broad areas face extended in-zone walking time, norms alone cannot resolve the dilemma, and spatial interventions that absorb the time cost of stopover behaviors become essential. The EDB visualization makes these regional differences explicit, identifying where stopover behavior turns an otherwise survivable configuration into an infeasible one.

5.4 Designing Measures to Reduce the EDB

The comparison between Taro and Rikuzentakata clearly showed that even when stopover time increases by the same amount, the expansion patterns of the Ethical Dilemma Band (EDB) differ according to regional characteristics. Therefore, in policy design, it is reasonable to optimize two types of interventions—increasing spatial time margins (+Margin) and reducing behavioral delays (–Stopover)—based on the specific conditions of each region.

Improvement measures that contribute to +Margin by reducing T_{Walk} include:

1. shortening the distance to higher ground or designated shelters,
2. enhancing evacuation routes to prevent reductions in walking speed (e.g., removing steps, improving pavement, installing lighting).

These interventions reduce T_{Walk} directly and thereby increase the Margin. In addition, preparing multiple routes and alternative shelters does not reduce T_{Walk} directly but makes the Margin more reliable by giving alternatives when the main route becomes unavailable due to debris, congestion, or infrastructure damage.

The slope-dependent sensitivity analysis gives a quantitative basis for prioritizing +Margin investment by terrain. In regions with strong terrain effects, such as Taro, where slope

correction newly produced Red cells absent under the constant-speed analysis, route improvements that reduce the effective slope (switchback paths, stairs with handrails, graded paths) yield large +Margin gains. In flatter regions like Rikuzentakata, the benefit of slope mitigation is smaller, and interventions targeting evacuation distance, destination density, or congestion reduction may be more relevant.

Measures that contribute to –Stopover include:

1. pre-arranged family agreements or coordinated action rules at the school or community level,
2. prioritization protocols for emergency messaging,
3. pre-assigned responsibilities for assisting people requiring support, and
4. predetermined evacuation routes or meeting points.

These interventions reduce $T_{Stopover}$ and thus also increase the Margin. Early warning systems and real-time alerts, while not directly reducing $T_{Stopover}$ as defined here, can complement –Stopover measures by prompting evacuees to initiate the evacuation sequence earlier.

An advantage of this framework is that it allows both types of interventions to be evaluated on the same temporal scale. For example, if the installation of an additional shelter reduces T_{Walk} by three minutes, and if family-level agreements reduce $T_{Stopover}$ by three minutes, these effects can be compared directly as equivalent improvements to the Margin. However, comparing measures on this temporal scale does not by itself resolve their ethical, physical, and economic implications, which require further assessment.

5.5 Post-Disaster Life and the Sustainability of Recovery

Decisions made during evacuation may have long-lasting effects on post-disaster life and community relationships. Feelings such as “I escaped alone” or “I could not go back to help” may persist for years as guilt or mutual distrust, and these psychological burdens can hinder community recovery and sustained mutual aid. Because the present study does not measure these outcomes directly, the following discussion outlines plausible implications rather than empirical findings.

This study does not seek to judge individual decisions as morally right or wrong, but to design a social system that reduces the burden of decision-making itself. Effective strategies may include improving physical conditions so that delays do not easily lead to fatal outcomes (+Margin), strengthening pre-event agreements and education to reduce delays (–Stopover), and fostering cultural norms that avoid blaming individuals for unavoidable decisions. Reducing the EDB can increase survival rates and reduce guilt and social division, supporting a more sustainable foundation for post-disaster recovery, though confirming this remains a question for future empirical work.

Treating ethical dilemmas not as reflections of personal character or morality but as issues rooted in temporal and spatial constraints provides a promising direction for disaster management. Visualizing the EDB offers a practical tool for pre-event consensus building and priority setting in evacuation planning.

5.6 Implications for Implementation

The EDB framework offers practical value across several domains of disaster management. First, it supports municipal evacuation planning by identifying priority intervention zones. These zones are concentrated and threshold-based in steep areas like Taro, but broad and area-level in low-lying areas like Rikuzentakata. Second, it informs evacuation drill design by clarifying where +Margin and –Stopover interventions are most needed. Third, it supports public education by helping residents understand evacuation feasibility under realistic stopover scenarios. Fourth, it can be overlaid on existing tsunami arrival-time and inundation maps as complementary information.

The relationship between the EDB and evacuation drills is bidirectional. The EDB framework supports the design of training scenarios by identifying where stopover behavior becomes critical, while drills provide empirical data to calibrate the indicators, particularly walking-speed parameters and the temporal cost of typical stopover behaviors. Drill data may inform region-specific $T_{Stopover}$ estimates that move beyond the generic stopover durations adopted in this study, and may help validate the spatial extent of predicted EDBs against observed evacuation patterns. This provides a pathway for the iterative improvement of evacuation planning.

These pathways point toward what we call ethically informed disaster management, which treats relational responsibilities not as deviance to be removed by exhortation but as a persistent feature of behavior that planning must accommodate. By placing spatial (+Margin) and behavioral (–Stopover) interventions on a common temporal scale, the framework aligns evacuation planning with relational responsibility while preserving the need for timely evacuation.

5.7 Summary of the Discussion

This section reinterpreted ethical dilemmas in tsunami evacuation as outcomes of interactions between spatial structure and behavioral timing. The section positioned them as “reducible risks” through the Margin indicator. In steep areas such as Taro, EDB expansion was non-linear, with a clear threshold at 10 minutes of stopover. In flat areas such as Rikuzentakata, EDB expansion was also non-linear, but it had an earlier onset, from 5 minutes, and a wider spatial spread. These differences show that the consequences of relationally motivated delays vary with regional topographic and network characteristics.

The analytical framework proposed in this study, based on the dual axes of +Margin and –Stopover, offers a new integrated perspective for evaluating evacuation behavior through

ethical, spatial, and temporal dimensions. The next section summarizes the implications and limitations of the study.

6. CONCLUSION

6.1 Key Findings

This study proposed the Ethical Dilemma Band (EDB) as a new analytical framework for quantifying and visualizing the divergence between planned rational evacuation strategies and the ethical realities of human behavior during tsunami evacuation.

The EDB is defined based on the evacuation time margin (Margin), which integrates the minimum tsunami arrival time (T_{Arrival}), walking evacuation time along the road network (T_{Walk}), and departure delay caused by stopover behavior (T_{Stopover}):

$$\text{Margin} = T_{\text{Arrival}} - (T_{\text{Walk}} + T_{\text{Stopover}}) \tag{11}$$

Using this indicator, locations where immediate evacuation is feasible but an assumed stopover delay ($T_{\text{Stopover}} > 0$) renders evacuation infeasible or reduces the residual margin to a practically critical level can be spatially identified, allowing the mapping of critical areas where life-or-death thresholds emerge.

Comparative analysis of the Taro district and Rikuzentakata City showed that EDB expansion does not simply increase in proportion to longer stopover time but is a non-linear phenomenon strongly shaped by road network structure and topographic characteristics. Taro showed a threshold-type EDB expansion, with very few Yellow cells at a 5-minute stopover (6 cells), followed by rapid acceleration over the 10 to 25 minute range. Rikuzentakata showed an earlier onset of Yellow, at 5 minutes, and a broader spatial spread.

These differences indicate that spatial structural factors—such as the extent of the inundation footprint and the resulting evacuation distances—shape how stopover behavior amplifies temporal risk. Thus, ethical dilemmas should be understood not only as psychological choices but also as phenomena embedded within region-specific temporal structures.

A slope-dependent sensitivity analysis (Parajuli et al., 2023) confirmed that these qualitative patterns persist under terrain-sensitive walking times, while enlarging the Red and Yellow zones most strongly in the steep ria-coast terrain of Taro.

This study also introduced a unified analytical framework that evaluates two directions of intervention on the same temporal scale. These two directions are creating additional time (+Margin) and reducing behavioral delays (−Stopover). This enables a direct comparison of the effects of spatial improvements and behavioral measures for “minutes gained or lost.” It provides a practical tool for assessing policy effectiveness in a way that aligns with ethical rationality.

Furthermore, while cultural norms such as *tsunami tendenko* and *Smong* effectively reduce stopover time, they cannot substitute for physical spatial constraints. By integrating cultural and spatial measures through the common indicator of Margin, this study reframes ethical dilemmas as structural challenges, while complementing the psychological and normative perspective on individual responsibility.

Overall, the findings reinterpret the tension between the ideal of "rapid evacuation" and the ethical reality of "relationally motivated behavior" not simply as a moral dilemma but as a spatio-temporal structure that can be quantified.

6.2 Limitations and Future Directions

This study has limitations in four areas. Each limitation also indicates a direction for extending the framework.

First, the geographic scope and the network coverage are limited. The analysis focused on only two regions, Taro and Rikuzentakata. Future work should extend to other areas with diverse topographies, urban structures, and behavioral patterns. Mixed landforms and island regions are especially worth further study. Within the two regions, a non-trivial share of starting points was classified as Gray because of limited road-network connectivity. In Taro, 39 of 713 evacuation origins (5.5%) were affected. In Rikuzentakata, 976 of 6,553 evacuation origins (14.9%) were affected. These origins lay more than 100 m from the road network, or they could not be linked to a valid evacuation route, and they were excluded from the Margin and EDB calculations. If Gray cells cluster in places with poor evacuation access, the reported EDB counts may underestimate dilemma-prone areas. This is most likely in Rikuzentakata. Examining their spatial distribution and adding off-road footpaths is left as future work.

Second, the representation of evacuees is simplified. Stopover behavior was modeled as a uniform time delay, which does not reflect variation between individuals or groups. In reality, stopover duration varies with family structure, role-based responsibilities, time of day, and season. For example, a young single resident may evacuate almost immediately, whereas a caregiver may have 15 to 25 minutes of delay (Table 2). The fixed-stopover EDB maps can be read as two ends of a range, with the 5-minute map showing the low-delay case and the 25-minute map the high-delay case. A full analysis of heterogeneous stopover would need population-level data on role-specific delays, obtainable through social network analysis or agent-based simulations. In addition, origins were represented by uniformly distributed centroids of 50-m grid cells within the inundation zone (see Section 3.2), not by population or residential-location data. The references to "residential areas" in Sections 4.2 and 4.3 describe topographic settings rather than the actual distribution of analysis origins. Population distribution varies substantially by time of day, so incorporating residential and daytime population distributions would provide a more comprehensive evaluation of EDB exposure.

Third, the evacuation means and the network conditions are fixed. The analysis assumed that all evacuation occurs on foot to higher ground, without explicit modeling of vehicle-based evacuation, vertical evacuation to designated tsunami evacuation buildings (TVEBs), or use of

intermediate shelters. The relative effectiveness warrants region-specific examination in future research. The analysis also did not incorporate dynamic changes in the evacuation network caused by road blockages, traffic congestion, or building collapse. Integrating these time-dependent factors would allow the EDB to be expanded from a static to a dynamic risk concept.

Fourth, the physical models of the tsunami and of walking speed are simplified. The Margin formulation adopted here uses a simplified inland propagation model that does not represent dynamic interactions between tsunami advance and evacuee movement. In particular, the inland tsunami front is approximated by a single constant propagation speed of 4.0 m/s. This does not capture local changes in run-up speed caused by terrain, land use, or inundation depth, as no detailed run-up simulation was performed. Integration with high-resolution propagation models and agent-based simulations would extend the framework to scenarios where evacuees may be overtaken in transit, which fall outside the present scope (Section 3.3). Furthermore, the main analysis used a constant walking speed of v = 0.622 m/s. The slope-dependent sensitivity analysis (Section 4.5) confirmed the robustness of the qualitative patterns but showed larger Red and Yellow zones in steep terrain. For this reason, the constant-speed maps should be supplemented with an explicit safety margin in steep terrain such as Taro. Despite these limitations, the framework visualizes ethical dilemmas as challenges that involve social structure, information flow, and spatial design. Future research could develop EDB-based indicators for evaluating evacuation drills and urban planning, and could implement the framework in real-time evacuation support systems. These systems would support the design of communities where people can “evacuate without hesitation.”

Ethical dilemmas should not be attributed to individual character or moral capacity. They arise from structural constraints created by time, space, information, and culture. Visualizing the EDB offers a foundation for sharing these constraints socially and for building consensus on the prioritization of measures and the distribution of responsibilities.

Therefore, disaster planning must aim not only for “evacuations that reduce casualties,” but also for “evacuations that do not generate regret or social division.” The quantitative framework for the EDB presented in this study represents a first step toward achieving both sustainable recovery and ethically informed disaster management.

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