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Construction of an evacuee placement model for tsunami shelters considering physical distancing to prevent COVID-19 infection

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ABSTRACT

Earthquakes and tsunamis are expected to occur within the next 30 years along Japan's Nankai Trough. Existing disaster prevention plans and calculated evacuation capacities in the coastal areas that would be affected do not account for physical distancing in the context of COVID-19. Therefore, we developed a tsunami evacuation placement model incorporating physical distance guidelines for infection control and living space per person into calculations of evacuation center accommodation capacities in Aki City, Kochi Prefecture. Using available administrative, population, and tsunami inundation data, we counted and mapped evacuation centers in the estimated inundated area within three zones constructed for smooth evacuation using the ArcGIS software Build Balanced Zones Tool. We calculated the space per evacuee using the Sphere handbook standard of 3.5 m^2 or double the Sphere standard at 7 m^2 plus the recommended physical distance of 11 m^2 per person. We then compared the results with planned capacities. A total of 27 shelters are located in the area projected to be inundated at depths of 0.3–10 m, and their planned capacity, 2 m^2 for each evacuee, would accommodate 32.9% of Aki's population and result in 9639 unaccommodated evacuees. Allotting 14.5 m^2 (living space) or 18 m^2 (living space plus space to maintain physical distancing) would reduce accommodation capacities to 57.1% and 28.6% (12,133 and 12,371 unaccommodated evacuees, respectively). Given these accommodation shortages, we recommend that evacuation centers are set aside for vulnerable people and that alternative evacuation sites such as parking lots and mountain campsites are preplanned.

1. Introduction

Global warming has increased the severity of tropical cyclones and subsequent heavy rain events in Japan [22,39]. By the middle of the 21st century, a strong earthquake is considered likely to occur along the Nankai Trough in the coastal areas of Shikoku Island, facing the Pacific Ocean [35]. In anticipation of potential tsunamis caused by a Nankai Trough earthquake, the coastal municipalities have designated public facilities as evacuation shelters, and have made public the capacity of these shelters [7]. According to the latest survey of the Greater Tokyo area of Japan, the evacuation area there is calculated to be approximately 2.0 m^2 per person [9]. The 2020 coronavirus disease 2019 (COVID-19) pandemic has complicated disaster evacuation and shelter management. Close physical distancing (PD) between people is a risk factor for COVID-19 infection, and PD is an effective measure to prevent viral transmission [5,32]. However, PD was not taken into account under current disaster plans, and overcrowding could easily occur in the event of a flood or other disaster. Furthermore, it is recommended that public shelters comply with PD measures [11,33]. Overcrowding in evacuation shelters while COVID-19 is circulating may cause a secondary disaster in the form of an outbreak. In the coastal areas of Japan, existing buildings are designated as "tsunami evacuation buildings" for temporary evacuation in the event of a tsunami [26]. It is hoped that temporary evacuees will be transferred to shelters outside the flooded area after the tsunami has subsided. To prevent secondary damage caused by COVID-19 infection resulting from shelter overcrowding, it is necessary to distribute evacuees according to the number of evacuees, the location of shelters, the area per capita considering infection prevention, and the tsunami inundation area. The Build Balanced Zones (BBZ) tool, which uses the Geographic Information System (GIS), is suitable for balancing the number of evacuees and determining the range of distribution. However, no studies have been conducted using the GIS to distribute temporary evacuees in a tsunami evacuation building to prevent shelter overcrowding.

It is important to identify high-risk disaster zones to enable safe evacuation before a disaster occurs [40]. One case study examined

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safe evacuation of elderly people and the securing of a transportation infrastructure to meet their needs [30]. Previous studies have also estimated human damage to tsunami vertical evacuation shelters using buffer analysis [4], and have constructed models for proper shelter placement [20]. One analysis of shelter selection based on hurricane strength and shelter demand used an interdiction and median model [3]. Zhang et al. developed a simultaneous multicity evacuation simulation for hurricanes [41] and Li et al. generated a shelter placement and transportation planning model for hurricane conditions [23]. Goerigk and colleagues developed an evacuation model to facilitate bus evacuation planning [15]. The BBZ tool can help to formulate and prepare a transportation and placement plan for residents in the flooded area before the disaster, assuming that the tsunami will prevent them from being transported by car or on foot.

Recent research has examined the effect of the COVID-19 pandemic on evacuation behaviors and resources. One estimate states that approximately 50% of Japanese people are unlikely to evacuate for fear of COVID-19 infection owing to shelter congestion [36]. Recommendations have been published to protect vulnerable groups from COVID-19 and flood damage [18]. Borowski et al. examined the willingness to share a vehicle in a flood evacuation during the COVID-19 pandemic [6], and Parr et al. analyzed the effect of the pandemic on traffic flow [31]. One study assessed the spatial accessibility of COVID-19 patients to medical facilities in the United States [14]. However, no studies have focused on using GIS to evenly distribute people to safe areas, assuming a dual COVID-19 pandemic and tsunami disaster.

This study presents an evacuee placement model that assumes that people who temporarily evacuate to a nearby building will subsequently move to an evacuation center outside the flooded area. This model could also be useful for design of new shelters, operational training, stockpiling, and response planning.

2. Material and methods

2.1. Target area

The target area is Aki, Kochi Prefecture, in the Shikoku region of Japan. Aki is located on the Pacific coast and has a population of 169,000 [2].

Within the next 30 years, an earthquake and associated tsunami is likely along the Nankai Trough (Fig. 1) [13]. A magnitude 8–9 Nankai Trough earthquake would create a tsunami with an estimated inundation depth of 15 m [1]. The area analyzed in this study was the area of Aki that is expected to be inundated based on tsunami inundation prediction data (Fig. 2) [27].

2.2. Data collection

Terms used in this study

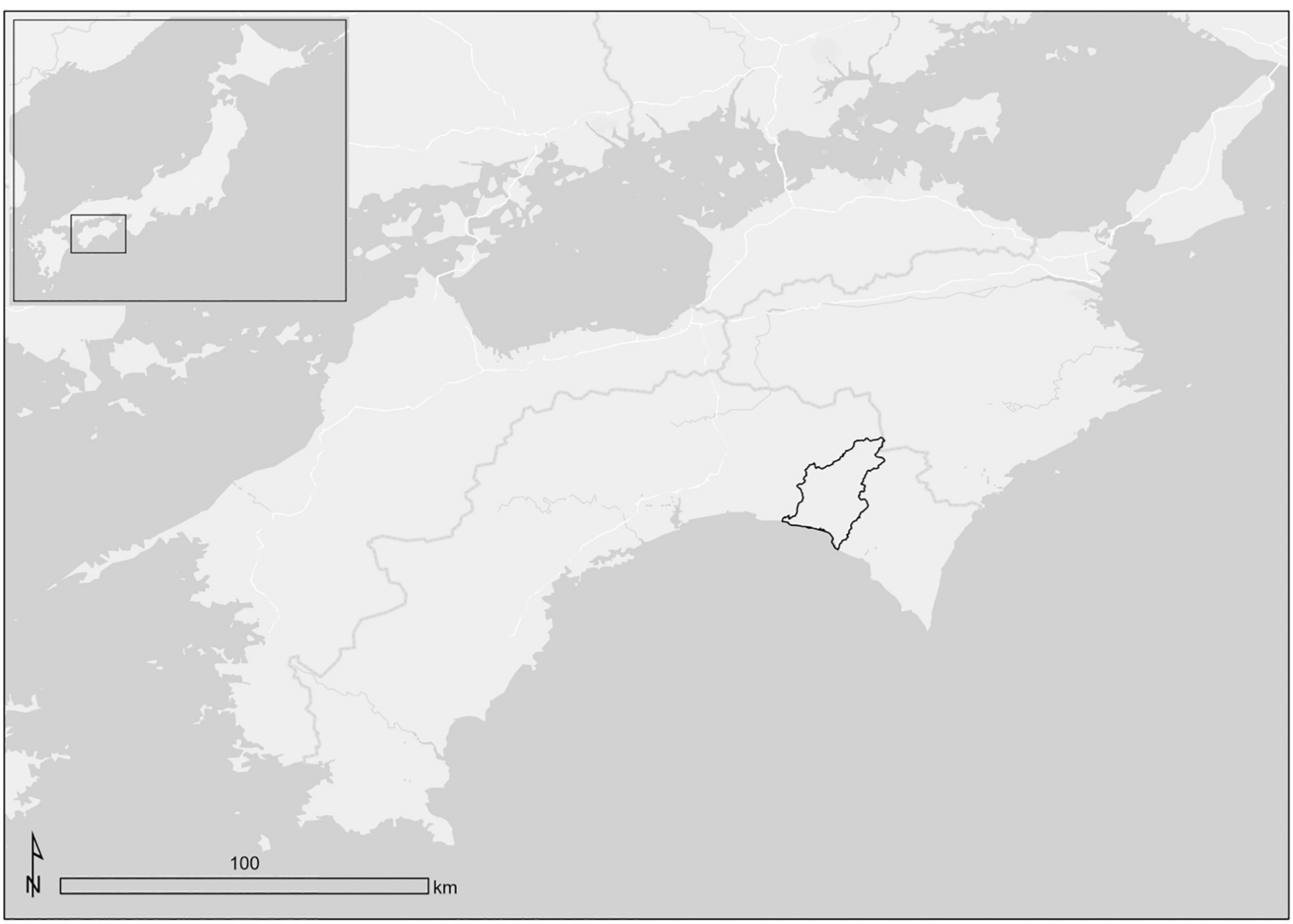

Fig. 1. Location of Aki. The outlined area shows Aki City, located on Shikoku Island, Japan.

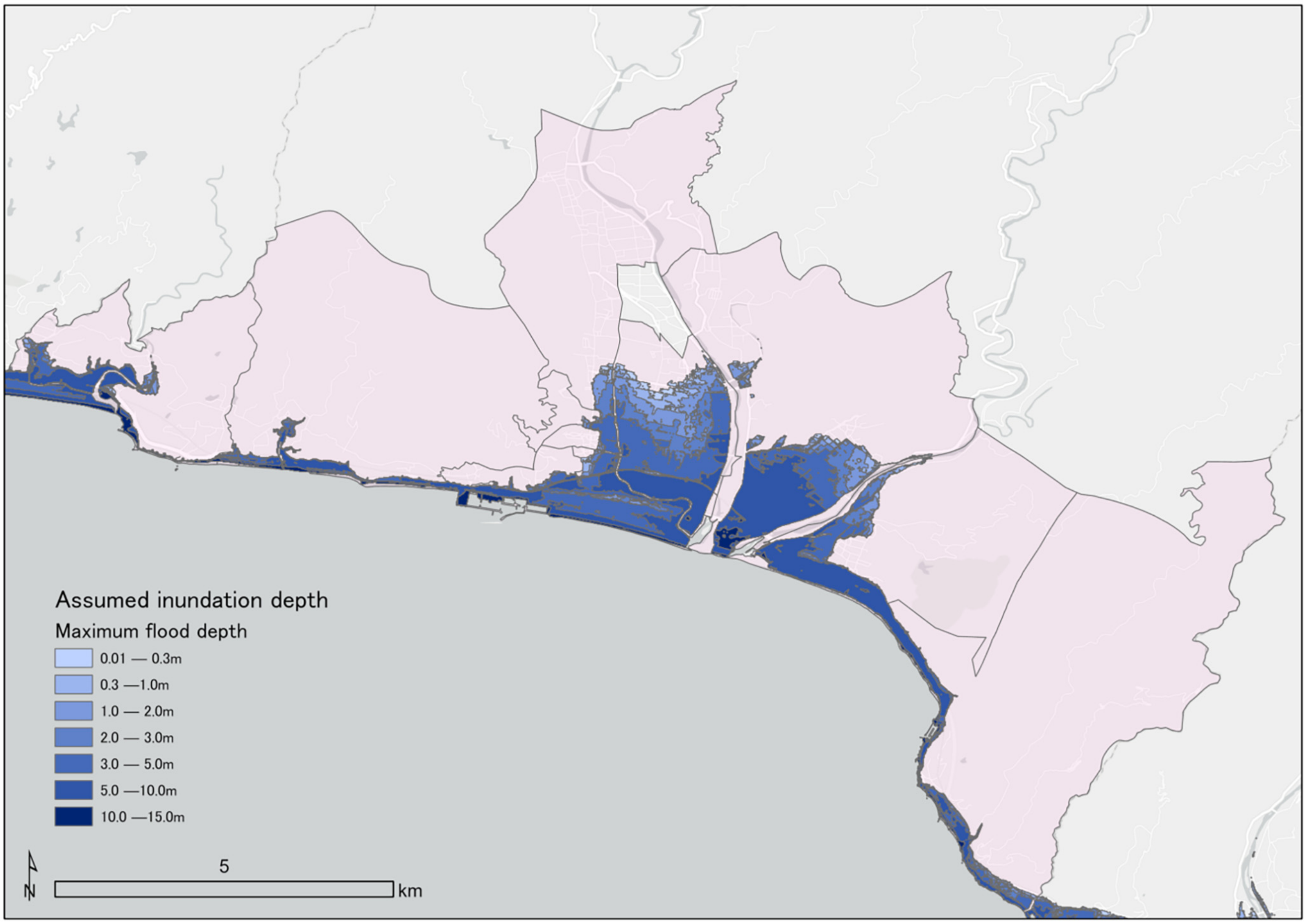

Fig. 2. Potential tsunami inundation area of Aki. The area of potential inundation from the tsunami is shown in shades of blue.

Physical Distancing: PD

It has been recommended that maintaining PD between people is the most practical way to control disease outbreaks [29].

Sphere standard

Allowing people affected by disaster to live with dignity in any postdisaster environment is essential. This standard is described in the Sphere handbook, which states that the minimum living space required at evacuation centers is 3.5 m^2 per person, excluding cooking and bathing facilities. In cold regions and urban areas, the minimum living space is set at 4.5–5.5 m^2 [34].

2.3. Capacity and living space of shelters in Aki

The Aki Cite website [1] provided data on addresses, living space, and capacity of Aki evacuation shelters. We referred to the infection control guidelines and calculated the number of evacuees with PD set to 11 m^2 and the occupied area per person set to the Sphere standard (3.5 m^2) and double the Sphere standard (7.0 m^2) [17,34].

2.4. Tsunami inundation area and shelter locations in Aki City

Aki administration area data and population information, as well as Kochi Prefecture tsunami inundation data, were plotted using a GIS map [24]. Fig. 3 shows the shelter locations and tsunami inundation area. The estimated inundation depths range from dark blue (15.0 m) to light blue (0.01 m) (see map in Fig. 4).

2.5. Construction of evacuee placement model in the Aki plain

The Aki plain (Aki, Doi, Ioki, and Kawakita areas) was selected as the target. This area is expected to experience extensive flooding in the event of a tsunami.

Our model assumes that residents will temporarily evacuate to a nearby building or tsunami evacuation tower and then move to a shelter outside the inundation area. We implemented zone division to distribute the number of evacuees, taking into consideration the number of residents in the target area and the distance from the residential area to the nearest evacuation center outside the inundation area. The Aki plain is zoned into three areas based on the natural features that separate the Aki and Ioki rivers. The BBZ tool implemented in ArcGIS Pro (Esri) was used to distribute the evacuees and build the zones [12].

2.6. Number of evacuees by zone and shelter capacity

Using the BBZ, we calculated the living space and capacity of the evacuation shelters for each zone. The number of people accommodated was calculated for per person evacuation spaces of 14.5 m^2 and 18.0 m^2. We then calculated the difference between the currently planned capacity

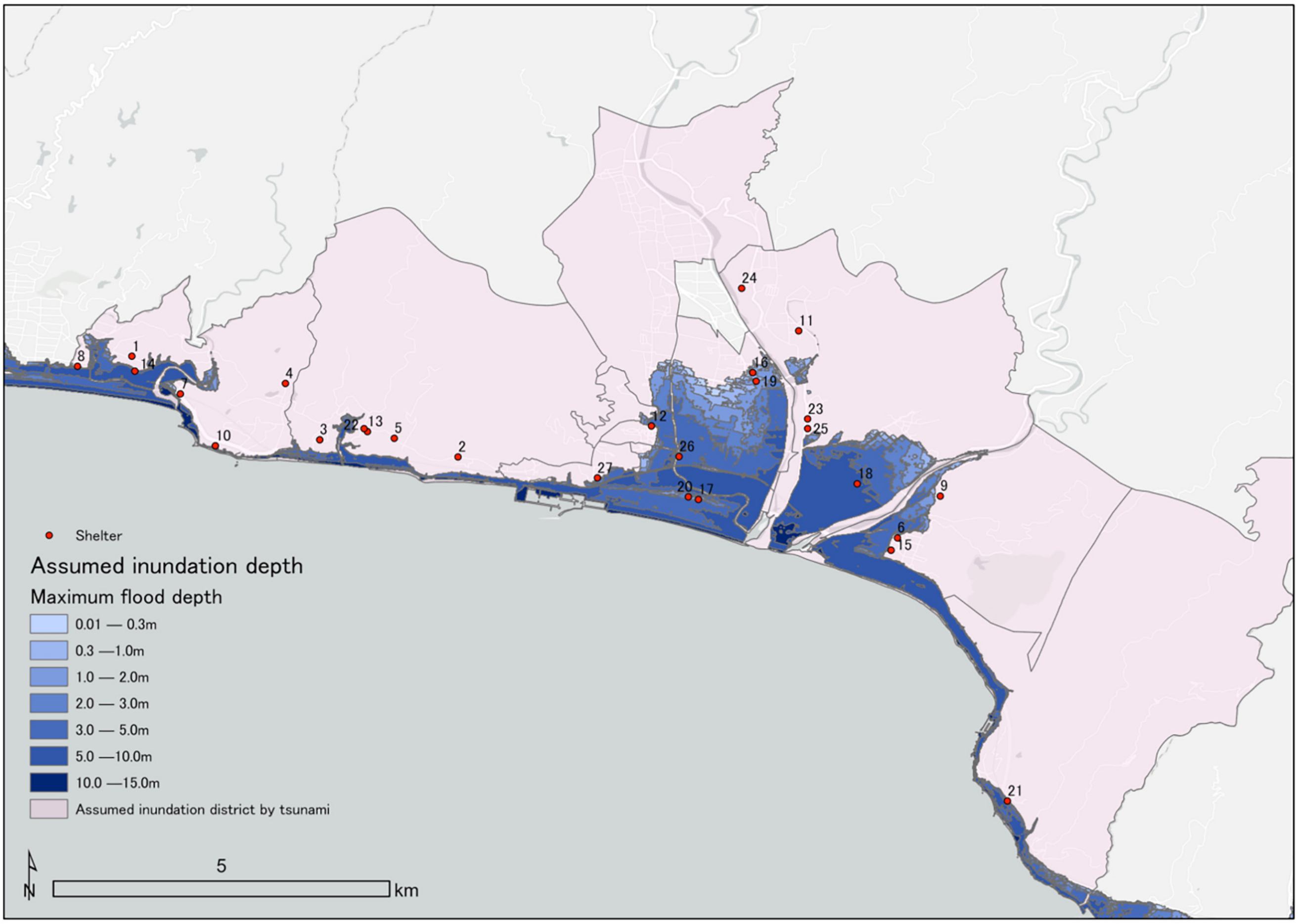

Fig. 3. Shelter locations and tsunami inundation area. The shelter positions are plotted with numbered red points. The inundation depth is shown in shades of blue.

stated by Aki City and the number of evacuees that could be sheltered when the area per person was increased to 3.5 m^2 and 7.0 m^2. Using the median evacuation shelter space, we calculated the number of shelters that would be required if the per person space was expanded to 3.5 m^2 and 7.0 m^2. Fig. 5 shows the flow of data collection and analysis.

3. Results

3.1. Inundation depth, capacity, and accommodation rate of evacuation shelters

Table 1 presents the data for the evacuation shelters in Aki, including the tsunami inundation depth, living space, and capacity. There are 27 evacuation shelters in Aki, with a total capacity of 5589 people. The median shelter capacity is 175 people (range: 12–1623), which gives an accommodation rate of 32.9%. The current Aki tsunami evacuation plan stipulates a 2 m^2 per person shelter area without space for maintaining PD. The median total living space of the evacuation shelters is 350 m^2 (range: 24–3246 m^2). With an evacuation area per person of 3.5 m^2, the accommodation rate would be 28.6%, and at 7.0 m^2 it would be 14.3%.

3.2. Location of shelters and the tsunami inundation area

Fig. 2 shows the locations of the evacuation shelters and the tsunami inundation area in Aki. The Pacific Ocean is at the bottom of the figure, to the south. A tsunami would flow from the bottom to the top of the figure; that is, from south to north (Fig. 2). Details of the evacuation shelters located in the inundation area and the inundation depth are presented in Table 1 and shown in Fig. 3. Nine (33.3%) shelters (Nos. 12, 14, 16–21, and 26) are located in the inundation area. The potential inundation depth range is 0.3–10.0 m.

3.3. Area of the evacuation shelters located outside the inundation area by zone, and occupant capacity when PD is maintained by expanding the per person evacuation area

Fig. 6 shows the Aki plain layer overlaid with the inundation area, the locations of shelters outside the inundation area, and the BBZ layer.

The currently planned accommodation rate of shelters for the population of Aki is 32.9%. Table 2 shows the number of people that can be accommodated, the number of evacuees calculated by BBZ, the evacuation space per person, the number of people that can be accommodated when PD is maintained, the number of excess people, and the number of additional evacuation shelters that would be required to maintain PD. Zone 1 had six shelters with a total capacity of 1270 people, and Zone 3 had one shelter with a capacity of 1623 people. There was no shelter in Zone 2. Assuming that evacuees would move out of the flooded area, it was estimated that there would be 9639 excess evacuees that would not be accommodated if 2 m^2 per person was allocated. The excess number of evacuees was

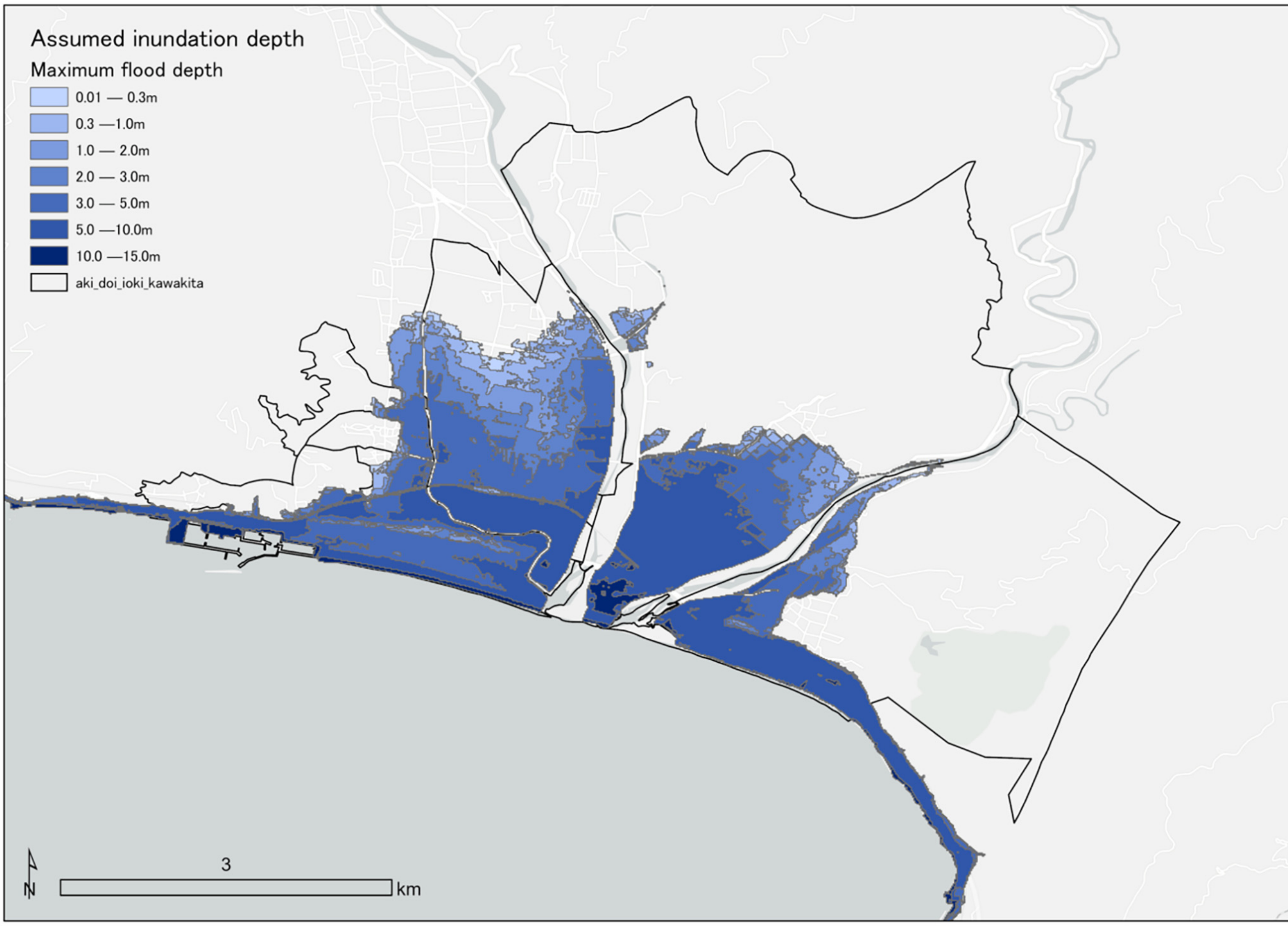

Fig. 4. Aki plain tsunami inundation area.

estimated to be 12,133 and 12,371, respectively, when PD was maintained at 11 m^2 (14.5 m^2) and 18 m^2 per person.

4. Discussion

By expanding the planned evacuation area to 3.5 m^2 or 7 m^2 per person to maintain PD, the number of accommodated evacuees will be significantly reduced. The area per person in Japanese evacuation shelters is extremely small. The per person evacuation area for the Great Hanshin Awaji Earthquake in 1995 was 1.0–1.7 m^2 [25]. The current average per person evacuation area planned by Tokyo, Chiba, Saitama, Kanagawa, and Ibaraki prefectures is 2.3 m^2 [25]. However, the minimum area for the humanitarian assistance of refugees and disaster victims set by the Sphere standard is 3.5 m^2 per person [34]. Aki City has set its per person evacuation area to 2 m^2 and made public the number of people that can be accommodated in its shelters. Because the incidence of infection can be lowered by avoiding contact between people and maintaining PD to prevent COVID-19 outbreaks [19], it is necessary to reconsider disaster prevention plans and expand the per person evacuation area. Overall, 37% of the shelters in Aki are small shelters of < 40 m^2 (Table 1). In cases where the capacity would be significantly reduced by ensuring PD, the operation of evacuation shelters must be reconsidered. For example, it may be effective to designate the use of evacuation shelters for 10 or fewer people for neighboring residents in advance. Appropriate staffing at shelters is an important consideration for providing care to vulnerable populations [37]. Limiting smaller shelters to the evacuation of households that include vulnerable people could be an effective strategy.

Given the persistent risk of COVID-19, we recommend the following two points when considering the establishment of evacuation shelters: (1) Assume that the shelter capacity will be insufficient if PD is maintained, and (2) Reserve the smaller shelters for the evacuation of vulnerable people. Most shelters that are outside the inundation area are in Zone 1, and no shelters outside the inundation area are located in Zone 2 (Fig. 6). Approximately 2100 people reside in the inundation area (Table 1), and it is necessary to consider that these evacuees may move from nearby temporary evacuation areas to the mountainside areas. Using the estimated number of evacuees in the planned evacuation rate of Aki, it is estimated that there will be a shortage of approximately 165 evacuation shelters if the evacuation area is expanded to the 3.5 m^2 Sphere standard and 11 m^2 of PD area is added. Because the population of Aki is concentrated in the plains, and because there are few facilities located on the mountainside, it will be difficult to accommodate all the residents of the inundation area. Accordingly, evacuation to neighboring municipalities that have not been damaged by the tsunami should be considered. However, before people can move to neighboring municipalities, there will be an immediate shortage of shelters in Aki, so more evacuation shelters are needed. Initially, this could require evacuation of overflow by car or bus. Many people were evacuated by car during the 2012 Emilia earthquake and the 2016 Kumamoto earthquake

Literature review

(1) Securing transportation infrastructure for safe evacuation of elderly people (Ozguven et al., 2016).
(2) Placement, transportation, and evacuation simulation of hurricane shelters (Alisan et al., 2020; Goerigk et al., 2014; Li et al., 2012; Zhang et al., 2013).
(3) Effect of COVID-19 pandemic on traffic volume (Parr et al., 2020).
(4) Assessment of spatial access to hospitals for COVID-19 patients (Ghorbanzadeh et al., 2021).

→No studies have focused on evenly distributing people to safe areas, assuming the dual disaster of a COVID-19 pandemic and a tsunami. Using GIS analysis to evenly distribute the population could help evacuation personnel to better understand shelter demand before a disaster.

↓

Capacity and living space of shelters in Aki City

We obtained the following information from the Aki City website (Aki City, 2013):
Address, living space, and capacity of Aki evacuation shelters
We calculated the evacuation space for each person by referring to the infection control guidelines (Hyogo prefecture, 2020; Sphere, 2018).
Physical distancing (PD): 11 m^2, Sphere standard: 3.5 m^2, twice the Sphere standard: 7.0 m^2.

↓

Tsunami inundation area and shelter locations in Aki City

Aki administration area data and population information, as well as Kochi Prefecture tsunami inundation data, were plotted using a Geographic Information System map (Ministry of Internal Affairs and Communications, 2018a).
The depth range was dark blue (15.0 m) to light blue (0.01 m).

↓

Zone division to distribute evacuees

Zone division was implemented to distribute the number of evacuees, taking into account the number of residents in the target area and the distance from the residential area to the nearest evacuation center outside the flooded area.

↓

Number of evacuees by zone and shelter capacity taking into account PD

(1) The number of people accommodated was calculated for per person evacuation space of 14.5 m^2 and 18.0 m^2.
(2) We calculated the difference between the currently planned capacity stated by Aki City and the number of evacuees that could be sheltered when the area per person was increased to 3.5 m^2 and 7.0 m^2.
(3) Using the median evacuation shelter space, we calculated the number of shelters that would be required if the per person space was expanded to 3.5 m^2 and 7.0 m^2.
(4) From the excess number of people who would not be sheltered owing to the reduced shelter capacities, we estimated the extra evacuation shelter capacity that would be needed if the space per person was expanded to 3.5 m^2 and 7.0 m^2.

Fig. 5. Flow of data collection and analysis.

[21]. Evacuation by car increases the risk of pulmonary embolism and deep vein thrombosis [16,38]. Specifically, the use of campsites in mountain areas, parking lots, and vacant lots adjacent to villages should be considered. According to the Japan Act on Regional Development for Tsunami Disaster Prevention, the government has designated areas at high risk of tsunami damage [10]. The 2011 Great East Japan Earthquake tsunami arrived 30–40 min after the earthquake [28]. Learning from this tsunami, the government asked local governments to designate facilities located in tsunami inundation areas for rapid tsunami evacuation [8]. Approximately 13,000 facilities had been designated as of August 2018 [10], but secondary damage caused by COVID-19 has not been considered regarding temporary evacuation and evacuation to shelters outside the flooded area. To prevent COVID-19 infection, municipal planners should review the evacuation shelter placement plan, taking into account not only the number of temporary evacuees, but also the PD, evacuation area, and population outside the flooded area. We contend the model presented here, which considers the number of evacuees, the per person evacuation area, and COVID-19 PD measures, has great utility.

There are some barriers to implementing these measures. Evacuation from the suburbs to the mountainside is likely; however, there are few facilities suitable for use as shelters. Immediate provision of such shelters is necessary, which creates an economic burden. In addition, the population-based placement plan does not take into account the transportation of elderly people and those with special needs.

5. Conclusions

The Aki Province current disaster prevention plan assumes a large excess of evacuees in the event of a tsunami. Considering the risk of COVID-19 infection, it is recommended that municipalities formulate a disaster prevention plan that expands the per person evacuation area.

It is recommended that to maintain PD, evacuation shelters with a capacity of 10 or fewer people be designated in advance as evacuation destinations for households that contain vulnerable people with special needs. Assuming that residents of the inundation area will evacuate to the mountainside area when a tsunami occurs, evacuation by car and the use of parking lots and vacant lots for camping may be an effective evacuation strategy for these residents.

The model presented here may be useful for local governments in managing their existing resources and in developing emergency plans that take COVID-19 preventive measures into consideration.

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Table 1
Shelter area, inundation depth, capacity, and capacity when physical distancing is maintained.

Shelter number	Tsunami inundation depth (m)[a]	(1) Aki's shelter capacity using 2 m^2 per person[b]	(2) Shelter area (m^2)	(3) Median shelter area	(4) Capacity when 3.5 m^2 (evacuation area) and 11 m^2 (PD area) are allocated per person	(5) Accommodation rate when 3.5 m^2 is allocated per person (%)	(6) Capacity when 7.0 m^2 (evacuation area) and 11 m^2 (PD area) are allocated per person	(7) Accommodation rate when 7.0 m^2 is allocated per person (%)
			(2) = 2 m^2*(1)		(4) = (2)/14.5 m^2	(5) = (4)/(1)*100	(6) = (2)/18.5	(7) = (6)/(1)*100
1	0	12	24	350	1.7	14	1.3	11
2	0	13	26		1.8		1.4	
3	0	13	26		1.8		1.4	
4	0	14	28		1.9		1.5	
5	0	14	28		1.9		1.5	
6	0	16	32		2.2		1.7	
7	0	17	34		2.3		1.8	
8	0	17	34		2.3		1.8	
9	0	17	34		2.3		1.8	
10	0	19	38		2.6		2.1	
11	0	30	60		4.1		3.2	
12	0.3–1.0	140	280		19.3		15.1	
13	0	174	348		24.0		18.8	
14	5.0–10.0	175	350		24.1		18.9	
15	0	200	400		27.6		21.6	
16	0.01–0.3	200	400		27.6		21.6	
17	1.0–2.0	200	400		27.6		21.6	
18	5.0–10.0	210	420		29.0		22.7	
19	1.0–2.0	222	444		30.6		24.0	
20	1.0–2.0	260	520		35.9		28.1	
21	1.0–2.0	260	520		35.9		28.1	
22	0	270	540		37.2		29.2	
23	0	330	660		45.5		35.7	
24	0	343	686		47.3		37.1	
25	0	350	700		48.3		37.8	
26	3.0–5.0	450	900		62.1		48.6	
27	0	1623	3246		223.9		175.5	
Total		5589	11,178		3194		1597	

[a] Ministry of Land, Infrastructure, Transport and Tourism [27].
[b] Aki City [1].

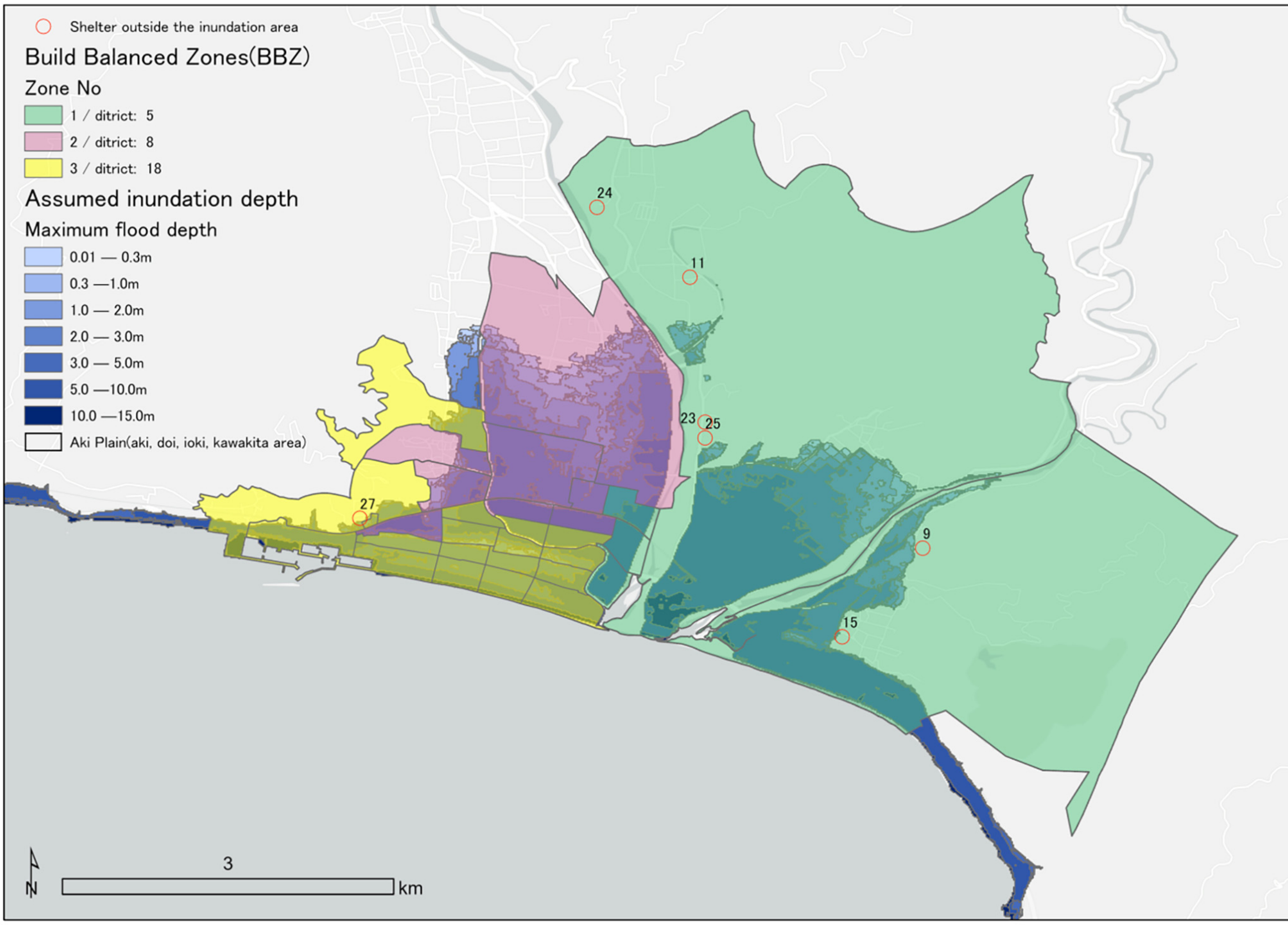

Fig. 6. Zones built considering a smooth distribution of the number of evacuees and the distance to the shelter.

Table 2
Number of people that can be accommodated in each zone, the number of excess evacuees if the evacuation area is expanded, and the number of shelters that will be lacking.

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
Zone	Shelter number	Aki's shelter capacity when allocating 2 m^2 per person[a]	Zone area (m^2)	Capacity per zone	No. of evacuees calculated by BBZ	No. of excess evacuees when allocating 2 m^2 per person	No. of people able to evacuate when allocating 3.5 m^2 evacuative area and 11 m^2 PD area per person	No. of excess evacuees when allocating 3.5 m^2 evacuative area and 11 m^2 PD area per person	No. of people able to evacuate when allocating 7.0 m^2 evacuative area and 11 m^2 PD area per person	No. of excess evacuees when allocating 7.0 m^2 evacuative area and 11 m^2 PD area per person	No. of evacuees based on the Aki shelter accommodation rate (32.9%)	No. of people able to evacuate using an evacuation rate of 32.9% and 7.0 m^2 evacuation area and 11 m^2 PD area per person	No. of excess evacuees using an evacuation rate of 32.9% and 7.0 m^2 evacuation area and 11 m^2 PD area per person	No. of shelters lacking when allocating 3.5 m^2 per person	No. of shelters lacking when allocating 7.0 m^2 per person
						(7) = (6)–(3)	(8) = (6)/3.5	(9) = (6)–(8)	(10) = (6/7.0	(11) = (6)–(10)	(12) = (2) * 0.329	(13) = (9) * 0.329	(14) = (11) * 0.329	(15) = (13) * −1 * 3.5/350	(16) = (14) * −1 * 7.0/350
1		1270	2540	1270	4705	(3435)	175	(4530)	71	(4634)	1548	(1490)	(1525)		
	9		34	17			2		1						
	11		60	30			4		2						
	15		400	200			28		11						
	23		660	330			46		18						
	24		686	343			47		19						
	25		700	350			48		19						
2	none	0	0	0	4192	(4192)	0	(4192)	0	(4192)	1379	(1379)	(1379)		
3	27	1623	3246	1623	3635	(2012)	224	(3411)	90	(3545)	1196	(1122)	(1166)		
Total		2893		2893	12,532	(9639)		(12,133)		(12,371)	4123	(3992)	(4070)	165	209

[a] Ministry of Land, Infrastructure, Transport and Tourism [27].

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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