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Tsunami Evacuation Planning as a tool for Tsunami Risk Reduction: A case study in Palu Bay, Central Sulawesi

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ABSTRACT

Situated in one of the most complicated tectonic zones of the world, Palu is classified as one of the most susceptible places to earthquake and tsunami in Indonesia. This study aim to develop near-field tsunami evacuation simulation, as the primary strategy to reduce casualties in disaster risk reduction, based on daytime and night-time population scenarios in a tsunami-prone area in Palu Bay, Central Sulawesi. Least Cost Distance, a geospatial evacuation analysis approach in ArcGIS, is applied involving three main variables, namely population exposure, the arrival time of tsunami and walking speed of evacuees. These variables were analysed to calculate distribution of populations in daytime and night-time scenario; to identify and calculate the capacity of potential existing evacuation shelter buildings (ESB); and to analyse suitable locations, and to calculate the number and capacity of additional ESBs based on the most effective evacuation route. This study found that of the population in the study area, about 62.60 % cannot be sheltered in the seven existing ESB in the daytime as well as 63.98% of total population in the night-time scenario. Meanwhile,only 60.13% and 61.83% of the population in the service area of existing ESBs, can be evacuated in daytime and night-time scenarios, respectively. Therefore, eleven and twelve additional ESBs are proposed to be established for daytime and night-time scenarios, respectively, to accommodate people who currently cannot be sheltered.

Keywords: Tsunami; Evacuation Planning; Evacuation Building; Evacuation Route

1. INTRODUCTION

Tsunamis, although less common than other natural disasters (e.g., storm surges or high waves), have brought catastrophic consequences, and are the biggest killers of coastal populations and communities, especially in Indonesia since 2004. Situated in one of the most complicated tectonic zones of the world, Palu-Koro Fault system, Palu is classified as a high seismic risk area and one of the coastal areas that is most susceptible to tsunamis in Indonesia [1]–[3].Furthermore, the impact of a tsunami in Palu will be exacerbated because Palu Bay has a narrow “V” topographic shape, long and deep bay that makes tsunami waves more powerful and more devastating [4].At the same time, most of tsunami prone areas in Palu Bay are located in low-lying coastal areas and high ground is far inland.

The 7.5 magnitude earthquake, followed by a devastating tsunami and liquefaction of land, that killed approximately 3,475 people in Palu, Indonesia 28 September 2018 [5], showed a lack of disaster preparedness, including knowledge about the tsunami and insufficient tsunami evacuation planning.

In tsunami disaster mitigation, quick evacuation of people from tsunami prone areas to the safe areas before the tsunami hits the coastal areas is considered as the primary strategy to reduce casualties [6], [7]. The knowledge and application of effective evacuation routes could minimise population vulnerability to tsunamis and make them more resilient[8]. In addition, the establishment of vertical evacuation has become an effective risk reduction option for coastal communities who have less time to evacuate and have no accessible high ground to evacuation to, in case of near-field tsunami [9].

Based on these descriptions, it is necessary to conduct a study about tsunami evacuation planning as a part of disaster risk reduction in Palu Bay.This research aims to develop the simulation of tsunami evacuation based on daytime and night-time population scenario in a tsunami-prone area in Palu Bay.That aim was met by operationalising several objectives: (1) to calculate daytime and night-time populations (distribution of populations) in daytime and night-time scenario; (2) to identify and calculate the capacity of potential existing evacuation shelter buildings (ESB); and to analyse suitable locations, and to calculate the number and capacity of additional ESBs based on the most effective evacuation route

A. Tsunami Evacuation Time

Tsunami evacuation time analysis is beneficial for improving the tsunami evacuation process. Evacuation time is the time required for people to start the evacuation up until the population reaches the safe points. The total evacuation time can be estimated using following equation:

$$T_{evacuation} = T_{tsunami} - (T_{response} + T_{reaction})$$

$T_{evacuation}$: Estimation time required for people to evacuate (time travel)

$T_{tsunami}$: Estimation time required for tsunami waves to reach the coastal area

$T_{response}$: Estimation time required to transmit a tsunami warning alert by responsible authority up until the warning is received by the whole community

$T_{reaction}$: estimated time required for people to start evacuating

B. Pedestrian and Vehicular Evacuation

There are two decision on travel mode for evacuation, pedestrian and vehicular evacuation. In near field tsunamis, where evacuation time is limited by quick tsunami arrival time, and where the road network is dense, and the roads' capacity is low, pedestrian evacuation is recommended. Pedestrian evacuation reduces the demand on roads, thus avoiding congestion and bottlenecks [10]–[14].Vehicular evacuation, on the contrary, is more suitable for hazards in a large geographical area with advance notice and a long evacuation window (for example a hurricane) [15].

C. Vertical and Horizontal Evacuation

The tsunami evacuation process is categorised into two types, horizontal evacuation and vertical evacuation buildings [14], [16]–[20]. Horizontal evacuation refers to the strategy of people moving from inundation areas to the accessible safe zones at a distant location, or higher elevation ground as the assembly point. Vertical evacuation is related to people's strategy to reach accessible higher floors in a building [16], [17].

The experience from prior tsunami events indicated that if enough evacuation time is available, then evacuation of people to the inland (horizontal evacuation) is the main priority to reduce mortality rates [14]. However, in particular conditions, especially when near-field tsunamis occur in low-lying areas causing the evacuation time to be limited, vertical evacuation is more appropriate resulting in fewer casualties.Vertical evacuation is considered as another option to limit vehicle use when people are concentrated in hazard areas [15].

D. Service Area

Service area in this study is defined as the minimum area developed considering travel time and the number of population on tessellations [16], [21]. The two types of service area are based on evacuation time (travel time) and capacity.The service areas based on travel time represents the number of people who can reach the nearest ESB in a given time. Meanwhile, the service area based on capacity defines the number of people who can be accommodated in an ESB considering the tsunami evacuation building capacity (TEBC)that can be reached in a given time [16].The two important variables to create this service area are the shortest travel time and the number of people in the nearest tessellation.The service area based on travel time is possibly broader than the service area based on capacity or vice versa.

2. METHODOLOGY

The population in the study area was calculated based on the configuration and the number of houses and facilities in each hexagon tessellation in daytime and night-time scenario, which are identified and interpreted through satellite images.The number of people in the houses was calculated based on equation by Budiarjo

[22], while the occupants at other facilities, was obtained using architectural design space requirements approach as developed by Budiarjo [22] and Dewi [16]. This architectural approach was also applied to identify and calculate the capacity of potential existing evacuation shelter building (ESB).

The tsunami evacuation planning was developed using least-cost distance (LCD) analysis through Network Analysis, an extension of ArcGIS. The two command of network analysis, *service area* and *find closest facility,* were applied to create service area of existing potential ESBs and proposed location for additional ESBs as well as the fastest evacuation route from the origin point to the shelter's location, respectively.

The arrival time of tsunami was assumed to be 40 minutes, although based on the recent tsunami event in Palu, the arrival time of the tsunami was less than 12 minutes [23], [24]. Therefore, it would be intricate and complicated to develop a tsunami evacuation plan based on this tsunami travel time.Another assumption is that 13 minutes are needed to transmit the early tsunami warning from the the responsible authority Badan Meteorologi, Klimatologi dan Geofisika(BMKG) until the local government can inform the entire community. Furthermore, people will spend 5 minutes to start evacuating after receiving the tsunami alert.Adapting the scenario from [16], of the 22 minutes available, 5 minutes are needed for people to reach the upper floor. The remaining 17 minutes are the evacuation time which evacuess spent to run and find an evacuation shelter.

This study focuses on pedestrian-based evacuation. In addition, this study applied 0.7 m/s evacuation speed by assuming that if the slowest evacuees can reach the safe areas within a particular time, the fast population could do the same, theoretically.

3. RESULTS AND DISCUSSION

A. Calculation of daytime and night-time populations

The results of population estimation for each building are presented on Table 1.Figure 1 and Figure 2 presents the difference of population distribution during the daytime and night-time.

Table 1 The estimation of population in each type of building during daytime and night-time.

Type of building	Total number of people	
	Daytime	Night-time
House	6,780	11,152
Office	1,419	12
House shop	134	212
Mosque	476	76
Hotel	190	300
Cafeteria (recreation area on beach)	360	360
School	3,274	401
Hospital	363	342
Mall	577	527
Total	13,599	13,382

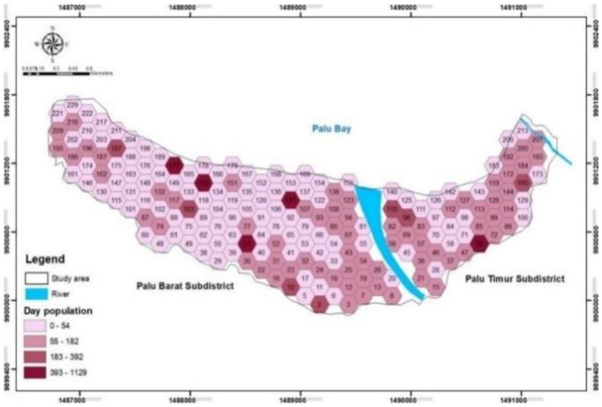

Figure 1 Population distribution in the daytime in study area

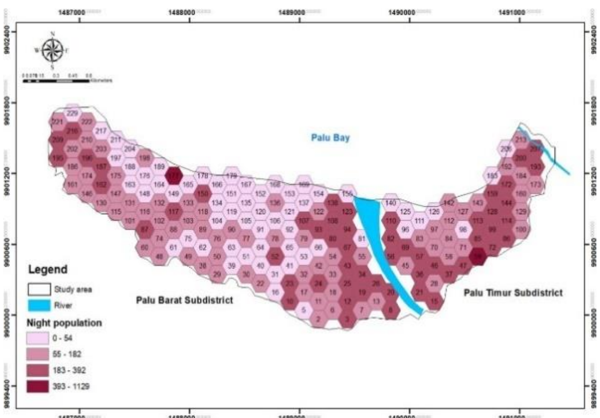

Figure 2 Population distribution in the night-time in study area

There is no significant difference exists between the number of people present in the daytime and in the night-time. This difference is because the population in the daytime is coming from residential areas and facility areas, such as offices, schools or campus and other facilities such as retail centres and commercial buildings.

B. Identification and calculation of capacity of potential existing buildings for evacuation shelter

From a field survey, seven buildings were selected to be potential evacuation shelter buildings (ESB), as presented in Figure 3, which meet all the requirement for an evacuation building. Based on observations, those buildings exhibit sound building construction, resistant to earthquake and suffered only minor damage after the large earthquake on 28 September 2018.

Using the architectural approach, Table 2 presents the calculation of the maximum number of evacuees that can be accommodated in each potential ESB.

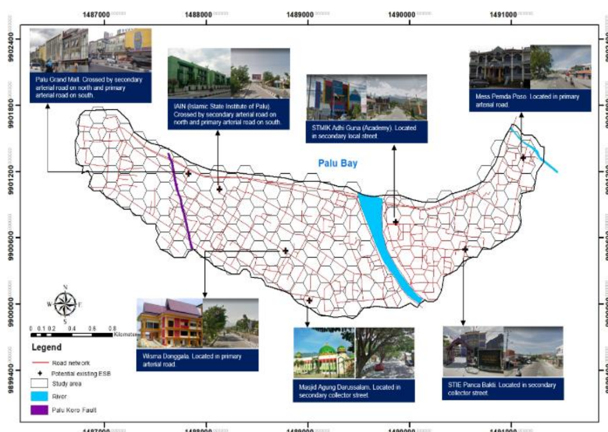

Figure 3 The location and accessibility of potential existing ESB

Table 2 Capacity of existing potential ESB.

Building	**Function**	**Capacity (person)**
IAIN Palu	School - Institutional	2,079
Palu Grand Mall	Department store - commercial	2,151
Mess Pemda Poso	Commercial housing	137
STIE Panca Bakti	School - institutional	571
STMIK Adhi Guna	School - institutional	416
Masjid Agung Darussalam	Religious and social – institutional	1,658
Wisma Donggala	Commercial housing	763

The number of evacuees to be sheltered in ESBs is then determined using two types of service areas for ESBs—namely, service areas based on evacuation time and the other based on capacity. Figure 4 illustrates the service area of each ESB based on a 17-minute evacuation time. In other words, each polygon in the figure represents the coverage area of a ESB that evacuees are able to reach within 17 minutes. The total number of people in the tessellations within the coverage area of each ESB was calculated in Table 3, and the results show that 8,458 and 7,793 evacuees can be potentially sheltered during daytime and night-time, respectively.

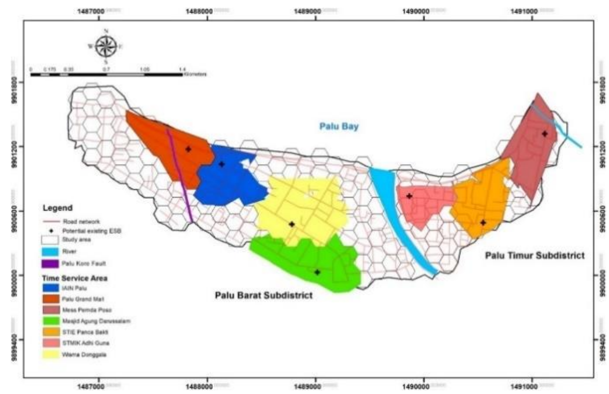

Figure 4 Service areas of the existing potential ESB based on 17 minutes evacuation time

Table 3 Number of sheltered people for each service area based on evacuation time.

Name of Potential Existing ESB	**Total Number of people in tesselations**	
	Daytime	Nighttime
IAIN Palu	1,541	809
Palu Grand Mall	1,139	1,062
Mess Pemda Poso	1,240	1,547
STIE Panca Bakti	742	1,062
STMIK Adhi Guna	871	933
Masjid Agung Darussalam	835	1,060
Wisma Donggala	2,090	1,320
Total	8,458	7,793

The results, taken from the analysis of service areas of ESBs based on capacity during daytime and night-time shown in Figure 5 and Figure 6, reveal that it is possible that a service area based on capacity is smaller compared to a service area based on evacuation time. Wisma Donggala, STIE, STMIK and Mess Pemda Poso cannot cover all of the population in the relevant tessellations because of the limitations of their maximum capacities. On the other hand, the large capacities of the other three ESBs enabled them to accommodate more than the

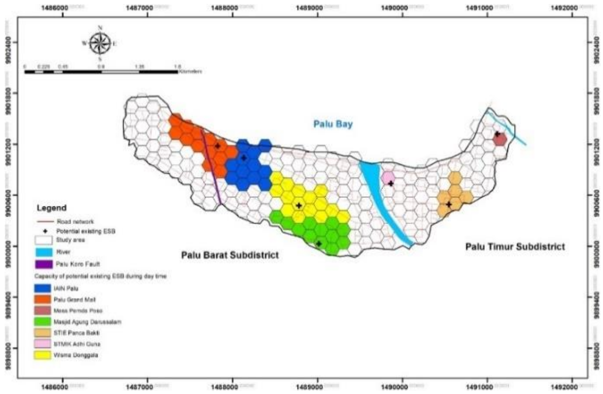

Figure 5 Service areas of the existing potential ESB based on evacuation time and capacity during the daytime.

total number of evacuees in the service area based on evacuation time. This is reflected by the polygon of same service area based on evacuation time and capacity. However, the remaining capacity of each of those ESBs cannot be maximised due to the 17-minute constraint for evacuees to reach the ESBs (see Table 4).

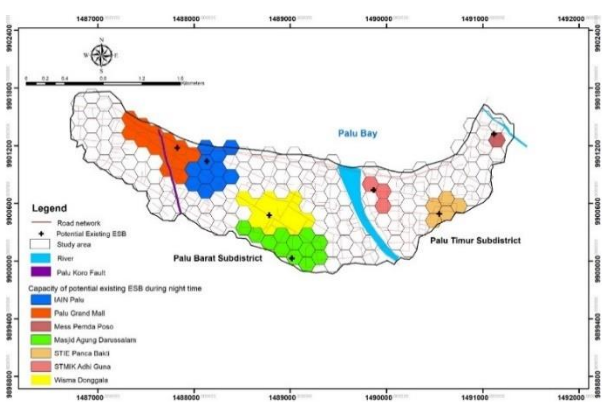

Figure 6 Service areas of the existing potential ESB based on evacuation time and capacity during the night-time.

Table 4 The number of sheltered evacuees in potential existing ESBs considering the capacity of each ESB.

Name of Potential Existing ESB	TEBC*	Number of people in tesselations	
		Daytime	Nighttime
IAIN Palu	2,079	1,541	809
Palu Grand Mall	2,151	1,139	1,062
Mess Pemda Poso	137	69	135
STIE Panca Bakti	571	562	568
STMIK Adhi Guna	416	202	451
Masjid Agung Darussalam	1,658	835	1,060
Wisma Donggala	763	738	734
Total	7,775	5,086	4,819

*total evacuation building capacity

From Table 4, it can be concluded that even though TEBC is larger than the number of people in the service area based on capacity, not all people can be evacuated. Only 60.13 % (5,086 people from 8,458) and 61.83 % (4,819 of 7,793) of the population in the service areas of those six ESBs can be evacuated to the existing shelters in a daytime and a night-time scenario, respectively. Furthermore, of the population in the study area, about 62.60% cannot be sheltered in the existing buildings in the daytime, and as well as 63.98% of the total population in the night-time. Therefore, additional shelter buildings are proposed to rescue the evacuees.

C. Analysis of suitable locations, and the number and capacity of additional ESBs based on the most effective evacuation route

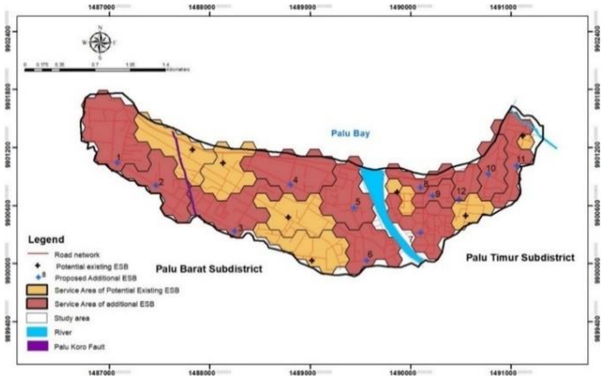

Figure 7 The location of existing and additional ESBs based on a daytime scenario

Using *service area* command for network analysis, eleven additional ESBs based on a daytime scenario and twelve based on a night-time scenario are proposed to be established. Moreover, the number of evacuees in the service area will determine the size of the additional ESB as shown in Table 5. As all the evacuees within the coverage area of the Palu Grand Mall, IAIN and Masjid Agung Darussalam can be sheltered, the distribution of additional shelters during daytime and night-time scenario, especially on the western side of Palu River is almost the same for the two scenarios as presented in Figure 7 and Figure 8.

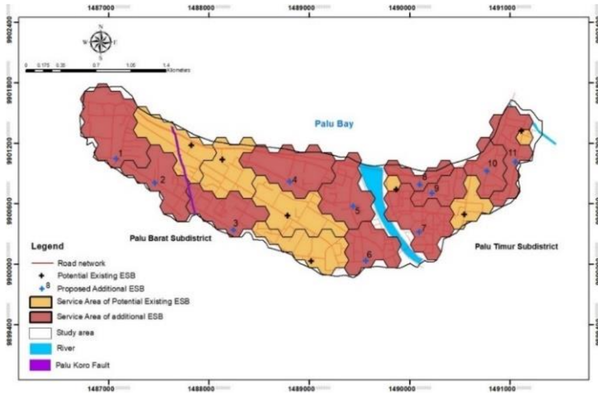

Figure 8 The location of existing and additional ESBs based on a night-time scenario

Table5 The capacity of the proposed additional ESBs based on a daytime and night-time scenario

Additional ESB Number	**Proposed TEBC (person)**	
	daytime	night-time
1	956	956
2	518	518
3	1,436	1,592
4	984	984
5	649	649
6	613	689
7	1,379	922
8	148	148
9	341	291
10	567	527
11	922	988
12		299

In addition, besides travel time as an impeding factor, the process to determine the most suitable location for additional ESBs involved some considerations. Open space or an unoccupied area is the first priority. The second priority is an area surrounded by some facilities like schools, offices, recreational area, mosque and any other facilities. The next alternative is a mixed crops area, which are usually located near to settlement areas. However, since the study area is dominated by densely populated settlements, the difficulty is to find vacant areas. Some of the ESBs are proposed to be established in residential areas. Regarding the accessibility factor, in general all the proposed additional ESBs are reachable. Most of the proposed additional ESBs are on arterial roads and collector streets, except for ESB number 7, 9 and 10, which are located on residential streets. Figure 16 describes the distribution and accessibility of proposed additional ESBs in the study area.

Furthermore, using the *find closest facilities* command of the network analysis, the shortest time and path to reach each ESB in the daytime and night-time scenarios were generated.It takes from 0.33 to 16.75 minutes for the evacuees to reach the ESB. Meanwhile, the evacuees need to walk between 14 to 746 metres to make the evacuation process. Moreover, Figure 9 and Figure 10 illustrate the evacuation route of each ESB based on daytime and night-time scenarios. The black dots represent the origin point of evacuees to make an evacuation, and the arrow symbol shows the route from the origin point to reach the nearest ESB.

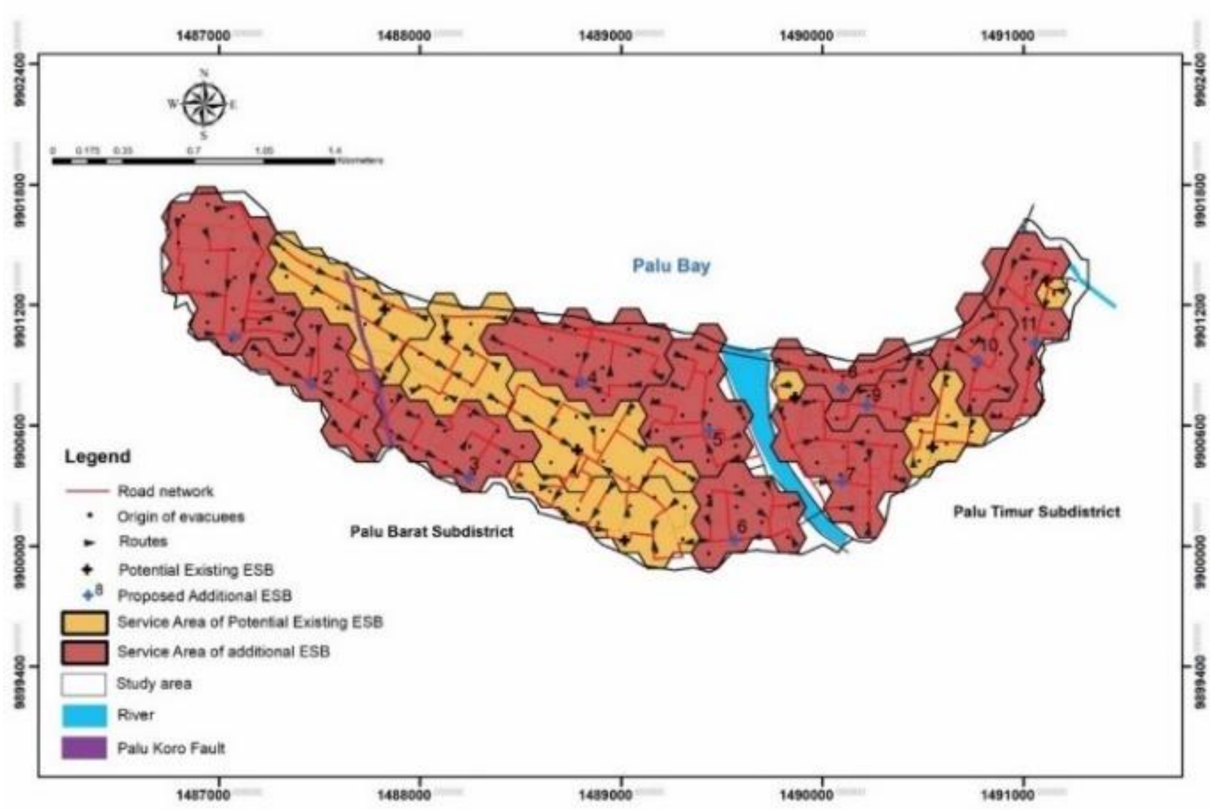

Figure 9 Evacuation route of each ESB based on a daytime scenario

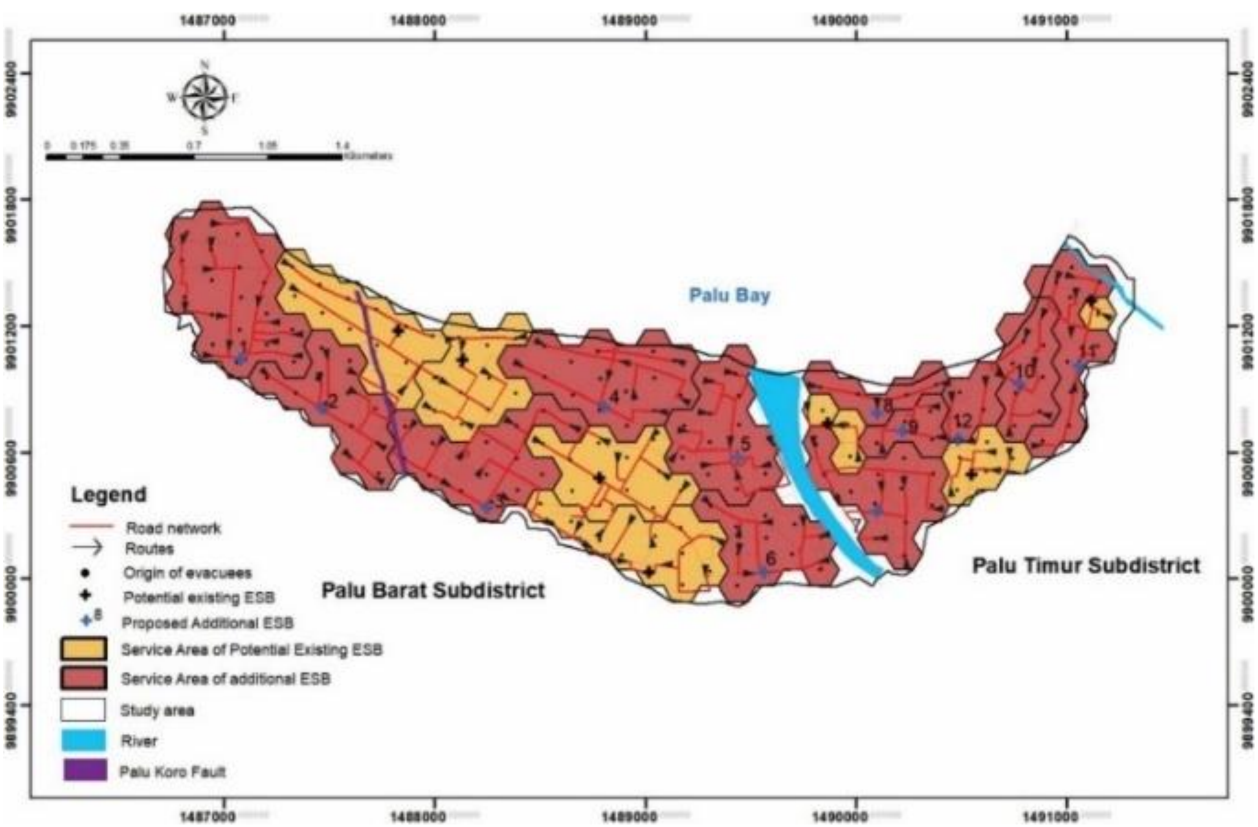

Figure 10 Evacuation route of each ESB based on a night-time scenario

D. Implications for the simulation

In practice, encouraging people to evacuate by foot is a big challenge, even for Japan as a world leading country in disaster prevention. Therefore, this issue should be addressed, and measures for vehicular evacuation need to be considered in the simulation.

The availability of detailed road network data is an important element in tsunami evacuation planning. More detailed road network data would produce more reliable evacuation modelling. This includes the identification of potential congestion areas generated by critical facilities (in this case schools and hospital). Critical bottlenecks can be caused by a high population density combined with a lack of evacuation routes, or by the concentration of highly frequented evacuation routes [25]. In addition, more detailed population data, such as number of populations by age group, and number of vulnerable populations, is required to improve knowledge of evacuee distribution as one of the main components of the simulation. The importance of detailed population data is related to distribution of travel speeds which determine evacuation time, as studied by Fraser et al. (2014).

Some issues about accessibility arise regarding the location planning of new ESBs in the study area. It is regarding to limited number of roads that are perpendicular to the shoreline, which are all required to lead evacuees move away from coast. Another issue is the inadequate capacity of the road used to reach some ESBs, which should become an important input in the current revision of spatial planning of Palu City, which is currently in progress.

The underestimation of departure time is also need to be concerned. This study assumed that people only need 5 minutes to start their evacuation after receiving an alert from the local government. This scenario is difficult to apply because people's behaviour to delay evacuation for various reasons, which is identified*psychological and logistical preparation*.

E. Implications for Urban Design Planning

Establishing additional ESBs faces big challenges regarding the availability of land and high cost of construction. However, there are alternative ways to provide shelter besides the construction of new buildings. First option is utilising existing public facilities' buildings, such as city hall, schools, mosques and other structures through two methods of retrofitting: (a) strengthen the structural components to improve the rigidity and strength of the building; (b) raise the elevation of the building [26].

Another alternative to address the limitations of budget is to provide new ESBs through public private partnership mechanisms [16], [27]. This mechanism is implemented in the form of cost sharing and various incentives provided for the private sector to build high-standard multi-storey buildings, or to build additional floor-space for evacuation purposes.

Another challenge regarding ESB is coming from the trust and distrust of people to choose evacuation buildings as safe points. This challenge is related toprotection motivation theory which revealed that the strongest social influence to choose evacuation destination is coming from close social proximity, such as family and friends, while the influence became weaker when it comes from socially distant entities, for instance government offices [28].

One solution that could answer the problem above is to optimised function of the shelter building through the utilisation of the shelter building as public facilities, such as library or museum, as has been applied in Japan[29]. The combination use of evacuation purposes and public facilities in a shelter building can increase the level of people's trust in and familiarity with these buildings.Consequently, it is expected that in the case of tsunami occurring, people will immediately evacuate to the building without any hesitation.

Another consideration that must be understood is that the evacuation process included in disaster risk management is also related to the way the public is educated regarding the importance of evacuation, how a tsunami simulation is conducted, and how land-use regulation is enforced and how early warning systems are maintained. Those factors all contribute to successful evacuation [30]. Therefore, continuous tsunami evacuation drills are needed to be conducted to educate and raise public awareness, as well as to increase public understanding on appropriate measures that need to be undertaken during emergencies.

Finally, since constructing evacuation shelters is not appropriate for the medium or long-term due to the increase in population, land use planning has become an essential variable that must be taken into consideration fortsunami risk reduction. An effective scenario on the evacuation process cannot solely guarantee to produce zero casualties, as evacuation in densely populated areas and the shorter arrival times of tsunamis are big challenge with many factors involved. Enforcing land use regulations through preventing further urban development in tsunami prone areas is expected to reduce physical destruction and potential casualties. This policy may generate tenure rights problems and livelihood problems for relocated people. However, through comprehensive risk management strategies, the enforcement of land use regulations is expected to overcome these problems and help reduce future disaster risk leading to safer coastal communities.

4. CONCLUSIONS

There are seven potential existing ESB in the study area, which only can shelteredonly 60.13% and 61.83% of the population in the service area. Meanwhile, of the total population, about 62.60 % cannot be sheltered inexisting ESBs in the daytime as well as 63.98% in the night-time scenario. Therefore eleven and twelve additional ESBsare proposed to be establishedbased on a daytime and a night-time scenario, respectively.

Some aspectsthat should be taken into consideration for further research are: (a) the availability of high resolution of satellite image, which is essential to minimise bias when identifying building blocks, road networks and types of land cover; (b) the combination pedestrian-based evacuation with vehicular evacuation, as well as the combination of vertical evacuation with horizontal evacuation options in simulation; and (c) finally, the shortcomings from the application of GIS, which cannot cover individual human behaviour aspects in an emergency situation, can be answer by applying an agent-based model approach. This approach is better than GIS-based approaches to reflect on a real evacuation, which incorporates the complexity and diversity of individual's behaviour to start evacuation, to choose an evacuation method (pedestrian or vehicular) and a destination safe point (vertical or horizontal), and to move at a particular speed.

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