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Discussions

Development of a decision support system for tsunami evacuation in the South China Sea region

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Abstract: Major tsunami disasters often cause great damage in the few hours following an earthquake. The possible severity of such events requires preparations to prevent tsunami disasters or mitigate them. This paper develops a decision support system for rapid tsunami evacuation for local decision makers in the South China Sea region. Based on an analysis of tsunami seismic source characteristics in the South China Sea region, this system uses Geographical Information System techniques to quickly assess the extent of tsunami impact and the tsunami propagation time. Because numerical models are not calculated, this system can save some time. Some vulnerability factors, such as elevation, offshore distance and population distribution are analyzed to identify areas of high-risk of tsunami. Combined with some kinds of spatial data, this system can constrain evacuation costs and forecast road congestion to support decision-making for tsunami evacuation in high-risk areas. When an earthquake and tsunami occur, this system can rapidly determine areas of high risk of tsunami and provide the evacuation cost and congestion-prone roads to assist with tsunami evacuation operations.

Key words: tsunami, GIS, evacuation, decision support system

1 Introduction

Tsunami can cause some of the worst marine disasters possible, and they affect many coastal countries around the world. Since the beginning of the 21st century, there have been a large number of global tsunami disasters, and over the last decade, two to three tsunami have occurred every year in the Pacific (IOC, 2013). Although tsunami are low-probability events, they are often accompanied by huge economic property loss and casualties (Papathoma et al., 2003). In addition, tsunami can cross oceans and influence areas far from their sources, resulting in large-scale disasters (Hébert et al., 2001). Following the 2004 Indian Ocean tsunami (Suppasri et al., 2011) and the 2011 Japanese tsunami (Wei et al., 2011), many governments and international organizations around the world have increased research into tsunami disaster prevention and mitigation. As an important part of tsunami mitigation, tsunami risk assessment is listed as a primary focus for tsunami disaster prevention and mitigation by the United Nations Intergovernmental Oceanographic Commission (IOC, 2015).

Tsunami risk assessments undertaken prior to the arrival of a tsunami are considered to be important and necessary (Sato et al., 2003; Strunz et al., 2011; Kurowski et al., 2011). According to natural disaster risk assessment theory, risk assessment provides a means to quantify risk by analyzing potential hazards and evaluating vulnerability conditions. Tsunami evacuation research has been conducted in high-risk areas around the world, based on evaluations of tsunami hazard, vulnerability and risk assessments. When a tsunami disaster happens, the first task for emergency rescue personnel is to evacuate people to safe areas (Mück, 2008). Tsunami evacuation research needs related information, such as the degree of hazard, and the distribution of people, roads and shelters (Scheer et al., 2011). Currently, many governments (e.g., Japan, the United States and Chile) issue tsunami evacuation plans (Bernard, 2005) to help citizens plan for tsunami disaster.

In the face of a potential disaster, the main concern of affected people is to mitigate the effects of hazards. Geographic information system (GIS) applications play an increasingly important role in risk assessment and mitigation planning by sorting out and analyzing a large number of useful spatial information. GIS technology and software developments are making such systems more intelligent. Data collection capability is stronger, and can handle more types of data. Cova (1999) states that GIS can be used in multiple aspects of disaster management. Johnson (2000) suggests that GIS could play an important role in disaster mitigation, preparedness, response and recovery. Without GIS data, decision makers will be unprepared, resulting in a waste of manpower and resources. Cutter (2003) suggest that the combination of GIS, Global Positioning System (GPS) and Remote Sensing (RS) can improve emergency management. Recently, GIS technology has been applied to the tsunami evacuation analysis by some experts. Sugimoto et al. (2003) used numerical calculations combined with GIS methods to estimate tsunami damage, incorporating evacuation activities. Dewi (2012) determined appropriate tsunami shelters and effective evacuation routes using GIS. Wood and Schmidtlein (2013) combined disaster information and geographic data to identify potential disaster locations and affected populations. Mas et al. (2015) used GIS datasets as spatial input information for agent-based tsunami evacuation simulations.

2 Methods

This paper aims to develop a support system for decision makers in the South China Sea region to facilitate planning of rapid tsunami evacuations. Based on tsunami hazard and vulnerability analysis, such a system can quickly provide evacuation information that can be useful when an earthquake and tsunami occur. The Python language and ArcGIS software were used to develop the system.

Two main evacuation models have been proposed in previous studies: the least-cost model and the agent-based model (Wood and Schmidtlein, 2013). The static least-cost model is suitable for tsunami planning over relatively large areas with multiple scenarios, whereas the dynamic agent-based model is developed for tsunami drills in a localized area with one specific tsunami scenario. The agent-based model mainly focuses on spatial and temporal changes of population in a coastal area, which the decision makers often do not know well. Additionally, a focus of this system is to understand the natural and social environments of evacuation operations, rather than individual behaviors. Therefore, the least-cost model for a relatively large area is used in this paper.

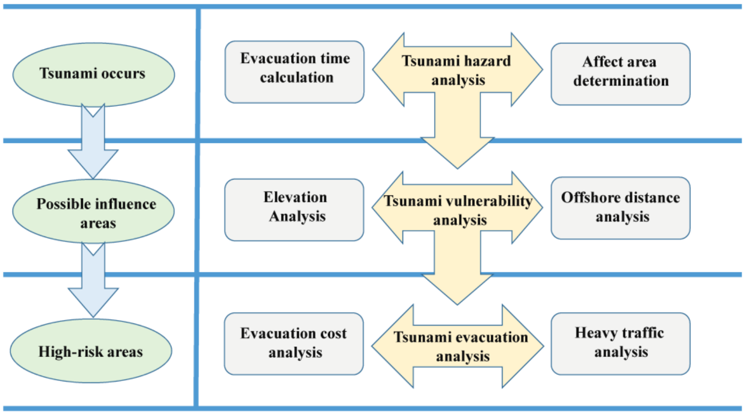

Figure 1. Framework of the system

A framework for this system is shown in Fig. 1. The system development process has three stages: hazard analysis, vulnerability analysis and evacuation analysis. First, all potential tsunamis are simulated by numerical models, considering the range of possible magnitudes. The calculation results are used to determine the effected region of the tsunami, which is then imported into a database. Once a tsunami occurs, the affected region of the tsunami can be rapidly determined from the database. Second, the vulnerability of the affected region is analyzed and high-risk areas are determined. Vulnerability considers factors including offshore distance, elevation and population distribution. Third, specific information required for evacuation is displayed in the system, including congestion-prone roads and evacuation costs.

3 Tsunami hazard in the South China Sea region

The South China Sea, located in the western Pacific Ocean, and covering an area of about 3.5×10^6 km^2, is one of the largest marginal seas in East Asia (Liu et al., 2007). This region includes the South China Sea and small adjacent basins, the Sulu Sea and Sulawezi Sea.

The Manila Trench, an active subduction system, lies in this region where the Eurasian Plate subducts beneath the Philippine Plate. The Manila and Sulawesi subduction zones have been identified as potential tsunami sources by the United States Geological Survey (USGS; Kirby, 2006). Written records can be found of historical tsunamis in the northeastern South China Sea (Lau et al., 2010; Megawati et al., 2009). For example, Sun et al. (2013) reported preliminary evidence from the Xisha Islands in the South China Sea for a large tsunami around AD 1024.

Modern earthquake records may overlook the tsunami potential of the region (Okal et al., 2011). Modern seismic analysis suggests that the 1918 Morro Bay and 1934 Luzon earthquakes were larger than their officially reported magnitudes. Although the probability of a major earthquake in the Manila Trench is not high, this does not mean that a major earthquake will not occur in the future (Megawati et al., 2009). Dao et al. (2009) simulated a worst-case tsunami scenario for the Manila Trench using a numerical model, estimating a tsunami height of 14 m in the vicinity of the Philippines and southwest of Taiwan. A tsunami triggered by a giant earthquake from the Manila Trench could cause devastating damage to the Philippines, southern China, and Vietnam (Megawati et al., 2009; Ren et al., 2015).

In this paper, we consider a number of potential tsunami scenarios in the South China Sea region. The historical earthquakes and tsunami from the region are shown in Fig. 2. Earthquake data (1976-2016) are from the USGS, whereas the tsunami data (2000-2016) are from the US National Geophysical Data Center (World Data System, 2016). These data contain event times, locations, types and other information.

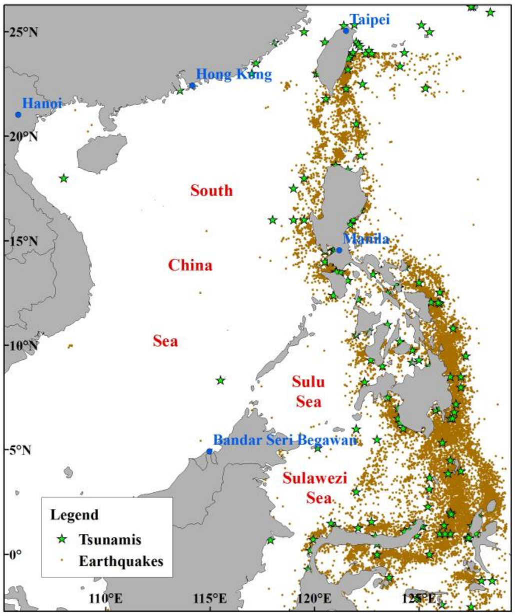

Figure 2. Location map of the study area

4 Case study for the Jiyang District of Sanya City

4.1 Overview of case study area

This paper focuses on the Jiyang District of Sanya City in China to provide an example of the development of the decision support system for tsunami evacuation in the South China Sea region. Sanya, located at the southern tip of Hainan Island, is a transportation and communication hub in southern Hainan Province and an important port on the southeast coast of China. Sanya has a unique geographical advantage in international economic relations as it lies close to many ASEAN countries. The Jiyang District (Fig. 3) lies in the heart of Sanya City. The topography is high in the north and low in the south. Most of this area lies between elevations of 10 and 300 m, with a maximum elevation of 604 m. Plains dominate the terrain in this coastal area.

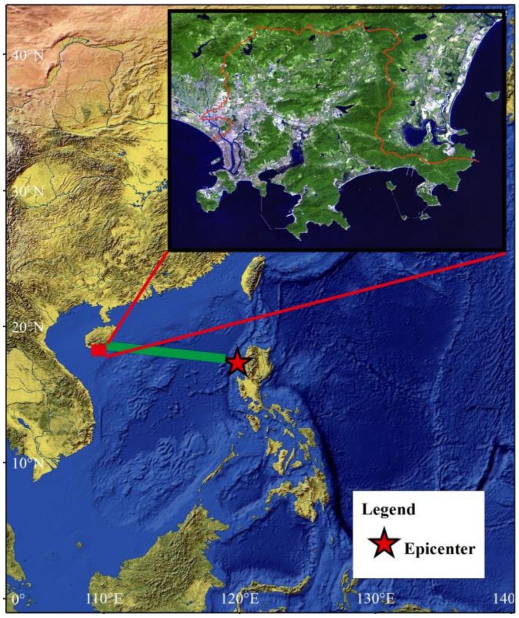

Figure 3. Location map of the case study

4.2 Tsunami travel time analysis

Tsunami travel time is a very important factor for tsunami evacuation systems. Tsunami evacuation time is the time that remains after the tsunami warning time and public reaction time are taken away from tsunami travel time. The type of evacuation method that should be adopted: horizontal or vertical evacuation, mainly depends on the amount of evacuation time available. In order to quickly determine the tsunami travel time, the system calculates the approximate tsunami travel time through an average water depth, according to equation 1. In Eq. (1), h denotes water depth, and C represents tsunami velocity.

$$C = \sqrt{gh}. \tag{1}$$

An earthquake off the northwest coast of Luzon Island is assumed as the tsunami source. The green line in Fig. 2 represents the tsunami propagation distance in this case study. The tsunami travel distance is 1097 km, and the average velocity is 155.8 m/s. For this example, tsunami travel time is 2 hours. This calculation is comparable to the result from numerical tsunami travel time models. Figure 4 shows the depth profile for the tsunami travel path in this case study.

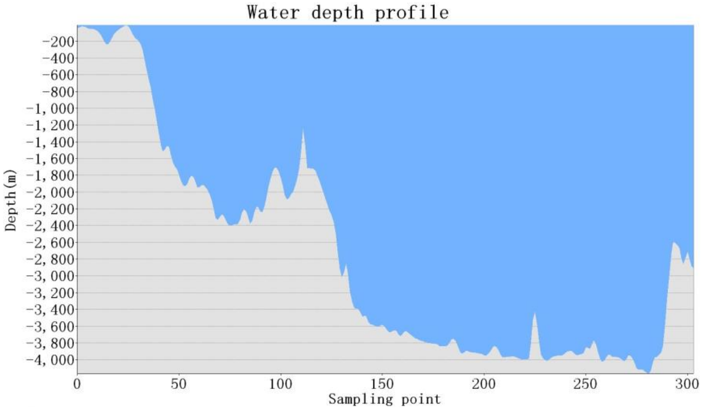

Figure 4. Depth profile

4.3 Determination of the area of influence

A database is used in this system to quickly determine the influence area of tsunami. A number of potential tsunami sources, covering a wide range of magnitudes, are simulated by numerical modeling, and the numerical results are used to determine the influence areas (a circle) of the tsunami, which are then stored in the database. Once a tsunami is triggered, the system can retrieve the possible influence area from the database. The seismic source parameters used are as shown in Table 1 (Igarashi, 2013). The nodal plane parameters of the moment tensor are based on Slab 1.0 (Hayes et al., 2012). Fig. 5 shows the influence areas of the hypothetical earthquake modeled with a number of different magnitudes.

Table 1. Fault parameters for a number of hypothetical earthquakes

Magnitude	Rupture length (km)	Rupture width (km)	Strike (°)	Dip (°)	Slip (°)	Focal depth (km)
9.0	398.1	199.1	1	41	70	24.6
8.5	223.9	111.9	1	41	70	24.6
8.0	125.9	62.9	1	41	70	24.6
7.5	70.8	35.4	1	41	70	24.6
7.0	39.8	19.9	1	41	70	24.6

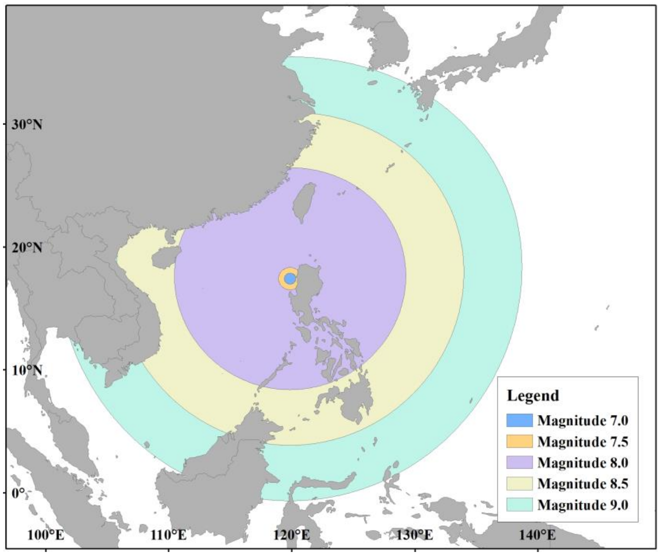

Figure 5. Influence areas of different magnitudes

4.4 Vulnerability analysis

After determining the possible influence areas, the system analyzes the vulnerability of the most important regions to identify areas of high-risk. The Jiyang District of Sanya City is an example of an important region lying within the area of possible influence from the hypothetical earthquake (Fig. 5), and an appropriate locality for vulnerability analysis.

Vulnerability analysis is not only an important way to understand tsunami hazard. It is also a critical part of tsunami risk assessments (Strunz et al., 2011). Vulnerability analysis, which attempts to make a qualitative and quantitative assessment of tsunami loss, involves many factors, including geographic, social, economic and political factors. Vulnerability analysis results can help government to enhance vulnerability management and reduce vulnerability degree. Vulnerability analysis in this system includes offshore distance, elevation and population density analyses.

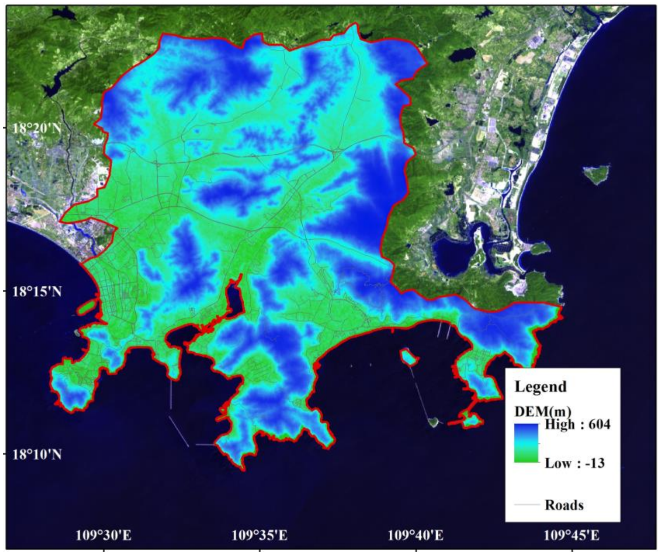

Figure 6. Vulnerability map based on elevation

Elevation is a preferred consideration for vulnerability analysis undertaken in a certain area. The physical nature of tsunami (e.g., wavelength and magnitude) is of particular concern in shallow water. Although wave heights may be less than 1 m in the ocean, when they reach the shallow coastal zone, the wavelengths are shorter and wave heights increase sharply, up to tens of meters. For example, the 2011 Japan tsunami had a maximum height of 38 m (Lekkas et al., 2011).

This system analyzes the elevation using ASTER GDEM data. ASTER GDEM data are obtained from Terra Earth observation satellites, with a spatial resolution of 30 m. Elevation analysis is shown in Fig. 6, from which we can see that there is a vast low-elevation area in the coastal zone of the Jiyang District. Low elevations indicate high vulnerability and potentially high risk.

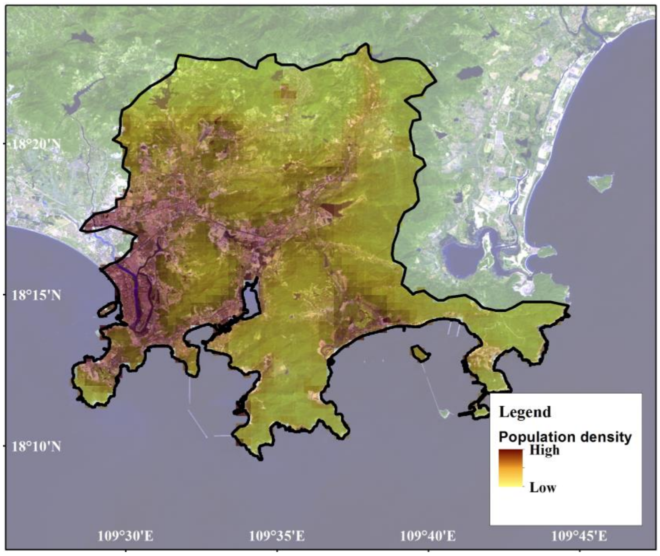

Figure 7. Vulnerability map based on population density

Population distribution is also an important factor for tsunami vulnerability analyses. Population data can illuminate where evacuations should take place and what kind of evacuation should be adopted. Such information will help decision makers develop measures to mitigate tsunami disasters (National Research Council 2007). GIS can be used to identify the locations and numbers of people in hazard zones by superimposing hazard and demographic data (Wood and Schmidtlein 2013). This system analyses population distributions through recent population census data. Jiyang District has a population of about 240,000, covering an area of 372 km^2. The population distribution of Jiyang District is shown in Fig. 7, from which we can see that densely populated areas of Jiyang District are mostly located in coastal and estuarine areas.

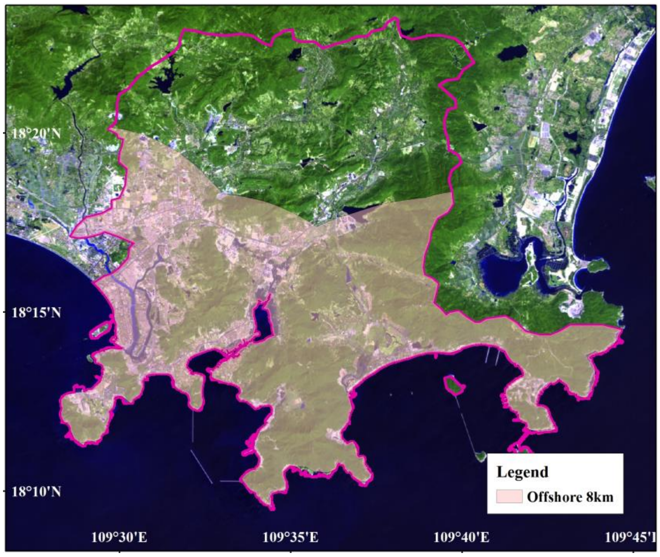

Figure 8. Vulnerability map based on offshore distances

The offshore distance of an earthquake correlates to how exposed and vulnerable a section of coastline is to tsunami. The maximum distance of tsunami inundation can be calculated by Eq. (2), according to historical tsunami data (Sinaga et al. 2011),

$$\log X_{max} = log1400 + \frac{4}{3} log\left(\frac{Y_0}{10}\right). \qquad (2)$$

In Eq. (2), X_{max} is the maximum reachable distance of a tsunami, and Y_0 is the tsunami wave height at the coast. The maximum distance obtained for the 2011 Japan tsunami is 8.3 km, corresponding to a maximum tsunami runup of 38 m (Lekkas et al. 2011). In this case study, the 8 km distance from shore is shown in Fig. 8. Generally, places that are nearer to shore will result in greater tsunami vulnerability. The distance from shore can be obtained from the Operational Land Imager (OLI) sensor of Landsat 8, with a resolution of 30 m using the ArcGIS buffer extension.

From these tsunami vulnerability factors, managers should know where vulnerable areas are located and which of these are the high-risk areas. By overlaying different layers, managers also can obtain a lot of other information in this system. For example, the possible affected population could be known from the overlay of distance from shore layer and population distribution layer.

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4.5 Tsunami evacuation analysis

Evacuation, with the purpose of saving lives, plays a crucial role in tsunami disaster mitigation plans. NTHMP (2001) indicated that the primary strategy of tsunami disaster mitigation is to evacuate people from the hazard zone as quickly as possible – and before the tsunami arrives. There are two main evacuation methods: horizontal evacuations and vertical evacuations. The former method evacuates people away from the coast to safe zones (that may have a higher elevation, such as a hill); the latter approach evacuates people to nearby tsunami-resistant buildings.

When managers make a decision about whether to evacuate and how to evacuate, they need current information on elevation, roads, shelters, etc. In this paper, the Jiyang District is assumed to be an area of high tsunami risk. Evacuation analysis includes analyses of evacuation costs and road congestion.

4.5.1 Evacuation cost analysis

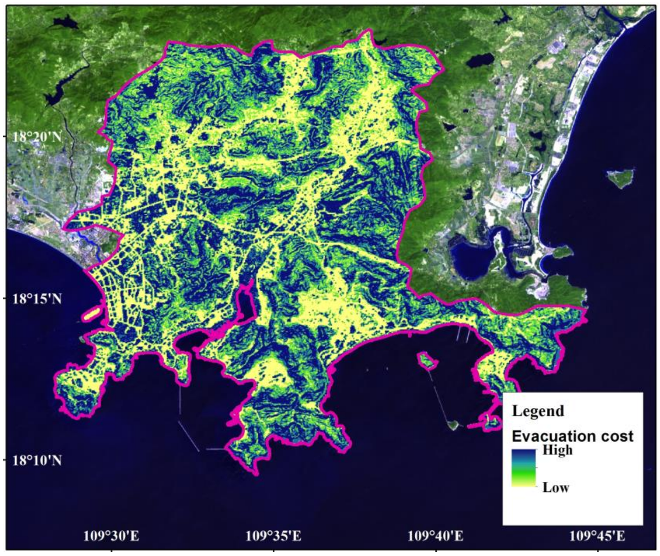

Figure 9. Evacuation cost map based on land use and slope

The environment in which people evacuate can influence the efficiency of evacuations. The evacuation cost should therefore be analyzed to provide information and suggestions to help managers make appropriate decisions (Sugimoto et al., 2003).

The best evacuation routes are not always short straight lines. Different types of land use can impact evacuations. For instance, evacuation by road is significantly faster than across agricultural land. An evacuation cost raster, which quantifies the degree of difficulty for each cell in an evacuation area, can be used to compute the influence of different environment on evacuation routes (ADPC, 2007). Evacuation cost is a combination of land use and slope. Land use data can reflect the locations, types and prosperity of social and economic activities in a certain area, whereas slope data mirror the difficulty of walking through such an area (Mück 2008). The best evacuation route should correspond to the lowest evacuation cost area.

Evacuation costs are analyzed in this system according to the approach of Wood and Schmidtlein (2013). The spatial analysis of ArcGIS is used here to create a cost surface raster that considers the difficulty of evacuation through each cell. Each cell of this raster represents an inverse speed required for evacuation. Fig. 9 shows the evacuation cost as applied to the Jiyang District.

4.5.2 Congestion-prone road analysis

If there is enough evacuation time, people should be able to evacuate horizontally to a safe area outside the tsunami inundation zone after receiving the tsunami warning. If there is not enough time to evacuate, people can evacuate vertically to higher terrain or structures near the coast (Heintz and Mahoney, 2012). When a tsunami occurs, decision makers need to know whether or not there is road congestion and where to evacuate to before inundation starts. This system provides congestion-prone road analyses and shelters to support evacuation actions.

Road condition is very important in both horizontal and vertical evacuations, as the evacuation of a large number of people in a short time may lead to road congestion, especially in a populous coastal city. For example, on April 11, 2012, thousands of people were stuck in traffic congestion after a tsunami warning was issued in Indonesia (Wu et al. 2015). Evacuation managers need to know which roads are prone to congestion. In this system, congestion-prone road analysis is based on population census data and road classification data, which are shown in Fig. 10.

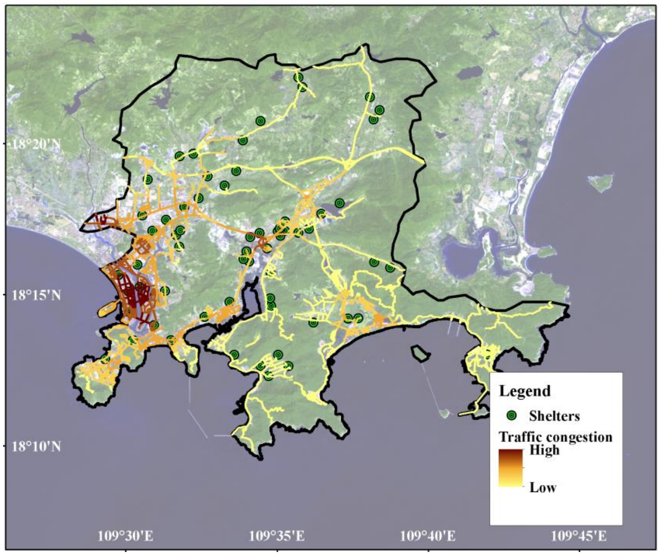

Figure 10. Congestion-prone roads based on population census data

Evacuation shelter buildings provide a destination for an evacuation and significant political factors are involved with their construction and inclusion in evacuation studies. New shelters could be added to this system as required (Fig. 10). Evacuation shelters are usually selected in lower cost and higher-lying areas, preferably with a road connection, following the principles of good accessibility, and large capacity, among others. In addition, the structure, function and security of candidate shelters should also be investigated (Budiarjo, 2006). Generally, places with social functions often are used as shelters, e.g., schools, hospitals, shopping malls, convention centers, stadiums, hotels, parks, etc.

5 Conclusion

Tsunami evacuation research involves not only tsunami hazard factors, such as tsunami travel time and possible influence areas, but also the socio-economic situation and population distributions. The selection of an appropriate evacuation method is based on the range of possible geographical environments and evacuation times. Evacuation decision makers need a variety of information to direct evacuation actions appropriately.

With the help of GIS technology, the system can quickly assess the influence of possible tsunami areas and tsunami high-risk areas, analyze the vulnerability and provide information to support evacuation actions. The development of this system requires a variety of geographic data, including catalogs of historic earthquakes and tsunami, water depth, digital elevation models, satellite images, evacuation shelters, and roads. Note that the tsunami risk of a certain region should be assessed roughly before the development of this system. The system is best developed in an area that is likely to suffer future tsunami disaster.

A framework for an evacuation system has been developed in this paper. However, some other factors were not considered here, such as population types, walking speeds and dynamic changes in population. In future studies, we will add some factors to improve this system.

Acknowledgements

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