GIS IN DISASTER MANAGEMENT:
A CASE STUDY OF TSUNAMI RISK MAPPING
IN BALI, INDONESIA

Thesis submitted by

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BSc, University of Diponegoro, Indonesia

in August 2006

For the degree of Master of Science

in the School of Earth and Environmental Sciences

James Cook University of North Queensland, Australia

To God

for His blessing.

To my parents, my grandma and my brother

for their love and support in making this possible.

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Abstract

Tsunami events in many regions of the world show that this hazard is highly significant and has had a considerable impact at the local level, bringing death or injury to human beings and damage to the environment. The tsunami risk cannot be eliminated, but it can be effectively analyzed and possibly reduced by using the proper tools and models to produce reliable and meaningful estimates of the tsunami risk facing the coastal communities. A method for assessing the tsunami risk is by modeling using Geographic Information System (GIS) technology since the tsunami risk is spatially variable and GIS can help to understand such variability once the data base have been constructed.

The overall aim of this thesis is to create a model of tsunami risk assessment that can be applied and used anywhere in coastal Indonesia by using Geographic Information System (GIS) technology. The research outcome will give information to local people that live in tsunami–prone areas, and local governments to aid them in the development of tsunami mitigation planning that includes city development planning, land use zoning and regulation, economic improvement activities, education and awareness campaigns, and evacuation planning. A quantitative and qualitative approach is used to achieve the following objectives: (i) develop a generic model of tsunami risk assessment that incorporates physical, social, economic and city infrastructure factors that can be adapted for other coastal locations and jurisdictions, (ii) develop a spatial methodology to integrate multiple factors and measure the hazard, vulnerability and risk of tsunami hazard, and (iii) apply the tsunami risk assessment framework in Kuta and Sanur Regions as a case study.

Kuta and Sanur Regions that are located in Bali are vulnerable to the tsunami hazard because Bali is located on the boundary of the Eurasian and Indo–Australian Plates, which move occasionally. This movement can generate submarine earthquakes which are one of the factors that can generate a tsunami. Despite the fact that Kuta and Sanur Regions are at risk from tsunami impact, there is no information about the distribution of vulnerability in these regions and their risk of tsunami hazard.

The model presents hazard, total vulnerability and risk maps. The hazard map is based on the inundation zones. The total vulnerability map is based on the combination of physical, social and economic factors. The risk map is based on the combination of hazard and total vulnerability scores. The results show that Kuta, Legian and Sanur Villages in Kuta and Sanur Regions may possibly be at risk from future tsunamis. Therefore, local governments should focus on these villages. In this thesis, the author also included the research frameworks for each assessment that can be applied in other parts of coastal Indonesia and used by local government staff who have GIS knowledge to create maps based on the available resources in their areas.

The outcome of this thesis will be useful for local government to create regulations that relate to the construction of new buildings in the coastal area, for disaster planners and emergency managers to create tsunami mitigation in the future, and for coastal communities in the study area to be aware, prepare, know and learn the early signs of tsunamis in the future.

Keywords: *GIS, tsunami, spatial modelling, Bali.*

Acknowledgements

This thesis would not have been possible without the valuable support and contribution of many great people. I am most grateful to Associate Professor David King, who is the chair of my supervisory panel, for his support and guidance through this journey. His style of supervision, constructive intellectual advice and patience inspired me to navigate through the complex issues of this study.

I am also grateful to Dr. James Moloney who is another member of my supervisory panel, for his valuable support and guidance. James's guidance and encouragement helped me to get through some of the most difficult moments in this journey.

This study would not have been possible without the financial support of the Australian Government through the Australian Development Scholarship and the James Cook University.

I am also thankful to Firdaus Agung, Adhi Nugroho and Kellie Johns for their guidance at various stages of this study.

Finally, and most of all, I would like to thank my mom Diana Elina, my dad Supardy, my grandma Minah and my brother Handi for their love and sacrifices during this journey. Their support, love and patience are the cornerstones of this work.

Contribution of Others

The scholarship for this research was provided by the Australian Government. Additional financial assistance was provided by the School of Earth and Environmental Sciences of the James Cook University.

Editorial assistance was provided by my supervisors, Associate Professor David King and Dr. James Moloney. Additional assistance was provided by Kellie Johns, Rae Wiseman and Dr. Rosemary Dunn.

The data required for this study was substantial and would not have been possible without the unlimited access provided by the Badung Regency and Denpasar City Planning Boards, the Bali Provincial Public Works Agency, the Bali Provincial Central Agency for Statistic, the Bali Provincial Tourism Agency and the National Coordinating Agency for Survey and Mapping to their databases.

I am also thankful to Taka, Gabby, Thuan, Edina, Monica (office mates), Alex, Katherine, Chris (ISC staffs), Glen, Beth, Melissa, Penny, Clive, Rob, Paul (SEES staffs), Adit, Arthur, Ludi, Gustaf, Egy, Tony, Sarah, Conni, Diana, Dewi, Rofiq, Esti, Mahpud, Saini, Yusuf, Bambang, Mira, Imron, Basit (JCUISA members), Saldy, Rosette, Rolf, Debbie (landlords), Dorce, Morris, Wigid, Matthew, Peter, Arla, Lasmi, Deanne, Russ (Townsville’s friends), Choo Poh Leem (special friend) and all my other friends that I did not mention here for their friendship, kindness and help while I was staying in Townsville.

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CHAPTER ONE – Introduction

1.1. Background

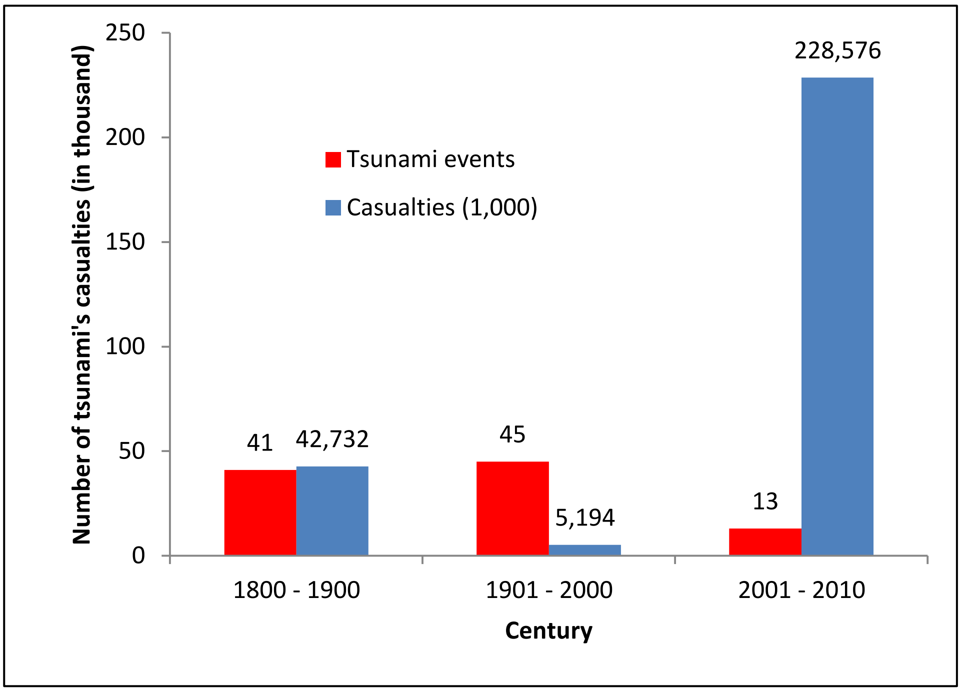
Tsunami events in many regions of the world show that this hazard is highly significant and has had a considerable impact at the local level, bringing death or injury to human beings, and damage to the environment, including coastal infrastructure, properties, businesses, social and economic activities (Papathoma et al., 2003). The continued probability of the occurrence of a large tsunami, together with a growing population, increases the tsunami risk in coastal communities. The tsunami risk cannot be eliminated, but it can be effectively analysed and possibly reduced by using the proper tools and models to combine information, in order to produce reliable and meaningful estimates of the tsunami risk facing the coastal communities. A tsunami risk assessment can be applied to help urban planners, emergency managers, and public policy or decision makers understand the impact, study the effect of mitigation techniques and incorporate the results into preparedness programs and urban development plans.

A method for assessing the tsunami risk is by modelling using Geographic Information System (GIS) technology. GIS creates new opportunities for managing the large amount of data (natural, hazard, social and economic information), interfacing with the external analysis programs and presenting the results in a manner that can be useful for disaster planning, hazard and risk mitigation (Cutter et al., 1997, Wood and Good, 2004).

The 2004 Indian Ocean tsunami was the most devastating tsunami in history. It affected 13 Indian Ocean countries, killed more than 227,000 people, and destroyed billions of dollars worth of property in coastal areas. Indonesia suffered the greatest damage because it was both the epicentre of the earthquake (9.3 Richter scale) and the tsunami initiation area (Levy and Gopalakrishnan, 2005). Because of its huge impact and casualties, there have been many studies to assess tsunami risk for coastal communities, and tsunami hazard studies have concentrated on evaluating and determining the frequency, magnitude, and inundation areas during the past two decades. Most studies are related to physical and numerical models, such as those of Qinghai and Adams (1988), Tinti (1991), Tsuji, et al. (1995), Satake and Tanioka (1999), Fernandez, et al. (2000), Lange and Healy (2001), Prasetya, et al. (2001), Sato, et al. (2003), Clague, et al. (2003), and Kulikov, et al. (2005).

However, only a few case studies have been done to assess the coastal community vulnerability, mostly focusing on Greek coastal areas (Papadopoulos and Dermentzopoulos, 1998, Papathoma and Dominey-Howes, 2003, Papathoma et al., 2003). Moreover, these studies mention which specific user will benefit from their end result, such as local authorities, disaster planners and insurance companies. However, it is difficult to find examples of tsunami vulnerability for coastal cities or villages in other countries, for example Bali, Indonesia.

Problems arise because Indonesian coastal areas are very prone to natural hazards such as tsunami. For example, 99 tsunami events occurred in coastal areas of Indonesia from 1800 to 2010 (NGDC, 2010). If we accept the accuracy of all data before 20th century, the return period for tsunamis in Indonesia is 99/210 or approximately once per 2 years. Tsunami hazards are devastating and have considerable impact on human lives. Figure 1.1 shows the record of tsunami events in Indonesia since the 19th century and the detail of the events are shown in Appendix 1. Although there were only 13 tsunami events in Indonesia from 2001 to 2010, however there were many casualties on that period of time. It is because most casualties were caused by the 2004 Indian Ocean tsunami (227,898 casualties) and the 2006 south coast of Java tsunami (664 casualties) (Levy and Gopalakrishnan, 2005, Reese et al., 2007, NGDC, 2010).



Source: NGDC (2010).

Figure 1.1. The number of tsunami events and casualties that occurred in Indonesia.

Generally tsunamis are generated by submarine earthquakes. Therefore, geological and seismological conditions are important factors for assessing the tsunami hazard. Regions that are situated on an active plate margin have a greater probability of earthquakes and tsunamis. For example, coastal villages that are situated on the south coast of Bali are vulnerable to tsunamis because it is situated on a very active margin (Eurasian and Indo–Australian Plates) in the Indian Ocean that is prone to tsunamigenic earthquakes (Nugroho, 2006, Prasetya et al., 2001).

Economic development and population growth in Indonesia has led to the growth of infrastructure development, business properties, and settlements in coastal areas and makes them vulnerable to natural hazards, especially tsunamis (Boulle et al., 1997, Clague et al., 2003). Tsunami risk assessment can demonstrate and prioritize areas for more attention to tsunami events, and guide local governments in land use planning, regulation, and economic planning for future tsunamis.

1.2. Problem Statement

Bali has two famous beaches that attract both local and international visitors, namely Kuta and Sanur. Kuta beach is located in Kuta, Legian and Seminyak villages, on the south–west coast of Bali. Sanur beach is located in Sanur and Sanur Kaja villages, some 30 km away on the south–east coast of Bali. These are large coastal villages that have become administrative and economic centres for the province, and also provide a large amount of income to the country from its tourism sector. However, because Bali is located on the boundary of the Eurasian and Indo–Australian Plates, it is vulnerable to the tsunami hazard.

Despite the fact that Kuta and Sanur Regions are at risk from tsunami impact, few efforts have been made to assess the tsunami risks to Bali. There is no information about the distribution of these villages' vulnerability and risk of tsunami hazard. This information is essential for mitigation efforts. Therefore, it is important to evaluate the tsunami potential, to assess and to map the physical, social and economic vulnerabilities, and to evaluate and map the risk of tsunamis for these villages. The problem statement can be illustrated in a simple line framework (see Figure 1.2).

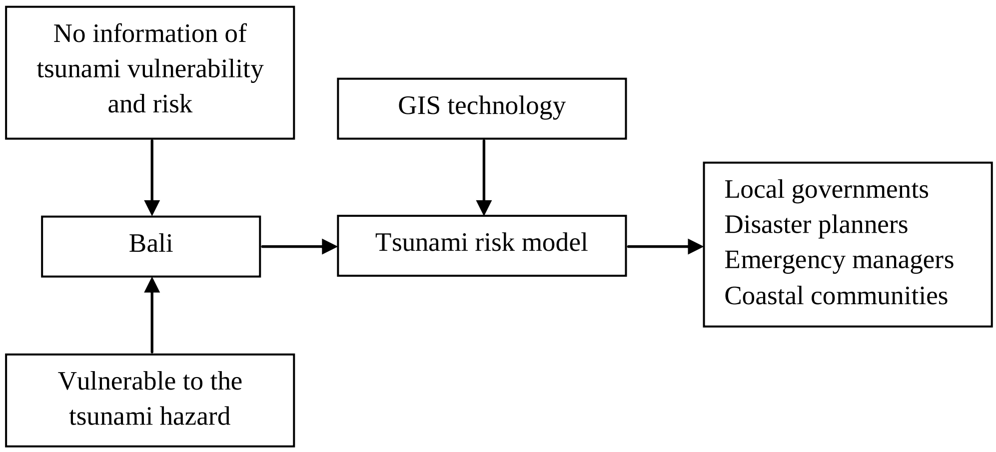


Figure 1.2. The problem statement framework.

In this study, the creation of a model in order to evaluate tsunami risk has placed the needs of local governments, disaster planners, emergency managers and coastal communities ahead of the bigger picture of hazard science scenarios. The model that is explained here uses data that are available at the small scale community level, so that local leaders and public servants can prepare risk assessments for their towns and villages right down to the level of individual houses. In the case of a disaster, information is needed at this detailed level. Sophisticated scientific analysis may provide more information on seismicity and tsunami run–up probability, but such data were not available at the community level anyway. As data become available, information can be added and tsunami run–up may be modified and extended.

1.3. Research Aims and Objectives

Because Kuta and Sanur Regions are vulnerable to the tsunami hazard, a tsunami risk assessment has been used as a case study to create a model of the tsunami risk assessment that can be applied and used in other parts of coastal Indonesia. The results will give information to local people who live in tsunami–prone areas, and local governments for the development of tsunami mitigation planning that includes city development planning, land use zoning and regulation, economic improvement activities, education and awareness campaigns, and evacuation planning.

Specifically the objectives of the study are to:

- Develop a generic model of tsunami risk assessment that incorporates physical, social, economic and city infrastructure factors and can be adapted for other coastal locations and jurisdictions.
- Develop a spatial methodology to integrate multiple factors and measure the hazard, vulnerability and risk of tsunami hazard.
- Apply the tsunami risk assessment framework in Kuta and Sanur Regions as a case study.

1.4. Thesis Outline

The thesis comprises six chapters:

- Chapter one provides background information and problem statements, which explain why the study area is vulnerable to tsunami hazards in the first place. Moreover, this chapter gives the aims and objectives of the study.

- Chapter two gives a review of the tsunami risk assessment modelling that have been done in the context of disaster management. This chapter provides information about geographic information system (GIS) technology that has been used as a tool in natural hazard assessment and also in tsunami risk assessment.
- Chapter three provides background information, which explains the geography, social and economy factors of the study area.
- Chapter four presents a simple research framework for the tsunami risk assessment that is used in this study. Moreover, this chapter gives the details of the materials and methodologies that are needed for conducting the study.
- Chapter five presents the details of the results that are found in this study. This chapter also provides the hazard, vulnerability and risk maps of the study area.
- Chapter six presents an assessment model, discussion, conclusion and recommendation, which brings all of the assessments together and discusses their results for future potential development.

CHAPTER TWO – Tsunami Risk Assessment and Geographic Information System (GIS) Technology

2.1. Introduction

In recent years many natural disasters, such as floods, tsunamis, earthquakes and storms have claimed hundreds of thousands of lives, cost billions of dollars of material losses and caused a terrible toll on developing countries in particular. Based on these facts, many studies have been carried out to cope with disasters from natural hazards with the focus on addressing and understanding risk by analysing the vulnerability of communities and assets that can reduce the impact of disasters (ISDR, 2002). The World Conference on Natural Disaster Reduction in Yokohama on May 1994 established the Yokohama Strategy that consists of prevention, preparedness and risk mitigation guidelines by emphasizing the risk assessment, disaster prevention and preparedness, vulnerability reduction, early warning and disaster reduction policies (ISDR, 2002, Briceno, 2004). Furthermore, the World Conference on Natural Disaster in Hyogo on 18–22 January 2005 established the Hyogo Framework to identify the specific gaps and update the Yokohama Strategy. It consisted of five areas: (i) governance frameworks, (ii) risk identification, assessment, monitoring and early warning, (iii) knowledge and education, (iv) risk factors reduction and (v) preparedness and recovery (ISDR, 2005).

Tsunamis are considered a catastrophic hazard such that many studies have been done to assess its risk for coastal communities. The goal of a tsunami risk assessment is to quantify the potential damage and losses in a region due to future tsunamis (Clague et al., 2003, Tinti, 1991). A tsunami risk assessment requires the synthesis of data and the mapping of the spatial relationships between the tsunami hazard and the elements at risk, such as human casualties and damage to property or infrastructure. A geographic information system (GIS) is mapping software that provides an environment to accomplish the objectives of a tsunami risk assessment study because it has the ability to store, manipulate, analyse and display the large amounts of spatial and non–spatial information needed for a tsunami risk study. This chapter begins with a description of the major components of a tsunami risk assessment, followed by a broad overview of GIS and concludes with an explanation of how the tsunami risk assessment can be conducted in the GIS environment.

2.2. Tsunami Impact

The occurrence of natural hazards in coastal areas is not a recent phenomena, but the desire for better understanding about the potential, vulnerability, risk, and impact is a relatively new trend (Dwyer et al., 2004). Moreover, the impact is usually greater in poor or developing countries due to the historical development of these countries; especially the legacy of colonialism which has caused social, economic, political and cultural instability and problems of good governance. These act as factors heightening vulnerability to natural disasters (Alcantara-Ayala, 2002).

Tsunamis have always posed a risk to coastal communities and have impacted on human settlements and ecosystems. Physically, the impact is caused by a tsunami's run–up, bores, return flow, oscillation in the bay, estuary or harbour, and floating debris. Tsunami run–up is a measurement of the wave's height on the coastal area. Tsunami bores are waves that travel up a river or estuary against the direction of the river or estuary's current. Many people drown in the return flow of the tsunami waves, which may also carry floating debris. Debris is the remains of something broken or destroyed, such as trees, cars, metal, etc. Tsunamis may also force oscillations within semi–enclosed basins, such as estuaries and rivers, and this force can produce a strong reversing current within the basin (Lange and Healy, 2001). The impact can vary from short term, such as injury, death, and material loss to long term, such as health, social and economic problems. In coastal areas with ports, industries and sewage treatment, a tsunami can generate secondary impacts, such as fire, contamination and disease (Lange and Healy, 2001, Clague et al., 2003).

The occurrence of tsunami events in many regions of the world is significant and has serious consequences for life, infrastructure, property, economy, business and the environment (Clague et al., 2003, Papathoma et al., 2003). Highly destructive tsunamis have been recorded at a number of locations in Indonesia, such as in Flores, in December 1992 (Tsuji et al., 1995), in Aceh, in December 2004 (Levy and Gopalakrishnan, 2005), and in South Java (Cilacap and Pangandaran), in July 2006 (Reese et al., 2007) and affected almost every sector of the economy, including agriculture, fishery, tourism, transportation, housing, and health (Levy and Gopalakrishnan, 2005).

Mangrove forest plays a fundamental role as an effective barrier in reducing the effect of tsunamis on human dwellings and coastal landforms. Sirikulchayanon, et al. (2008) analysed the impact of tsunami on land cover based on mangrove coverage. They found land cover with low mangrove coverage sustained major damage to land cover around 26.87% change. On the other hand, less damage is in regions with high mangrove coverage, representing only around 2.77% change. Therefore, the preservation of mangrove forests is important because they not only maintain the stability of the tropical ecosystem, but also indirectly provide protection to coastal communities.

2.3. Tsunami Risk Assessment

Several studies have assessed the tsunami risk for coastal communities. For example, Clague, et al. (2003) analysed the tsunami hazard in Canada based on historical data; Hebert, et al. (2001) assessed the tsunami risk in the Marquesas Islands based on numerical modelling; and Kulikov, et al. (2005) estimated the tsunami risk in the Peruvian and Northern Chilean shoreline based on historical data of submarine earthquake events.

However, tsunami study areas and objectives differ, depending on the researchers' prospective. For example, scientists will be interested in the distribution, the generative mechanism and the frequency recurrence periods of tsunami events, whereas disaster planners and emergency managers will be interested in the tsunami's maximum run–up, the impact, and the need for response, recovery and rehabilitation. Urban planners will be interested in the tsunami's flood area and the vulnerability of buildings and human land uses, whereas insurance and reinsurance companies will be interested in the tsunami frequency magnitude relationships, so they can determine the risk and exposure, and establish suitable insurance premium levels (Papathoma and Dominey-Howes, 2003). All of those concerns and interests are beneficial because the determination of hazard risk has an important practical benefit for the protection of the population and economy, and for defence and mitigation planning (Tinti, 1991).

In order to make a comprehensive assessment of tsunami risk for a region, procedures identified in tsunami and other natural hazard studies can be used to create a framework (see Table 2.1).

Table 2.1. The steps in a tsunami hazard assessment.

Step	Source
Step 1. Assessment of: • Hazard identification, frequency, and delineation • Hazard frequency and magnitude • Hazard potential • Hazard exposure	 Cutter et al. (1997), Ferrier and Haque (2003) Zbinden et al. (2003) Dwyer et al. (2004) Greiving et al. (2006)
Step 2. Assessment of: • Vulnerability • Vulnerability and risk estimation	 Cutter et al. (1997), Dwyer et al. (2004), Greiving et al. (2006), Zbinden et al. (2003) Ferrier and Haque (2003)
Step 3. Assessment or production of: • Data integration • Hazard mapping of affected area • Social consequence • Risk • Risk map • Special needs and infrastructure • Financial calculation	 Cutter et al. (1997) Zbinden et al. (2003) Ferrier and Haque (2003) Dwyer et al. (2004) Greiving et al. (2006) Cutter et al. (1997) Zbinden et al. (2003)

Table 2.1 shows three important stages in tsunami hazard assessment, (i) hazard identification (potential, frequency and exposure), (ii) vulnerability assessment (physical, social, economic and environmental), and (iii) risk assessment (physical and social consequences, and financial calculations). All of the stages use maps and databases to analyse, manipulate and display the results to increase the value and readability of the information.

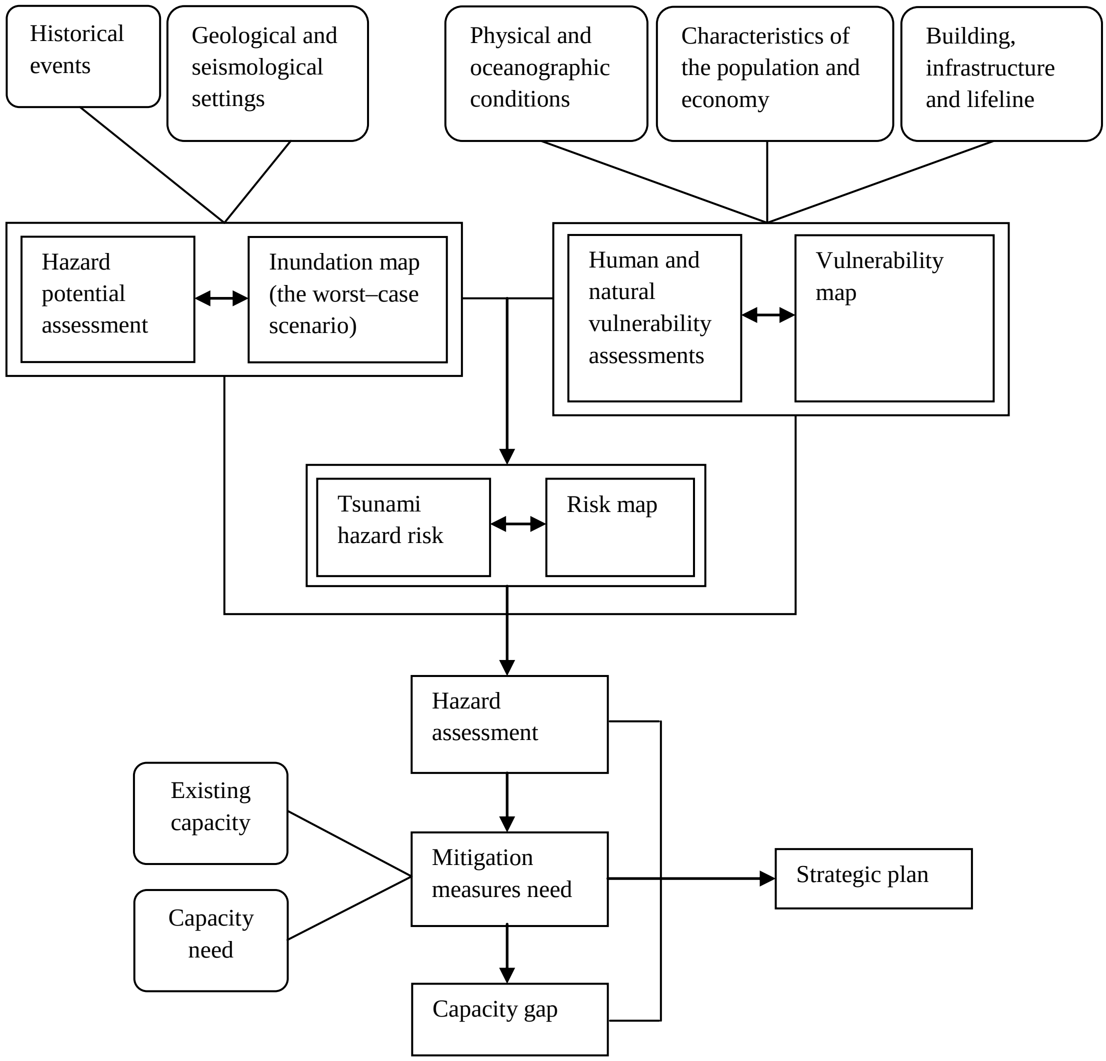


Figure 2.1. The framework analysis for tsunami hazard assessment and mitigation.

Source: Alcantara–Ayala (2002), Cutter et al. (1997), Dwyer et al. (2004), Ferrier and Haque (2003), and Greiving et al. (2006).

From Table 2.1, it is possible to create the overall framework (see Figure 2.1) for tsunami hazard assessment that consists of three important stages (hazard identification, vulnerability and risk assessments): (i) mitigation measures to reduce the risk, (ii) analysis of existing and needed capacity (as well as the gap between both factors) to develop and implement mitigation measures, and (iii) strategic plans developed as action plans to reduce the risk from tsunami hazard.

2.3.1. Hazard Assessment

Hazard identification is an important key in hazard risk assessment. For example, in the United States of America (USA), hazard identification is a basic element in national hazard mitigation programs that accompany the risk assessment (Cutter et al., 2000). The understanding of the hazard process, pattern, probability and potential are important for preventing and reducing the hazard impact (Alcantara-Ayala, 2002). In tsunami hazard assessment, both tsunami and submarine earthquake history data are important in determining the probability of tsunamis. Moreover, historical events are used to assess the hazard frequency and geophysical conditions to assess possible hazard magnitude (Clague et al., 2003). However, tsunami events are unpredictable. They may occur at any time and at any place (Sato et al., 2003, Alcantara-Ayala, 2002). Therefore, we need to reduce the impact if a tsunami occurs in coastal areas. For example, for an area with a higher probability of tsunami occurrences, the government can give funds to build jetties or seawalls to protect against future tsunamis in that area. However, these are very expensive options.

The important questions of “when”, “where” and “cause” need to be answered in hazard identification. Although the questions sometimes overlap with the vulnerability assessment, they are still useful to be considered for hazard identification (Ferrier and Haque, 2003). For example: When did the event occur? Was there any mitigation effort at that time? What are the localised likely causes? Are there any local characteristics that prevent or exacerbate the event? Is there any periodic pattern for the event? Is there any building standard in the area? Where is the most vulnerable area for this event?

2.3.1.1. Historical Data Analysis

Historical data analysis is the first step in the hazard assessment process. Various readily–accessed resources can be used to achieve this, such as material held in local libraries, newspaper archives, similar studies and discussions with local people that were impacted in a past event. Moreover, The National Geophysical Data Center (NGDC, 2010) from NOAA Agency and The Institute of Computational Mathematics and Mathematical Geophysics (ICMMG, 2010) in Novosibirsk, Russia provide detailed catalogues about natural hazards, such as earthquake and tsunami events that occur all over the world, that can be accessed online. These information sources can be used also as a verification tool if there is inconsistency with the hazard occurrence data sets (Cutter et al., 1997). Several studies on tsunami hazard assessment use historical data. These studies used the event or earthquake history, especially submarine earthquakes in order to analyse the probability of tsunami. For example, Clague et al. (2003) used historical data about damaging tsunamis recorded in Canada. Lange and Healy (2001) used historical tsunamis to model the potential tsunami events in the Auckland region and Hauraki Gulf, New Zealand. Qinghai and Adams (1988) used historical data to analyse the tsunami risk in China.

Moreover, historical data can be used to calculate the frequency of the hazard occurrence. However, data prior to the 20th century, is usually less accurate because of the less sophisticated instruments used to measure it (Kulikov et al., 2005).

The probability of occurrence can be calculated by several methods. Although not highly accurate, they are still useful for giving an approximate probability of a future event (Ferrier and Haque, 2003). One method that is used to calculate the probability of occurrence is to divide the number of hazard occurrences by the number of years in the historical record. For example, if a tsunami occurred 10 times in an area over 100 years, the probability of a tsunami occurrence in that area is 10/100 or 10% per year (Cutter et al., 1997, Zahibo and Pelinovsky, 2001). Some researchers calculate the tsunami occurrence return period by inverting the calculation i.e. 100/10=10, meaning a tsunami has a probability to reoccur in that area after 10 years (Kulikov et al., 2005, Lange and Healy, 2001).

The probability calculation is used to improve coastal communities' awareness about tsunamis because their rarity leads to a gradual lessening in peoples' awareness and preparedness over time. Hazard experience is a fundamental limitation in risk assessment (Ferrier and Haque, 2003). To make people prepare for a tsunami, they have to be concerned about it, have enough awareness, and agree with the potential magnitude and impact that is possible from a tsunami event. For example, during the Indian Ocean Tsunami on 26 January 2004, mortality on Simelue Island, located near the earthquake epicentre, was low, because they knew what actions to take based on past tsunamis (Levy and Gopalakrishnan, 2005).

2.3.1.2. Geological and Seismic Analysis

The geological and seismic conditions in an area are very important to assess the probability of a tsunami. There are two factors that contribute to the hazard occurrence in such an area: the geographical location and geological–geomorphologic setting (Alcantara-Ayala, 2002). Bush et al. (1999) stated that the geological setting and oceanographic conditions are important in increasing or decreasing the coastal hazard.

Most catastrophic tsunamis are generated by submarine earthquakes. Thus submarine earthquake data can be used to predict a future tsunami. The tsunami magnitude generated by a submarine earthquake is different from one fault to another (Sato et al., 2003). Generally, the longer the gap period, such that seismic zones have not ruptured, the greater energy will be released when they rupture in future (Tinti, 1991). This was also noted by Qinghai and Adams (1988) in their study that strong earthquakes are more likely to occur in structural zones that have not experienced strong earthquake recently. They also suggested that geological analysis is important and useful in predicting future earthquakes and tsunamis.

Tinti (1991) showed that most tsunamis in the sea surrounding Italy were generated by earthquake with magnitude more than 6.0. It is also agreed by Lange and Healy (2001) that the minimum earthquake magnitude to generate tsunamis is 7.3. However, the Papua New Guinea tsunami in 1999 that killed 2,200 people was generated by 7.1 magnitude which was a relatively small earthquake, but the wave was funnelled by an undersea canyon that generated a destructive tsunami along a short stretch of coastline (Kulikov et al., 2005). Therefore destructive tsunami waves are not always generated by extreme earthquakes like the 2004 Indian Ocean tsunami that was generated by 9.1 magnitude.

Regions that are situated on active margins will have a greater probability of earthquakes and tsunamis. A famous region for tsunamis is Trans–Pacific along the Pacific Ring Belt. This region comprises areas of Alaska, Aleutian Islands, Kuril Islands, Japan, Philippines, Indonesia and Melanesia. Indonesia is vulnerable to tsunamis because it is situated on a very active colliding plate in the Indian Ocean that is prone to earthquakes that can generate tsunamis. The area along the Andaman Islands and Nicobar Islands is an unstable fault line that can trigger powerful earthquakes. This area represents the active plate margin between the Burma Plate and Indian Plate with the drift approximately 5 cm per year (Levy and Gopalakrishnan, 2005). According to NGDC (2010), 99 tsunami events occurred in coastal areas of Indonesia from 1800 to 2010 If we accept the accuracy of all data before 20th century, the return period for tsunamis in Indonesia is 99/210 or approximately once per 2 years, a very short time.

2.3.2. Vulnerability Assessment

Vulnerability assessment is the next step to undertake after evaluating tsunami potential and probability. It is important because the hazard impact is different from one place to another. Vulnerability assessments depend on how close the communities are to the hazard source, and their social and economic characteristics (Cutter et al., 2000).

The vulnerability identification is central to the mitigation, preparedness and response process, which directly affects the community resiliency of an area (Ferrier and Haque, 2003). Vulnerability assessment is also important in order to make disaster planning and mitigation activities both sensible and effective. Mitigation efforts could be carried out effectively by analysing the vulnerability variables (Clark et al., 1998). However, in practice, vulnerability assessments often are given less attention in the tsunami hazard assessment than the mitigation and preparedness. For example, the tsunami mitigation activity in the Pacific Northwest that was provided by numerous Pacific Northwest organizations, such as the Cascadia Region Earthquake Workgroup (CREW), the Oregon Natural Hazards Workgroup (ONHW) and the California Seismic Safety Commission (CSSC) did not include a community vulnerability assessment in the overall program. Research focussing on community vulnerability assessment is very important so results can prioritize insufficient resources for preparing mitigation and preparedness steps at the local level (Wood and Good, 2004).

Vulnerability is a function of two attributes, (i) hazard exposure and (ii) ability to cope with the hazard. Expressed more analytically, the vulnerability should be assessed in three stages, (i) exposure (hazard potential), (ii) resistance (during the event) and (iii) resilience (post hazard) (Clark et al., 1998).

There is a general consensus about the major factors that influence social vulnerability. These include: limited access to resources (including information, knowledge and technology), political power, social capital (including social networks), beliefs and customs, building, age, type and density of infrastructure, and lifeline (Cutter et al., 2003, Alcantara-Ayala, 2002).

Vulnerability to natural hazards is related to the amount of development and poverty. Development can actually raise the vulnerability as the poverty reduction programs often pay no attention to risk reduction (Briceno, 2004). Often a natural hazard impact is intensified when it occurs in the populated and developed areas or areas with strong economic activities (Greiving et al., 2006). However, for a coastal city, the development in the water–front area is unavoidable because of the function of harbours, marinas, hotels and recreational facilities (Wood and Good, 2004). The consequence is that coastal cities are vulnerable to disaster because they are in a hazardous area, they are in an economic centre, contain much infrastructure and are highly populated (Boulle et al., 1997). Therefore, coastal zone planning needs a comprehensive assessment of the coastal hazard in developing zoning and land suitability analyses (Solomon and Forbes, 1999).

2.3.2.1. Vulnerability Components

The four components of vulnerability are physical, social, economic, and environmental. These components represent categories that can be influenced by a natural hazard (Boulle et al., 1997, Cutter et al., 2003). The physical component refers to the location of the built environment, such as density levels, remoteness of an area, its setting and the quality of building construction. Density is one of the variables that determines the severity of a disaster. Where people are concentrated in a limited area, any hazard event can cause more injury and death than would occur if these people were more dispersed (Boulle et al., 1997). People who live in a remote area will experience difficulty for the evacuation if any hazard occurs in that area (ISDR, 2002). The setting of the environment also determines the severity of a disaster. For example, people who live in a hazard prone areas will be more vulnerable than people who live in less hazardous areas (ISDR, 2002). The quality of building construction is very important in relation to physical vulnerability. For example, more than 80% of the casualties from earthquakes are associated with collapsing buildings (ISDR, 2002, Boulle et al., 1997).

The social component is related to the level of wellbeing of individuals, communities or societies, such as age and gender issues. The very young and very old affect movement out of harm's way. Children and elderly may have mobility constraints or mobility concerns increasing the burden of care and lack of resilience (Cutter et al., 2003). Gender issues, particularly the role of women are also important. In many societies, women have a primary responsibility for domestic life, essential shelter and basic needs. Therefore, women are more likely to be burdened, or more vulnerable in times of crisis (ISDR, 2002).

The economic component is related to the economic status of individuals, communities or societies. People with different income levels are likely to be affected differently by the same event. For example, the poorest people who live in the lowest quality housing in the most hazard prone locations will have the fewest reserves or opportunities to lessen potential disaster impacts. They also have fewer options because of their lack of resources (Boulle et al., 1997). Wealth enables communities to absorb and recover from losses more quickly due to insurance, social safety nets and entitlements programs (Cutter et al., 2003).

The environmental component covers many issues about social, economic and ecological actions of sustainable development and is related to the reduction of disaster risk (ISDR, 2002). Furthermore, the environmental component plays an important role in reducing or raising the hazard impact. For example, the interaction between people and the environment is one important aspect in understanding flooding hazards, such as in Manila, Philippines. The reason why flooding has come to pose such a risk to Manila residents is constructed through the lack of sustainability of environmental impacts and human activities over time. Rainfall, topography and subsidence combine with population increase, urban growth and the volume of waste products to prevent run–off and impede drainage. Therefore, after the widespread flooding of Manila in 1972, a major flood-mitigation program was undertaken by Philippines Government, such as the Mangahan Floodway Project (MFP) (Bankoff, 2003).

Vulnerability is not only caused by human actions, but also interactions with the natural, cultural and political settings. Therefore, vulnerability can be divided into two groups – human and natural vulnerability – where human vulnerability depends on the social, economic, political and cultural systems and natural vulnerability depends on the threatening natural hazard that is related to the geographical location, such as volcanic, flooding, tsunami and cyclone or hurricane vulnerabilities (Alcantara-Ayala, 2002).

Moreover, there are social and biophysical vulnerabilities. The social vulnerability indicator is measured by social, economic and demographic characteristics, while the biophysical vulnerability indicator is measured by the total event frequency and affected area (Cutter et al., 2000).

Local context, character and conditions will influence the choice of appropriate risk factors with which to assess the vulnerability of an area. The hazard vulnerability in tsunami risk assessment is a function of factors such as distance from the shoreline, depth of inundation, building construction, preparedness, perception of the hazard, ability to escape from the hazard, social and economic factors (Papathoma et al., 2003). Furthermore, each coastal area has different conditions and these factors make the coastal area more or less vulnerable to tsunami hazards. Therefore, in tsunami hazard assessment, the inclusion of vulnerability factors gives a more realistic pattern or trend to spatial and temporal vulnerabilities (Papathoma et al., 2003).

Gender and age are two important variables in tsunami vulnerability assessment. This was evident in the 2004 Indian Ocean tsunami, where a third of the total victims were children, and there were more female casualties than male (Levy and Gopalakrishnan, 2005). According to Doocy, et al. (2007), from interviews with survivors, many men were fishing at that time, while most of the women and children stayed at home on that Sunday morning. Moreover, many women and children were unable to swim or stay afloat in the powerful waves, tiring easily and drowning quickly (Levy and Gopalakrishnan, 2005, Cutter et al., 2003).

A variable that can be used as an indicator is particularly useful in measuring vulnerability. For example, in Australia, 13 easily accessed indicators that are used in quantifying the social vulnerability for natural hazards are age, income, gender, employment, resident type, household type, tenure type, health insurance, house insurance, car ownership, disability, language skill, and debt or saving (Dwyer et al., 2004). This comprehensive approach measures and assesses a range of social aspects, and covers different levels of vulnerability; individual, community, regional and institutional.

For tsunami hazard assessment, the condition of a building is another parameter to determine vulnerability. Factors include the shape and position of the building. For example, a building and road perpendicular or parallel to a beach experience different impacts from surges and tsunamis (Bush et al., 1999). If they are parallel to the shoreline or perpendicular to a river course, they are more vulnerable to the tsunami force (Papadopoulos and Dermentzopoulos, 1998). Also one–storey buildings in coastal areas are more vulnerable to tsunami impact than two or three–storey buildings because of their height. Buildings with more than one–storey can be used for vertical evacuation (Clague et al., 2003).

2.3.2.2. Data and Information

To create a vulnerability assessment for physical, social, economic and environmental factors, a range of spatial and non–spatial data are needed; for example, land elevation, beach slope, bathymetry, age, population, income, market, and land use. Land elevation and beach slope relate to the inundation area (Bush et al., 1999). Bathymetry relates to the run–up of tsunami waves (Nugroho, 2006). Age and population relate to social factors (Cutter et al., 2003). Economic status (such as income, status and political power), market and land use relate to economic factors that are used to calculate the potential for damaged areas (Nugroho, 2006, Cutter et al., 2003). These data should represent the information that is needed to create the vulnerability assessment. For those assessments, data from the census is important because it is sufficiently detailed and easily accessible. However, there are some things to consider, such as data availability, spatial resolution and time since census data collection (McLaughlin et al., 2002).

Moreover, the use of geo–indicators, such as elevation, vegetation, offshore setting, erosion rate, beach width and slope, presence of sand dunes, solid structures, and drainage and soil type are very useful in providing information for natural vulnerability to coastal hazards and can be accessed through field observation (Bush et al., 1999).

2.3.2.3. Risk and Vulnerability Methodologies

The assessment method is based on the objective to reveal the physical, social, economic, and environmental conditions that will increase or decrease vulnerability to tsunami hazards. Schroter, et al. (2005) have developed an eight–step assessment method which includes:

- Defining the study area. It is important to talk with the stakeholders in the process of selecting the study area, because they are the people who take actions based on information from the assessment result.
- Situation analysis over time. Once the study area has been selected, it is important to develop the knowledge through a literature review and gather information about the study area through discussion with stakeholders.
- Developing the hypothesis. Researchers should create a hypothesis as to which people and environments are vulnerable to the hazard.
- Developing a causal model. This model describes and assesses the factors, including strengths of the interactions between factors that lead to vulnerability.
- Developing indicators of exposure, sensitivity and adaptive capacity. It is important to develop indicators that are replicable, meaningful, understandable by stakeholders, and spatial so they can be mapped.
- Creating an operational model of vulnerability. It is produced by weighting and combining the indicators.
- Developing future projections. Projections should be based on the scenarios of values for the relevant variables.
- Communicating the result. The communication should encourage a two–way direction of information between researchers and stakeholders.

Quantifying and weighting vulnerability and risk are often very subjective, because they depend on many factors, such as research objectives, involvement of experts and statistical methods (Chen et al., 2001). Besides the subjectivity, weighting in vulnerability assessment depends on the importance of the variables. This is because each natural hazard is specific and cannot be classified in one classification of vulnerability or risk (Greiving et al., 2006).

There are five criteria to evaluate for a vulnerability assessment: (i) the knowledge base for analysis should be varied and flexible, (ii) vulnerability should be based on place or study area and the analysis should be aware of other spatial scales, (iii) the results should be multiple and interacting, (iv) the assessment should allow for differential adaptive capacity and (v) the information should have both prospective and historical analysis (Schroter et al., 2005). Furthermore, the vulnerability assessment will be especially useful if it illustrates the relationship between humans and the environment. There should be an understanding of meeting the needs of the group or society while sustaining the systems and conditions of the environment. Therefore, it requires communication between scientists and decision makers (Turner II et al., 2003).

2.3.3. Risk Assessment

The risk for each natural hazard, including a tsunami, is different from one area to another, depending on its vulnerability. The result of a risk assessment allows all parties (disaster planners and emergency managers) to focus limited resources on areas with the highest priority for evacuation, recovery or rehabilitation (Wood and Good, 2004). The ultimate goal of the hazard risk assessment is to reveal different areas with different levels of risk from the hazard through mapping (Wu et al., 2004).

The hazard risk assessment should consider three dimensions of hazard exposure: economic, social and ecological dimensions. The economic dimension refers to the factors that affect the region or economic system. The social dimension refers to the people that are considered highly vulnerable, such as the disabled and poor people. The ecological dimension refers to the ecosystems and environmental vulnerability of a region. Moreover, disaster planners and emergency managers need to locate the risk and determine the significance of the risk both qualitatively and quantitatively. This is very important, especially for tsunami hazards which have impacts that are spatially distributed (Greiving et al., 2006).

However, the risk assessment is not able to be separated from individual or institutional perceptions about the risk. Therefore, the risk assessment method should be flexibly applied and easy to understand for the local managers who usually have different backgrounds and levels of education (Ferrier and Haque, 2003).

There are some different approaches in defining and calculating risk. However in principle, they are the same in the application of the approach. The different risk approaches by different references, included their explanation can be seen in Table 2.2.

Table 2.2. The risk calculation.

Risk Calculation	Explanation
1. Hazard x Vulnerability x Manageability (Shook, 1997).	In this analysis, he used a questionnaire to get the result. Participants were selected on the basis of their deep understanding of Thai society, the government organisations related to disasters and knowledge of disaster management in the country, and NGOs involved in disaster response and rehabilitation.
2. Hazard x Vulnerability x Value (Papadopoulos and Dermentzopoulos, 1998).	In this analysis, real tsunami data and tsunami wave numerical simulations combined with probabilistic approaches provide a good basis for quantitative tsunami hazard assessment. To assess the "vulnerability" and "value", they used qualitative or semi–quantitative methods for the tsunami risk description.
3. Hazard probability x Vulnerability (Ferrier and Haque, 2003, Cutter et al., 2000, ISDR, 2002).	In this analysis, they defined risk occurrence with the hazard probability and result in a vulnerability to loss, such as people and property.
4. Hazard x Element exposed x Vulnerability (Dwyer et al., 2004, Tran et al., 2009, Nott, 2006).	In this analysis, "hazard" refers to hazard occurrence, the magnitude and the spatial extent of the hazard's impact. "Elements exposed" refers to the factors, such as people, buildings and networks that are subject to the impact of a specific hazard. "Vulnerability" refers to the capacity of an element exposed during the impact of a hazard event, such as roads, buildings and people.
5. Hazard x Vulnerability x Time (Hennecke et al., 2004).	In this analysis, hazard was considered to be the probability of occurrence of a major hazard event in one area. Vulnerability comprises the exposure of human assets, here land and property values, to these hazards. They also included time as a variable over which risk can change as a consequence of changes in hazard and/or vulnerability.
6. Hazard probability x Extent of impact (Plattner, 2005).	In this analysis, he defined the risk as the product of frequency (or probability) of event occurrence and the extent of the associated consequence.
7. Hazard probability x Impact x Exposure x Vulnerability (Hollenstein, 2005).	In this analysis, he defined hazard as a probability or the return period and an intensity (comprising a description of the impact, together with its spatiotemporal distribution). The risk is also characterized by two factors, the exposure (describing the spatiotemporal distribution of the target objects) and the vulnerability.

As can be seen from these methods, an increase or decrease of each element will influence the degree of risk. Therefore, the calculation of risk by multiplying each sub–variable of vulnerability should be considered carefully because this multiplication will give a low value if one of the involved factors is low. Furthermore, the risk assessment result should be interpreted on a specific temporal and spatial scale. The consequence is that area A and B cannot be compared if they are different in spatial scale or their risk assessments are conducted at different times (Rashed and Weeks, 2003).

To create a complete analysis for the tsunami risk assessment, some processes or steps are needed. For example, Papadopoulos and Dermentzopoulos (1998) describe their steps as: (i) Collecting and analysing the data related to various parameters influenced by tsunami waves. In the first step, they used geomorphological, geological and environmental features to create a natural environment map; land use to create a land use map; road network to create a road network map; functions, lifelines and important installations to create functions and lifelines maps; and socio–economic and population parameters to create socio–economic and population maps. (ii) Analysing the potential impact of the tsunami waves. In the second step, they created tsunami impact maps based on the first step maps, such as tsunami hazard impact potential on soil foundation conditions and on the natural environment, tsunami wave surge impact force, relative magnitude characteristics on land, land use property damage, road damage, lifeline damage, population and socio–economic impact maps. (iii) Developing a series of mitigation and prevention approaches. In this step, they created a tsunami risk management map, included the prevention and mitigation measures based on the combination of all potential impact maps.

Papathoma et al., (2003) have developed their steps as: (i) Identifying the field site based on historical tsunami records. The study area was chosen because it has a historical record of tsunami floods and reliable information documenting specific tsunami wave heights and/or distances of inundation. (ii) Estimating the worst–case scenario of the inundation areas. Based on the historical data, they identified the extreme inundation zone as the area between the coastline and the contour of the highest ever recorded wave. (iii) Identifying the parameters that contribute to the vulnerability. Since the vulnerability to tsunami damage and destruction is not uniform within the study area, a variety of parameters were identified and then information concerning each parameter was collected to generate the primary database, such as built environment, sociological, economic and physical data. (iv) Establishing a GIS based map. All data sets were combined and analysed in order to answer the questions being investigated using GIS technology.

Papathoma and Dominey–Howes (2003) explain their steps as: (i) identifying the inundation depth zones. Based on the historical data, they identified the inundation depth zone as the area between the coastline and the contour of the highest ever recorded tsunami wave. (ii) Identifying the vulnerability factors and collecting the data. In this step, they used buildings and people as vulnerability factors. They collected data, such as characteristics of buildings and population in those buildings. (iii) Calculating the vulnerability. They calculated building and people vulnerabilities using a multi criteria evaluation method. (iv) Displaying the vulnerability. They displayed the result in a GIS map form.

As the assessment takes place prior to the actual event occurring, a certain scenario, usually a "worst–case" one, is developed as a basis for the assessment. The worst–case scenario is preferable for the tsunami risk assessment because it is very difficult to predict the scale and magnitude of a tsunami. To make tsunami risk assessment simple, realistic, easy to adopt and flexible to apply in other places, some researchers have made simplifications, such as omitting off–shore bathymetry and wave run–up calculations. Papathoma and Dominey–Howes (2003) did not use these parameters because of the time needed for the processing and due to data costs. Therefore they used historical data of past events to predict the worst–case scenario in a coastal area.

The tsunami risk scenario is therefore developed based on existing historical data, numerical modelling and the worst–case scenario. For example, maximum wave run–up can be expressed as vertical (elevation of water) or horizontal (distance of inundation) and any run–up more than 1 metre is considered dangerous. However, the horizontal inundation is influenced by topography, such that the vertical run–up is usually used in each scenario (Clague et al., 2003).

2.4. Tsunami Mitigation

Hazard mitigation is a further process after the hazard, vulnerability, and risk assessments have been completed. It is important that all results in the hazard assessment are incorporated into the decision–making process. Moreover, serious efforts must be made to integrate vulnerability analysis into the decision making. Tsunami and other coastal hazards cannot be prevented because they are beyond human influence. However, the damage that is caused by a tsunami can be minimized through mitigation (Turner II et al., 2003).

Strategies for natural mitigation are universal, but in the implementation stage one must consider the local characteristics (Alcantara-Ayala, 2002).

Nowadays, there is a trend away from hazard response issues to proactive mitigation issues (Pearce, 2003); the old methods in hazard management were to clean up and rescue the survivors. This has been changed to mitigation, preparedness, response and recovery (Cutter et al., 2000, Briceno, 2004). In the World Conference on Natural Disaster Reduction held in Yokohama, Japan in 1994, the United Nations (UN) has made and implemented the Yokohama strategy for all members, from small or developing countries to developed countries. It is a set of strategies for action on prevention, preparedness and mitigation of natural hazard risks based on principles in risk assessment, disaster prevention, vulnerability reduction, disaster preparedness, early warning systems, and political responsibility for creating, developing and implementing disaster reduction policies (Briceno, 2004). The World Conference on Disaster Reduction in Hyogo, Japan in 2005 updated the Yokohama Strategy and enhanced it into the Hyogo Framework. This framework identified the specific gaps and challenges from the previous strategy that focuses on five areas, namely (i) governance frameworks (included organizational, legal and policy frameworks), (ii) risk identification, assessment, monitoring and early warning, (iii) knowledge management and education, (iv) risk factors reduction and (v) preparedness for effective response and recovery. These are the key areas for developing a relevant framework for action for the decade 2005 – 2015 (ISDR, 2005). For example, Italy has taken disaster risk reduction elements into consideration in all phases of the emergency management cycle. Following the L'Aquila Earthquake of 2009, an extensive rebuilding plan named "CASE Project" has provided over 27,000 homeless people with fully anti–seismic, modern houses compliant to the most recent building standards. Following the 1988 Spitak Earthquake, new master plans of development were established for 80% of the cities and towns in Armenia. Each master plan includes plans for land use, inventory valuation and zoning on both the degree of hazard and risk assessment of buildings and the plans for economic and social development. The government also invested in areas at risk for flooding, particularly in northern regions of the country, which have experienced substantial flooding over the past decade (ISDR, 2009).

In the hazard assessment process, the risk is not only influenced by human and natural vulnerabilities, but is also a function of mitigation and preventative actions that are implemented before the event (Ferrier and Haque, 2003). The tsunami hazard can be reduced by a mitigation policy and alternatively can be exacerbated by poor or even non–existent mitigation plans (Cutter et al., 2000).

According to this definition, many activities can be included as part of mitigation. They can be structural – by developing structures such as seawalls, jetties and groynes; or non–structural – by developing land use planning, awareness campaigns, preparedness and public education, hazard and risk maps (Clague et al., 2003).

2.4.1. Structural Measures

In structural mitigation, actions to reduce the impact of tsunamis include preventing waves from flooding areas, breaking the wave before it reaches the shore, or protecting buildings, houses and coastal infrastructures from the wave energy. The problem with structural measures is that they are expensive and may only protect certain parts of the shore (Clague et al., 2003).

For example, dykes and walls can be built in coastal areas. These offshore barriers can deflect tsunami waves, lessen their energy and prevent them from reaching residential or business areas. These protections are expensive, but are economically possible for wealthy developed countries, such as Japan and the United States, where large populations are at risk and the shorelines are at the head of bays or inlets (Clague et al., 2003). Moreover, in areas with a high probability of tsunami hazard, buildings can be designed to reduce water damage by being built on piers and elevated 2 to 3 m above ground level. This has been done on some houses near the shoreline in the Hawaiian Islands (Clague et al., 2003).

2.4.2. Awareness and Education

Public education must be conducted regularly, especially for areas with a high probability of tsunamis. Issues such as the characteristics, probability and magnitude of the tsunami, likelihood of being flooded, proper response and community preparation are necessary for public education, especially for coastal communities (Clague et al., 2003). Pictures, maps, questionnaires, and event scenarios are very useful in the awareness and education programs. A tsunami–resilient community must understand the characteristics of the tsunami, be able to mitigate its impact, disseminate and change information as necessary and have a tsunami mitigation plan. These aspects are used as a basis for action plans, such as developing tsunami information for all stakeholders, evacuation signs and routes, training materials, inundation maps, guidelines, zoning, public meetings, workshops, planning development and legislation (Jonientz-Trisler et al., 2005, Clague et al., 2003).

A public mitigation program will be effective if there is education and a good understanding of risks, susceptible areas and human vulnerability (Ferrier and Haque, 2003). For example, in coastal areas with tourism activities, education of the hotel operator and staff has improved community resilience to future tsunamis in Washington, USA (Johnston et al., 2005). Having tsunami material in the curricula is a good option for the younger generation. Early warning systems are also important because people are warned before the tsunami occurs. However, they are only effective for tsunamis with long distance waves; for distances less than 100 km they are not effective because there is limited time to warn and evacuate people (Clague et al., 2003). Therefore, in coastal communities people should run to higher buildings (more than 2 storeys) for vertical evacuation.

2.4.3. Strategic Plan

For tsunami mitigation, the change in the natural hazard paradigm is reflected in greater community planning, including land use planning, inundation management plans, reduction of vulnerability, and increased coastal community resilience (Clague et al., 2003). Hazard identification is done through scientific studies, workshops, tsunami modelling and the development of tsunami inundation maps.

Developing the inundation maps (showing areas that are likely to be flooded during a tsunami event) is an important activity in tsunami mitigation. These maps can also be used as a guide for local government in directing investment development and specific land uses to safer and sustainable places (Clague et al., 2003). Moreover, an inundation map is also important in public education. The community will see and evaluate the vulnerability of their area and be as prepared as possible for the worst situation. Therefore, inundation map development is a priority in tsunami mitigation planning in the United States (Jonientz-Trisler et al., 2005).

An integrated hazard mitigation plan is important especially in very developed coastal areas. This plan can provide guidance for stakeholders in reducing their vulnerability to coastal hazards over a long period. Hazard mitigation or management plans should be directed to reduce different forms of human vulnerability. They should cover activities to reduce human vulnerability, improve access to resources, and increase social integration, institutional coordination, public awareness, and building safety. The plan must be discussed and communicated with other jurisdictional areas because the hazard is not limited by the administrative boundaries (Montoya and Masser, 2005).

Focus group discussions, coastal communities and school surveys can assess the understanding of coastal communities and their preparedness for the future tsunami hazard. These surveys can be used as feedback for the local governments in evaluating the effectiveness of mitigation programs. Moreover, some critical views are very constructive in assessing coastal community preparedness. For example, local people will prepare medical or emergency kits just once and after a certain time never renew them. In other cases, they do not prepare because they know that a hazard event will imply a financial burden, such as building or repairing a house. These conditions are caused by the irregular dissemination of information, the complex nature of impacts, and a low risk perception because a tsunami is a rare event (Johnston et al., 2005).

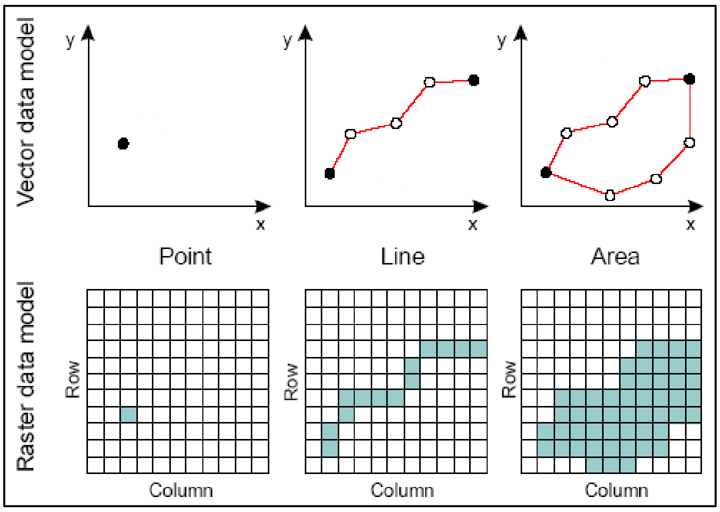
2.5. Geographic Information System (GIS) Technology

In this tsunami risk assessment study, GIS technology is utilised. GIS is essentially a set of tools in a computer based information system that can store, retrieve, create a model, manipulate, transform, analyse, share, and display the data which are referenced to the Earth spatially for a specific purpose (Cutter et al., 1997, Davis, 2001, Heywood et al., 2006).

2.5.1. GIS Data Structures

Geographic data comes in three basic forms, (i) map data, (ii) attribute data, and (iii) image data. Map data contains the location and shape of geographic features and is known as spatial data. GIS uses three basic shapes to present real–world features, (i) points (such as buildings and hospitals), lines (roads and rivers), and polygons (forests and urban areas). Attribute (tabular) data is the descriptive data that GIS links to map features. Attribute data is collected and compiled for specific areas, such as territorial authorities, census tracts and cities. Image data ranges from satellite images and aerial photographs to scanned maps (Heywood et al., 2006, Davis, 2001).

In GIS, there are two main ways for displaying spatial data models, namely raster and vector spatial data (see Figure 2.2). The raster spatial data model is described as tessellations. In the raster world, individual cells are used as the building blocks for creating images of point, line, area, network and surface entities. In the raster world, the basic building block is the individual grid cell, and the shape and character of an entity is created by the grouping of cells. The size of the grid cell is very important as it influences how an entity appears. A vector spatial data model uses two–dimensional Cartesian (x,y) coordinates to store the shape of a spatial entity. In the vector world, the point is the basic building block from which all spatial entities are constructed. The more complex the shape of a feature, the greater the number of points required to represent it (Heywood et al., 2006).



Source: Davis (2001).

Figure 2.2. The raster and vector data model.

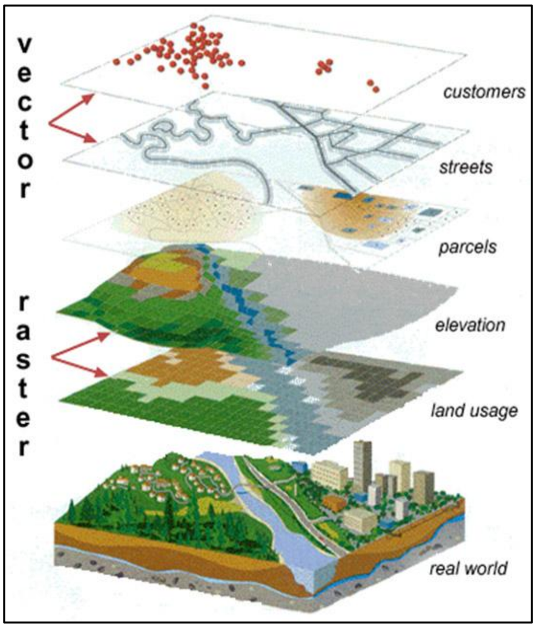
Spatial information that is used in the risk assessment process, including land use, slope, elevation, building stock and total population can be represented in GIS as features and their associated attributes. The features are represented by the basic data structures of the GIS: points, lines and polygons and the associated attributes stored in database tables.

2.5.1.1. Mapping Scale

Scale is an important issue in GIS analysis. Since it is important to simplify the spatial data in order for it to be represented on a map, features should be generalized. This generalization depends on the map scale. For example, maps with large scales can represent much more detail than maps with small scales. Due to this combination of simplification and generalization, it is very important to recognize the limitations of given map scales for certain type of analysis. Therefore, it is very important to establish a reasonable scale of analysis and a corresponding scale of display (Cutter et al., 1997).

2.5.2. Analysis and Modelling Capabilities

One of the most important features of GIS is the manipulation and analysis of both spatial and non–spatial data. Both traditional database management systems and GIS support database analysis, but GIS also supports map analysis. It is useful to think of GIS map analysis in a layered–model context (see Figure 2.3). The layered GIS model is analogous to transparent maps that can be accurately stacked upon one another. Typically each layer contains only one mapped theme. GIS provides a set of tools or computer programs which are in the form of operating commands, permit spatial inquiry, manipulation and analysis; which allow the user to perform a specific set of operations on map and attribute data (Heywood et al., 2006).



Source: Hill (2006).

Figure 2.3. The layered GIS model.

2.5.3. GIS in Natural Hazard Risk Assessment

A geographic information system can be used to integrate the various steps in a tsunami risk assessment process. The system is independent of analysis scale and geographic location, allowing analysis at any level and in any area where the necessary information is available. GIS technology also provides a powerful tool for displaying outputs and permits users to see the geographic distribution of risk (Rashed and Weeks, 2003).

GIS serves as an important tool in establishing data and analytical modelling, and assists the decision making for the natural hazard mitigation (Chen et al., 2003). In natural hazard assessment, GIS can support pre–impact planning, post event response, and the mitigation process. However it needs high–quality data input and verification to make it effective. Moreover, GIS software also requires some principal understanding of how the hazards relate to each other in space and over time (Cutter et al., 1997).

In the disaster risk management process, it is important to combine local knowledge, GIS and maps (Tran et al., 2009). There are three reasons for this integration, (i) A hazard map is an effective tool in making local knowledge visible or understandable in the disaster risk identification stage. Hazard maps are fundamental to the development of a community–based methodology for collecting and displaying the disaster vulnerabilities and risks that comprise the core content of local knowledge. It is one of the first steps of producing a community vulnerability inventory. These maps can provide clear, attractive pictures of the geographic distribution of potential hazards that can be appreciated by local people with no specialist knowledge. (ii) Local knowledge is important for disaster risk management. Local people can provide information about their surroundings and are able to indicate the hazard–prone areas in their environment. (iii) A GIS map has more advantages than a conventional map. Mapping hitherto required a very cumbersome and time–consuming process for transforming field maps into a wide range of finished cartographic products. Once these map products were produced, they were difficult to correct or expand. The situation began to change rapidly in the mid 1980s when early versions of GIS came into use. Since then its importance as a tool to link non–geographic attributes or geographically referenced data with graphic map features and to assist with the management, storage, display and query of socio–economic data has become well established.

Natural hazard risk assessments use GIS as a tool to process the data because of the spatial methodologies that can be investigated throughout the whole risk assessment process, (i) data integration, (ii) risk assessment tasks, and (iii) risk decision making (Chen et al., 2003). Furthermore, GIS has an ability to combine natural, hazard, social and economic information in the hazard risk assessment process. The GIS approach is also considered as a method to identify and prioritize the area that is prone to hazards for further detailed assessment, including scale of assessment and specific issues that relate to that area (Wood and Good, 2004). One output from GIS processing, for example, would show the areas with different levels of risk from hazards (Wu et al., 2004, Tran et al., 2009).

A large number of GIS applications for natural hazard risk assessments have been developed, particularly during the past two decades. For example, in a landslide risk assessment for the Wondogenet area, Ethiopia, GIS has been used to evaluate landslide occurrences and their relationships with various event–controlling parameters, such as lithology, drainage pattern, geological structure, slope aspect, slope angle, and vegetation biomass. Temesgen, et al. (2001) combined remote sensing methods with GIS methods to produce hazard and risk maps. They used Landsat TM, SPOT panchromatic images (remote sensing data) and DEM data to create several spatial maps, such as a lithological, drainage pattern, landslide distribution, slope aspect, slope angle and structural maps of the study area. Furthermore, these maps were classified, weighted and given priority values depending on landslide occurrences. They integrated these single maps to produce a multi–thematic map (the landslide hazard map) that contains all information from each of the single maps using a specific formula.

$$\text{Risk map} = \frac{\left[\left(\frac{\text{I1}}{\text{Max Slope}}\right)+\left(\frac{1-\text{ABS}\,(270-\text{I2})}{270}\right)+\left(\frac{(\text{I3}+1)}{2}\right)+\left(\frac{\text{I4}}{\text{Max I4}}\right)+\left(\frac{\text{I5}}{\text{Max I5}}\right)+\left(\frac{\text{I6}}{\text{Max I6}}\right)\right]}{6}$$

Source: Temesgen, et al.(2001).

GIS spatial analysis has also been used to assess urban vulnerability to earthquakes in Los Angeles County, USA. To create the vulnerability map, seven stages were completed: (i) identify the evaluation criteria, (ii) run the earthquake scenarios, (iii) fuzzify criteria, (iv) apply the spatial decision rules, (v) aggregate the fuzzy criteria, (vi) identify the hot spots of vulnerability, and (vii) analyse the sensitivity (Rashed and Weeks, 2003). Fuzzify criteria in the third stage is known as a fuzzy model and is one of the methods of standardization that can handle linguistic, non–numeric descriptions and offer a powerful way to resemble human reasoning in its use of approximate information and uncertainty to generate decisions (Rashed and Weeks, 2003). They assessed the urban vulnerability by running scenarios based on a previous earthquake hazard that occurred in the study area.

GIS has also been carried out for assessment of the impact of sea level rise in the Rosetta Area, Egypt. El–Raey, et al. (1997) classified the impact of the sea level rise based on the contour level in the study area. The researchers created a vulnerability map by combining land use, topography, archaeological sites, land cover and population layers, and thus concluded that a rise in sea level will impact on the present population, economic activities, total regional revenue and on the tourism sector for both local people and local government near the study site.

GIS has also been used in risk assessment of the earth fracture hazards in Yuci City, Shanxi, China. Three maps were created to assess this hazard: (i) intrinsic (natural) vulnerability map, (ii) specific vulnerability map, and (iii) hazard map. Wu, et al. (2004) created the intrinsic vulnerability map by assessing the various natural factors that relate to the development of earth fractures, such as tectonic characteristics, groundwater exploitation, stratum properties and geomorphology. It is divided into three categories, namely highest, moderate and least risks. It is based on the natural factors that influenced the earth fracture development. The specific vulnerability map is created by combining the GIS technology and Analytical Hierarchy Process (AHP) and four elements that relate to the vulnerability of earth fractures, such as population density, buildings, railways, and streets. It is divided into three categories, namely strongly, moderately and least vulnerable. It is based on system risk when the earth fracture hazards are exposed to people activities. Furthermore, Wu, et al. (2004) proposed that a geo–hazard is the combination between intrinsic and specific vulnerabilities. Therefore the intrinsic and specific vulnerability maps need to be combined using GIS analyses to create a hazard map. It is divided into five categories, namely least risky or least vulnerable, less risky, risky, moderately vulnerable and strongly vulnerable.

Furthermore, GIS has been used at the local level in combination with indigenous knowledge in disaster management processes. Tran, et al. (2009) correlated hazard risk and loss caused by a disaster and analysed the contribution domestic risk maps in the community can make to reduce the risk. They used GIS for flood risk mapping in Thua Thien Hue Province, Vietnam. For this mapping and vulnerability assessment, the methods are: (i) They used hydrological information and flood records, topography and land use, river morphology (such as flood periods, duration and water level, and levels of danger), meteorological information relating to flood seasons, information about existing infrastructure (such as housing conditions and public facilities), social, economic and demographic conditions (such as poverty and education), and information about the damage and loss caused by the previous disaster. (ii) They showed that the local people in hazard prone areas have always understood their surrounding vulnerabilities and risks, and they then succeeded in creating the flood risk map by transferring the local knowledge into maps. Moreover, the maps and recommended actions are suited to the local situation. Therefore, they suggested involving local people – with their knowledge – in the disaster management process.

2.5.4. GIS in Tsunami Hazard Risk Assessment

Many studies have used GIS to assess tsunami hazard risk by creating hazard, vulnerability and risk maps (Papathoma and Dominey-Howes, 2003, Papadopoulos and Dermentzopoulos, 1998, Greiving et al., 2006, Garcin et al., 2008, Wood and Good, 2004, Papathoma et al., 2003). Moreover, many existing natural hazard assessment methods such as flood, landslide, bushfire and earthquake have been used as a basis for tsunami risk assessment. For example, in Sri Lanka, GIS has been integrated with numerical simulations and risk scenario modelling in coastal hazard assessment that proves useful for post–tsunami reconstruction and development planning. The GIS processing includes all data on the physical (bathymetry, topography and hydrography) and human environments (buildings, harbour facilities, road and rail networks and land use). The result is maps of different hazard levels to define the most suitable areas in current reconstruction projects and future development (Garcin et al., 2008).

GIS has been used to develop a tsunami risk management pilot study in Crete, Greece (Papadopoulos and Dermentzopoulos, 1998). There were three stages in the methodology, (i) collection and analysis of data related to the physical planning, such as land use or land cover, road networks, geomorphological and geological data, (ii) semi–quantitative description of the potential impact of an extreme tsunami, and (iii) development of a series of approaches for taking preventative and mitigative measures. Moreover, Papadopoulos and Dermentzopoulos (1998) used GIS to create 12 thematic maps that included information about the geographic variation of (i) physical planning parameters that describe the existing situation in the study area, (ii) the characteristic tsunami features on land, and (iii) the tsunami hazard impact and damage potential. The list of the thematic maps are: (i) state of the natural environment, (ii) potential tsunami impact on soil and natural environments, (iii) land use types, (iv) tsunami wave impact on land, (v) potential damage of the land use property, (vi) road network, (vii) potential damage of road, (viii) functions and lifelines, (ix) potential damage of lifelines, (x) parameters of social, economic and population factors, (xi) potential impact on social, economic and population factors, and (xii) tsunami risk management that relates to prevention and mitigation measurements.

GIS has also been used to assess the vulnerability of an Oregon port and harbour community in the USA to earthquake and tsunami hazards by integrating hazard, physical, social and economic information. Wood and Good (2004) organized four groups of GIS layers for assessing community vulnerability: (i) study portrayal layers, (ii) hazard potential, (iii) community assets, and (iv) community vulnerability. The study portrayal layers that have been used include digital orthophotoquads (a topographic map presented in quadrangle format and related to standard reference systems), elevation models, raster graphs and bathymetry. Hazard potential layers show the subduction zone hazard susceptibility on relative ordinal scales and are created by using maps from reviewed articles or digital data. The third set of GIS layers represents the important assets of the port and harbour communities, such as subsidence, landslides, population and essential facilities. The fourth set of GIS layers focuses on the aggregate of hazards, assets, and vulnerability of the study area in order to identify the areas of multiple hazards or community assets.

In Crete, Greece, GIS has been used to assess a new vulnerability assessment approach for tsunami hazard, which is the “Papathoma Tsunami Vulnerability Assessment Model or PTVAM” (Papathoma et al., 2003). It integrates multiple factors that contribute to tsunami vulnerability, such as the built environment (such as building surroundings, building material age and moveable objects), sociological data (such as population density and number of people per building), economic data (such as land use for business, residential and services), and environmental or physical data (such as land cover, physical or man–made barriers and natural environment). The result is vulnerability maps that combine all parameters for different end–users: disaster planners, local authorities and insurance companies in the study area (Papathoma et al., 2003).

Furthermore, the PTVAM has been used to apply a tsunami vulnerability assessment to two coastal villages in the Gulf of Corinth, Greece, using a worst–case tsunami scenario based on what occurred in those villages on the 7 February 1963. Papathoma and Dominey–Howes (2003) used GIS to create vulnerability maps that consist of three parameters, (i) the building vulnerability, (ii) the human vulnerability and (iii) the economic vulnerability. The building vulnerability was analysed by using a qualitative method and combined parameters that related to the vulnerability of individual buildings, such as condition, building surroundings and natural environment. The human vulnerability was analysed by using a quantitative method – multiplying the building vulnerability result by combining parameters that relate to the human vulnerability (such as population, population density and number of households). The economic vulnerability was analysed by way of a descriptive method, which multiplied the building vulnerability result by the land use for economic issues, such as residential, business and services. For the results, Papathoma and Dominey–Howes (2003) showed the distribution of buildings that are vulnerable to tsunami inundation, the number of households that are located within buildings that are highly vulnerable, and the number and percentage of businesses and services within each of the villages that are vulnerable to tsunami events.

Most of the tsunami risk assessments have been done in developed countries, such as the United States and Greece. There, most of the data that used hazard and vulnerability components are easily collected at a detailed scale, such as elevation, land use, bathymetry, topographic map data, satellite imagery, social and economic data. Moreover, local government provides and supports researchers to do the projects and collect as much data as they need, as long as they give results that are useful for local government, such as in land use planning and regulation, and local people, such as evacuation routes. In some developing countries, such as Indonesia, it is very difficult to collect data from local government. There are many requirements just to collect some data, such as letters from the university (for students) or agency (for researchers), administration letters from local government and administration fees. On the other hand, many developed countries such as the United States and Japan give authority for students or researchers to collect data that is related to their projects for free.

2.5.5. Potential and Limitations

There is clearly further potential to use GIS as a tool to process the data in natural hazard assessment. GIS can make the task more efficient and rational for pre–impact planning, post–event response, and the mitigation process (Cutter et al., 1997). Moreover, GIS technology supports spatial decision–making that is very common in natural hazard risk assessment by using a “what if?” analysis – by varying parameters and creating alternative scenarios in a spatial context (Chen et al., 2003, Rashed and Weeks, 2003).

However, there are some limitations and constraints to use GIS as a tool for hazard assessment. GIS capability depends on the quality and range of available input data. GIS faces problems obtaining reliable and valid geo–referenced data for the required detailed risk analysis, and how to store and maintain the data in high quality form (Gaspar et al., 2004). GIS also requires the right decisions to be made in overlaying and manipulating the data, because it cannot do all of those things automatically. In other words, GIS use still requires a strong understanding (expert opinion) of how the hazards relate to each other in space and over time (Cutter et al., 1997).

2.5.6. Data Sets

To make a comprehensive tsunami hazard assessment, certain data are required for GIS processing; the data set consists of: (i) human vulnerability (social, economic, building, infrastructure and lifeline) and (ii) natural vulnerability (land use, geology, bathymetry and topography). All of those elements can be attributed to a data theme and each theme will consist of several layers that include multiple data, such as building characteristics, social and economic parameters, land use types, and the bathymetry and topography of the study area.

The data used for the processing must support the objectives of the research and it is important to try to avoid collecting and managing too much data because it is expensive (Chen et al., 2003). Moreover, it is important to try to consider the spatial resolution in the risk assessment map in order to avoid a miscalculation or misinterpretation of a map. For example, an inappropriate mixing scale gives a potential error to the interpretation and conclusion of the hazard risk assessment (Cutter et al., 1997). This potential error is also highlighted by Mclaughlin, et al. (2002) by way of illustrating population data in a coastal area: the population data is allocated evenly for all areas in the map display even though no person is living in the beach area.

There are certain types of data that are more difficult to obtain than others. For example, elevation data at a detailed scale is very difficult to obtain because few local governments in developing countries have had projects for measuring elevation at a fine scale. There is an easy way to obtain elevation at a detailed scale by using RTK (Real Time Kinematic) GPS (Global Positioning System); but it is a very expensive and not every local government or agency has the capacity. Moreover, a trained operator is needed to operate it, and skills are often not available locally (Kumar et al., 2008).

Furthermore, data from satellite images for land use mapping can be very expensive. For creating a detailed land use map in the study area, a high resolution satellite image, such as IKONOS, SPOT and QuickBird is needed. However, it is very expensive and not many local governments in developing countries can afford to buy it. They have usually used a free satellite image to derive land use or land cover, such as Landsat ETM+ (Iverson and Prasad, 2007, Demirkesen et al., 2007, Sirikulchayanon et al., 2008).

The availability of hazard and vulnerability data can affect GIS processing and representation, and the diversity of risk map production following the implementation of specific models (Gaspar et al., 2004). Only some countries have the data availability, usually developed countries and some developing countries, such as the United States, Australia, Malaysia, Singapore, Indonesia and Japan. Most of the poor developing countries do not have the available data because it is expensive. Even if they have the data, the human resources to process it is rare due to the lack of GIS knowledge (Alcantara-Ayala, 2002).

2.6. Summary

There is a common theme to the tsunami risk assessment process, beginning with tsunami hazard identification, followed by a vulnerability and risk assessment leading to the calculation of direct and indirect physical damage, and concluding with the estimation of social and economic losses. The usual outputs of tsunami risk assessments are estimations of one, or a combination of direct social and economic losses, and indirect economic losses. Furthermore, GIS technology is a powerful tool that can be used in tsunami risk assessment as it provides an ideal framework for integrating the various components of a tsunami risk assessment model and it also provides a powerful visual tool for displaying outputs and permits users to see the geographical distribution of risk.

In this project, the author used Kuta and Sanur Regions in Bali as a study area for the tsunami risk assessment using GIS technology. It is because Bali is located on the boundary of the Eurasian and Indo–Australian Plates, which move occasionally. This movement can generate submarine earthquakes that are one of the factors that can generate a tsunami. Therefore, Bali is vulnerable to the tsunami hazard.

The aim of this project is to create a model of the tsunami risk assessment that can be applied and used in other parts of coastal Indonesia by using Kuta and Sanur Regions as a case study. The results will give information to local people who live in tsunami–prone areas, and local governments for the development of tsunami mitigation planning that includes city development planning, land use zoning and regulation, economic improvement activities, education and awareness campaigns, and evacuation planning. A quantitative and qualitative approach will be used to achieve the following objectives:

- Develop a generic model of tsunami risk assessment that incorporates physical, social, economic and city infrastructure factors and can be adapted for other coastal locations and jurisdictions.
- Develop a spatial methodology to integrate multiple factors and measure the hazard, vulnerability and risk of tsunami hazard.
- Apply the tsunami risk assessment framework in Kuta and Sanur Regions as a case study.

CHAPTER THREE – Study Area

3.1. Geography

This study focuses on two study areas in the island of Bali, namely the Kuta and Sanur Regions. The location of the study area is shown in Figure 3.1. First, the Kuta Region is located in the southwest of Bali, bordered on the east by the Denpasar Regency, on the west by the Indian Ocean, on the north by the Kerobokan Kelod Village and on the south by the Tuban Village. This region covers part of the Kuta coast, located between 8° 40’ 55” – 8° 44’ 27” south and 115° 9’ 2” – 115° 11’ 28” east. Moreover, this region covers three coastal villages, namely Kuta, Legian and Seminyak Villages. These villages belong to the Kuta Sub–District.

Second, the Sanur Region is located in the southeast of Bali, bordered on the east and south by the Badung Strait, on the west by the Sanur Kauh Village and on the north by the Sumerta Kelod, Kesiman and Kesiman Petilan Villages. This region covers part of the Sanur coast, positioned between 8° 40’ 55” – 8° 44’ 27” south and 115° 9’ 2” – 115° 11’ 28” east. Furthermore, this region covers the two coastal villages of Sanur and Sanur Kaja which belong to the South Denpasar Sub–District.

Both regions serve as centres for the administration and economic development of Bali province. However, these regions on the south coast of Bali are vulnerable to the tsunami hazard because they are located close to the Indian Ocean and relatively close to the active convergent margin between the Eurasian and Indo–Australian Plates, which is prone to tsunamigenic earthquakes (Nugroho, 2006, Prasetya et al., 2001). The location of the tectonic plate in Bali and the surrounding areas is shown in Figure 3.2. Moreover, both regions have a white sand coast and very flat areas with elevation below 10 metres.

3.2. Social and Economic Description

Administratively, Kuta Region belongs to the Kuta Sub–District. It has a total area of ± 17.50 km^2 and is divided into five villages. The total population is approximately 38,540 people. Trading, fishery and tourism sectors are the main occupations of the people living there. Sanur Region belongs to the South Denpasar Sub–District. It consists of ten villages and has a total area of ± 50 km^2, with a population of approximately 174,530 people. Government employees, the trading and tourism sectors are the main occupations for people who live there.

The main economic sectors in both regions are trading, services (such as accommodation and tourism), transportation, fishing, agriculture, and agroforestry. More than 40% of economic activities are related to hotels, villas, traditional markets, shops, malls, bars and restaurants. These activities serve as the main income for the people who live there and for village revenue.

In both regions, there are a range of public facilities such as clinics, hospitals, gas stations, electricity sub–stations, roads, schools (including private and government schools), private houses, private villas, and private investments such as industries along the coastal area that may potentially be damaged if a tsunami occurs. Furthermore, there are few mitigation efforts in place to reduce the impact of the tsunami hazard, both in terms of casualties and economic cost. For that reason, it is important to measure risk from and vulnerability to tsunami inundation and impact in the selected coastal villages of Kuta and Sanur Regions.

Figure 3.1. The study area of Kuta and Sanur Regions in Bali Island, Indonesia.

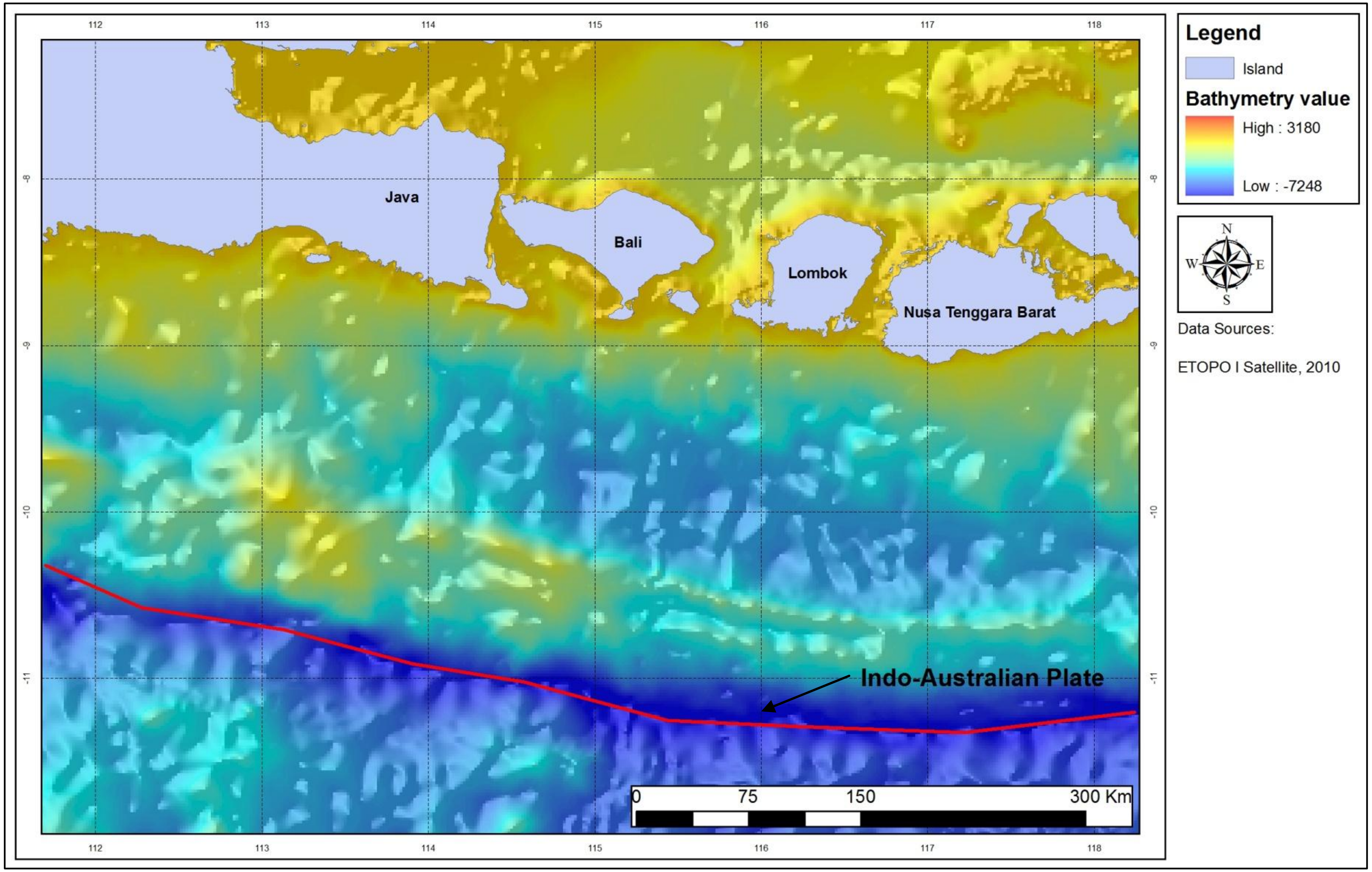


Figure 3.2. The Indo–Australian tectonic plate near Bali (ICMMG, 2010).

CHAPTER FOUR – Materials and Methods

4.1. Research Framework

The proposed framework for the tsunami hazard assessment that is developed and used in this study is based on the literature and previous studies in tsunami hazard assessment, namely Agung (2006), Greiving et al. (2006), and Papathoma et al. (2003). This framework is based on the fact that so far there is no existing tsunami risk assessment framework that can be used as guidance for coastal managers in Indonesia, particularly on Bali to evaluate, assess and implement tsunami risk assessments. The proposed framework in this study therefore integrated methods and approaches from a range of existing studies in a manner relevant and suitable for the tsunami risk assessment in Bali.

The research framework for this study consisted of three major stages (see Figure 4.1): (i) hazard assessment, including tsunami potential assessment (in red circle), (ii) vulnerability assessment, including physical, social and economic vulnerabilities (in blue circle), and (iii) risk assessment, including risk analysis (in green circle).

The framework will be simple to understand and reflect the activities to be carried out in the assessment process. Resulting maps that are produced using GIS will complete the assessment and provide information. Those criteria are especially important to ensure that the approach is easily implemented by local government and understood by local people.

Local government is interested in knowing which public or private buildings (such as private houses, hotels, villas, restaurants and schools) should be reinforced or even relocated because of their vulnerability and risk to tsunami impact. Moreover, they may also want information that allows them to create new planning regulations, such as land use and urban planning. Local people will be interested in safe areas to use in case of evacuation if a tsunami occurred. In this study, the information associated with the various parameters for tsunami risk assessments would allow the generation of a series of maps (such as hazard, vulnerability and risk maps) to address these needs.

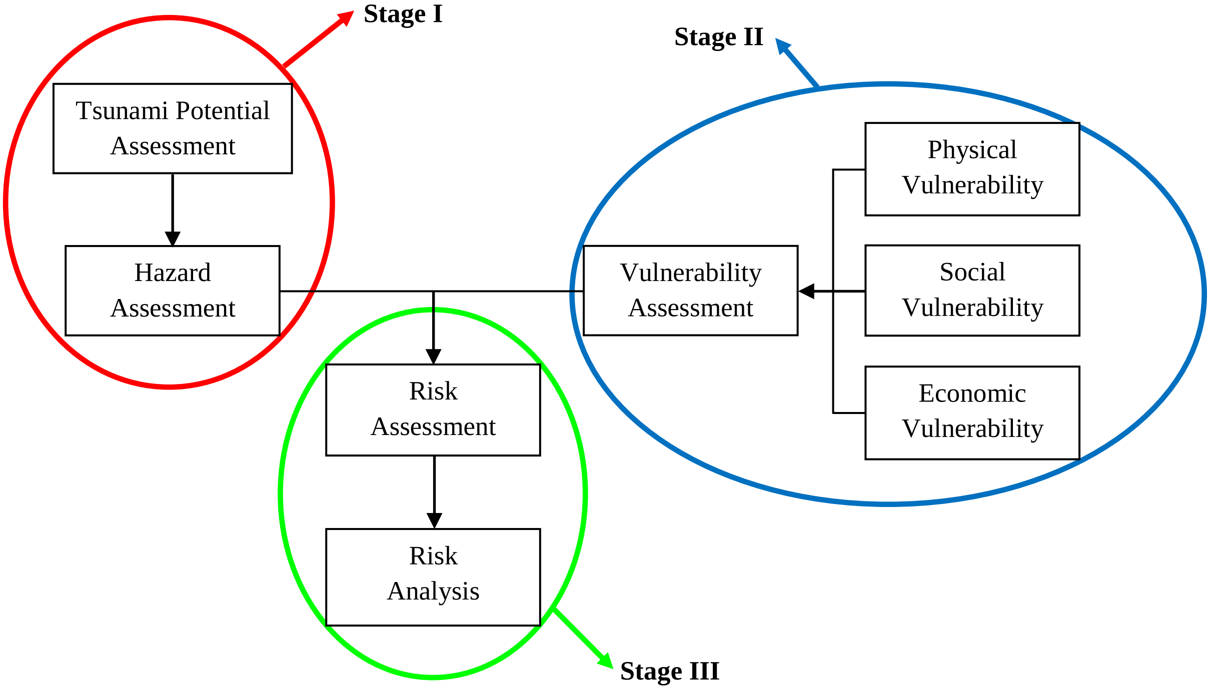


Figure 4.1. The simple research framework for a tsunami risk assessment.

4.2. Data Sources

The principal data collected for this tsunami risk mapping and vulnerability assessment included: tsunami and submarine earthquake records; geographical information including bathymetry, elevation and land use; and demographic, social and economic conditions (such as population, female, children, elderly, disabled people, poor family and fishermen numbers).

The detailed data explanations that were used for this study included:

1. The historical data of submarine earthquake and tsunami events

   The historical data are from 1800 to 2010. These data were obtained from published journals and agencies. Some researchers have published the detailed catalogues of earthquake and tsunami events for the Indonesian region, namely Hamzah, et al. (2000) and Rynn (2002). Moreover, the National Geophysical Data Center (NGDC) and the Integrated Tsunami Data Base for the Pacific (ITDB) provide detailed catalogues that can be accessed online. These data were used for analysing the probability of occurrence of submarine earthquake and tsunami events in the potential tsunami assessment. Moreover, it was used for deciding the worst–case tsunami run–up scenario in the hazard assessment.

2. Bathymetry data

   The bathymetry data were derived from ETOPO1 satellite image (Amante and Eakins, 2009). This satellite image was obtained from the National Aeronautics and Space Administration (NASA). These data were used for showing the location of tsunami events in Bali and surrounding areas in the hazard assessment. These data were obtained and analysed in raster format. The spatial resolution of bathymetry data are 2,000 x 2,000 m.

3. Elevation data

   The elevation data were derived from theodolite surveys in Kuta and Sanur coastal areas, spot heights, and elevation points from two topographic map sheets for the Denpasar and Banjar Kertajiwa Regions at a scale of 1:25,000 year 1999. These data were obtained from the Department of Public Works of

Indonesia, the Denpasar City and Badung Regency Public Works Agencies, and the National Coordinating Agency for Survey and Mapping (BAKOSURTANAL). These data were used for classifying the inundation zones in the hazard assessment and classifying the ground elevation and slope percentage in the physical vulnerability assessment. The elevation survey was conducted from 2005 to 2008. These data were obtained in vector format and analysed in raster format.

4. Land use data

   The land use data were derived from urban planning maps of Kuta and South Denpasar Sub–Districts year 2008. These data were obtained from the Bali Provincial Planning Board, and the Denpasar City and Badung Regency Planning Boards. These data were used for analysing risk factors, namely physical, social and economic factors in the risk assessment. These data were obtained and analysed in vector format.

5. Social and economic data

   The social and economic data that were used in this study, namely total population, female, children, elderly, disabled people, poor family and fishermen numbers. These data were obtained from the Indonesian Central Bureau of Statistics (BPS), and the Denpasar City and Badung Regency Statistic Offices. These data were used for analysing the social and economic variables in the social and economic vulnerability assessments. These data were analysed in raster format. These data were collected in 2009.

6. Survey data

These data were obtained from a field survey using GPS within the study area from October to November 2009. These data showed the location of public and private infrastructure, such as hotels, villas, restaurants, private houses, shops, malls, gas and electricity sub–stations. These data were used for ground truth in the risk analysis.

In this study, much of this data needed considerable processing and further transformation in order to generate the variable used in the spatial analysis. Furthermore, some of these data are easy to obtain because it was possible to download through the internet, such as historical and satellite image data. The elevation and land use data needed a letter from the university to obtain data from the local government. The social and economic data were easy to obtain by buying or copying the statistic book for the study area in Bali Statistics Office. These data were available from local government. Both Kuta and Sanur Regions are the biggest regions in terms of population and income from tourism sector in Bali. Many projects have been carried out for developing these regions, and these data were available from Kuta and Sanur governments.

4.2.1. Software

During this study, ER Mapper version 7.0 from ERDAS, Inc was used for image processing. For the GIS spatial analysis, ArcGIS version 9.3 from ESRI, MapInfo Professional version 8.5 from Pitney Bowes Business Insight, Inc, and AutoCAD version 2006 from Autodesk, Inc were used. Microsoft Excel was adopted for displaying data in bar and pie charts.

4.3. Methods

A database was developed based on the classification: i) baseline and raster, ii) infrastructure, iii) administration and planning documents, and iv) social and economic attributes. Sub–district and village boundaries are used as a basis for the database development and management. The analysis that was used in this study will be explained in the following chapter.

4.3.1. Tsunami Potential Assessment

The historical data of submarine earthquake and tsunami events were analysed to produce the recurrence time of submarine earthquakes and tsunamis (Cutter et al., 1997, Fernandez et al., 2000, Zahibo and Pelinovsky, 2001). The probability of occurrence for submarine earthquake and tsunami events was calculated by Cutter's formula (1997):

$$\textbf{Probability of occurrence} = \frac{\textbf{Number of events}}{\textbf{Number of years}}$$

In this study, the tsunami intensity scale (K_0) is based on Soloviev (1978). The detail of Soloviev's tsunami intensity scale description is shown in Appendix 2. The magnitude of earthquake is expressed in M_s or surface–wave magnitude because it is more suitable for shallow (depth < 70 km) earthquakes at teleseismic distances (20–180°) (Agung, 2006, Kanamori, 1983).

Moreover, the historical data were used to decide the worst–case tsunami run–up scenario for the hazard assessment. The worst scenario for tsunami run–up is based on the maximum run–up height that occurred on Bali on 2nd June 1994, which was 4.4 m (Rynn, 2002, Papathoma and Dominey-Howes, 2003, NGDC, 2010).

4.3.2. Hazard Assessment

Hazard is represented by the inundation zone that is produced by overlaying the elevation data and the worst–case run–up scenario. The inundation zone is defined as the area between the shoreline and the contour of the highest recorded tsunami run–up (Papathoma and Dominey-Howes, 2003, Papathoma et al., 2003). Therefore in Bali where the highest recorded tsunami run–up was 4.4 m (the author simplified it to 5 m), the inundation zone was the area between the shoreline and the 5 m contour.

The classification of the inundation zones based on the 5 m run–up scenario, included the scoring for each zone as follows:

Table 4.1. The classification, scoring and weighting for inundation zones.

Inundation Zones (above sea level)	Class	Score	Weight	Total
a. < 2 m	Very high inundation	5	100	500
b. 2 – 3 m	High inundation	4	100	400
c. 3 – 4 m	Medium inundation	3	100	300
d. 4 – 5 m	Low inundation	2	100	200
e. > 5 m	Very low inundation	1	100	100

4.3.3. Vulnerability Assessment

All selected vulnerability factors are based on previous studies and the aftermath surveys of tsunamis, especially the 2004 Indian Ocean tsunami and the 2006 south coast of Java tsunami (Levy and Gopalakrishnan, 2005, Reese et al., 2007). According to Levy and Gopalakrishnan (2005), in many locations in Aceh, Sumatra when the 2004 Indian Ocean tsunami occurred, the waves inundated 2 km inland and swamped coastal infrastructure, such as ports and power plants that were located in low–lying areas. Moreover, the casualties were dominated by children (one–third of the total deaths) and women. According to Reese, et al.

(2007), the height of waves were more than 7 m in some low–lying and flat areas and reached several hundred meters inland when the 2006 south coast of Java tsunami occurred. This tsunami damaged many houses, hotels, restaurants and shops. Furthermore, fishing gear and boats were found inland near coastal areas.

The social and economic vulnerabilities are standardized and combined with the physical vulnerability to produce the total vulnerability as modified from Cutter, et al. (1997) and Greiving, et al. (2006). The place or total vulnerability can be calculated as follows:

$$\mathbf{Tv} = \mathbf{Pv} + \mathbf{Sv} + \mathbf{Ev}$$

Where: Tv = total vulnerability; Pv = physical vulnerability;

Sv = social vulnerability; and Ev = economic vulnerability.

The total vulnerability of Bali is a combination of three factors that include:

1. Physical vulnerability: distance from the shoreline, ground elevation and slope.
2. Social vulnerability: total population, number of females, elderly and children (based on age), and disabled people.
3. Economic vulnerability: number of poor families and fishermen.

4.3.3.1. The Choice of Vulnerability Factors

Because vulnerability to tsunami devastation is not consistent within the study area, many factors were identified and then information for each factor was collected to produce the primary database. Therefore, it was possible to determine and display the spatial vulnerability within the study area. The physical, social and economic vulnerability factors to consider are:

1. Distance from the shoreline

   The distance from the shoreline will affect the damage and the casualties if a tsunami event occurs. The further the distance from the shoreline, the less will be the run–up height and inundation area of tsunami waves (Nugroho, 2006, Agung, 2006). The classification for distance from the shoreline is used from Bretschneider and Wybro’s formula (1976) in Bernard, et al. (1994):

   $$\boldsymbol{Log}\ \mathbf{Xmax} = \boldsymbol{Log}\ \mathbf{1400} + \frac{\mathbf{4}}{\mathbf{3}}\ \boldsymbol{Log}\ (\frac{\mathbf{Yo}}{\mathbf{10}})$$

   Where: Xmax = Maximum distance of tsunami inundation into the mainland.

   Yo = Tsunami height in shore.

2. Ground elevation

   The ground elevation will affect the run–up height of the tsunami. The higher the height of the tsunami waves in coastal areas, the further the distance of inundation inland unless controlled by rising elevation (Nugroho, 2006, Agung, 2006). The classification for ground elevation is based on Agung (2006).

3. Slope

   Slope affects the distance of inundation. The steeper the slope, the less the inundation area of tsunami waves (Nugroho, 2006). The classification for slope is based on van Zuidam (1985) in Bocco, et al. (2001).

4. Total population

   The larger the population in one village, the greater the difficulties for evacuation and higher potential number of victims if a tsunami occurs in that village (Papathoma et al., 2003). The population number therefore serves as an indicator of the extent of the social impact within the study area (Cutter et al., 1997). For example, where people are concentrated in one village, any single tsunami event can cause more injuries and deaths than if these people were more evenly distributed between other smaller villages (Boulle et al., 1997). In this study, the total population variable was used since there is the potential to mask important information. These data could also be used to determine population density. For example, two areas may have the same population density, but one area may have a vastly greater number of people. It is also an important consideration from an evacuation standpoint (Cutter et al., 1997).

5. Numbers of females

   In the 2004 Indian Ocean tsunami, female victims exceeded males because most of them stayed at home and tended to place the rescue of their children before consideration of their own safety. Females burdened with their children also tired quickly and drowned more easily (Levy and Gopalakrishnan, 2005, Reese et al., 2007). It is also suggested that females may have less ability to recover quickly after the hazard because of family care responsibilities (Cutter et al., 1997, Cutter et al., 2003).

6. Numbers of elderly and children (based on age)

   Both groups may be less able to withstand or resist a tsunami event or respond on their own, and need assistance during the event (Clark et al., 1998, Cutter et al., 1997). The elderly may have mobility issues that increase the burden of care from their family and reduce their resilience (Cutter et al., 2003). In the 2004 Indian Ocean tsunami, one third of the total deaths were children because most of them were at home on the Sunday morning. Both the young and the elderly are more vulnerable to the power of tsunami waves and are less likely to escape (Levy and Gopalakrishnan, 2005). These populations may also have less ability to recover quickly after the hazard through their dependence on other members of the family and community (Cutter et al., 1997). In this study, the definition of age groups is the total numbers of children (0 – 14 years old) and elderly ($\geq$ 60 years old) (Cutter et al., 1997). These data were obtained from the Indonesian Central Bureau of Statistics (BPS).

7. Numbers of disabled people

   This group has difficulty in taking any action to respond to a tsunami event and thus require assistance during the event (Clark et al., 1998, Cutter et al., 1997). Disabled people often have mobility issues that increase the burden of care for their family and contribute to a lack of resilience (Cutter et al., 2003). This group may also has less ability to recover quickly after the hazard because of their dependency (Cutter et al., 1997).

8. Numbers of poor families

   This group has a low capacity to build substantial houses that can be used as shelter, they have less access to health services, and have few resources available to aid in recovery from a tsunami event (Clark et al., 1998, Tran et al., 2009). Poor families living in the lowest quality housing may also have fewer chances to lessen the potential impact from the hazard (Boulle et al., 1997). This group may also have less ability to absorb losses such that their resilience to hazard impact is reduced. On the other hand, wealthy families are able to absorb and recover from losses quickly because of their insurance, and savings (Cutter et al., 2003). In this study, the definition of poor family is a family who live in the lowest quality house, has more than 4 people and their income is below Rp.500,000 (around $AUD 50) per month. This definition is based on the Indonesian Central Bureau of Statistics (BPS) where the data were obtained.

9. Numbers of fishermen

   Fishing activities are always in the greatest impact zone of tsunamis and suffer extensive loss of boats and fishing gear, damage that may take many years to recover (Agung, 2006). In the 2004 Indian Ocean tsunami, harbour and port infrastructure, boats and fishing nets in coastal areas were the first to be affected and become floating debris that generated further damage (Clague et al., 2003, Levy and Gopalakrishnan, 2005). In the 2006 south coast of Java tsunami, many boats and fishing nets were found well inland from coastal areas (Reese et al., 2007). In this study, the definition of fisherman is people who work as fisherman as their main occupation to cover their daily living needs and their family. This definition is also based on the Indonesian Central Bureau of Statistics (BPS) where the data were obtained.

4.3.3.2. The Weighting and Scoring Method

The weighting and scoring method for each factor was varied due to:

1. Demonstration of the factors which make a large or small contribution in determining the tsunami vulnerability area.
2. Demonstration of the differences in contribution of each level in the relevant factor.

Based on these considerations, the classification, weighting and scoring method of each factor is shown in Tables 4.2 and 4.3 respectively.

Table 4.2 shows that “distance from the shoreline” and “ground elevation” factors were weighted equally (40%) and were higher than the “slope” factor because both factors would have strong effects within the coastal area if a tsunami occurred there. Tsunami waves can inundate inland for several hundred meters (related to distance from the shoreline) and swamp most of the coastal infrastructure that is located in flat or low–lying coastal areas (related to ground elevation) (Levy and Gopalakrishnan, 2005, Reese et al., 2007).

Table 4.2. The classification, scoring and weighting for physical factors.

Factors	Class	Score	Weight	Total
1. Distance from the shoreline (Bernard et al., 1994)				
a. < 600 m	Very high vulnerability	5	40	200
b. 600 – 800 m	High vulnerability	4	40	160
c. 800 – 1000 m	Medium vulnerability	3	40	120
d. 1000 – 1200 m	Low vulnerability	2	40	80
e. > 1200 m	Very low vulnerability	1	40	40
2. Ground elevation (Agung, 2006)				
a. < 1 m	Very high vulnerability	5	40	200
b. 1 – 2 m	High vulnerability	4	40	160
c. 2 – 3 m	Medium vulnerability	3	40	120
d. 3 – 4 m	Low vulnerability	2	40	80
e. > 4 m	Very low vulnerability	1	40	40
3. Slope (Bocco et al., 2001)				
a. < 2%	High vulnerability	3	20	60
b. 2 – 6%	Medium vulnerability	2	20	40
c. > 6%	Low vulnerability	1	20	20

Table 4.3. The scoring and weighting for social and economic factors.

Factors (a)	Number (b)	Proportion * (c)	Score ** (d)	Weight
1. Social				
a. Total population	P	(b) / Total population	(c) / maximum value of proportion	25
b. Female	F	(b) / Total female	(c) / maximum value of proportion	25
c. Aged ***	A	(b) / Total aged	(c) / maximum value of proportion	25
d. Disabled people	D	(b) / Total disabled people	(c) / maximum value of proportion	25
2. Economic				
a. Poor families	PF	(b) / Total poor families	(c) / maximum value of proportion	50
b. Fishermen	F	(b) / Total fishermen	(c) / maximum value of proportion	50

* Determine percent of factors in each village to total number in one sub–district
** Place value on same scale for all social and economic variables
*** For numbers of elderly people and children

Source: Cutter, et al. (1997).

The method for calculating the social and economic vulnerability areas is the same for each factor, and is based on Cutter, et al. (1997). It showed one of the ways to summarize vulnerability values to a cumulative and spatially–based score. For the classification of social and economic vulnerabilities, the higher score will be more vulnerable than the lower score (Cutter et al., 1997). This method has the advantage of being easy to understand and flexible allowing the inclusion of other factors in a vulnerability assessment and applying it to different spatial levels, such as sub–district or county (Greiving et al., 2006).

The following steps and an example explain the calculation process:

1. Step 1: Calculate X to determine the percentage of the sub–district's female numbers in each village.

$$\mathbf{X = \frac{Number\ of\ females\ in\ census\ village}{Number\ of\ females\ in\ sub-district}}$$

2. Step 2: Calculate female number score by dividing X by maximum X to give values in the same scale as other social or economic factors.

$$\mathbf{Female\ number\ score = \frac{X}{Maximum\ X}}$$

Table 4.4. The example of calculating social vulnerability in the "number of females" factor.

Village	Number of females in census village	Number of females in sub–district	X	Female number score
Kedonganan	2,755	18,709	0.147	0.418
Tuban	6,587	18,709	0.352	1.000
Kuta	5,610	18,709	0.300	0.852
Legian	1,674	18,709	0.090	0.256
Seminyak	2,083	18,709	0.111	0.315

Thus, in this example, Tuban Village is most vulnerable, followed by Kuta, Kedonganan, Seminyak and finally Legian Villages.

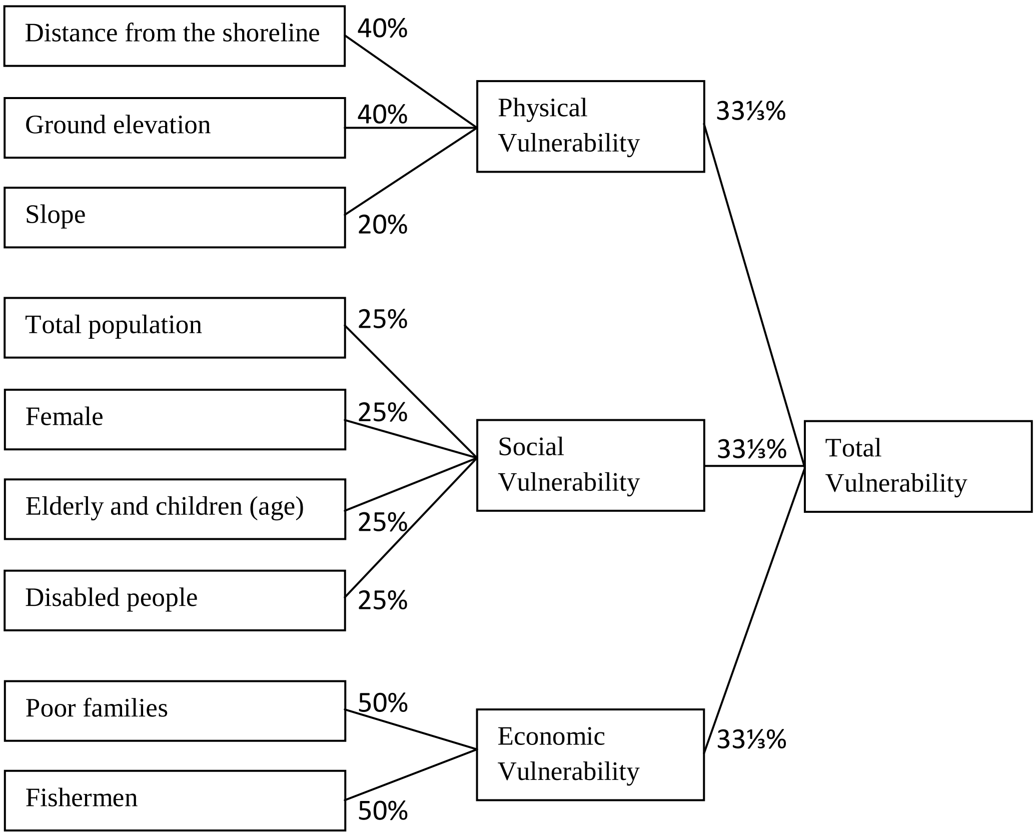


Figure 4.2. The weighting method for physical, social, and economic factors.

For the weighting method, all factors that affected the social and economic vulnerability were weighted equally because each factor was given the same proportion for each vulnerability (Cutter et al., 1997) and is shown in Figure 4.2.

The results are presented as vulnerability maps to show the spatial distribution for each vulnerability.

Weighting and scoring methods can be summarised as follows:

1. The “distance from the shoreline” and “ground elevation” factors in physical vulnerability are a big proportion followed by “slope” factors. In social and economic vulnerabilities, all factors are weighted equally.
2. Scores in each class are given different values in order to show a high score indicating high vulnerability.
3. The total score is the multiplication of the scores and weights of each class.

The weighting method in this study is based on justification by analysing the factors contribution in determining the tsunami vulnerable area where the factor that has the control functions will be given the bigger weight (Nugroho, 2006).

The scores and weightings that are outlined here are based on the references that are cited. It is important to rank and weight the variables according to their relative importance and impact, but it is equally important that the method is replicable and locally relevant at local government levels. Many more variables may be added to each level of the vulnerability assessment and weightings may be altered in importance. The weightings that have been used in this case study are not absolute, but they are based on the findings of other researchers (Nugroho, 2006, Agung, 2006, Cutter et al., 1997, Bernard et al., 1994, Bocco et al., 2001, Papathoma et al., 2003).

4.3.3.3. The Combination Method

All variables in this study were represented as spatial layers. It is a layer that contains geographic information, such as elevation, building types, etc. The three factors are combined using an overlay method to obtain one new layer (Nugroho, 2006). In this study, this method is used for combining the physical vulnerability factors, the total vulnerability and risk assessments for each region.

As outlined in Nugroho (2006), the class range can be calculated as follows:

$$\text{The class range} = \frac{\sum \text{highest score} - \sum \text{lowest score}}{\sum \text{class total}}$$

4.3.4. Risk Assessment

Risk is stated as a function of hazard and vulnerability. It means that an area with high inundation is not automatically at high risk. On the other hand, a highly vulnerable area is not necessarily or automatically also high risk.

According to the International Strategy for Disaster Reduction (ISDR) (2002), the risk assessment can be calculated as follows:

Risk (R) = Hazard (H) x Vulnerability (V),

For calculation purposes, the value for each component of risk is determined as: H = inundation zone score and V = total vulnerability score.

In this study, this formula was used because it is the basis for risk calculation. Hazard represents the location, intensity and probability of the hazards, while vulnerability represents the physical, social and economic components that affected the hazards (ISDR, 2002).

4.3.4.1. Risk Analysis

There are 5 stages to be analysed, which are:

1. Hazard analysis, including area administration and land use.
2. Buildings and infrastructure, such as private houses, hotels, hospitals, clinics, schools, roads, places of worship, shops, malls, small industries, government offices, banks, restaurants and traditional markets.
3. Social variables, such as total population, females, elderly, children and disabled people.
4. Economic variables, such as traditional markets, business centres (shops and malls), agriculture, agroforestry and small industries.
5. Special sites and lifelines, such as hospitals, clinics, schools, electricity and gas stations.

4.4. Data Processing

4.4.1. Maps Preparation

Three types of spatial data sources have been used, namely analogue maps, satellite images and digital data.

4.4.1.1. Paper Map Data Processing

Paper maps of the topography were scanned and rectified into the World Geodetic System (WGS) 84 zone 50S projection. From the resulting raster data, relevant information (such as elevation points and administration boundaries) was then digitized on–screen, resulting in vector outputs. Digitization is done for all objects in the map that is needed for the next process, such as roads, buildings, administration boundaries, etc. These data are processed with GIS software, namely ArcGIS version 9.3 (ESRI, 2008).

The paper maps that have been used in this study are two topographic map sheets for the Denpasar and Banjar Kertajiwa Regions at a scale of 1:25,000, from 1999.

4.4.1.2. Satellite Image Data Processing

Another input for GIS in this study is satellite imagery. This data were processed with software image processing, namely ER Mapper version 7.0 (Erdas, 2005).

Firstly, the image data were cropped to the study area to expedite processing. The image data were then rectified to correct the geometric and radiometric distortions to features on the Earth's surface (World Geodetic System (WGS) 84 zone 50S projection). Lastly, these data were enhanced to increase the image quality to facilitate easier image analysis.

The image satellite that has been used in this study is bathymetry image derived from ETOPO1 satellite.

4.4.1.3. Digital Data Processing

In this study, most of the digital data, such as land use, building types and elevation points, was acquired in AutoCad format. This data was therefore converted using MapInfo Professional version 8.5 (Pitney Bowes Business Insight, 2006) into shapefile format for analysis in ArcGIS.

For the hazard assessment, the DEM (Digital Elevation Model) layer that was derived from the elevation layer was used for classifying the inundation zones. For the vulnerability assessment, the DEM and shoreline layers were used for classifying the distance from the shoreline, ground elevation and slope classes in the physical vulnerability assessment. The total population, females, elderly and children (based on age group), disabled people, poor families and fishermen layers were used for analysing the social and economic vulnerabilities of each region based on the sub–district. For the risk assessment, the hazard layer was multiplied with the vulnerability layer using Map Algebra in ArcGIS to obtain the risk layer. Moreover, the risk layer was overlaid with the land use layer for the risk analysis for each region. The layers that were used in this study will be explained in the following chapter.

4.4.1.4. Digital Elevation Model (DEM) Preparation

DEM data is digital data in raster format that has information about coordinate positions (x,y) and elevation values (z) in each pixel. DEM data is used to describe the topographic condition in the study area. In this study, DEM data is used as important data for analysing the hazard and physical vulnerability assessments. In this study, the DEM data were analysed in raster format and had a spatial resolution of 5 m x 5 m.

The DEM was made by interpolating elevation data from different sources. In this study, the elevation data is derived from the theodolite surveys, spot heights, and elevation points from the topographic map sheets. These data are then combined into a single file containing individual data points with elevation values (z values). The elevation points were then interpolated using the kriging method, resulting in a raster DEM surface. In this study, the kriging method was used for the DEM interpolation because the kriging method is an appropriate way for creating elevation surface in flat low–lying areas as it generates a smooth surface through gaps between known points (Reuter et al., 2007). It can be seen that there were several gaps between elevation points in the study area. Moreover, most areas in Kuta and Sanur Regions were very flat; it is only around 12 m above sea level (see in Figures 4.3 and 4.4).

4.4.1.5. Land Use Mapping

The land use maps were created by using the extraction from urban planning maps. The method has been explained in the previous chapter (see Chapter 4.4.1.3). In this study, major land uses, namely buildings (such as hotels, villas, restaurants, shops, malls, private houses and temples), mangroves, lakes, rivers, bareland, agroforestry, grassfields, ricefields, open spaces and sand.

The land use maps were then used to calculate the area of each land use that is located within each zone at risk from tsunamis in the study area.

4.4.1.6. Social and Economic Vulnerability Mapping

Social and economic vulnerability maps were created by inserting the value of each social and economic factor in each village. Then, each layer was calculated through their attributes using the method that has been explained in the previous chapter (see Chapter 4.3.3.2). The administration (sub–district) layer provided the area units within which social and economic factors in each village were calculated.

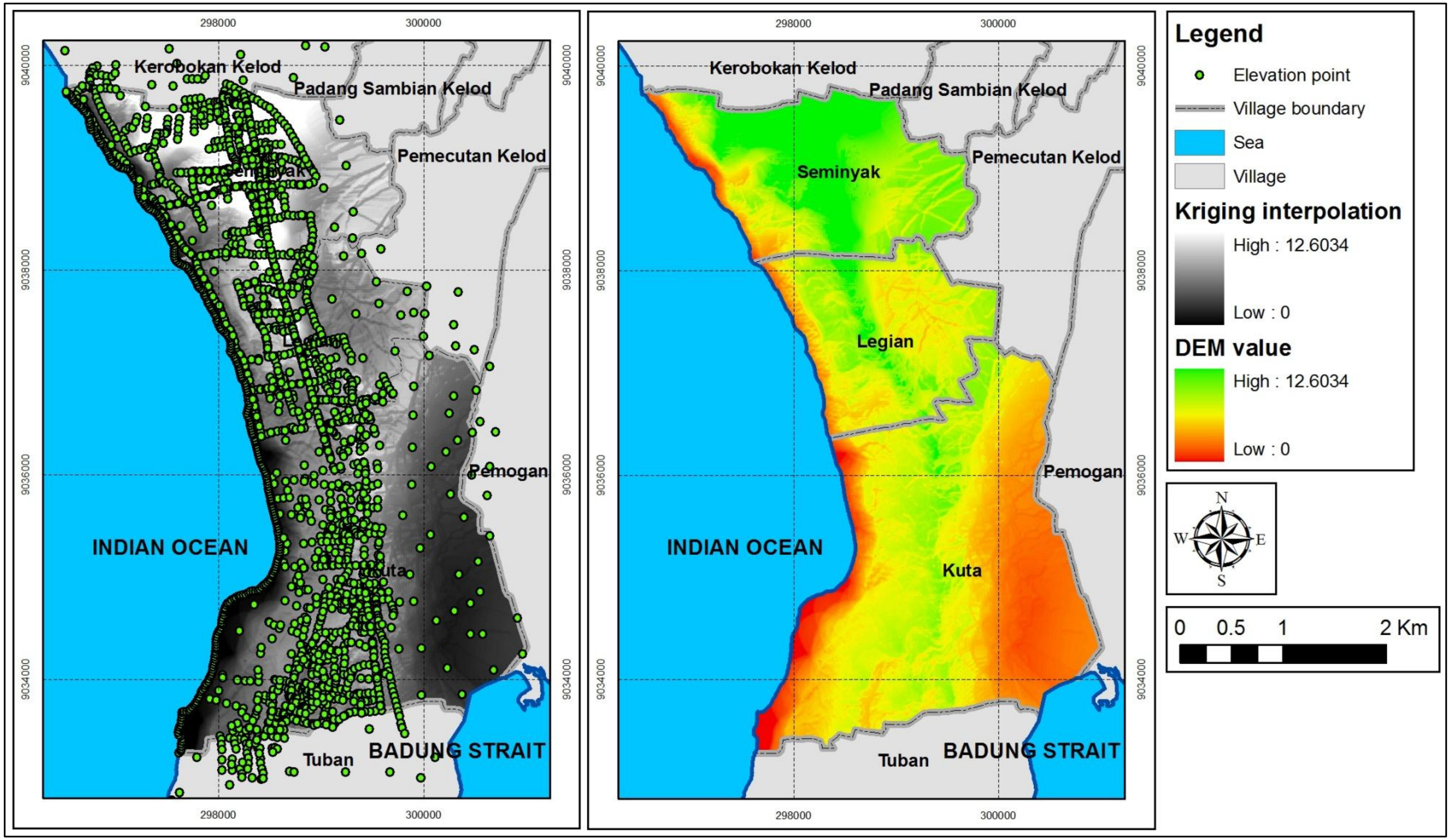


Figure 4.3. The distribution of elevation points and DEM in Kuta Region.

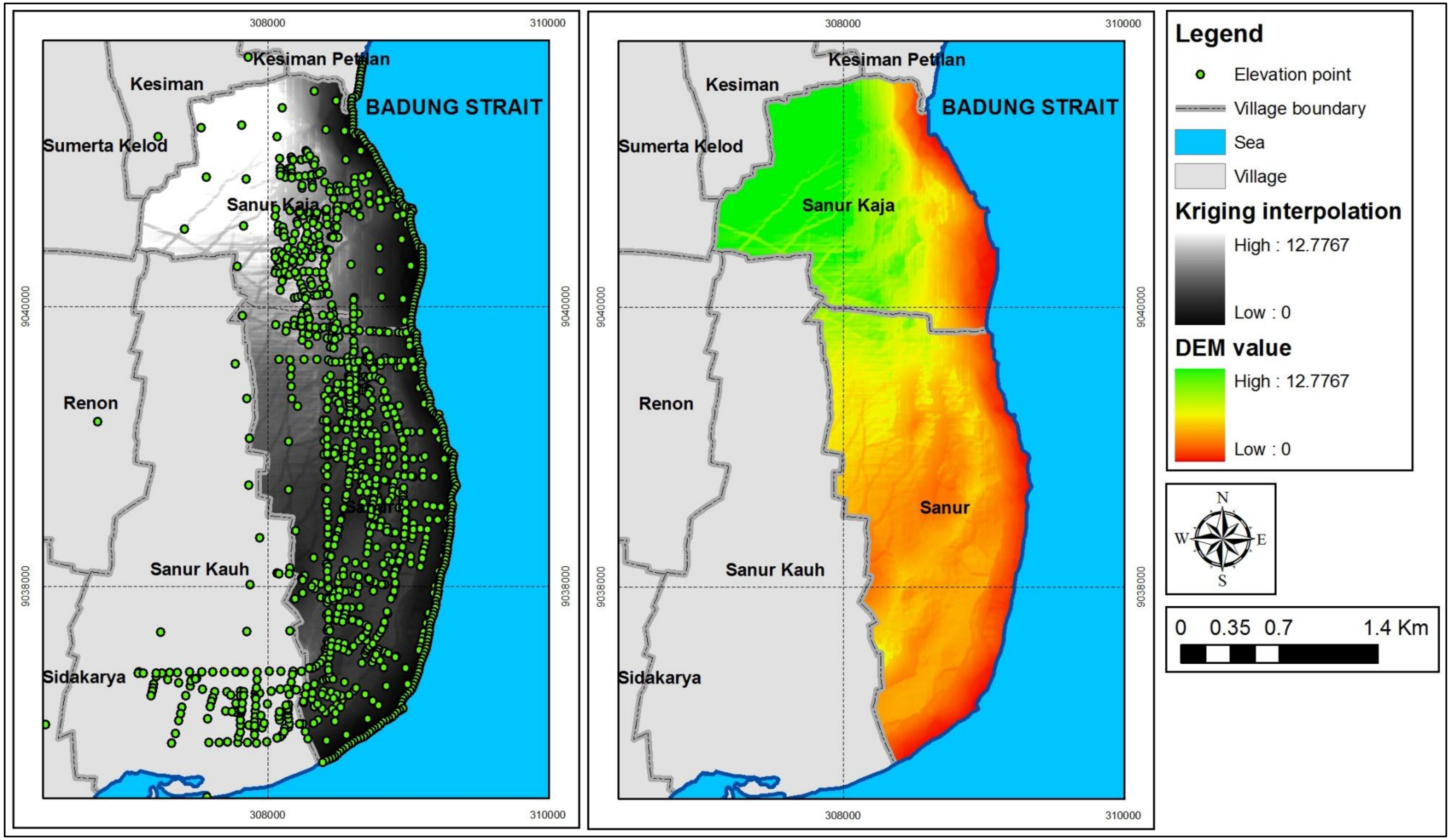


Figure 4.4. The distribution of elevation points and DEM in Sanur Region.

4.5. Mapping of Outputs

GIS is used to analyse, aggregate and operate the data and to visualize analysis results. The output of each analysis is presented in a separate map: (i) hazard map (inundation map), (ii) physical, social and economic vulnerability maps, and (iii) risk map. Because the difference in vulnerability is not an absolute number, rather it is a relative comparison, the vulnerability is shown in five different colors, from dark color as lower to bright color as higher intensity. However, for the analysis purpose, those five colors (from dark to bright color) are read as: i) very low, ii) low, iii) medium, iv) high and v) very high.

In this study, the spatial resolution that has been used in data processing was grid cell size of 5m x 5m. Moreover, the scale of mapping outputs that have been used was 1:500. The reasons for using this specific spatial resolution and scale was in order to synchronize all input data that are in different spatial resolution and scale to have one specific spatial resolution and scale mapping, and to create detailed maps for the risk analysis in the risk assessment method.

4.6. Summary

The methods, such as tsunami potential, hazard, vulnerability and risk assessments that have been explained in this chapter were applied in Kuta and Sanur Regions as a case study using GIS technology. The reason to choose Kuta and Sanur Regions in Bali as a case study is because Bali is located on the boundary of the Eurasian and Indo–Australian Plates that vulnerable to the tsunami hazard. The detailed reason has been explained in the previous chapter (see Chapter 1.2). The results of all assessments in this study will be explained in the following chapter.

CHAPTER FIVE – Results

5.1. Research Framework

The detailed research framework is deliberately simple to understand and reflects activities that need to be carried out in the assessment process (see Figure 5.1). It consists of three main stages, namely 1) hazard assessment, 2) vulnerability assessment, and 3) risk assessment. Hazard assessment is determined by the highest tsunami run–up that occurs in the study area. It also includes potential assessment that is determined on tsunami and submarine earthquake frequency and magnitude of occurrence. Vulnerability assessment is determined by the vulnerability factors of the study area to the tsunami hazard. It also includes three factors that influence vulnerability, namely physical, social and economic vulnerabilities. The variables of these vulnerabilities are selected based on the previous studies and the aftermath surveys of tsunamis, especially the 2004 Indian Ocean tsunami and the 2006 south coast of Java tsunami (Levy and Gopalakrishnan, 2005, Reese et al., 2007). Finally risk assessment is determined by the combination of hazard and vulnerability assessments. It also includes risk analysis for area administration, building and infrastructure analysis, social and economic variables, and special sites and lifelines. This research framework can also be used as a model for other coastal city managers in Indonesia for tsunami risk assessment studies.

Output maps play an important role in showing the tsunami inundation zones, physical, social and economic vulnerability distributions, and the tsunami risk pattern. These criteria are important, especially in ensuring that the approach is easily implemented by local government and understood by local people.

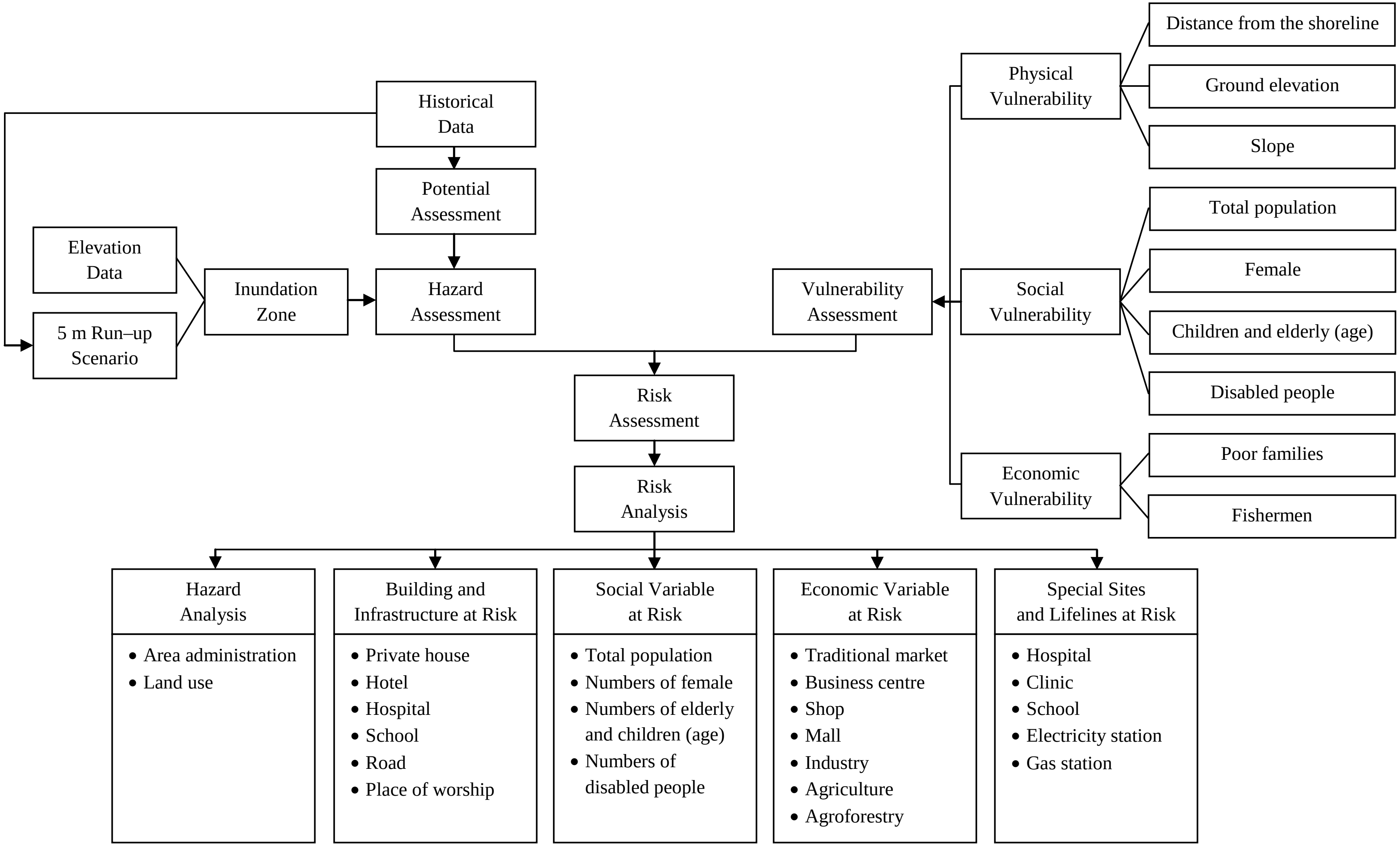


Figure 5.1. The research framework and analysis diagram for a tsunami risk assessment.

According to Ferrier and Haque (2003), the hazard assessment framework should consider the individual or institutional perception about the risk. Therefore, for practical matters, the methods in the risk assessment should be flexible to use and easy to understand by the local managers who usually have different levels of educational backgrounds. Cutter et al. (2000) emphasized the importance of hazard research helping to solve practical problems.

5.2. Hazard Assessment Analysis

5.2.1. Tsunami Potential Assessment

5.2.1.1. Historical Record

The historical data of tsunami and submarine earthquake events in Bali were collected (see Tables 5.1 and 5.3).

Table 5.1. The tsunami events in Bali.

Date	Location	Tsunamigenic Source			Tsunami Parameters	
		Earthquake		Volcano	Tsunami Intensity (K_0)	Run - up Height (m)
		Focal Depth (Km)	Magnitude			
22 Nov 1815	Bali	122	7.0		IV	No data
8 Nov 1818	Bali	600	8.5		III	3.5
13 May 1857	Bali	50	7.0		III	3.4
21 Jan 1917	Bali	33	6.6		III	2.0
8 Jan 1925	Bali	No data	No data		I	0.7
19 July 1930	Bali	33	6.5		I	0.1
30 Mar 1963	Bali			Agung	No data	No data
17 Dec 1979	Bali : Karang Asem	33	6.6		No data	No data
13 April 1985	Bali : Denpasar	99	6.2		III	2.0
2 June 1994	West Bali	18	7.8		IV	4.4
3 June 1994	Bali : Soka Beach	26	6.6		III	3.7
17 July 2006	Bali : Benoa Cape	34	7.7		I	0.4
12 Sep 2007	Bali : Benoa Cape	34	8.4		I	0.2

Source: Hamzah, et al. (2000), ICMMG (2010), NGDC (2010) and Rynn (2002).

From the historical dataset of tsunami events in Bali (see Table 5.1), it has been possible to calculate the probability (return periods) for tsunamis of different intensity based on Cutter's formula (1997) (see Table 5.2). The tsunami intensity scale (K_0) and the calculation method is outlined in Chapter 4.3.1.

Table 5.2. The probability of tsunami events in Bali from 1815 to 2007.

Tsunami Intensity (K_0)	Wave height for each tsunami intensity scale according to Soloviev (1978)	Number of events	Probability/return periods (years)
I	+ 0.5 m	4	48
II	+ 1.0 m	No data	No data
III	+ 2.0 m	5	38
IV	+ 4.0 m	2	96

This probability calculation was based on Table 5.1, but the author excluded the "no data" event.

Table 5.1 shows that from 1815 to 2007 (192 years), Bali has 13 records of tsunami events if we accept the accuracy of all data before the 20th century. Most of the tsunami events i.e. 92% (12 events) in Bali were caused by submarine earthquakes, while only one event was generated by volcanic eruption, from Mt. Agung. Mt. Agung is located in the Karangasem District in East Bali. It shows that submarine earthquakes are the major factor that triggers tsunami events in Bali. Therefore, both tsunami and earthquake historical datasets are very important in determining the probability of tsunamis in tsunami hazard assessment (Clague et al., 2003).

From the historical dataset of submarine earthquake events in Bali (see Table 5.3), it is also possible to calculate the probability of earthquakes of different magnitudes (see Table 5.4). The magnitude of earthquake (M_s) and the calculation method is outlined in Chapter 4.3.1. Clearly, submarine earthquakes with large magnitudes are less frequent than the small ones (see Table 5.4).

Table 5.3. The submarine earthquake events in Bali.

Date	Location	Earthquake Parameters		Associated with tsunami
		Focal Depth (Km)	Magnitude	
22 Nov 1815	Bali	122	7.0	Yes
8 Nov 1818	Bali	600	8.5	Yes
13 May 1857	Bali	50	7.0	Yes
29 Mar 1862	Bali : Buleleng	No data	5.9	No
11 July 1890	Bali : Negara	No data	5.9	No
21 Jan 1917	Bali	33	6.6	Yes
8 Jan 1925	Bali	No data	No data	Yes
27 April 1930	Bali	No data	No data	No
19 July 1930	Bali	33	6.5	Yes
30 Oct 1938	Bali	No data	No data	No
18 May 1963	Bali	65	6.0	No
14 July 1976	Bali : Seririt Busung Biru	40	6.5	No
26 Jan 1977	Bali : Bangli	33	5.2	No
21 May 1979	Bali	43	5.4	No
20 Oct 1979	Bali : Karang Asem	38	6.0	No
17 Dec 1979	Bali : Karang Asem	33	6.6	Yes
13 April 1985	Bali : Denpasar	99	6.2	Yes
2 June 1994	West Bali	18	7.8	Yes
3 June 1994	Bali : Soka Beach	26	6.6	Yes
1 Jan 2004	Bali	45	5.8	No
16 April 2004	Bali	96	5.5	No
17 July 2006	Bali : Benoa Cape	34	7.7	Yes
12 Sep 2007	Bali : Benoa Cape	34	8.4	Yes
18 Sep 2009	Bali : Denpasar	79	5.7	No

Source: Hamzah, et al. (2000), ICMMG (2010), NGDC (2010) and Rynn (2002).

Table 5.4. The probability of submarine earthquake events in Bali from 1815 to 2009.

Earthquake Magnitude (M_s)	Number of events	Probability/return periods (years)
5 – 6	9	22
>6 – 7	8	24
>7 – 8	2	97
>8	2	97

This probability calculation was based on Table 5.3, but the author excluded the "no data" event.

Table 5.3 shows that Bali has 24 records of submarine earthquake events from 1815 to 2009 (194 years) with a magnitude from 5.2–8.5 M_s and 50% (12 events) of the submarine earthquake events were associated with tsunamis. From

Table 5.4, 42% were earthquakes with a magnitude from 5–6 M_s, 38% were earthquakes with a magnitude from >6–7 M_s, and others 10% were earthquakes with a magnitude from >7–8 M_s and >8 M_s.

The historical dataset shows that tsunamis in Bali were generated by submarine earthquakes with a magnitude from 6.2–8.5 M_s and on focal depth from 18–600 km (see Table 5.1). Moreover, Figure 5.2 shows the plot of tsunami events that occurred in Bali and the surrounding areas. The plot of data is based on historical record (Rynn, 2002, ICMMG, 2010, NGDC, 2010, Hamzah et al., 2000).

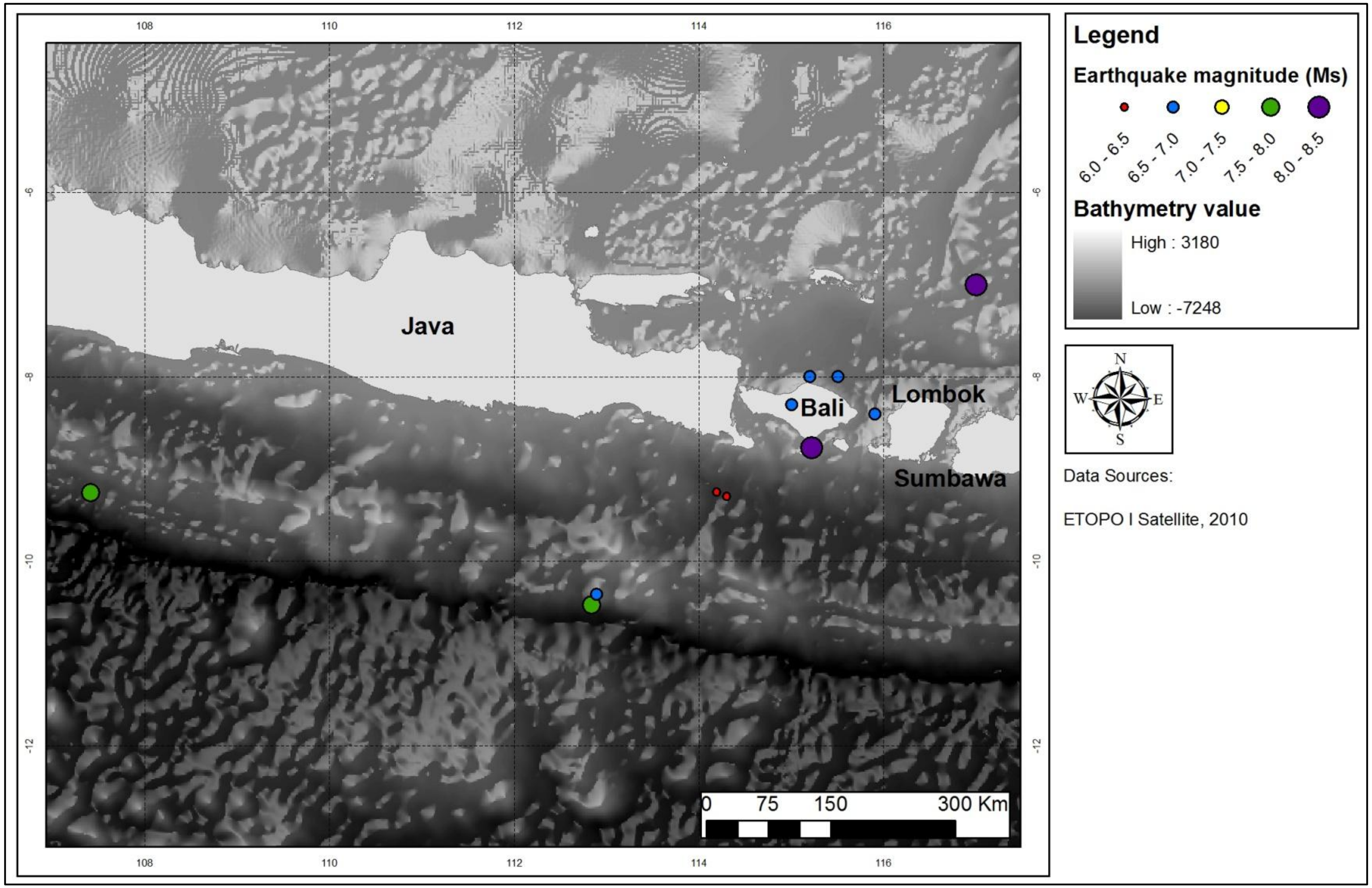


Figure 5.2. The tsunami events in Bali and surrounding areas.
Source: Hamzah, et al. (2000), ICMMG (2010), NGDC (2010) and Rynn (2002). This plot data was based on Table 5.1, but the author excluded the "no data" event.

5.2.2. Hazard Assessment

5.2.2.1. Estimation of the Worst–Case Scenario

Historical data was used to decide the worst–case tsunami run–up scenario for the hazard assessment. The worst–case scenario for tsunami run–up is based on the maximum run–up height that occurred in Bali on 2nd June 1994, which was 4.4 m (see Table 5.1) (Hamzah et al., 2000, ICMMG, 2010, NGDC, 2010, Rynn, 2002).

5.2.2.2. Tsunami Inundation Zones

In Kuta Region, Kuta Village would be most impacted if a tsunami hit Kuta Region's coast, because it is located in relatively flat low–lying areas (around 96% areas of Kuta Village has elevations below 5 m). It is followed by Legian and finally Seminyak Villages. On the other hand, Seminyak Village will suffer less because around 20% of the area has an elevation below 5 m (see Figure 5.3).

In Sanur Region, Sanur Village will suffer most from a tsunami event because around 87% of the area is flat (below 5 m). Sanur Kaja Village would be inundated less because it is only around 25% of the area has an elevation below 5 m (see Figure 5.4).

By overlaying these zones with the administrative boundaries, it is possible to locate and calculate all villages in both regions that may be inundated by future tsunamis (see Table 5.5).

Table 5.5. The administrative areas that are inundated by tsunami.

Region	Village	Type	The inundation zones (km^2)				
			Very high inundation (0 – 2 m asl)	High inundation (2 – 3 m asl)	Medium inundation (3 – 4 m asl)	Low inundation (4 – 5 m asl)	Very low inundation (> 5 m asl)
Kuta	Kuta	Urban	2.235	1.058	2.224	1.782	0.336
	Legian	Urban	0.092	0.149	0.823	0.988	0.803
	Seminyak	Urban	0.151	0.096	0.203	0.293	2.890
Sanur	Sanur	Urban	0.509	1.351	0.641	0.377	0.446
	Sanur Kaja	Urban	0.252	0.092	0.108	0.143	1.814

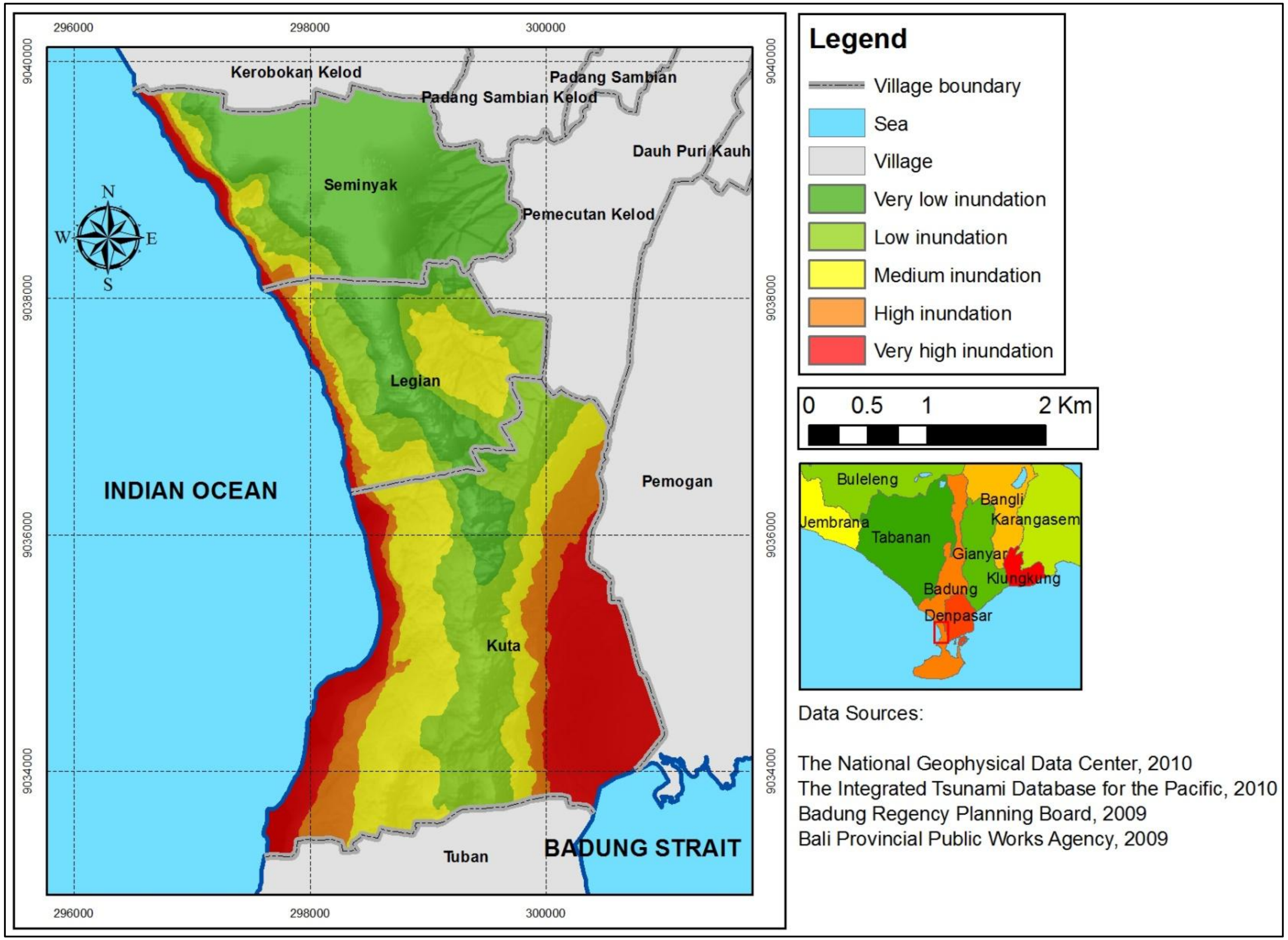


Figure 5.3. The hazard map of the Kuta Region based on 5 m run–up scenario.

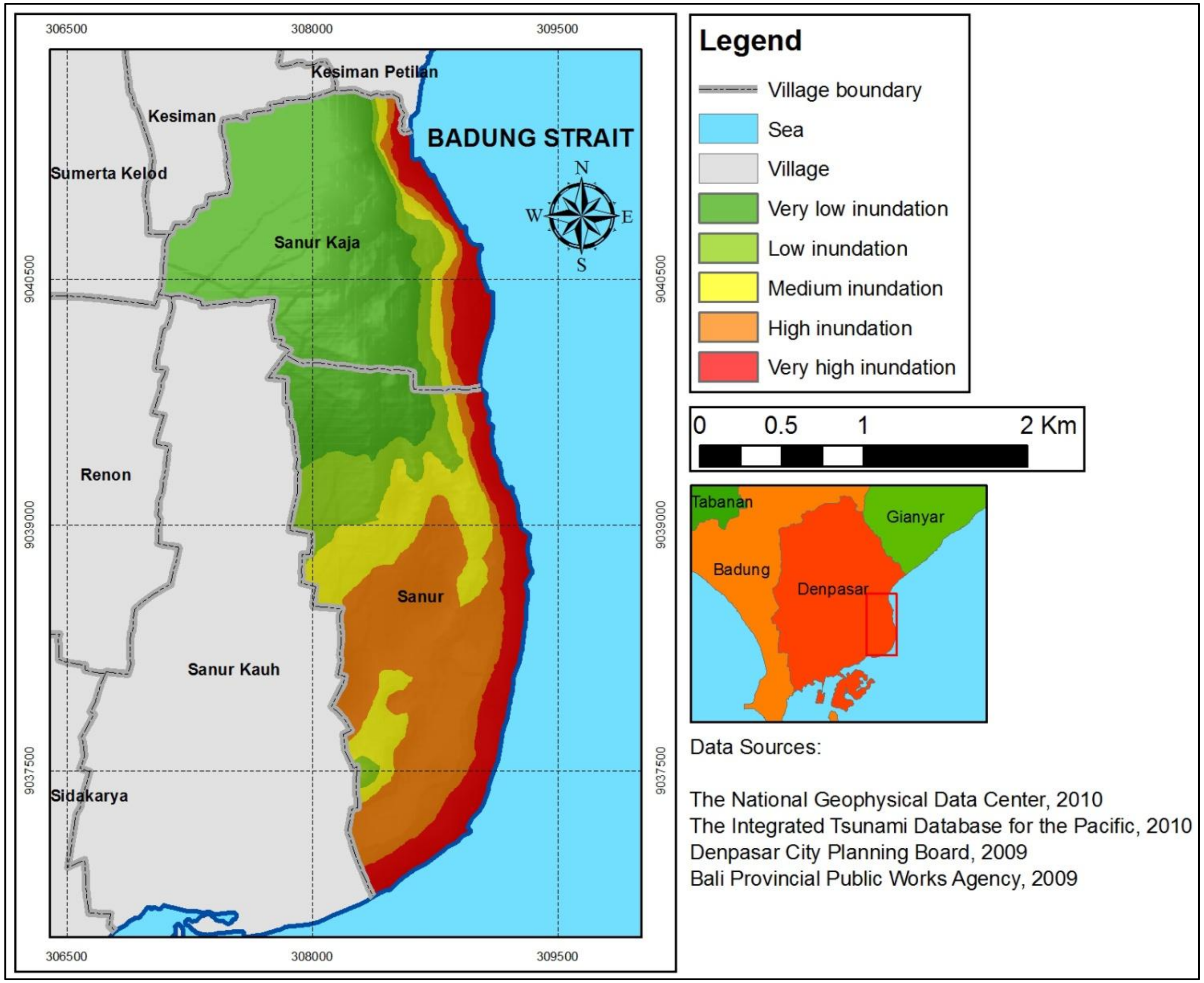


Figure 5.4. The hazard map of the Sanur Region based on 5 m run–up scenario.

Approximately 71% of the Kuta Region area would be inundated by a maximum tsunami run–up of 5 m (see Figure 5.5). The total area that will be inundated is approximately 10.102 km^2, mainly in Kuta and Legian Villages (see Figure 5.3). In Sanur Region, 60% of the area would be flooded if a tsunami hit the coastal area with run–up of 5 m, and the total inundation area is approximately 3.475 km^2 (see Figure 5.6). It will focus on Sanur Village located in flat low–lying areas (see Figure 5.4). The calculation of the inundation area is based on the maximum 5 m of tsunami run–up

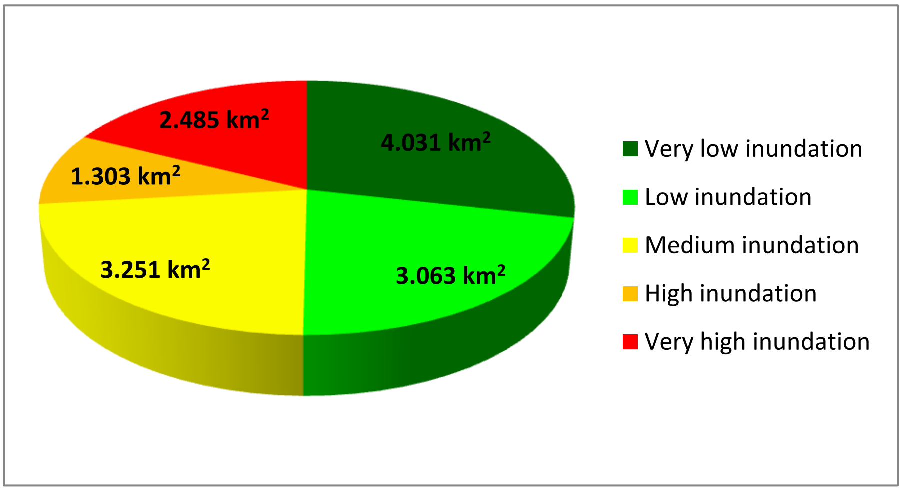


Figure 5.5. The total inundation area in Kuta Region.

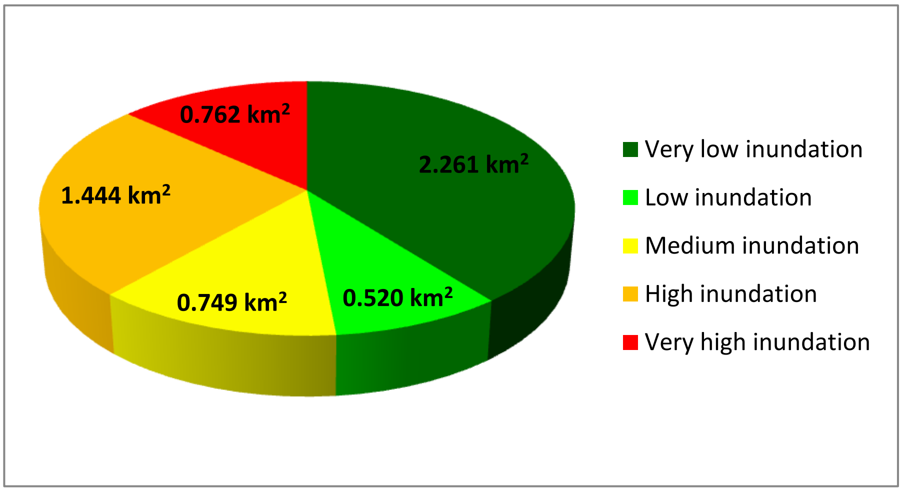


Figure 5.6. The total inundation area in Sanur Region.

5.3. Vulnerability Assessment Analysis

5.3.1. Physical Vulnerability

In this study, there are three factors that affect physical vulnerability, namely distance from the shoreline, ground elevation and slope. The reasons of choosing these physical factors have been explained in Chapter 4.3.3.1.

Based on the distance from the shoreline factor, over half (60%) of the Kuta Region lies within 1,200 m of the shoreline, and is therefore vulnerable to tsunami waves. On the other hand, Sanur Region has 94% of the total area vulnerable if a tsunami occurs there based on this factor (see Figure 5.7).

Based on the ground elevation factor, 50% of the Kuta Region area is vulnerable to tsunamis because it is very flat area close to the shoreline and below 4 m elevation. Similarly, 52% of the Sanur Region might be vulnerable if tsunamis occur there based on this factor (see Figure 5.8).

Based on the slope factor, both Kuta and Sanur Regions are highly vulnerable to tsunamis because their areas are very flat. It can be seen that most of both Kuta and Sanur areas have a slope of less than 2 % (95% of the Kuta Region and 93% of the Sanur Region), and are thus made more vulnerable to tsunamis based on this factor (see Figure 5.9).

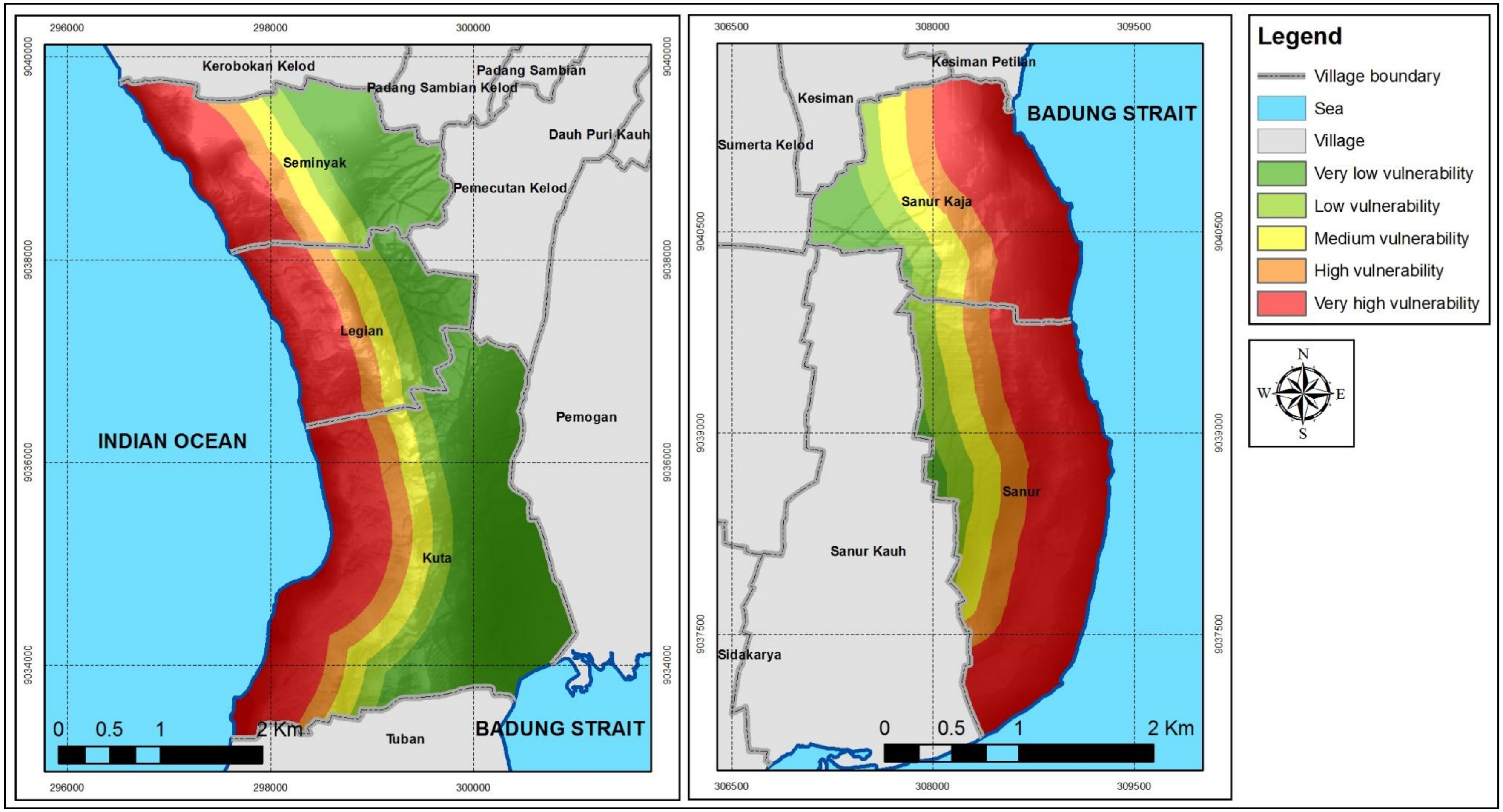


Figure 5.7. The physical vulnerability map of the Kuta and Sanur Regions based on distance from the shoreline.

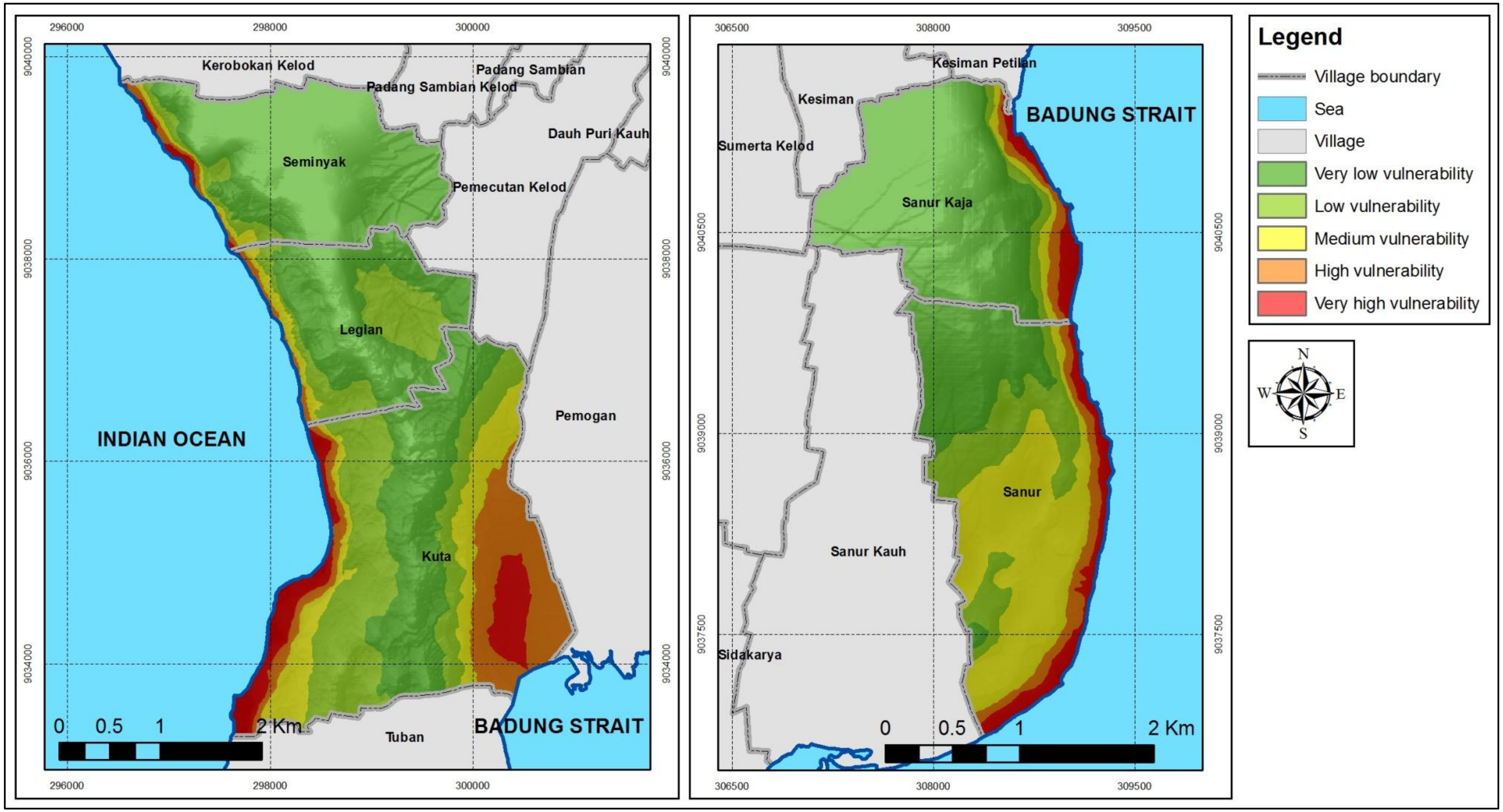


Figure 5.8. The physical vulnerability map of the Kuta and Sanur Regions based on ground elevation.

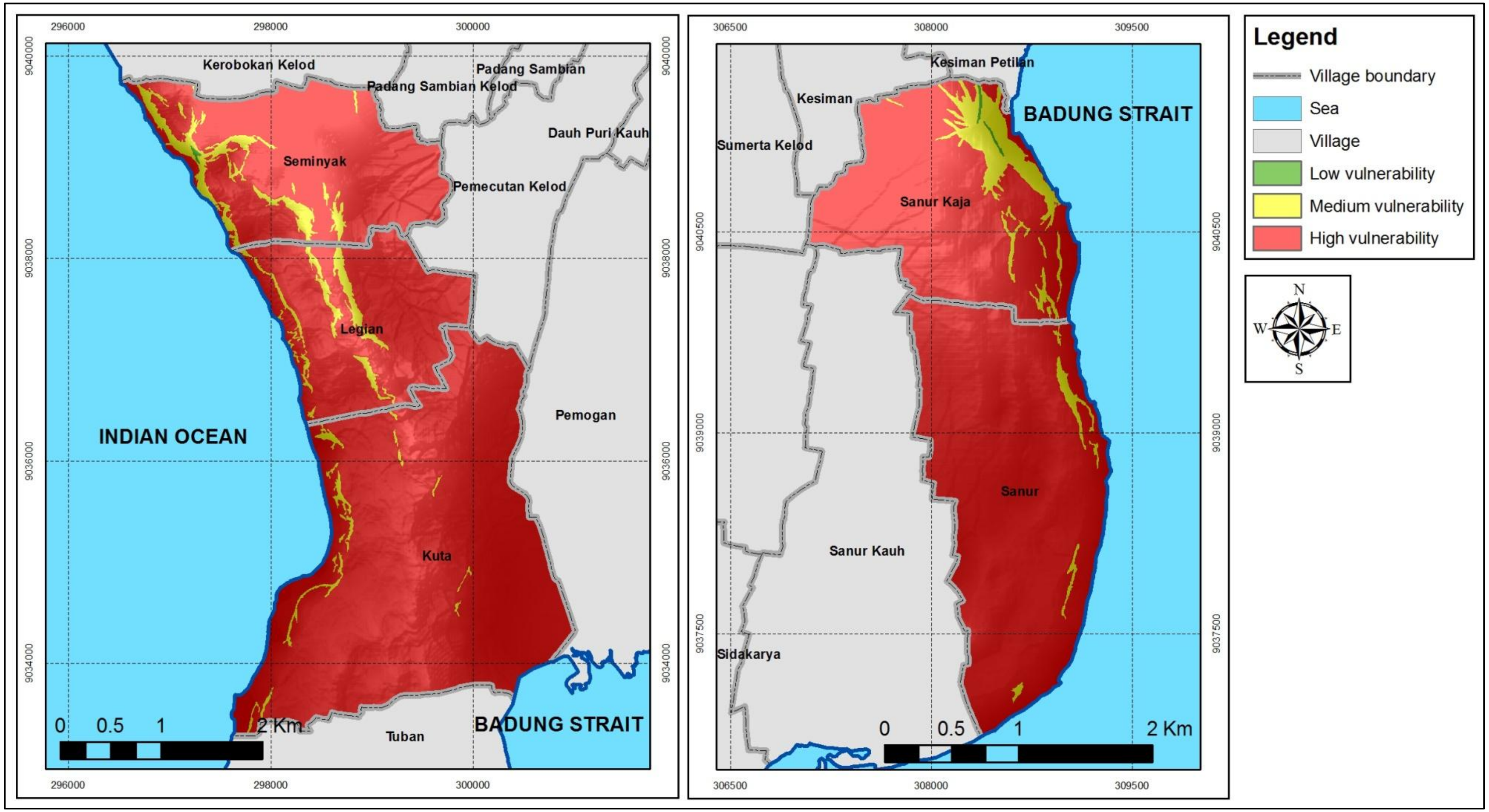


Figure 5.9. The physical vulnerability map of the Kuta and Sanur Regions based on slope.

The three physical vulnerability factors, represented as raster data layers, were overlaid through addition to obtain a "physical vulnerability" layer (see Chapters 4.3.3.2 and 4.3.3.3 for the scoring and combination methods). For Kuta Region, the highest score from the calculation is 460 and the lowest score is 120, so the class range can be calculated as follows:

$$\text{PV class range for the Kuta Region} = \frac{460 - 120}{5} = 68$$

From the class range result, the physical vulnerability assessment of the Kuta Region can be classified into five classes (see Table 5.6).

Table 5.6. The classification for physical vulnerability map of the Kuta region.

Physical Vulnerability Class Range	Class
a. ≤ 188	Very low vulnerability
b. 189 – 256	Low vulnerability
c. 257 – 324	Medium vulnerability
d. 325 – 392	High vulnerability
e. > 392	Very high vulnerability

For Sanur Region, the highest score from the calculation is 460 and the lowest score is 140, so the class range can be calculated as follows:

$$\text{PV class range for the Sanur Region} = \frac{460 - 140}{5} = 64$$

From the class range result, the physical vulnerability assessment of the Sanur Region can be classified into five classes (see Table 5.7).

Table 5.7. The classification for physical vulnerability map of the Sanur region.

Physical Vulnerability Class Range	Class
a. ≤ 204	Very low vulnerability
b. 205 – 268	Low vulnerability
c. 269 – 332	Medium vulnerability
d. 333 – 396	High vulnerability
e. > 396	Very high vulnerability

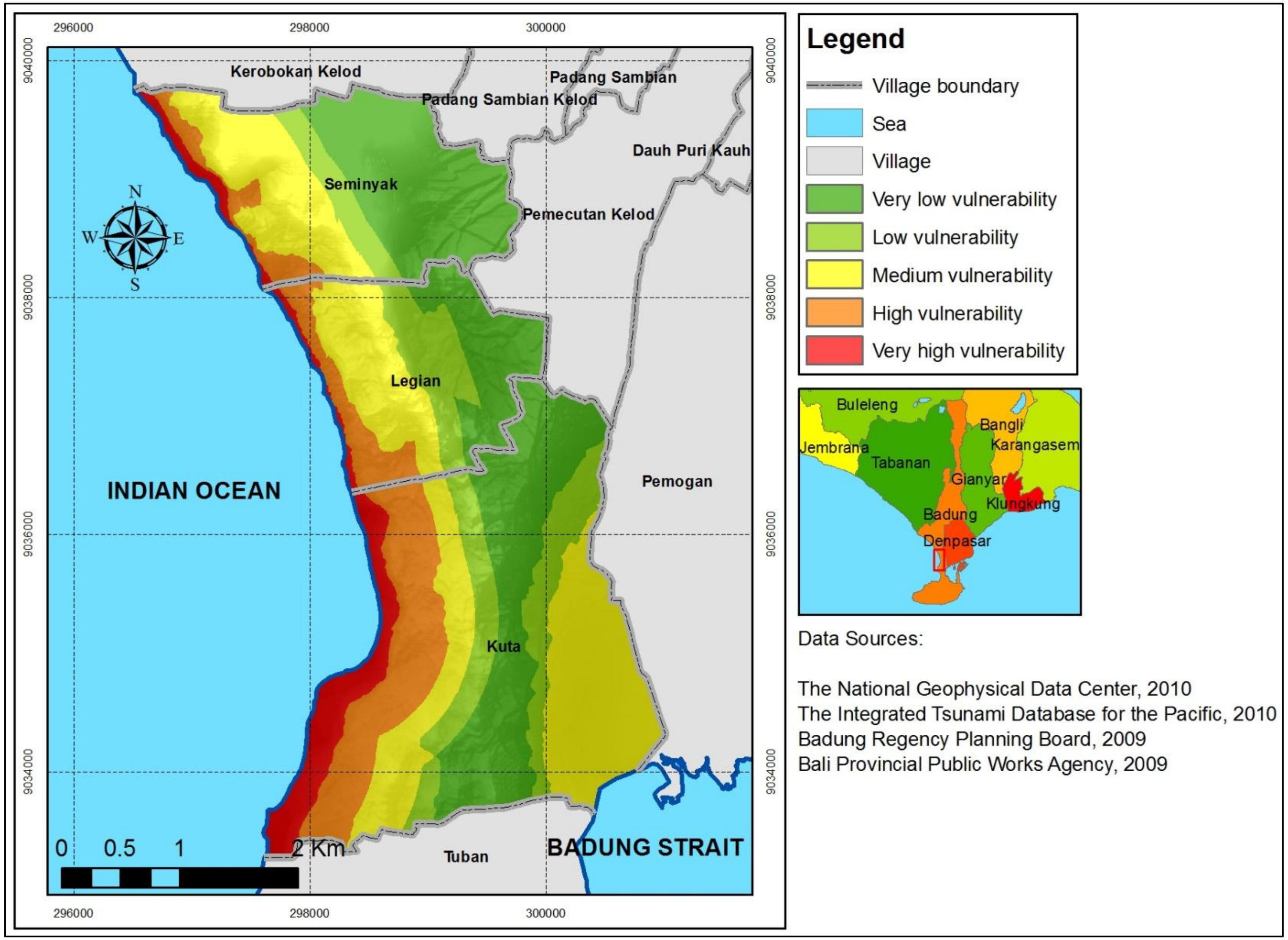


Figure 5.10. The physical vulnerability map of the Kuta Region.

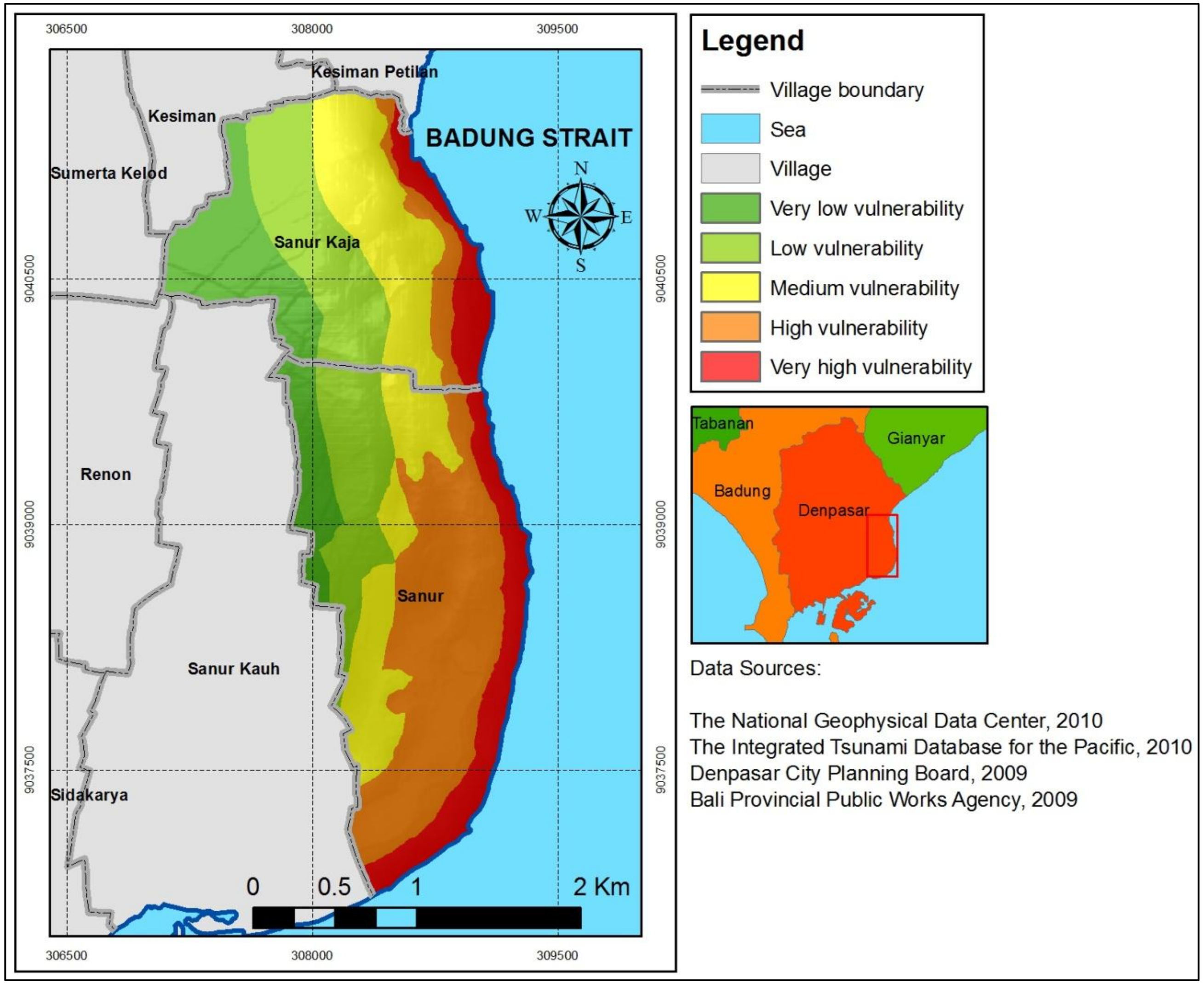


Figure 5.11. The physical vulnerability map of the Sanur Region.

Approximately 67% of the Kuta Region area is vulnerable to future tsunamis. The total area is approximately 9.526 km^2 (see Figure 5.12). In Sanur Region, 85% of the area is vulnerable to tsunami waves, and the total vulnerability area is around 4.875 km^2 (see Figure 5.13). The calculation of the vulnerability area is based on the physical factors that affect the vulnerability assessment in Kuta and Sanur Regions

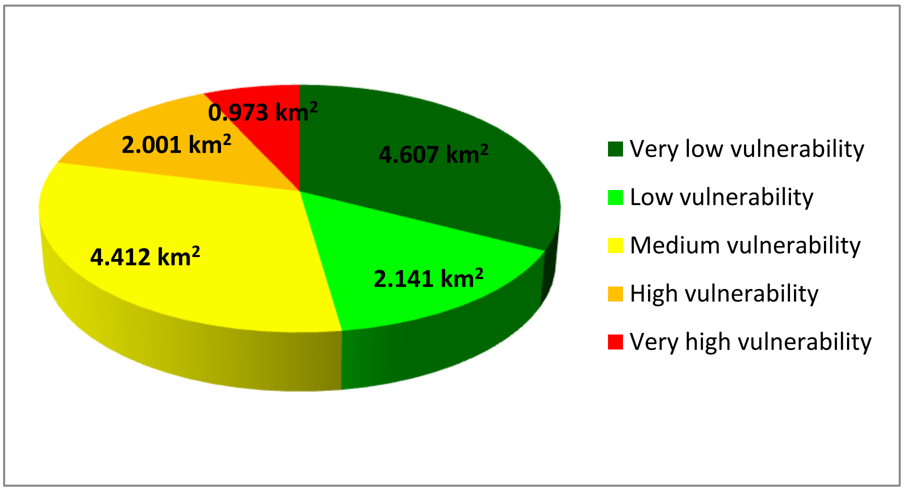


Figure 5.12. The total physical vulnerability area in Kuta Region.

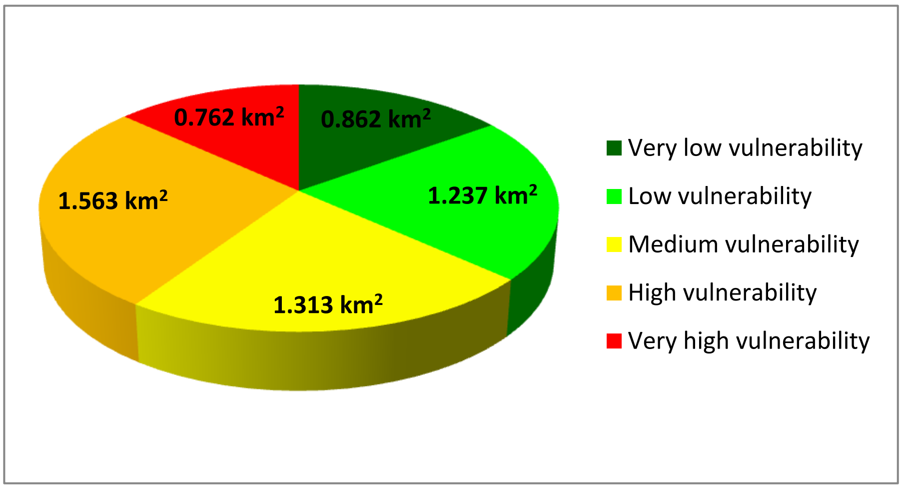


Figure 5.13. The total physical vulnerability area in Sanur Region.

5.3.2. Social Vulnerability

Social vulnerability reflects how areas in both Kuta and Sanur Regions are vulnerable in terms of population, females, age groups (children and elderly), and disabled people. The social vulnerability maps indicate where and what numbers of groups of people are more susceptible to tsunami than others. It is important to know villages with high population, and high numbers of females, children, elderly, and disabled people. They are more vulnerable to tsunami damage, injury, or loss because of their attributes that reduce their capacity to cope with tsunami.

Within Kuta Sub–District, Tuban Village has the highest social vulnerability, followed by Kuta, Kedonganan, Seminyak Villages, and finally Legian Village. In Kuta Region (study area), Kuta Village has the highest social vulnerability, followed by Seminyak Village, and finally Legian Village (see Figure 5.14). Table 5.8 shows the classification and scoring of the social vulnerability for Kuta Sub–District (see Chapter 4.3.3.2 for the scoring methods). Figure 5.15 shows the social conditions of Kuta Region.

Table 5.8. The classification and score for the social vulnerability of the Kuta Sub–District.

Kuta Sub–District	SV Score	Class
a. Tuban	91.66667	Very high vulnerability
b. Kuta	71.54851	↓
c. Kedonganan	57.32506	
d. Seminyak	40.88653	
e. Legian	35.43782	Very low vulnerability

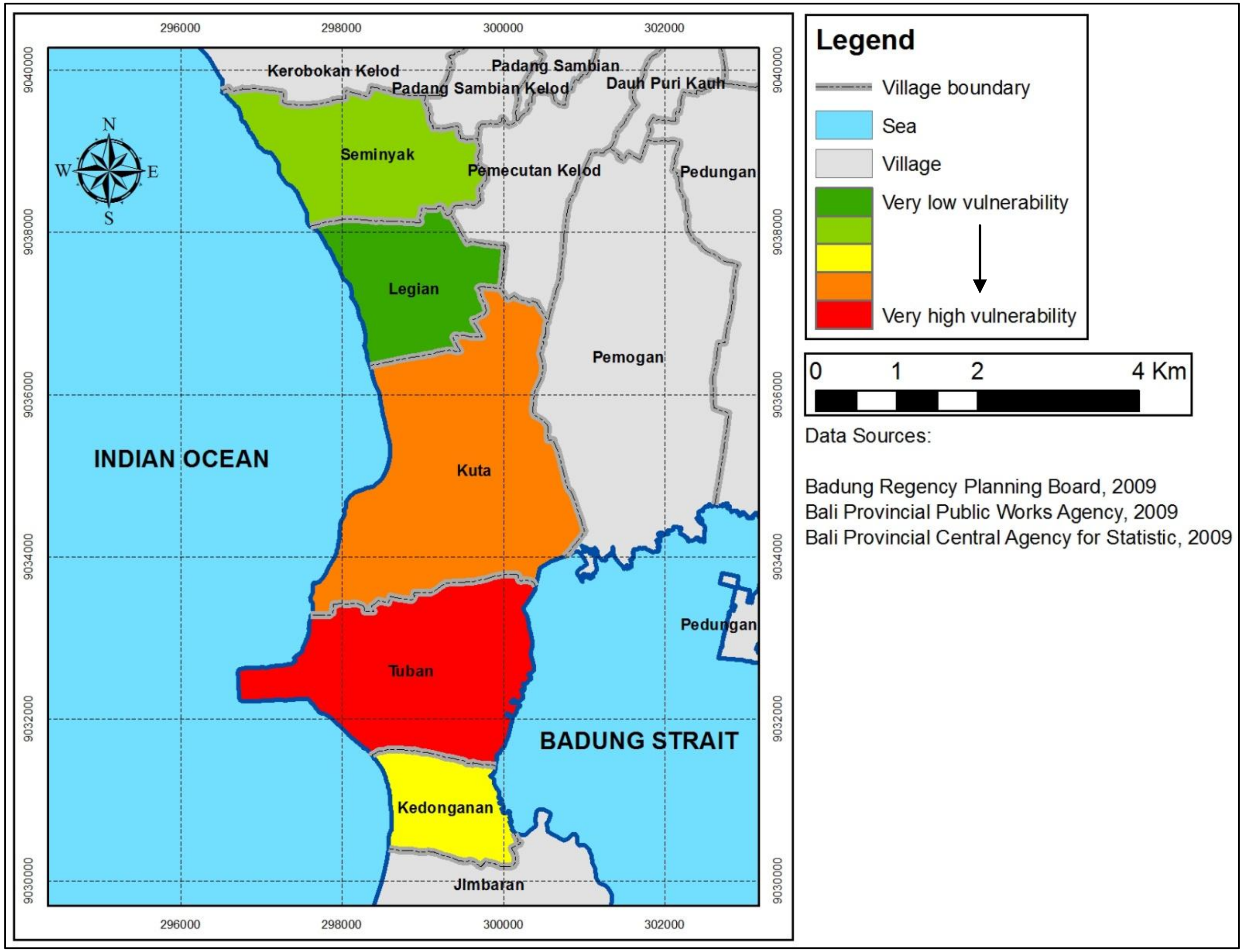


Figure 5.14. The social vulnerability map of the Kuta Sub–District.

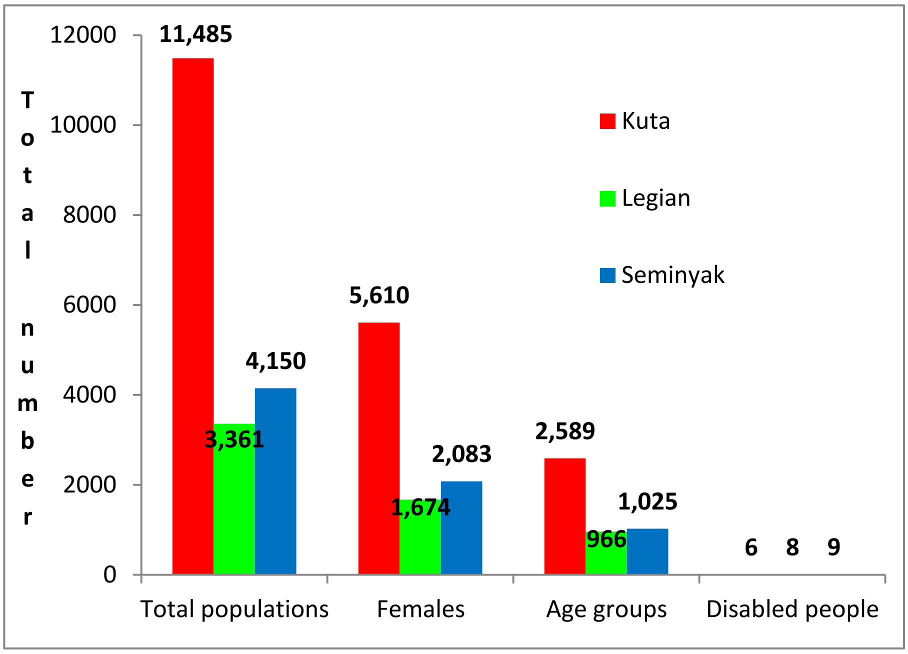


Figure 5.15. The social conditions of the Kuta Region.
Source: Bali Provincial Central Agency for Statistic (2009).

Kuta Village has the highest proportion in terms of total population, females, and age groups, but it has the lowest proportion in terms of disabled people. On the other hand, Legian Village has the lowest proportion in terms of total population, females, and age groups, but it has a higher proportion in terms of disabled people than Kuta Village (see Figure 5.15).

Within South Denpasar Sub–District, Sesetan Village has the highest social vulnerability, followed by Panjer, Pemogan, Pedungan, Sanur Kauh, Sanur, Sidakarya, Renon, Sanur Kaja Villages, and finally Serangan Village. In Sanur Region (study area), Sanur Village is the highest and Sanur Kaja Village is the lowest in social vulnerability terms (see Figure 5.16). Table 5.9 shows the classification and scoring of the social vulnerability for South Denpasar Sub–District. Figure 5.17 shows the social conditions of the Sanur Region.

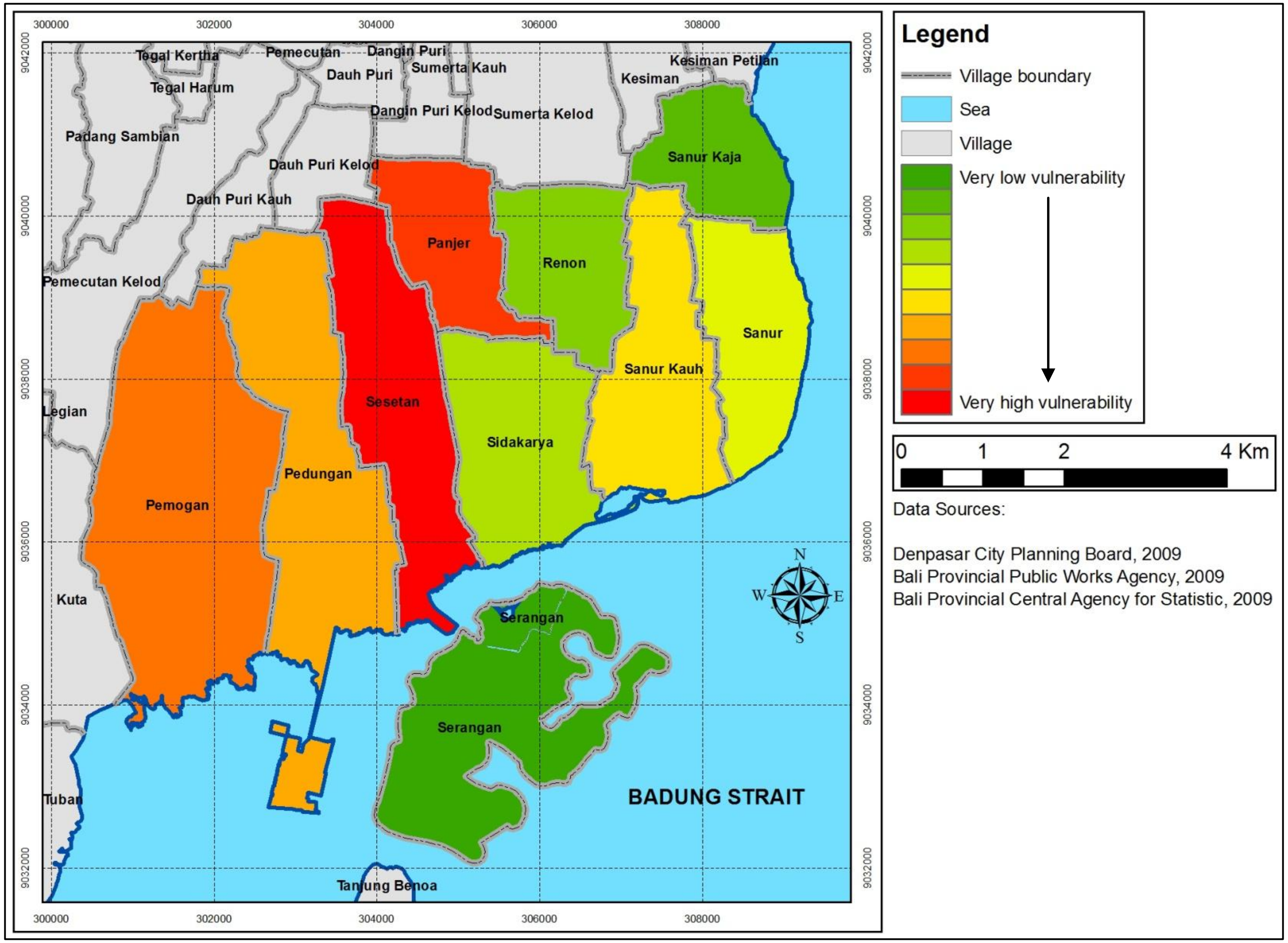


Figure 5.16. The social vulnerability map of the South Denpasar Sub–District.

Table 5.9. The classification and score for the social vulnerability of the South Denpasar Sub–District.

South Denpasar Sub–District	SV Score	Class
a. Sesetan	100	Very high vulnerability
b. Panjer	67.77759	↓
c. Pemogan	62.24464	
d. Pedungan	55.71620	
e. Sanur Kauh	38.46891	
f. Sanur	36.20693	
g. Sidakarya	31.78154	
h. Renon	29.27914	
i. Sanur Kaja	25.15365	
j. Serangan	15.44288	Very low vulnerability

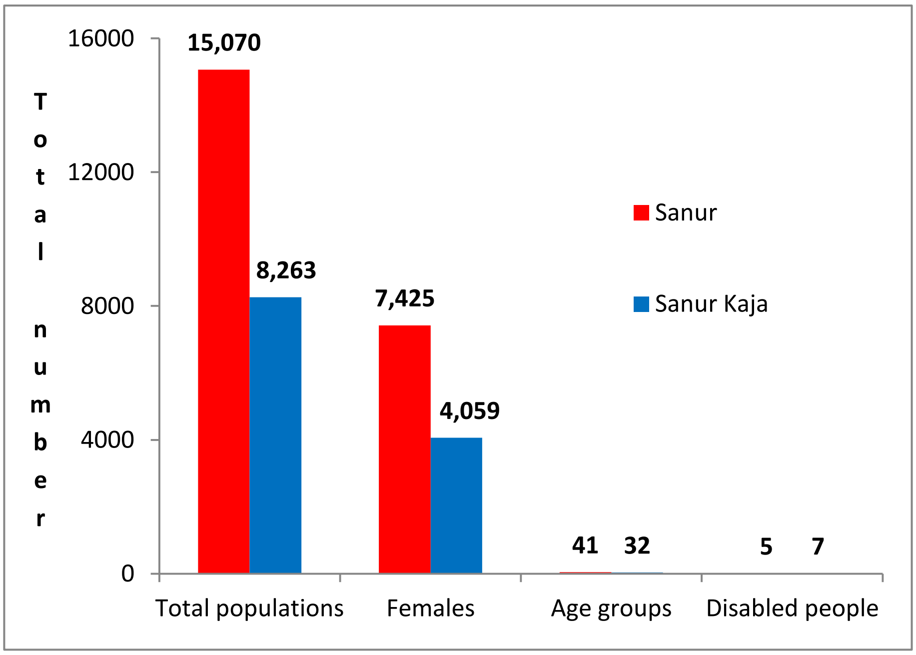


Figure 5.17. The social condition of the Sanur Region.
Source: Bali Provincial Central Agency for Statistic (2009).

Sanur Village has the highest proportion in terms of total population, females, and age groups (≤ 14 or ≥ 60 years old), but it has the lowest proportion in terms of disabled people. On the other hand, Sanur Kaja Village has the lowest proportion in terms of total population, females, and age groups, but it has the highest proportion in terms of disabled people (see Figure 5.17).

It should be noted that these social vulnerability factors were derived from other studies (Clark et al., 1998, Cutter et al., 1997, Boulle et al., 1997, Papathoma et al., 2003, Cutter et al., 2003, Levy and Gopalakrishnan, 2005, Reese et al., 2007). Furthermore, it represents accessible data at the local level. However, other social vulnerability factors could be added in the same method, such as population density and number of people per building.

5.3.3. Economic Vulnerability

Economic vulnerability, like social vulnerability, reflects how areas in both the Kuta and Sanur Regions are vulnerable in terms of number of poor families and fishermen, both of which are among the most vulnerable groups in terms of economic capacity.

Within Kuta Sub–District, Tuban Village has the highest economic vulnerability, followed by Kedonganan, Kuta, Legian Villages, and finally Seminyak Village. In Kuta Region (study area), Kuta has the highest economic vulnerability, followed by Legian Village, and finally Seminyak Village (see Figure 5.19). Table 5.10 shows the classification and scoring of the economic vulnerability for Kuta Sub–District (see Chapter 4.3.3.2 for the scoring methods). Figure 5.18 shows the economic conditions of Kuta Region.

Table 5.10. The classification and score for the economic vulnerability of the Kuta Sub–District.

Kuta Sub–District	EV Score	Class
a. Tuban	75.96154	Very high vulnerability
b. Kedonganan	69.23551	↓
c. Kuta	50.30839	
d. Legian	2.210910	
e. Seminyak	2.169790	Very low vulnerability

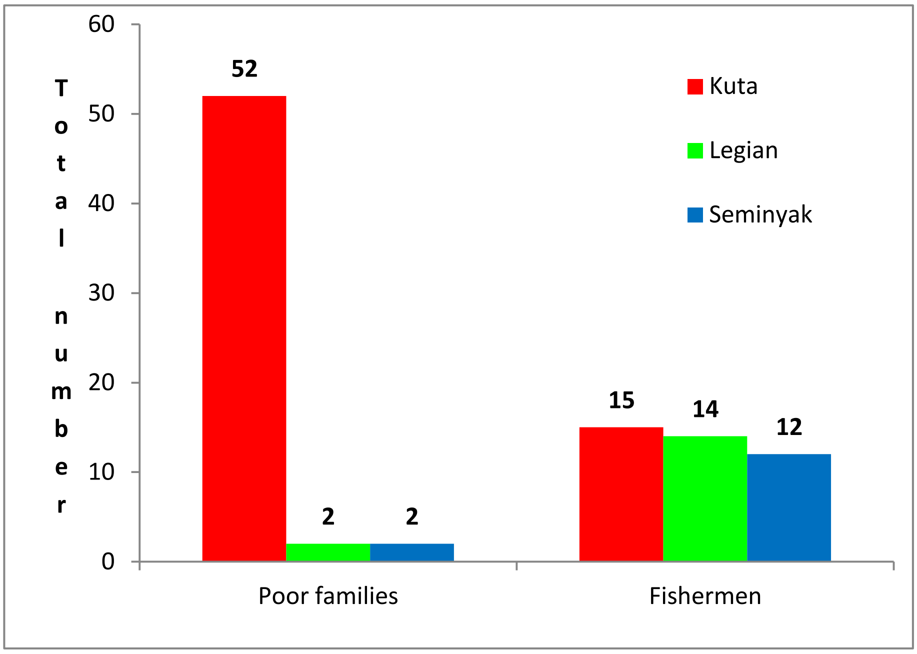


Figure 5.18. The economic condition of the Kuta Region.
Source: Bali Provincial Central Agency for Statistic (2009).

Kuta Village has the highest proportion in terms of poor families and fishermen. On the other hand, Seminyak Village has the lowest proportion in terms of fishermen, but it has the same number in terms of poor families as Legian Village (see Figure 5.18).

Within South Denpasar Sub–District, Serangan Village has the highest economic vulnerability, followed by Sesetan, Pemogan, Pedungan, Sanur Kaja, Sanur, Sanur Kauh, Panjer, Sidakarya Villages, and finally Renon Village. In Sanur Region (study area), Sanur Kaja Village is the highest and Sanur Village is the lowest in economic vulnerability terms (see Figure 5.20). Table 5.11 shows the classification and scoring of the economic vulnerability for South Denpasar Sub–District. Figure 5.21 shows the economic conditions of Sanur Region.

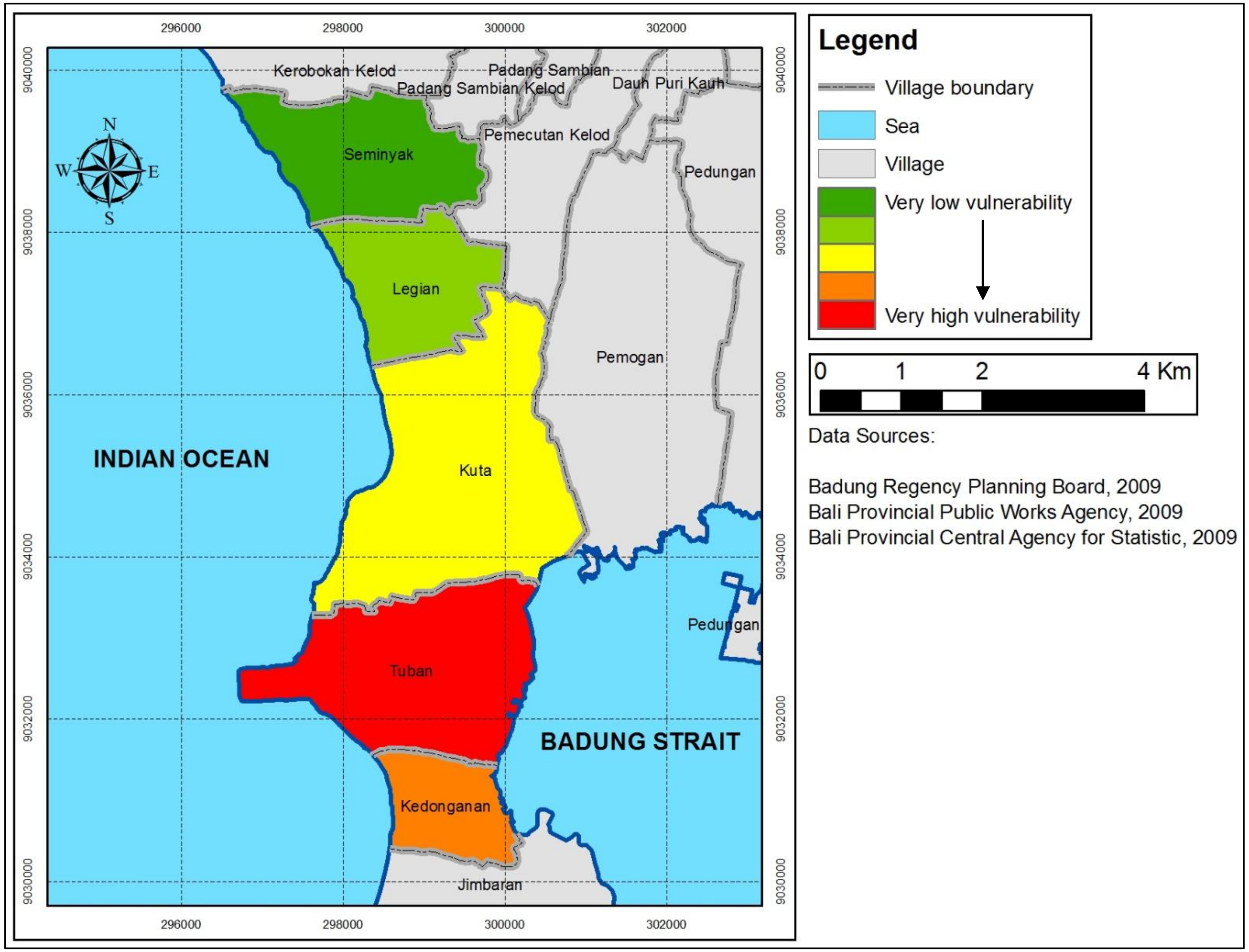


Figure 5.19. The economic vulnerability map of the Kuta Sub–District.

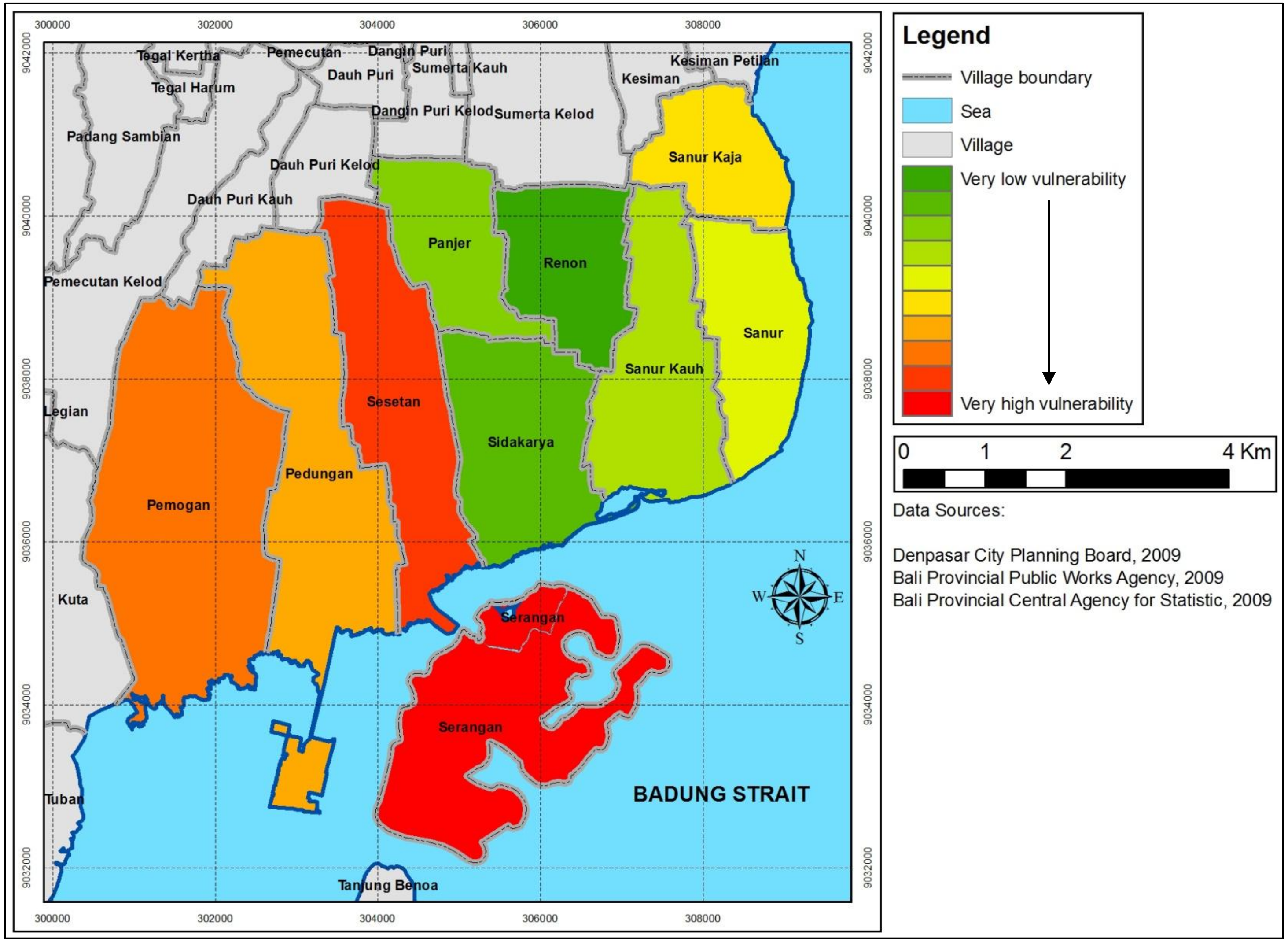


Figure 5.20. The economic vulnerability map of the South Denpasar Sub–District.

Table 5.11. The classification and score for economy vulnerability of the South Denpasar Sub–District.

South Denpasar Sub–District	EV Score	Class
a. Serangan	91.79104	Very high vulnerability
b. Sesetan	55.21271	
c. Pemogan	50	
d. Pedungan	36.88444	
e. Sanur Kaja	34.18313	
f. Sanur	29.90437	
g. Sanur Kauh	28.45875	
h. Panjer	19.77612	
i. Sidakarya	19.25999	
j. Renon	10.82090	Very low vulnerability

Sanur Village has the highest proportion in terms of poor families, but it has the lowest proportion in terms of fishermen. On the other hand, Sanur Kaja Village has the lowest proportion in terms of poor families, but it has the highest proportion in terms of fishermen (see Figure 5.21).

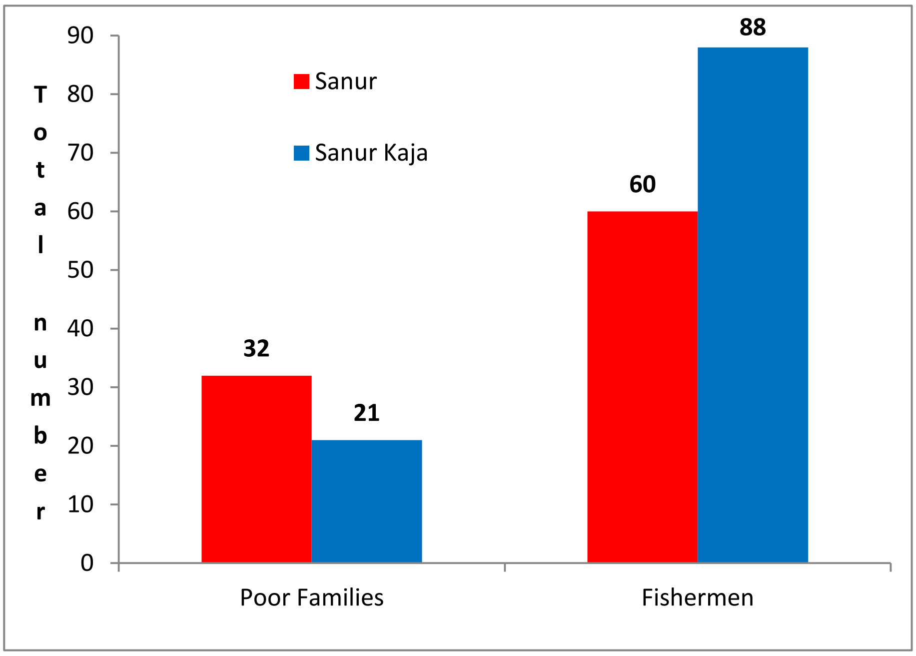


Figure 5.21. The economic condition of the Sanur Region.
Source: Bali Provincial Central Agency for Statistic (2009).

It should be noted that these economic vulnerability factors were derived from other studies (Clague et al., 2003, Boulle et al., 1997, Clark et al., 1998, Tran et al., 2009, Cutter et al., 2003, Agung, 2006, Levy and Gopalakrishnan, 2005, Reese et al., 2007). Furthermore, it represents accessible data at the local level. However, other economic vulnerability factors could be added in the same method, such as household income and number of tourists.

5.3.4. Total Vulnerability

The three vulnerability layers, represented as raster data layers, were overlaid through addition to obtain a "total vulnerability" layer (see Chapters 4.3.3.2 and 4.3.3.3 for the scoring and combination methods). For Kuta Region, the highest score from the calculation is 581 and the lowest score is 163, so the class range can be calculated as follows:

$$\text{TV class range for Kuta Region} = \frac{581 - 163}{5} = 83.6$$

From the class range result, the total vulnerability assessment of the Kuta Region can be classified into five classes (see Table 5.12).

In order to simplify the risk score calculation, the author gave score and weight to the total vulnerability classification for both Kuta and Sanur Regions (see Tables 5.12 and 5.13).

Table 5.12. The classification, scoring and weighting for total vulnerability map of the Kuta region.

Total Vulnerability Class Range	Class	Score	Weight	Total
a. ≤ 246.6	Very low vulnerability	1	100	100
b. 246.7 – 330.2	Low vulnerability	2	100	200
c. 330.3 – 413.8	Medium vulnerability	3	100	300
d. 413.9 – 497.4	High vulnerability	4	100	400
e. > 497.4	Very high vulnerability	5	100	500

For Sanur Region, the highest score from the calculation is 526 and the lowest score is 199, so the class range can be calculated as follows:

$$\text{PV class range for Sanur Region} = \frac{526 - 199}{5} = 65.4$$

From the class range result, the total vulnerability assessment of the Sanur Region can be classified into five classes (see Table 5.13).

Table 5.13. The classification, scoring and weighting for total vulnerability map of the Sanur region.

Total Vulnerability Class Range	Class	Score	Weight	Total
a. ≤ 264.4	Very low vulnerability	1	100	100
b. 264.5 – 329.8	Low vulnerability	2	100	200
c. 329.9 – 395.2	Medium vulnerability	3	100	300
d. 395.3 – 460.6	High vulnerability	4	100	400
e. > 460.6	Very high vulnerability	5	100	500

The very high vulnerability areas represent areas that are influenced very highly by physical, social and economic factors. Around 72% areas of the Kuta, 70% areas of the Legian and 52% areas of the Seminyak Villages are vulnerable to future tsunamis (see Figure 5.22). Around 91% areas of the Sanur and 76% areas of the Sanur Kaja Villages are vulnerable to tsunami waves (see Figure 5.23).

The overlaying of the "total vulnerability" layer with the administrative boundaries, allowed the calculation of tsunami vulnerability at the villages level (see Table 5.14).

Table 5.14. The administrative areas that are vulnerable to tsunami.

Region	Village	Type	The total vulnerability zones (km^2)				
			Very high vulnerability	High vulnerability	Medium vulnerability	Low vulnerability	Very low vulnerability
Kuta	Kuta	Urban	1.139	1.380	1.013	2.000	2.101
	Legian	Urban	0.004	0.223	0.898	0.875	0.854
	Seminyak	Urban	0.060	0.133	0.993	0.691	1.749
Sanur	Sanur	Urban	0.509	1.379	0.584	0.565	0.288
	Sanur Kaja	Urban	0.200	0.236	0.708	0.693	0.573

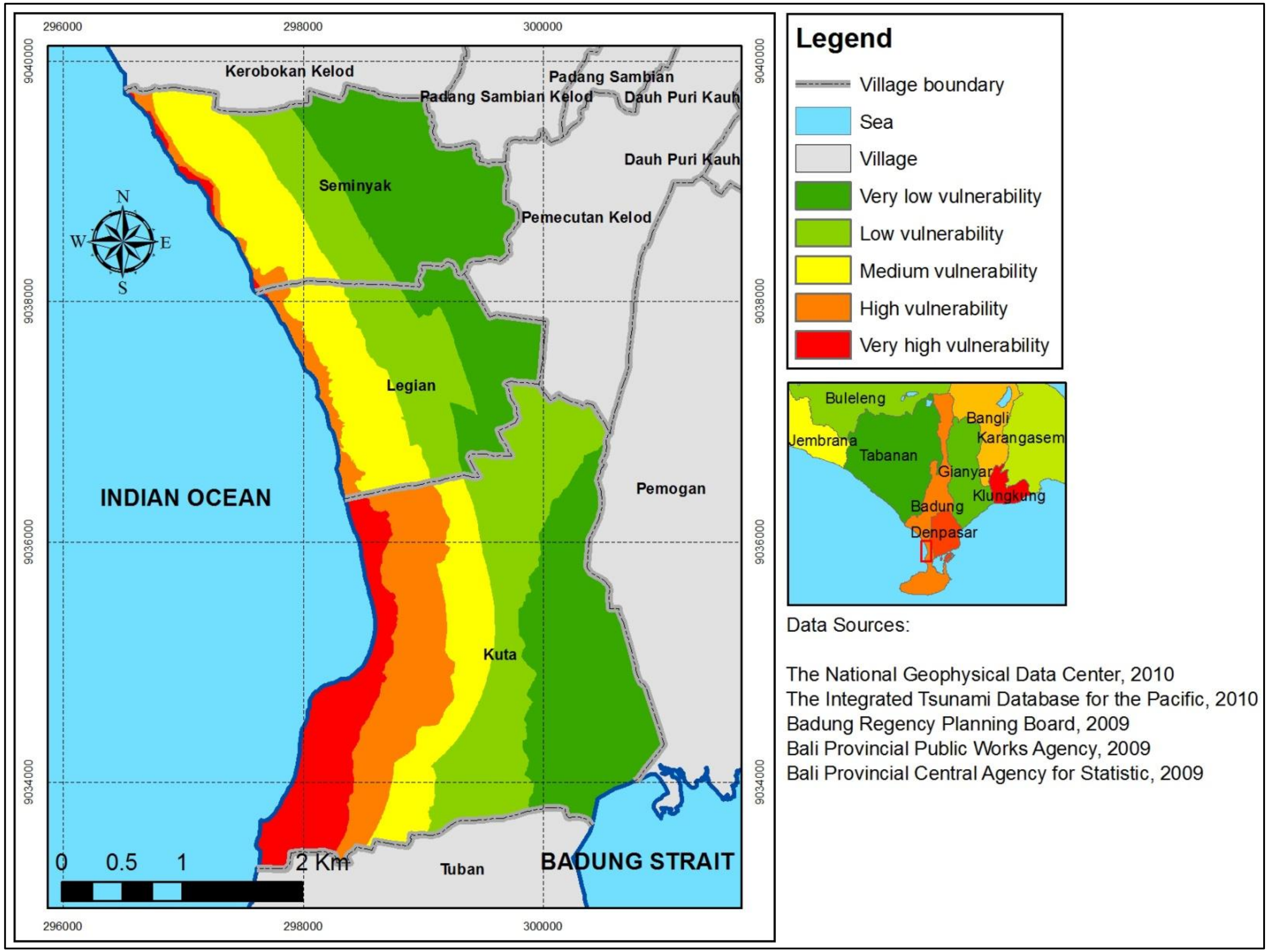


Figure 5.22. The total vulnerability map of the Kuta Region.

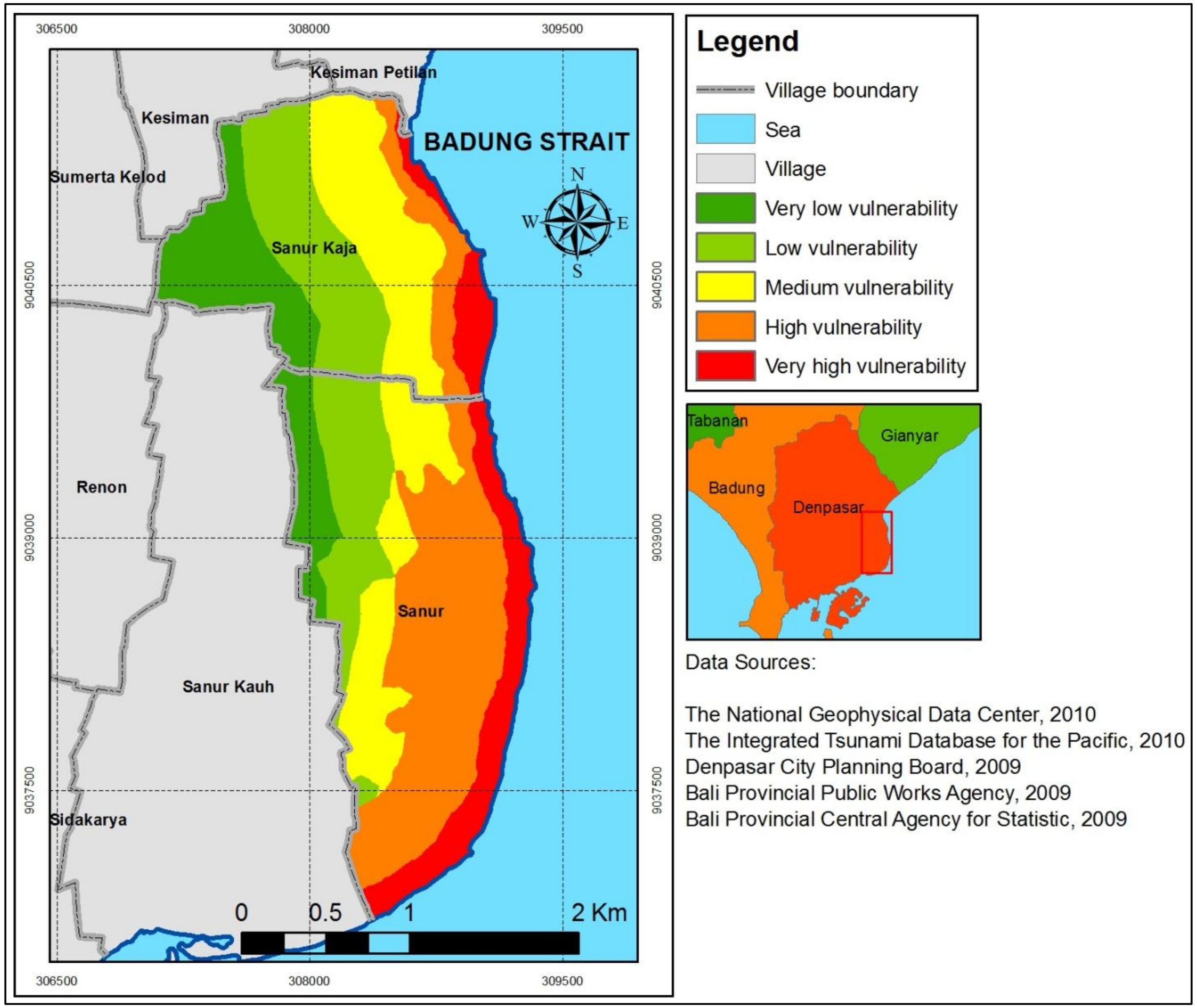


Figure 5.23. The total vulnerability map of the Sanur Region.

Most (67%) areas of the Kuta Region are vulnerable to tsunami waves. The total area that will be vulnerable is approximately 9.418 km^2 (see Figure 5.24). It will mostly focus on Kuta and Legian Villages (see Figure 5.22). In Sanur Region, 85% of the area is vulnerable to tsunamis, and the total vulnerable area is approximately 4.875 km^2 (see Figure 5.25), largely in Sanur Village (see Figure 5.23). The calculation of the total vulnerable area is based on the areas influenced by physical, social and economic factors

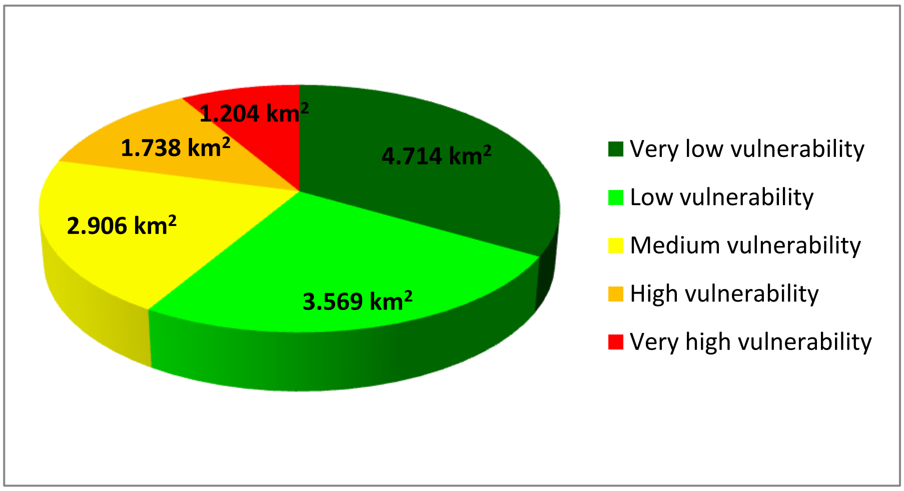


Figure 5.24. The total vulnerable area in Kuta Region.

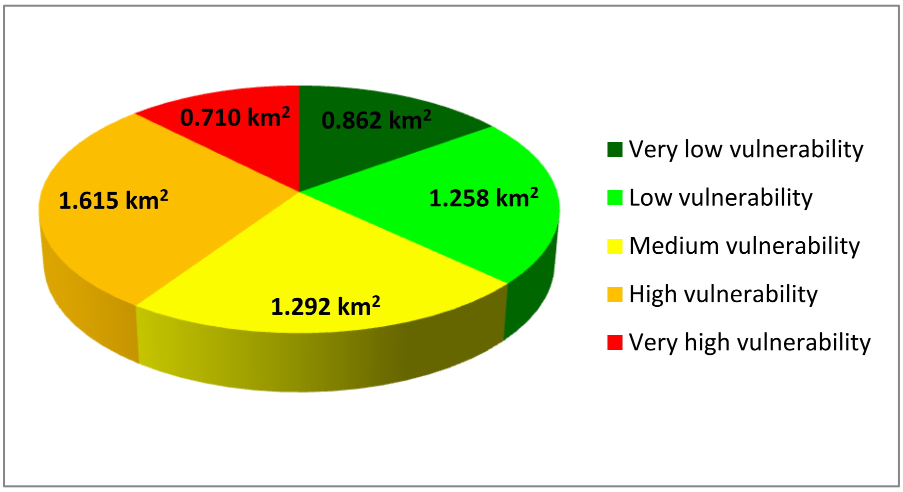


Figure 5.25. The total vulnerable area in Sanur Region.

5.4. Risk Assessment Analysis

The risk map is the result of overlaying hazard and total vulnerability maps that mean multiplying hazard and vulnerability scores (see Figures 5.26 and 5.27). All of the areas at highest risk are in the vicinity of the coastal zone. It makes sense because the tsunami wave force will destroy everything that is in its path. The area within 0 – 1.5 km from the shoreline will suffer the most destruction as was the case with the 2004 Indian Ocean tsunami; most of the areas within 0 – 2 km from the shoreline at low elevation were damaged by tsunami waves (Levy and Gopalakrishnan, 2005).

In this study, the risk assessment analysis differs from hazard assessment and total vulnerability assessment analysis. The risk assessment analysis was based on the risk zones that analysed by the combination of the inundation and vulnerability zones. It was used to analyse the area administration, land use, building and infrastructure, social and economic variables, special sites and lifelines that are at risk from future tsunamis.

The spatial hazard and vulnerability layers were overlaid using the same method as was used for the physical vulnerability factors (see Chapter 5.3.1) and the three vulnerabilities (see Chapter 5.3.4), except that layers were multiplied together rather than added to obtain the "risk" layer.

Scores and weights were allocated to the previous hazard and total vulnerability classifications in order to simplify the risk score calculation (see Table 4.1 for the hazard assessment and Tables 5.12 and 5.13 for the total vulnerability assessment). The combination method has been explained in the previous chapter (see Chapter 4.3.3.3). For Kuta and Sanur Regions, the highest score from the calculation is 250,000 and the lowest score is 10,000, so the class range can be calculated as follows:

$$\text{TV class range for Kuta and Sanur Regions} = \frac{25,000 - 10,000}{5} = 48,000$$

From the class range result, the risk assessment in both regions can be classified into five classes (see Table 5.15).

Table 5.15. The classification for risk map.

Risk Class Range	Class
a. ≤ 58,000	Very low risk
b. 58,001 – 106,000	Low risk
c. 106,001 – 154,000	Medium risk
d. 154,001 – 202,000	High risk
e. > 202,000	Very high risk

Around 44% of the area in Kuta Village is at risk from tsunami waves. On the other hand, only around 34% of the area in Legian and 20% of the area in Seminyak Villages those are at risk from future tsunamis. It means that Kuta Village is the most at risk among the other villages (see Figure 5.26). Around 78% of the area in Sanur Village is at risk from tsunami waves. In Sanur Kaja Village, only 25% of the area is at risk from tsunamis. Thus Sanur Village is the most at risk area in Sanur Region (see Figure 5.27).

The overlaying of the “risk” layer with administrative boundaries allowed the calculation of tsunami risk at the village level in both regions (see Table 5.16).

Table 5.16. The administrative areas that are at risk from tsunami.

Region	Village	Type	The risk zones (m^2)				
			Very high risk	High risk	Medium risk	Low risk	Very low risk
Kuta	Kuta	Urban	0.726	0.475	1.272	0.912	4.247
	Legian	Urban	0.005	0.226	0.019	0.723	1.882
	Seminyak	Urban	0.060	0.132	0.052	0.495	2.887
Sanur	Sanur	Urban	0.505	1.302	0.379	0.388	0.745
	Sanur Kaja	Urban	0.200	0.143	0.091	0.160	1.812

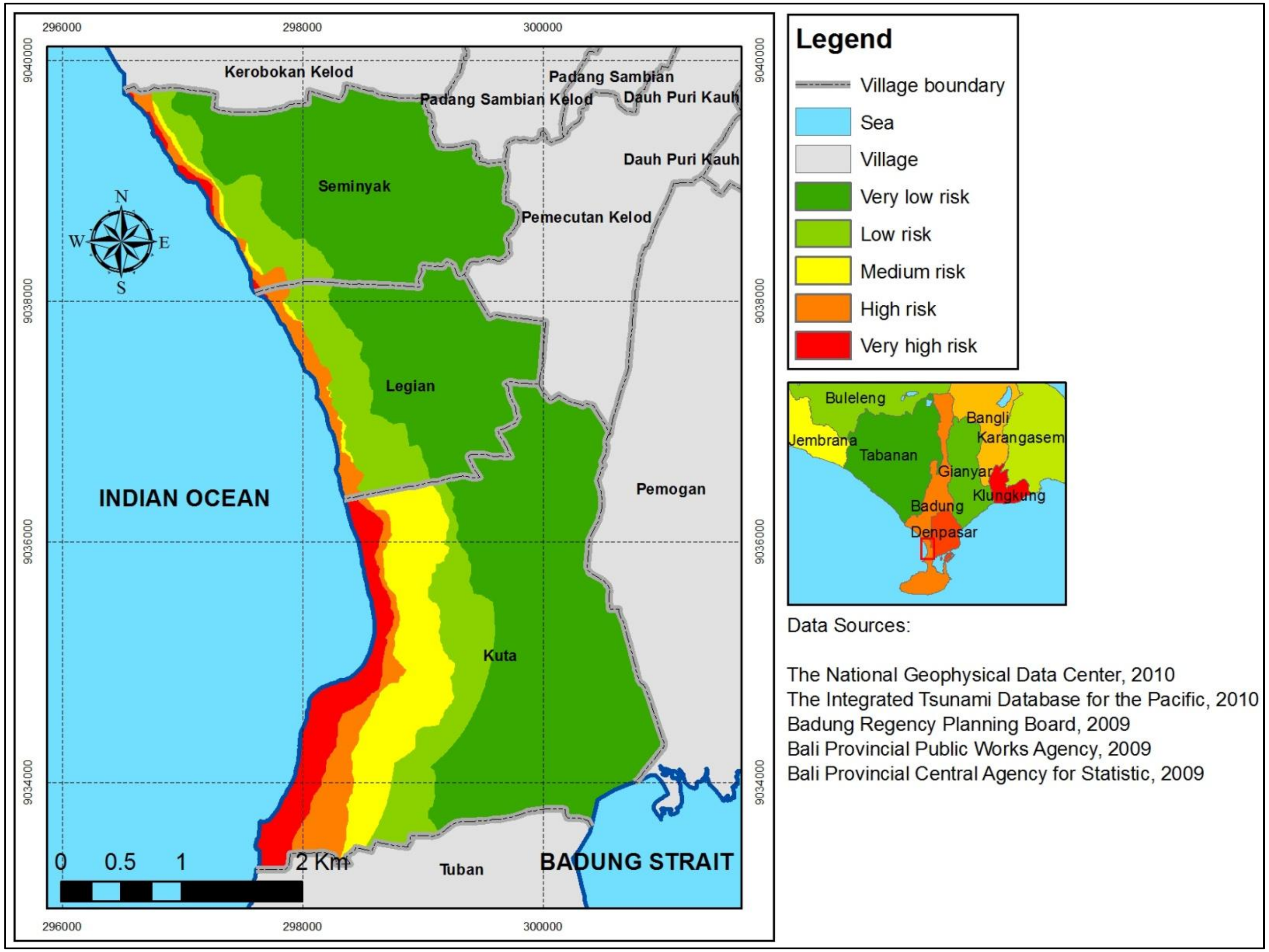


Figure 5.26. The risk map of the Kuta Region.

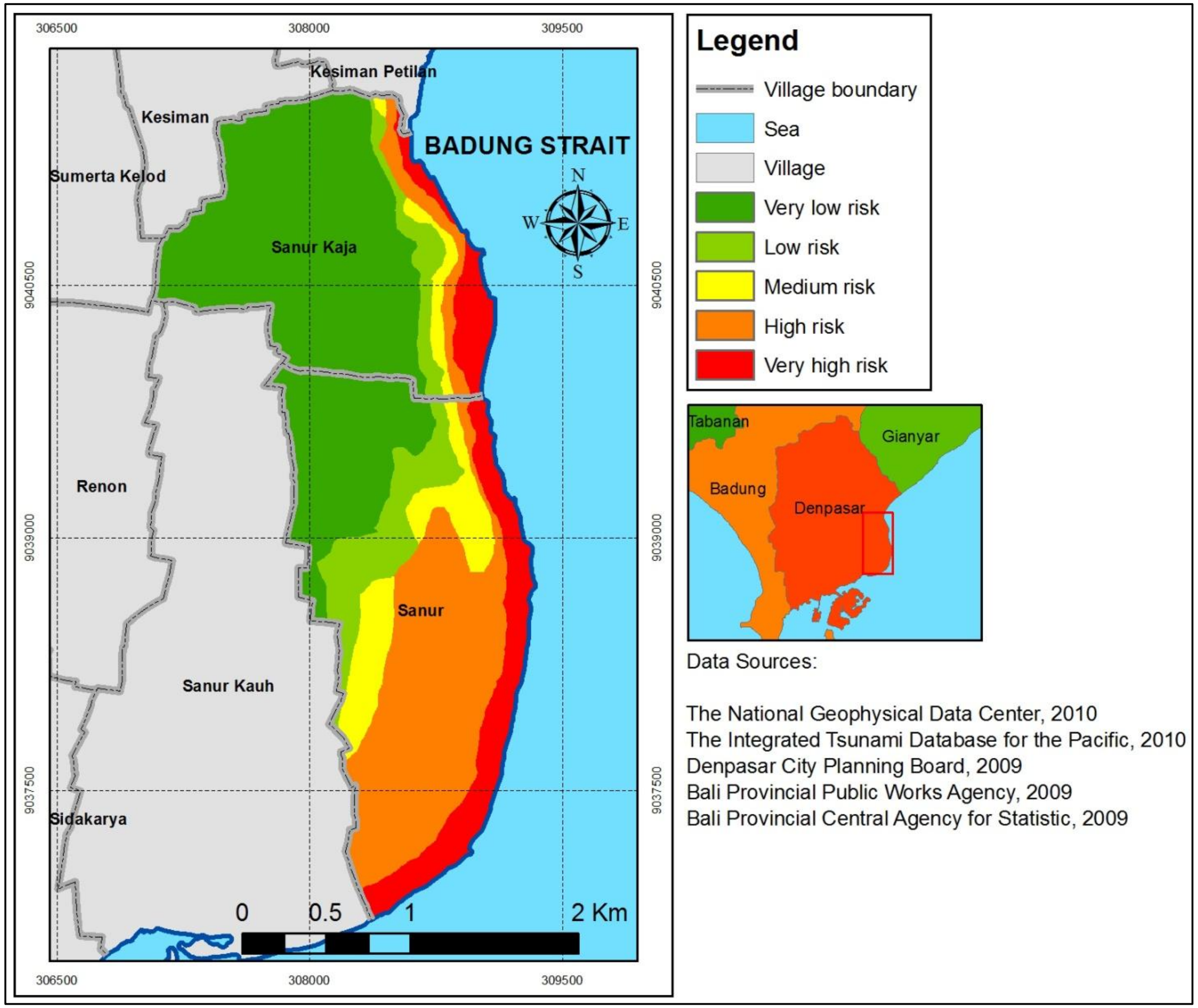


Figure 5.27. The risk map of the Sanur Region.

Around 36% of the Kuta Region area is at risk from tsunami waves. The total area that will be at risk is approximately 5.103 km^2 (see Figure 5.28). It will mostly focus on Kuta Village (see Figure 5.26). In Sanur Region, 55% of the area is at risk from tsunamis, and the total risk area is around 3.175 km^2 (see Figure 5.29). It will mostly focus on the Sanur Village (see Figure 5.27). The calculation of the risk area is based on the areas that are influenced by hazard and total vulnerability assessments

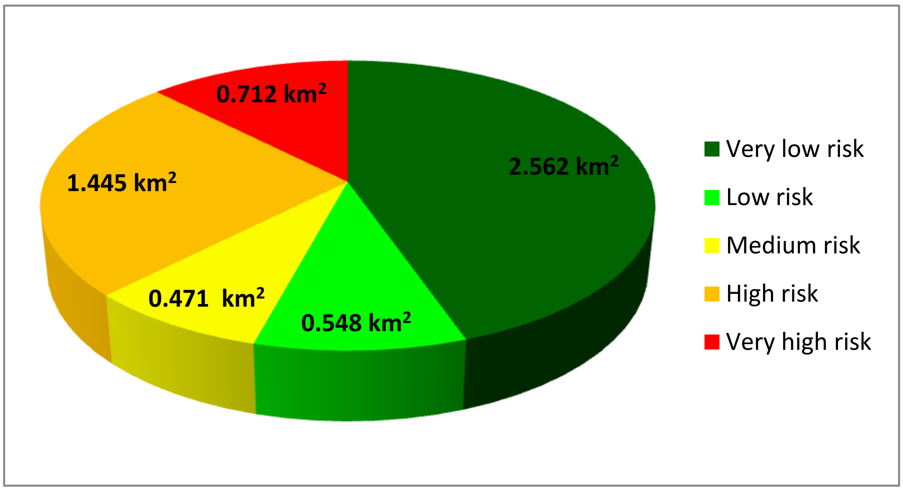


Figure 5.28. The total risk area in Kuta Region.

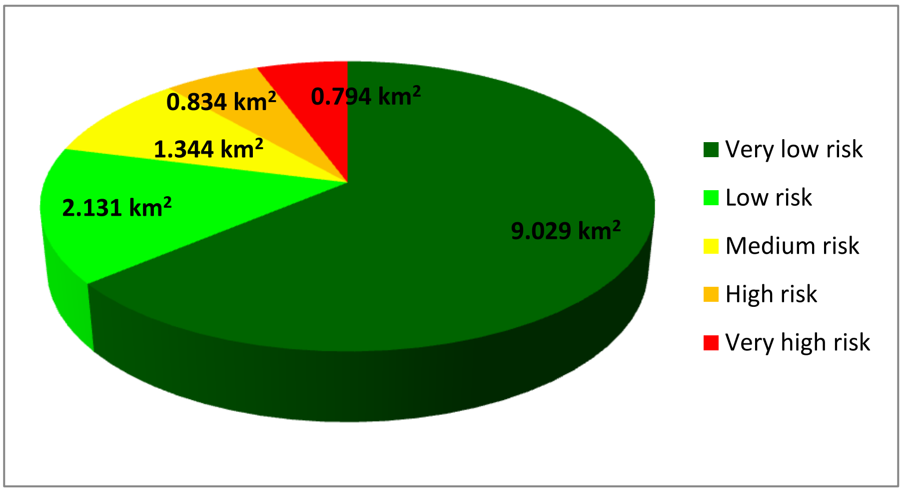


Figure 5.29. The total risk area in Sanur Region.

5.4.1. Risk Analysis

5.4.1.1. Hazard Analysis

The distribution of risk in each village in each region is not the same. It varies between villages and depends on the contribution of each variable (physical, social, and economic) to the total risk (see Figure 5.30). It is important for local government to know the most significant contributors for each village's risk if a tsunami occurs to allow the allocation of intervention resources and mitigation plans. It will reduce the duplication of activities in each village and optimize the fund allocation to the right place and right activity.

The risk proportion in all villages is influenced by the physical factors. Social factors contribute almost an equal value in each village. On the other hand, the economic factors only make a small contribution for the risk in Legian and Seminyak Villages. The calculation of risk proportion is based on the value of physical, social and economic vulnerabilities (see Figure 5.30).

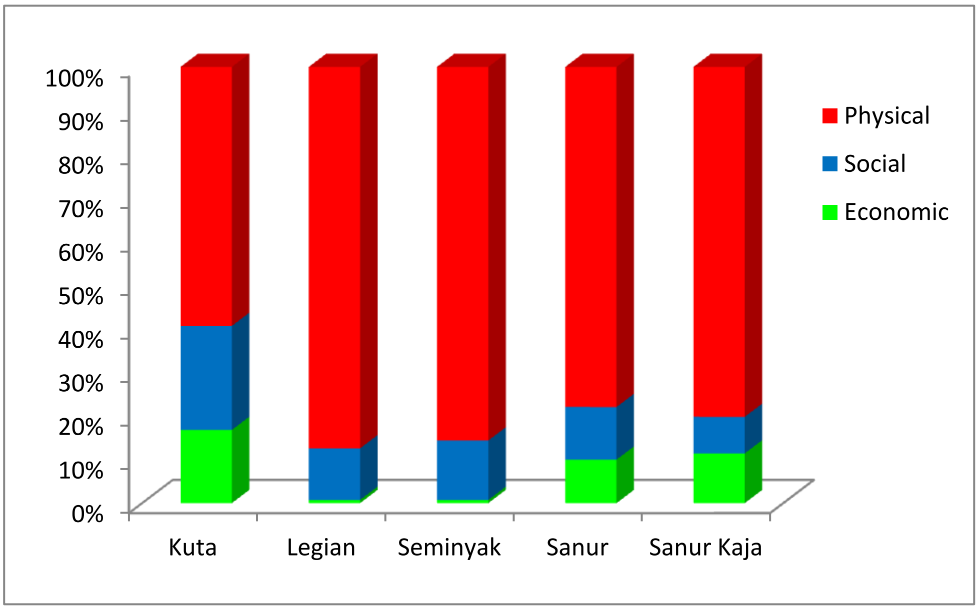


Figure 5.30. The proportion of risk in Kuta and Sanur Regions based on physical, social, and economic factors.

For the hazard analysis, the “land use” layer of each village in both regions is overlaid with the “risk” layer, so it is possible to locate and calculate land uses that are at risk from tsunami waves in each village.

There are 5 types of land use that at risk in Kuta Village, namely bareland, buildings, open space, roads and sand. On the other hand, 6 other land use types are located in tsunami least risk areas, such as agroforestry, grassfields, lakes, mangroves, ricefields and rivers (see Figure 5.32 and Table 5.17).

Table 5.17. The land uses that are at risk from tsunami in Kuta Village.

Land use types	The risk zones				
	Very high risk	High risk	Medium risk	Low risk	Very low risk
Agroforestry (km^2)	-	-	-	-	0.120
Bareland (km^2)	-	0.020	0.003	-	0.039
Building (unit)	356	661	2,330	2,020	2,699
Grassfield (km^2)	-	-	-	-	0.014
Lake (km^2)	-	-	-	-	0.346
Mangrove (km^2)	-	-	-	-	0.871
Open space (km^2)	0.365	0.286	0.814	0.540	1.858
Ricefield (km^2)	-	-	-	-	0.255
River (km^2)	-	-	-	-	0.081
Road (km)	2.645	3.505	14.082	12.207	31.405
Sand (km^2)	0.220	-	-	-	-

Approximately one–third of the bareland, two–third of the buildings, around half of all open space and roads, and all sand areas in Kuta Village are at risk from future tsunamis, due to their locations in low–lying flat areas and near the coast. Other land uses, such as agroforestry, grassfields, lakes, mangroves, ricefileds and rivers are potentially safe from future tsunamis in that village. These land use types are located in higher areas and far away from the coast (see Table 5.17).

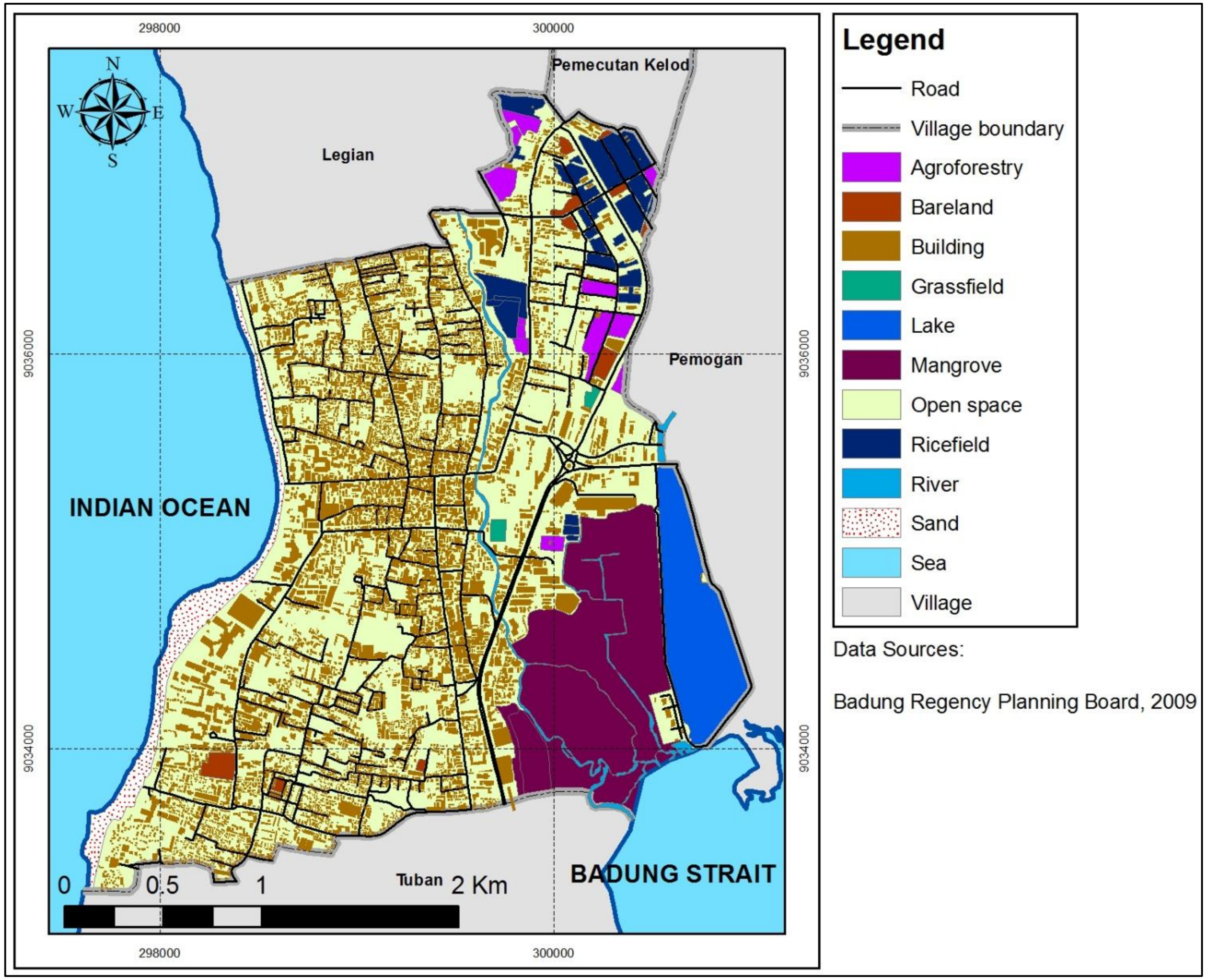


Figure 5.31. The land use map of the Kuta Village.

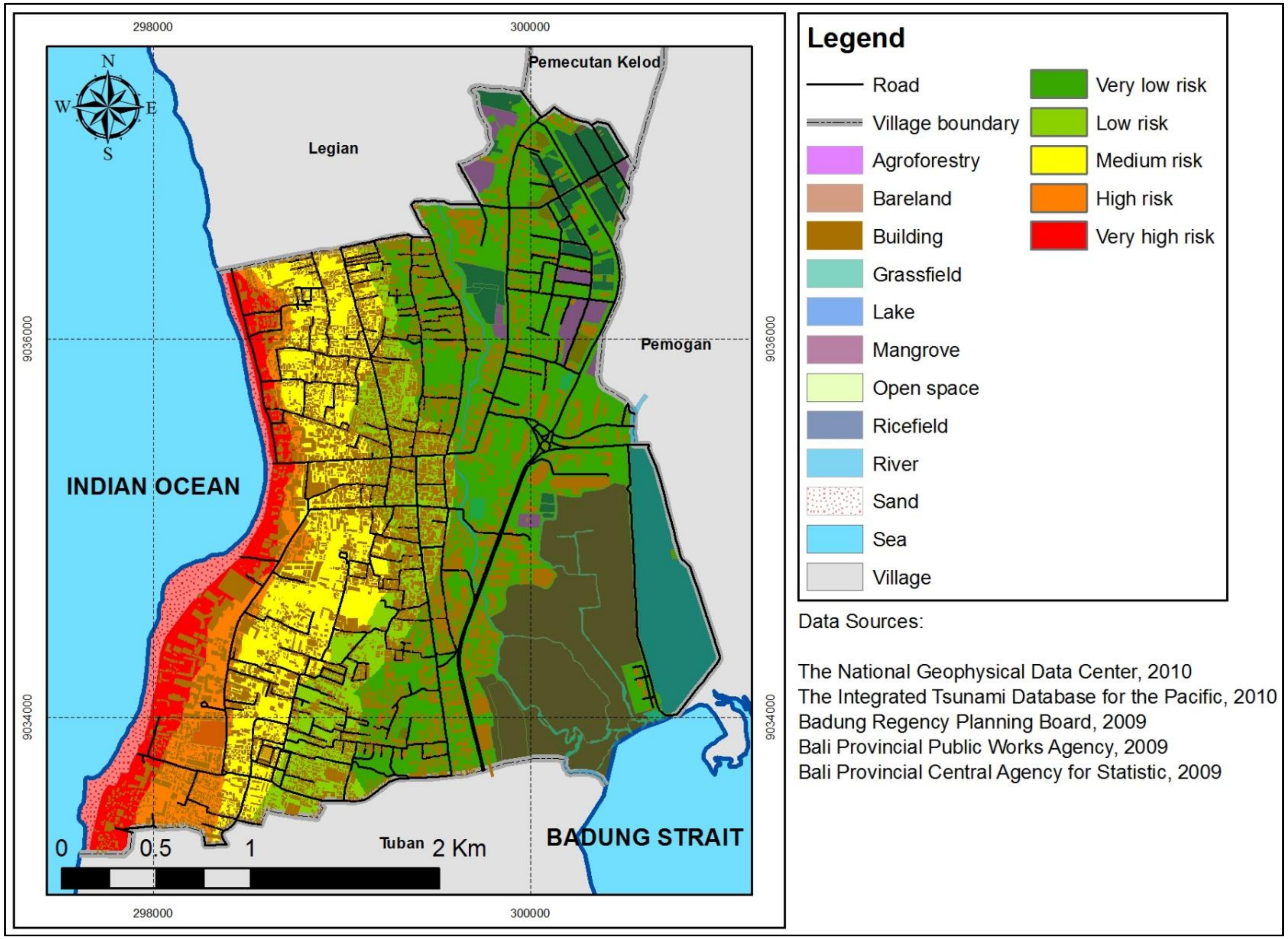


Figure 5.32. The land uses at risk in Kuta Village.

There are 4 types of land use that at risk in Legian Village, namely buildings, open space, roads and sand. On the other hand, 4 other land use types are located in tsunami least risk areas, such as agroforestry, bareland, ricefields and rivers (see Figure 5.34 and Table 5.18).

Table 5.18. The land uses that are at risk from tsunami in Legian Village.

Land use types	The risk zones				
	Very high risk	High risk	Medium risk	Low risk	Very low risk
Agroforestry (km^2)	-	-	-	-	0.542
Bareland (km^2)	-	-	-	-	0.017
Building (unit)	-	60	17	1,093	1,428
Open space (km^2)	0.0003	0.143	0.016	0.471	0.827
Ricefield (km^2)	-	-	-	-	0.212
River (km^2)	-	-	-	-	0.018
Road (km)	-	2.140	0.164	6.414	17.906
Sand (km^2)	0.005	0.063	-	-	-

Around half of all buildings and open space, one–third of the roads, and all sand areas in Legian Village are at risk from future tsunamis, due to their locations in low–lying flat areas and near the coast. Other land uses, such as agroforestry, bareland, ricefileds and rivers are potentially safe from future tsunamis in that village, due to their locations in higher areas and far away from the coast (see Table 5.18).

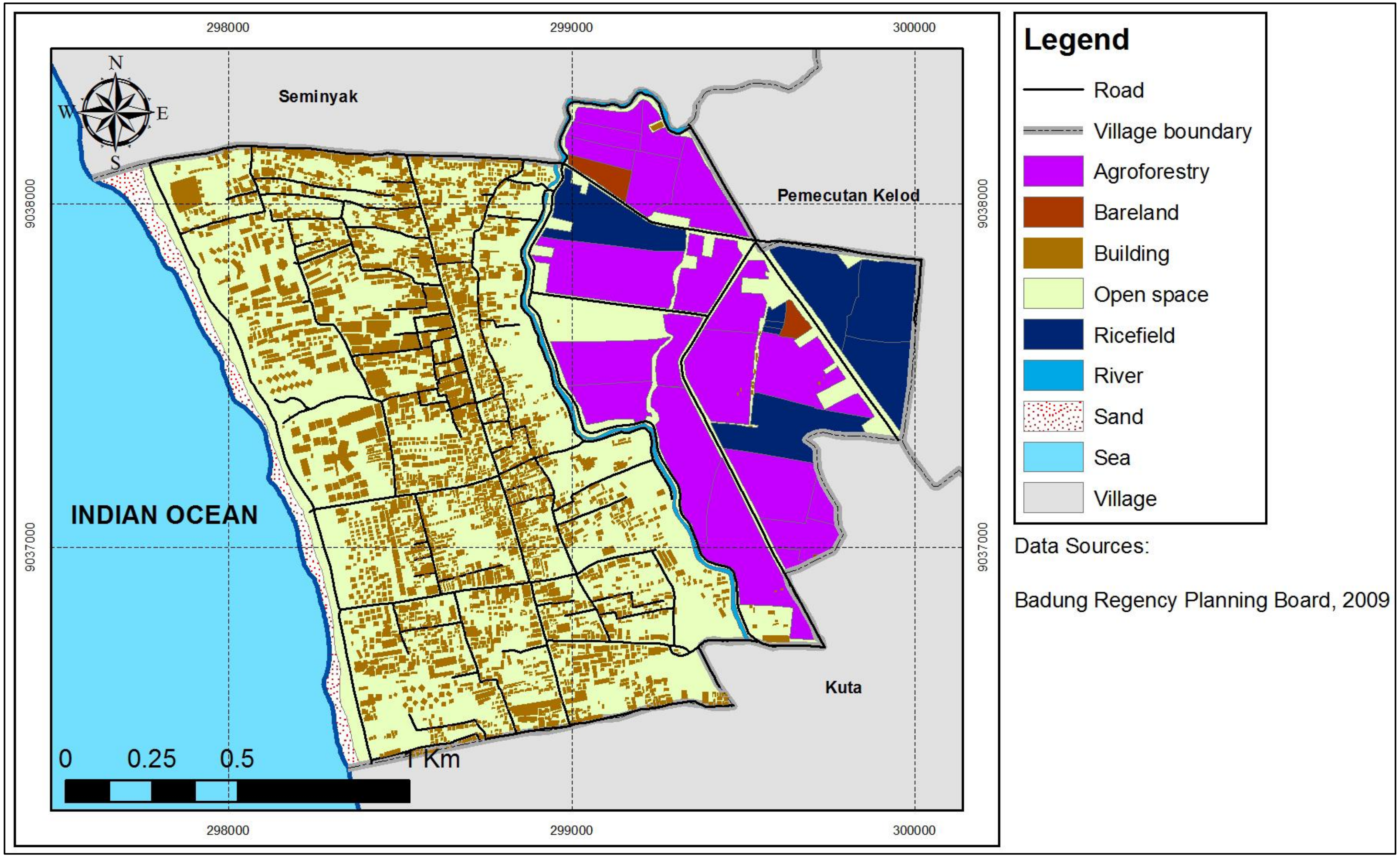


Figure 5.33. The land use map of the Legian Village.

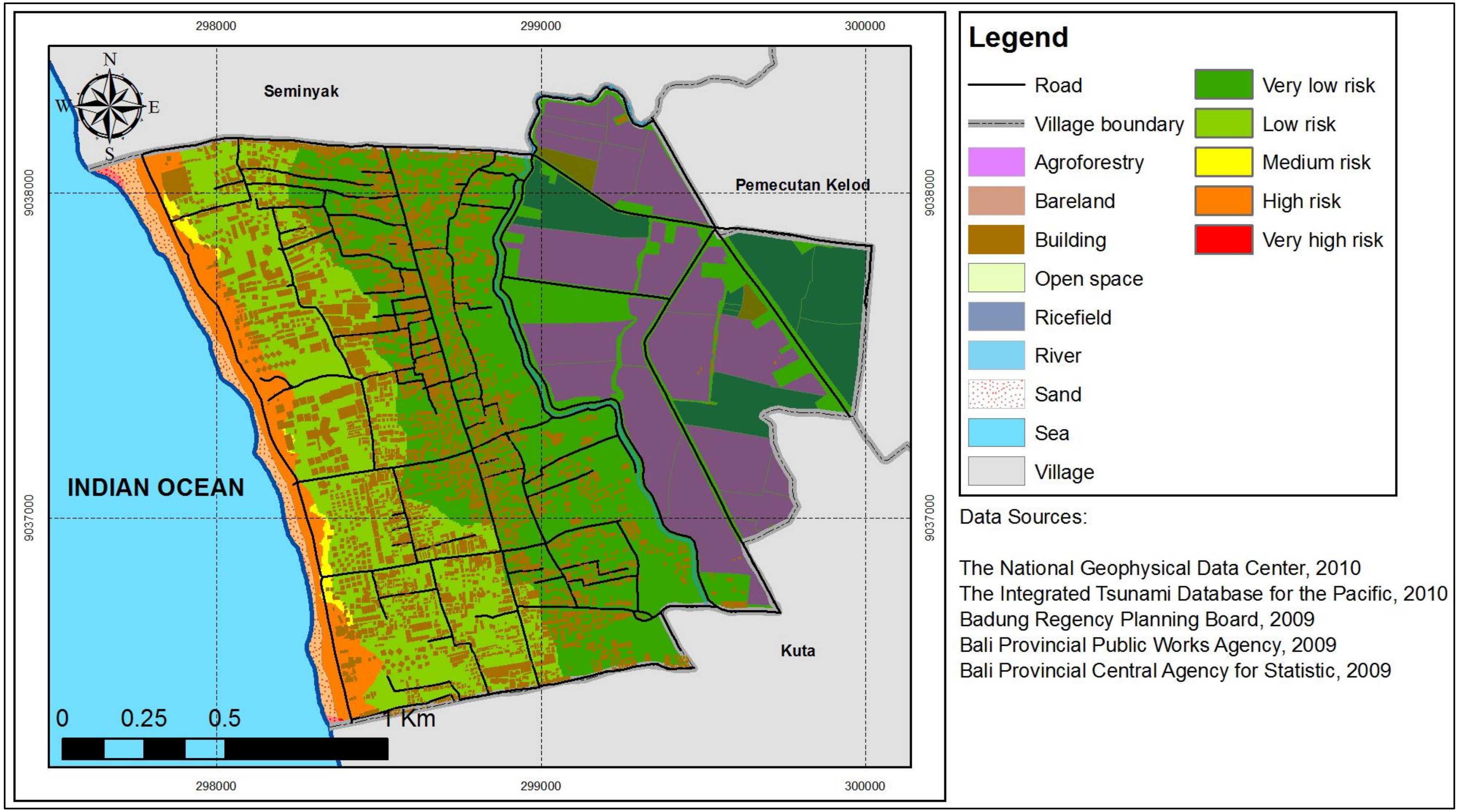


Figure 5.34. The land uses at risk in Legian Village.

Most of the land use types are at risk in Seminyak Village. It is only the rivers that are located in tsunami least risk areas (see Figure 5.36 and Table 5.19).

Table 5.19. The land uses that are at risk from tsunami in Seminyak Village.

Land use types	The risk zones				
	Very high risk	High risk	Medium risk	Low risk	Very low risk
Agroforestry (km^2)	-	-	-	0.006	0.185
Bareland (km^2)	-	-	-	0.008	0.262
Building (unit)	3	44	25	521	2,918
Grassfield (km^2)	-	-	-	0.004	0.191
Open space (km^2)	0.009	0.071	0.040	0.369	1.389
Ricefield (km^2)	-	-	-	0.012	0.468
River (km^2)	-	-	-	-	0.010
Road (km)	-	0.381	0.033	3.861	24.088
Sand (km^2)	0.050	0.053	0.006	-	-

Approximately 5% of all agroforestry, bareland, grassfields and ricefileds, less than 30% of all buildings, open space and roads, and all sand areas in Seminyak Village are at risk from future tsunamis, due to their locations in low–lying flat areas and near the coast. It is only rivers that are potentially safe from future tsunamis in that village. This land use types is located in higher areas and far away from the coast (see Table 5.19).

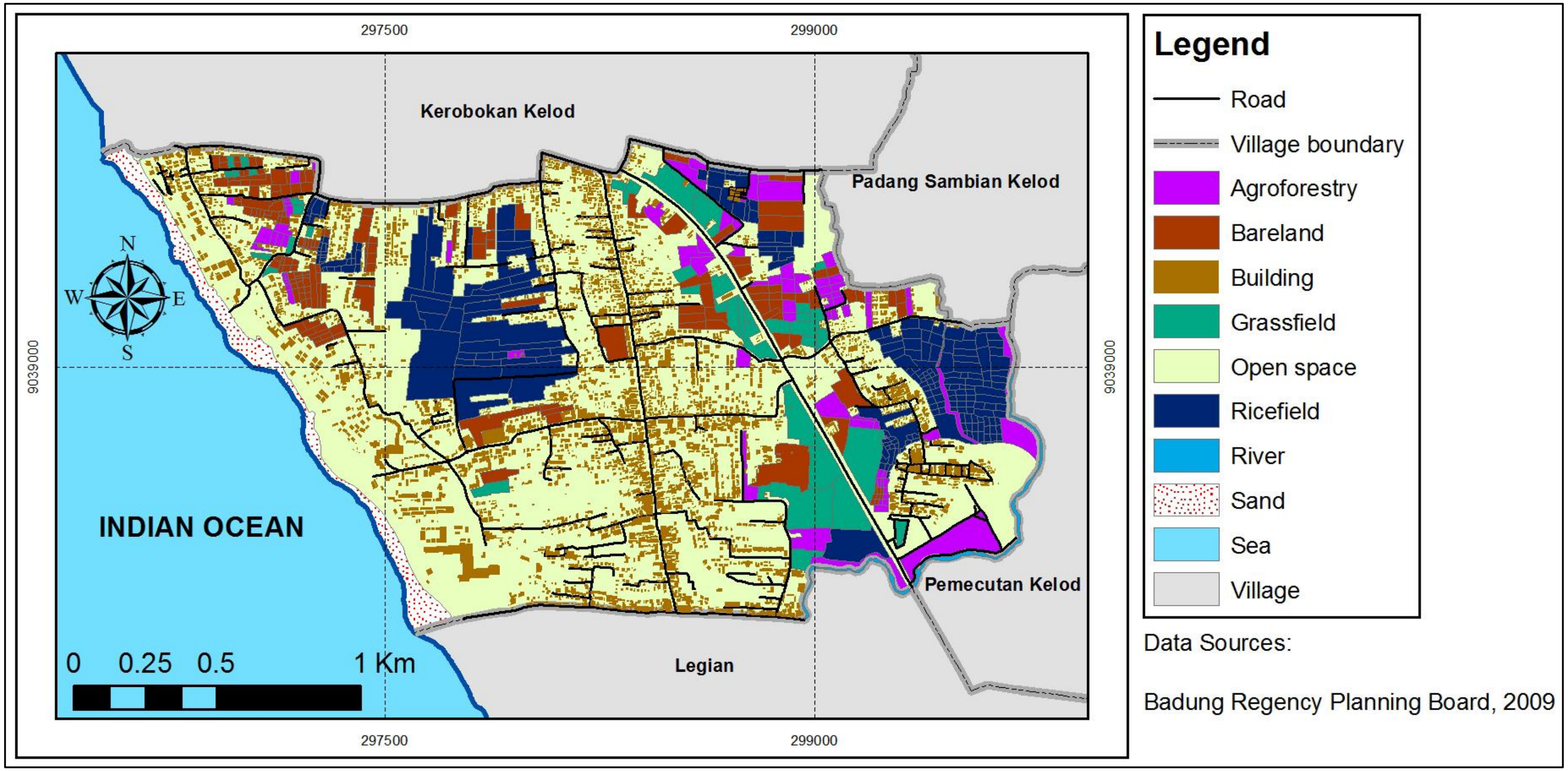


Figure 5.35. The land use map of the Seminyak Village.

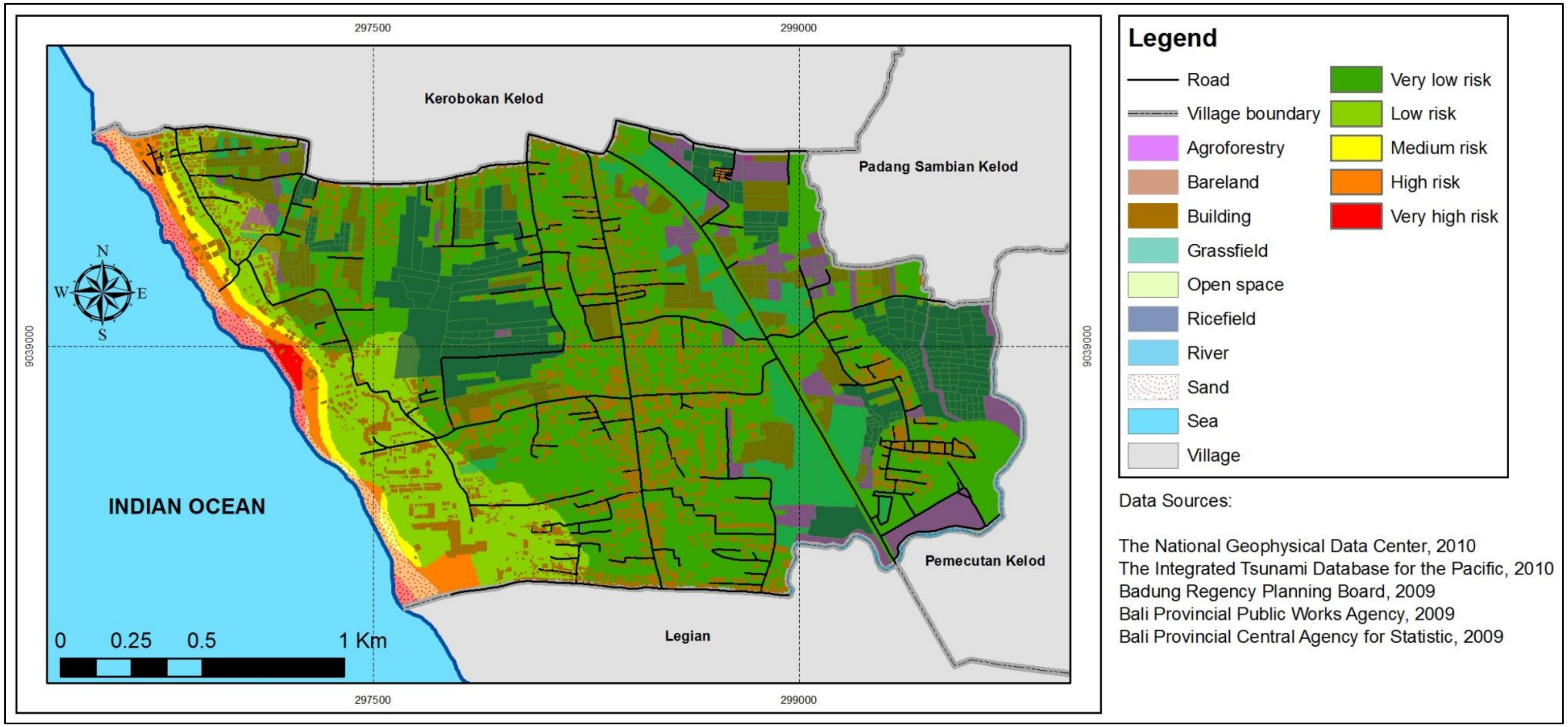


Figure 5.36. The land uses at risk in Seminyak Village.

All land use types are at risk from future tsunamis in Sanur Village. There is no land use type located in tsunami least risk areas in that village (see Figure 5.38 and Table 5.20).

Table 5.20. The land uses that are at risk from tsunami in Sanur Village.

Land use type	The risk zones				
	Very high risk	High risk	Medium risk	Low risk	Very low risk
Agroforestry (km^2)	0.086	0.101	0.017	0.001	0.066
Bareland (km^2)	0.013	0.026	-	-	0.016
Building (unit)	308	2,245	560	786	1,501
Open space (km^2)	0.265	0.911	0.285	0.301	0.492
Road (m)	4.604	12.707	3.459	3.508	8.613
Sand (km^2)	0.096	-	-	-	-

More than two–third of all agroforestry, bareland, buildings, open space and roads, and all sand areas in Sanur Village are at risk from future tsunamis. These land use types are at risk from tsunamis because they are located in the low–lying flat areas and near the coast (see Table 5.20).

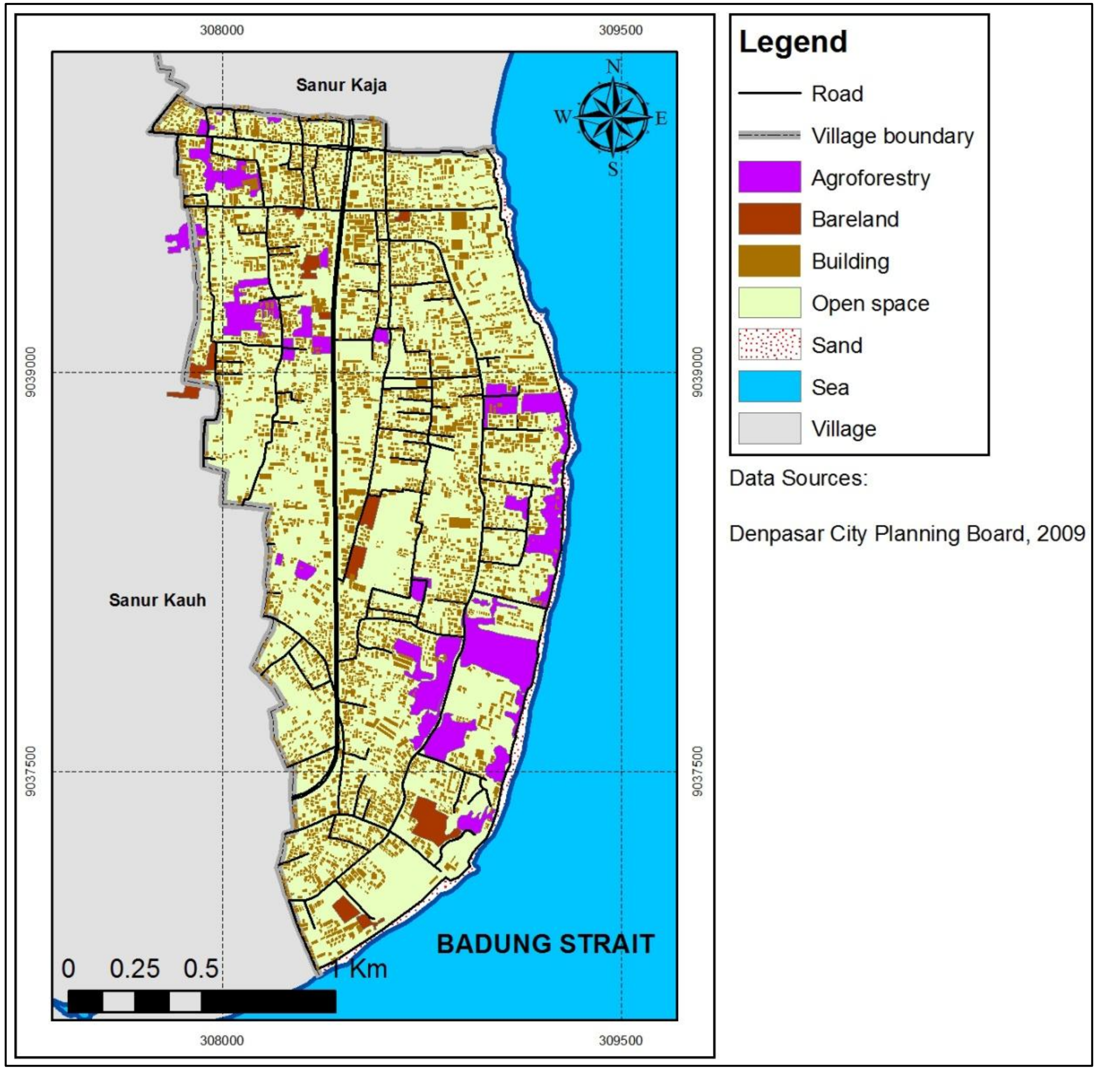


Figure 5.37. The land use map of the Sanur Village.

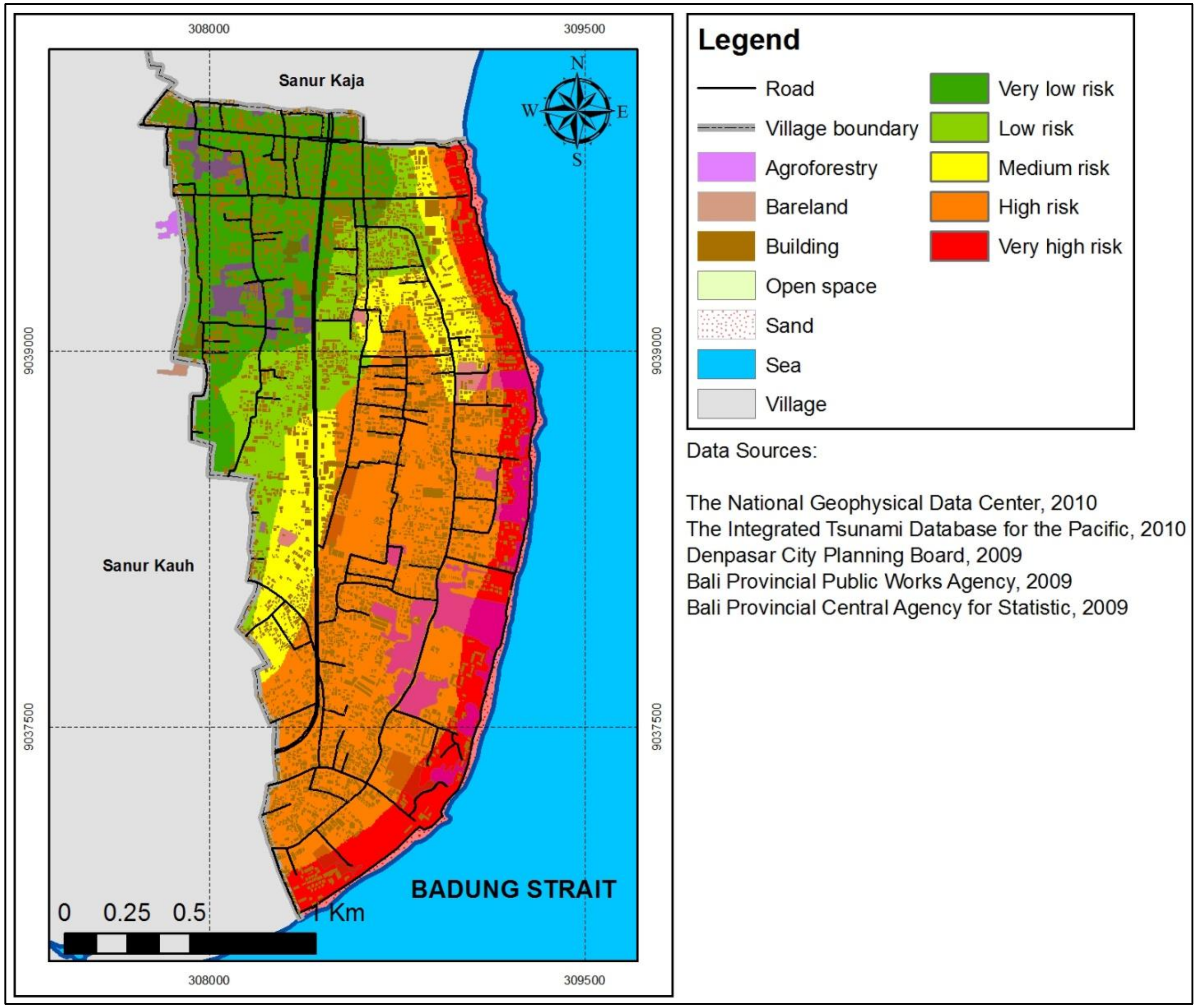


Figure 5.38. The land uses at risk in Sanur Village.

Most of the land use types are at risk in Sanur Kaja Village. It is only the bareland that are located in tsunami least risk areas in that village (see Figure 5.40 and Table 5.21).

Table 5.21. The land uses that are at risk from tsunami in Sanur Kaja Village.

Land use type	**The risk zones**				
	Very high risk	**High risk**	**Medium risk**	**Low risk**	**Very low risk**
Agroforestry (km^2)	0.008	0.007	0.015	0.030	0.208
Bareland (km^2)	-	-	-	-	0.100
Building (unit)	100	101	65	87	2,376
Grassfield (km^2)	-	-	0.001	0.007	0.003
Open space (km^2)	0.116	0.070	0.055	0.079	0.775
Ricefield (km^2)	0.011	0.053	0.010	0.030	0.477
Road (km)	1.668	0.883	0.782	1.592	18.748
Sand (km^2)	0.041	-	-	-	-

Approximately one–third of all agroforestry, buildings, open space, ricefields and roads, two–third of the grassfields, and all sand areas in Sanur Kaja Village are at risk from future tsunamis, due to their locations in low–lying flat areas and near the coast. It is only bareland that is potentially safe from future tsunamis in that village. This land use type is located in higher areas and far away from the coast (see Table 5.21).

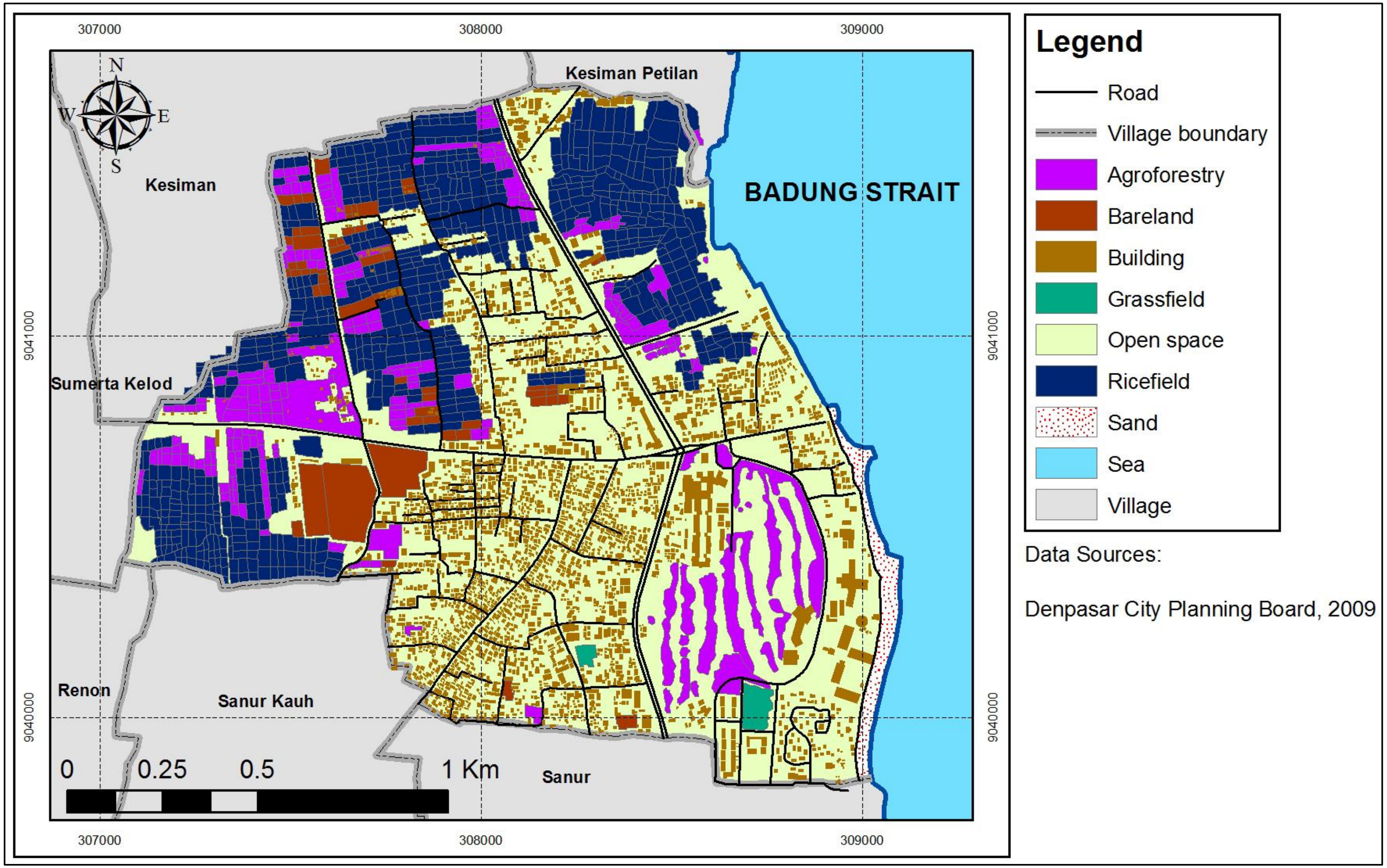


Figure 5.39. The land use map of the Sanur Kaja Village.

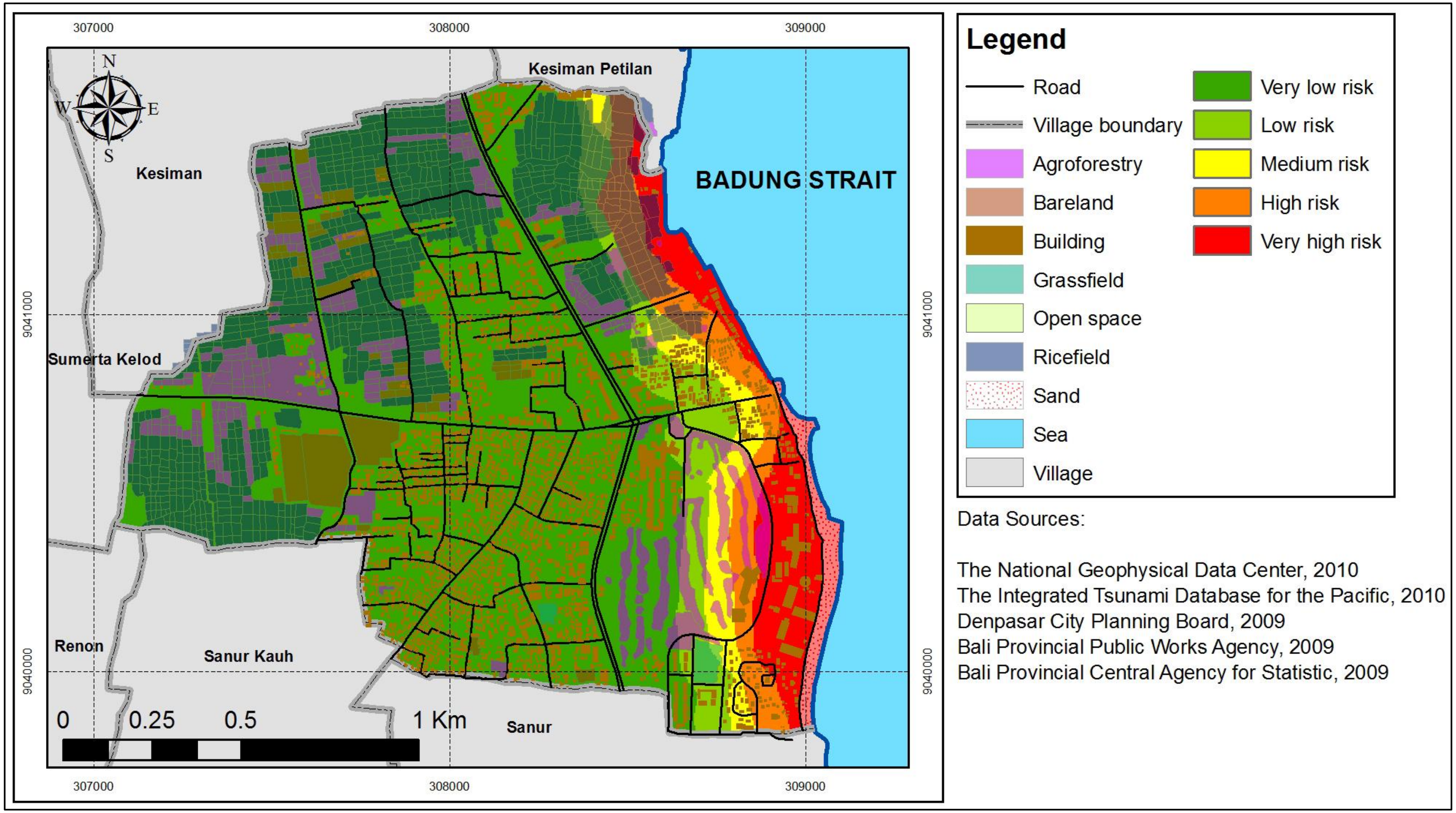


Figure 5.40. The land uses at risk in Sanur Kaja Village.

5.4.1.2. Building and Infrastructure at Risk

For the building and infrastructure analysis, the "building" layer of each village in both regions is overlaid with the "risk" layer, so it is possible to locate and calculate buildings that are at risk from tsunamis in each village. The building types classification was based on the urban planning map, google earth and field surveys.

Table 5.22. The building types at risk in Kuta Village.

Building types	The risk zones (unit)				
	Very high risk	High risk	Medium risk	Low risk	Very low risk
Bank	-	1	6	15	8
Church	-	-	6	1	-
Cinema	-	-	-	1	-
Clinic	-	1	-	3	2
Gas station	-	-	-	-	6
Government office	1	-	-	6	19
Hamlet meeting hall	-	1	5	3	3
Hospital	-	-	-	-	8
Hotel	186	363	1,327	1,120	1,116
House	-	93	105	187	521
Industry	-	4	4	24	84
Mall	1	-	8	1	19
Monument	-	-	1	-	1
Mosque	-	-	1	2	1
Police station	-	-	-	3	-
Post office	-	-	-	1	-
Pura temple	3	-	1	4	3
Restaurant	18	17	70	63	70
School	-	6	12	12	19
Shop	6	54	353	298	676
Traditional market	1	2	1	9	10
Travel agency	-	-	-	2	5
Vihara temple	-	-	-	1	-
Villa	140	119	408	263	125
Water park	-	-	22	-	-

Almost 67% of the total buildings that are located in Kuta Village are at risk from future tsunamis. Only 33% of the total buildings are located in tsunami least risk areas in that village. There are 2,996 units of hotels, 930 units of villas, 711 units of shops, 385 units of houses and 168 units of restaurants located in tsunami risk areas (see Table 5.22)

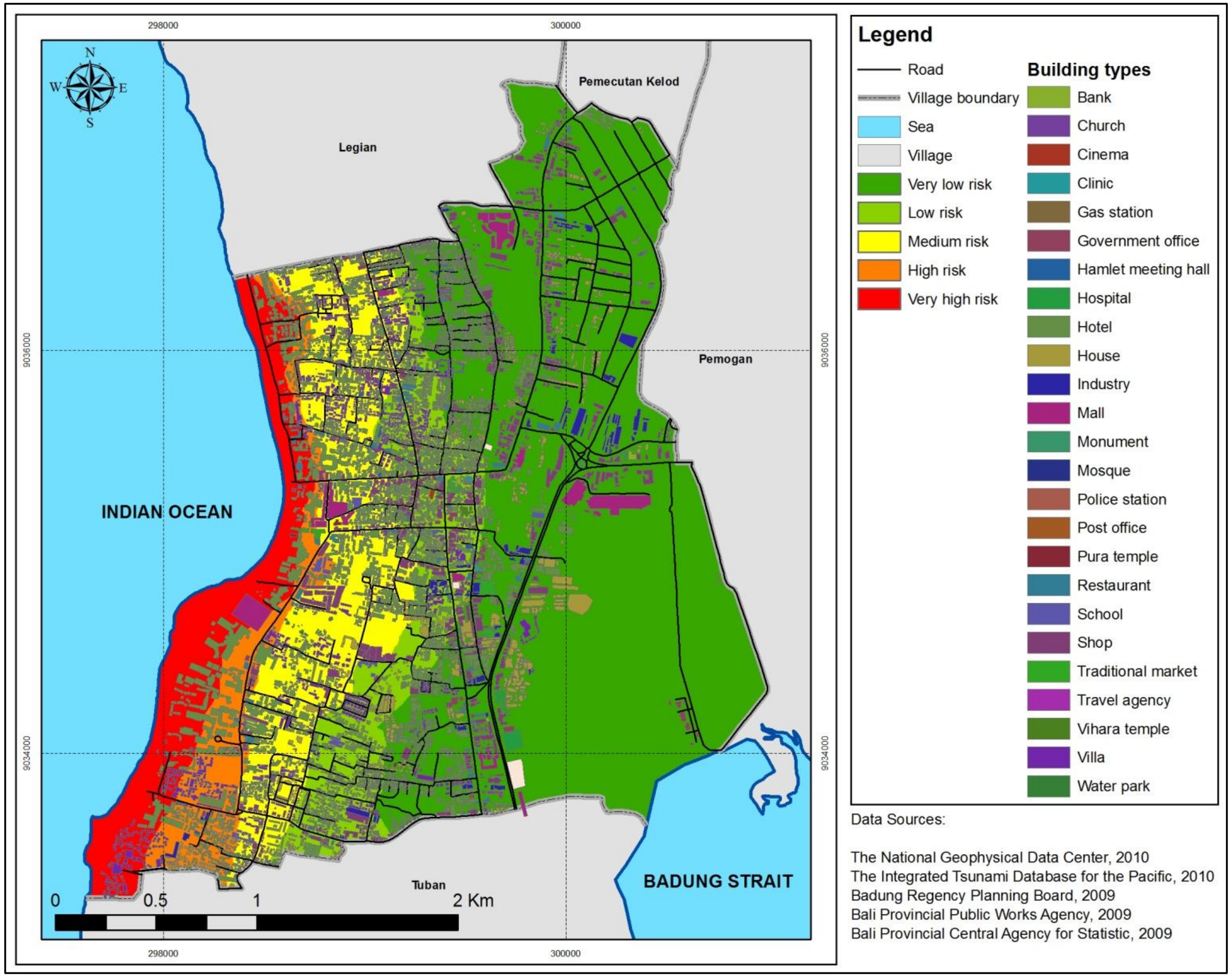


Figure 5.41. The buildings at risk in Kuta Village.

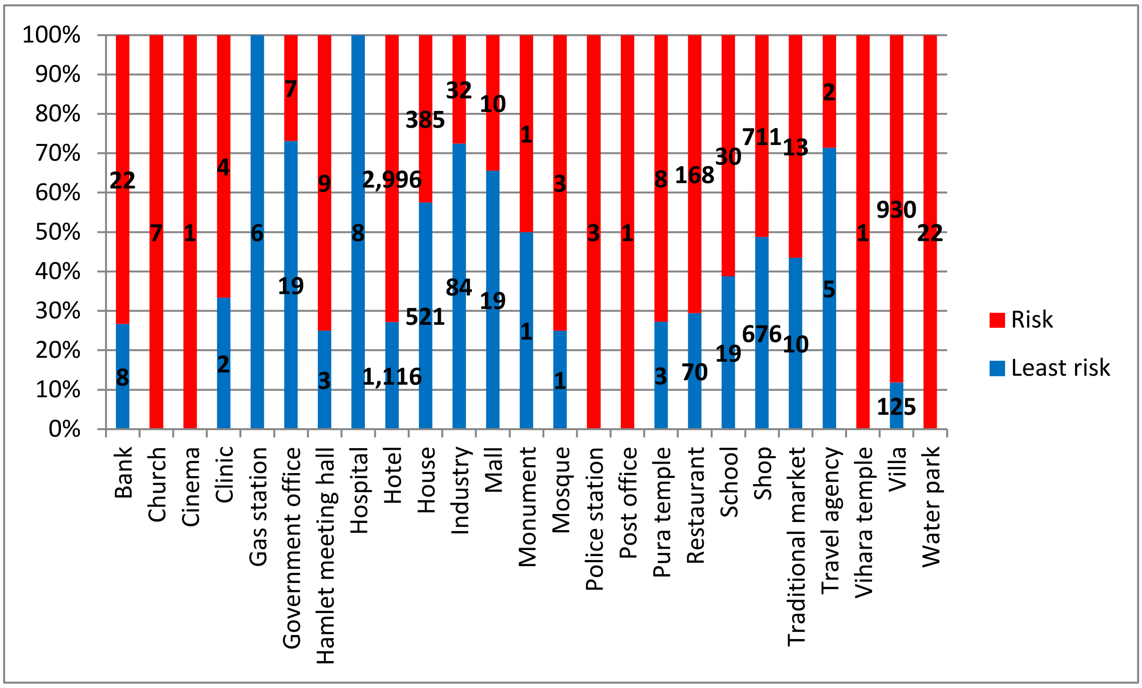


Figure 5.42. The building types at risk in Kuta Village.

All units of churches, cinemas, police stations, post offices, vihara temples and water parks are at risk from future tsunamis in Kuta Village. More than two–third of all villas, banks, hamlet meeting halls, hotels, mosques, pura temples and restaurants are also located in tsunami risk areas (see Figure 5.42). There are 2 building types which are located in tsunami least risk areas in that village, namely gas stations and hospitals. Only these buildings could serve as recovery centres.

Table 5.23. The building types at risk in Legian Village.

Building types	The risk zones				
	Very high risk	High risk	Medium risk	Low risk	Very low risk
Bank	-	-	-	2	1
Church	-	-	-	-	1
Clinic	-	-	-	3	1
Government office	-	-	-	-	3
Hamlet meeting hall	-	-	-	-	3
Hotel	-	50	14	732	588
House	-	-	-	7	229
Industry	-	-	2	2	24
Pura temple	-	-	-	-	4
Restaurant	-	5	1	27	4
School	-	-	-	-	22
Shop	-	5	-	212	206
Traditional market	-	-	-	1	-
Travel agency	-	-	-	4	1
Villa	-	-	-	103	340
Village cooperative unit	-	-	-	-	1

Around 45% of the total buildings that are located in Legian Village are at risk from future tsunamis, while 55% of the total buildings are located in tsunami least risk areas in that village. There are 796 units of hotels, 217 units of shops and 103 units of villas that are at risk from tsunami waves (see Table 5.23).

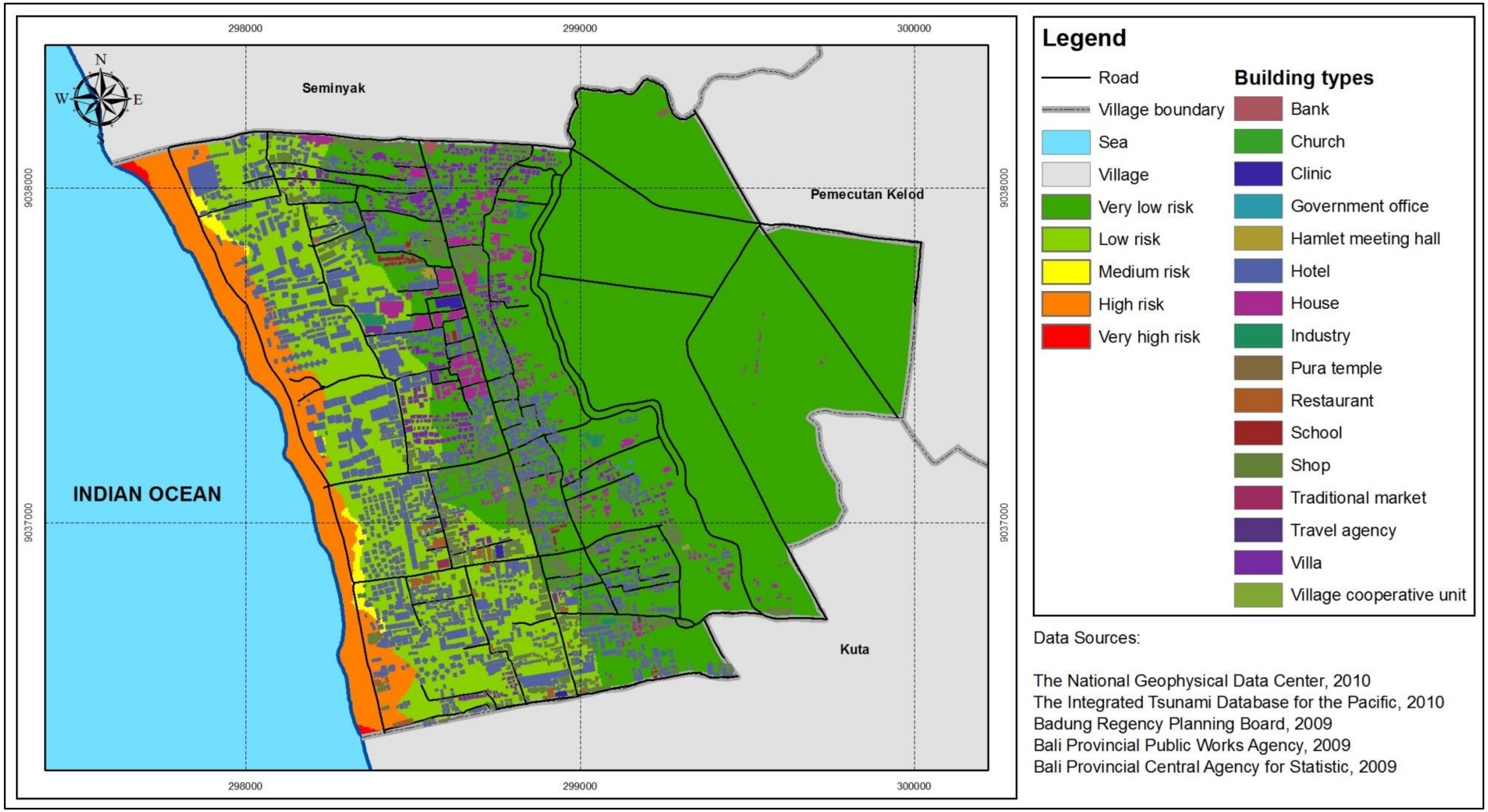


Figure 5.43. The buildings at risk in Legian Village.

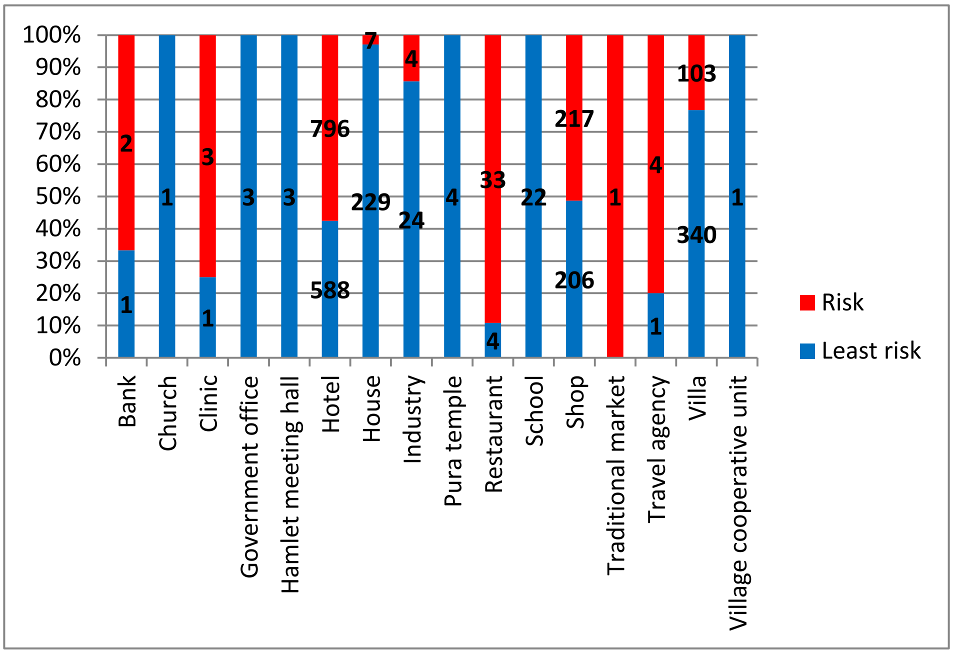


Figure 5.44. The building types at risk in Legian Village.

All units of traditional markets are at risk from future tsunamis in Legian Village. Almost 90% of the restaurants are also at risk from tsunamis (see Figure 5.44). There are 6 building types which are potentially safe if a tsunami occurs in that village because they are located in tsunami least risk areas, namely churches, government offices, hamlet meeting halls, pura temples, schools and village cooperative units. These buildings could serve as recovery centres.

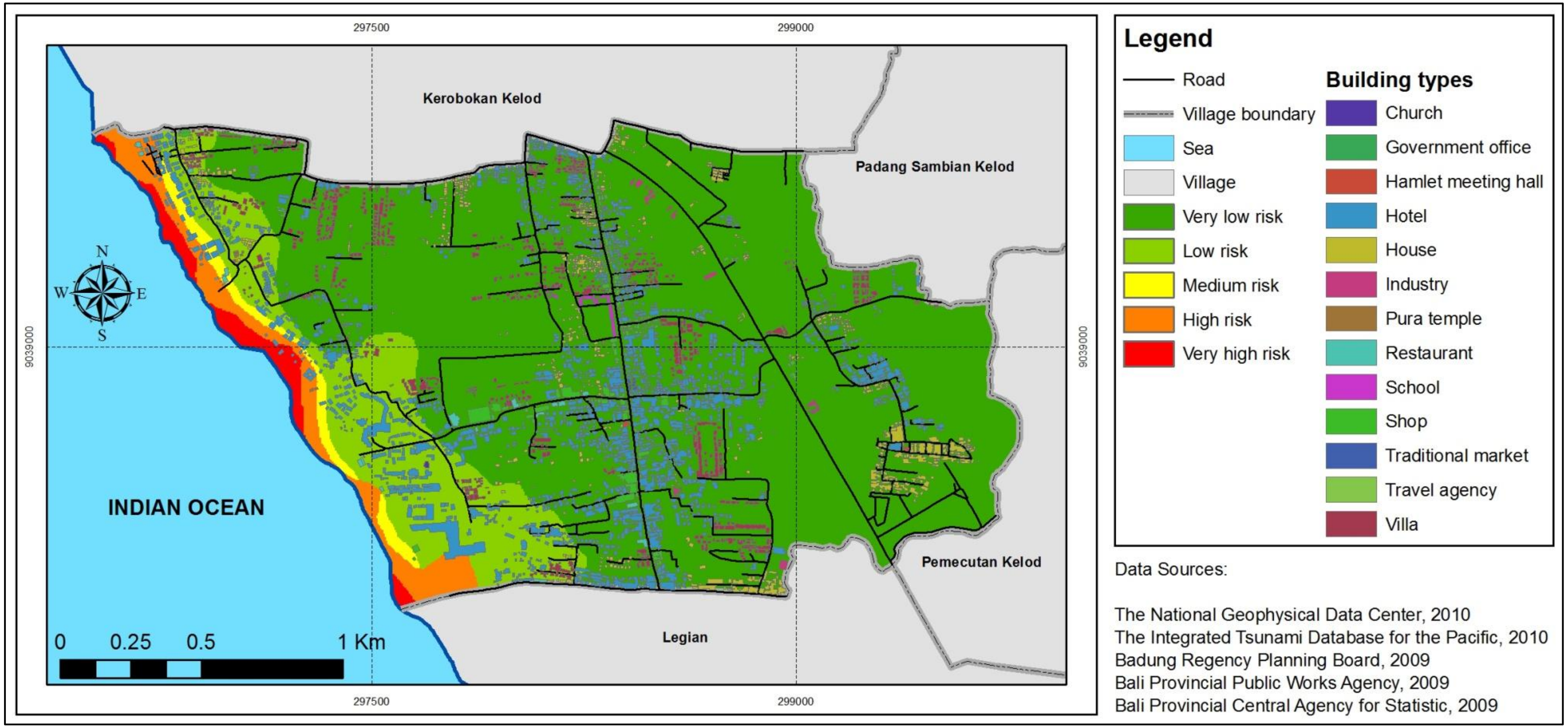


Figure 5.45. The buildings at risk in Seminyak Village.

Table 5.24. The building types at risk in Seminyak Village.

Building types	The risk zones (unit)				
	Very high risk	High risk	Medium risk	Low risk	Very low risk
Church	-	-	-	1	-
Government office	-	-	-	-	4
Hamlet meeting hall	-	-	-	1	3
Hotel	3	37	21	331	1449
House	-	-	-	45	610
Industry	-	-	-	-	30
Pura Temple	-	2	-	7	1
Restaurant	-	5	3	9	10
School	-	-	-	-	12
Shop	-	-	1	18	158
Traditional Market	-	-	-	-	8
Travel Agency	-	-	-	1	-
Villa	-	-	-	108	633

Only 17% of the total buildings in Seminyak Village are at risk from tsunamis, while 83% of the total buildings are located in tsunami least risk areas. Moreover, there are 392 units of hotels, 108 units of villas and 45 units of houses located in tsunami risk areas (see Table 5.24).

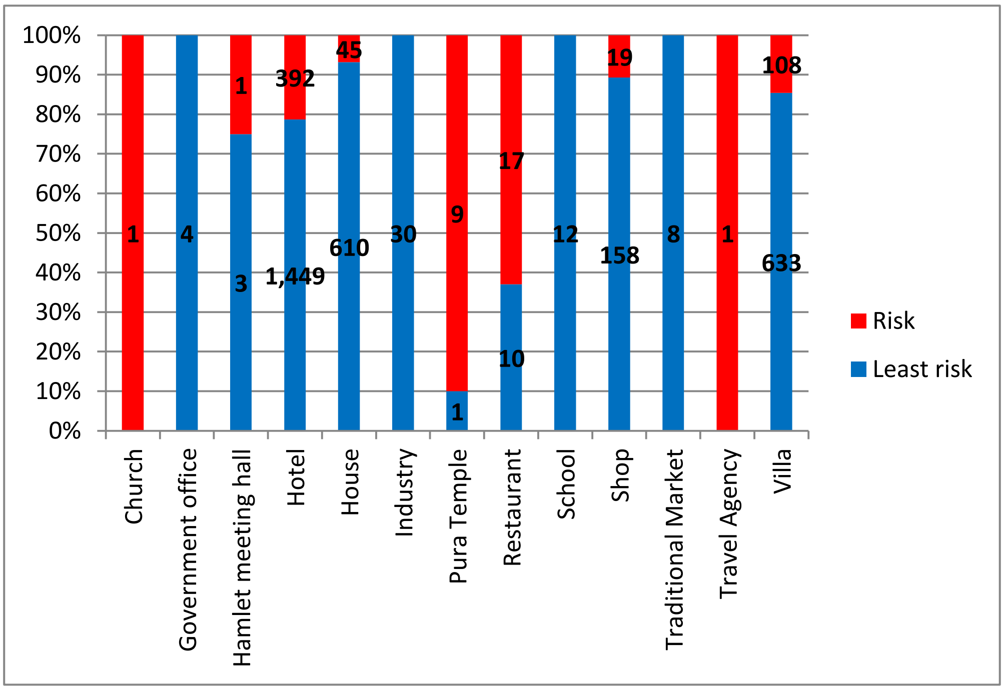


Figure 5.46. The building types at risk in Seminyak Village.

All units of churches and travel agencies in Seminyak Village are located in tsunami risk areas (see Figure 5.46). Around 90% of the pura temples are also at risk from future tsunamis. On the other hand, all units of government offices, industries, schools and traditional markets in that village are located in tsunami least risk areas. Some of these buildings could serve as recovery centres.

Table 5.25. The building types at risk in Sanur Village.

Building types	The risk zones (unit)				
	Very high risk	High risk	Medium risk	Low risk	Very low risk
Bank	-	6	-	2	3
Clinic	-	1	1	-	7
Diving agency	2	6	2	-	1
Electricity station	-	2	-	-	-
Gas station	-	-	2	-	-
Government office	5	16	9	-	-
Hamlet meeting hall	-	1	-	1	5
Hotel	140	1063	204	255	394
House	-	279	83	288	539
Industry	-	35	19	18	57
Mall	-	3	-	-	1
Post office	-	-	-	-	1
Pura temple	2	8	-	-	1
Restaurant	18	102	25	18	34
School	-	1	-	26	26
Shop	17	207	73	108	304
Traditional market	16	6	2	7	1
Travel agency	-	4	2	3	7
Villa	108	504	138	60	120
Village cooperative unit	-	1	-	-	-

Around 72% of the total buildings in Sanur Village are at risk from future tsunamis, and it is only 28% of the total buildings that are located in tsunami least risk areas. There are 1662 units of hotels, 810 units of villas, 650 units of houses, 405 units of shops and 163 units of restaurants potentially at risk if a tsunami occurs there (see Table 5.25)

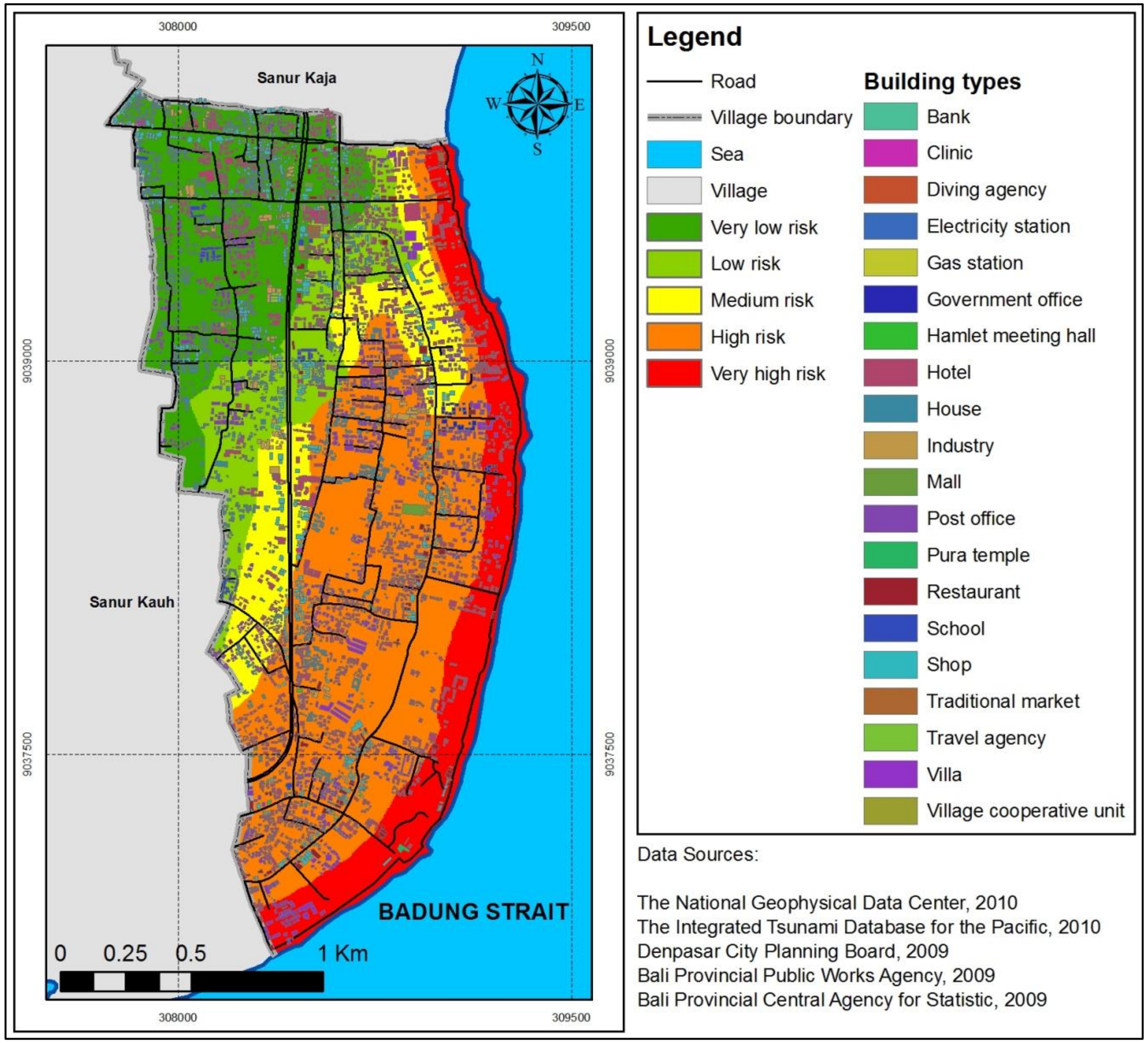


Figure 5.47. The buildings at risk in Sanur Village.

There are four building types in Sanur Village that are located in tsunami risk areas, namely government offices, village cooperative units, electricity stations and gas stations. On the other hand, all units of post offices in that village are located in tsunami least risk areas. More than two–third of all diving agencies, hotels, pura temples, restaurants, traditional markets and villas are also at risk from tsunami waves (see Figure 5.48).

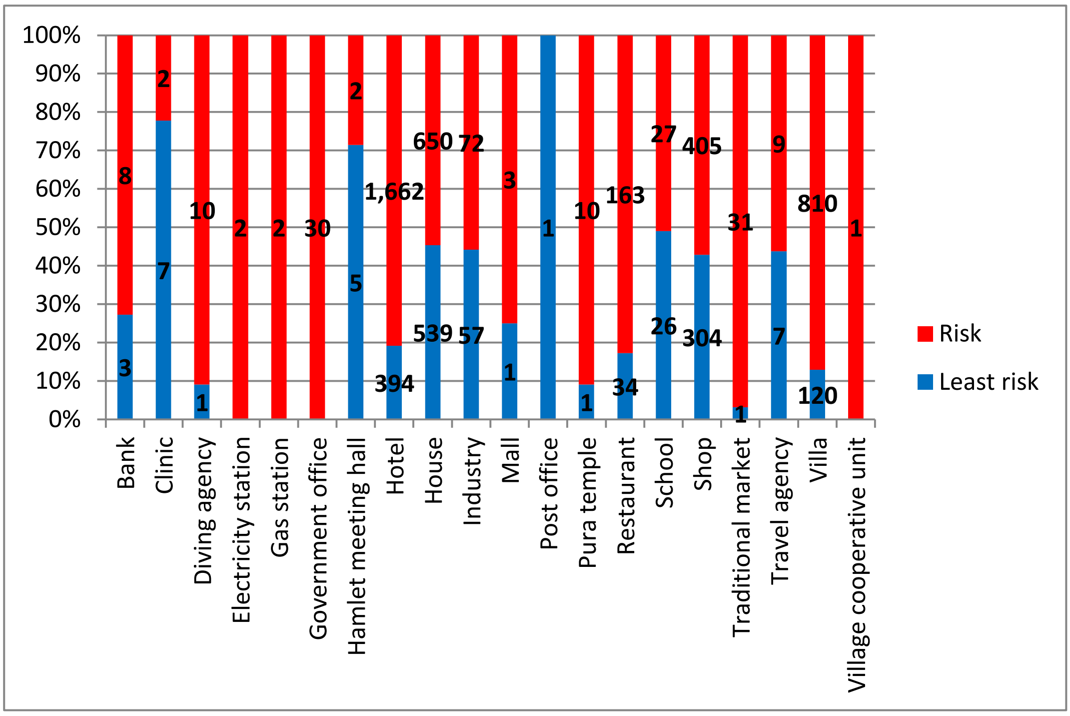


Figure 5.48. The building types at risk in Sanur Village.

Table 5.26. The building types at risk in Sanur Kaja Village.

Building type	Area of Risk (unit)				
	Very high risk	High risk	Medium risk	Low risk	Very low risk
Bank	-	-	-	-	1
Clinic	-	-	-	-	2
Electricity station	-	-	-	-	2
Gas station	-	-	-	-	1
Hamlet meeting hall	-	-	-	2	4
Hotel	55	54	36	26	166
House	7	-	1	10	1,609
Industry	-	-	-	-	69
Mall	-	-	-	-	8
Mosque	-	-	-	1	-
Museum	7	-	-	-	-
Police station	-	-	-	-	7
Pura temple	-	1	-	-	20
Restaurant	1	3	1	8	48
School	-	-	-	-	39
Shop	5	5	4	12	319
Sport Hall	-	-	-	-	2
Travel agency	-	-	-	-	11
Villa	25	38	23	28	68

Only 13% of the total buildings in Sanur Kaja Village are at risk from tsunamis, and around 87% of the total buildings are located in tsunami least risk areas. Furthermore, there are 171 units of hotels, 114 units of villas and 26 units of shops potentially at risk if a tsunami occurs there (see Table 5.26).

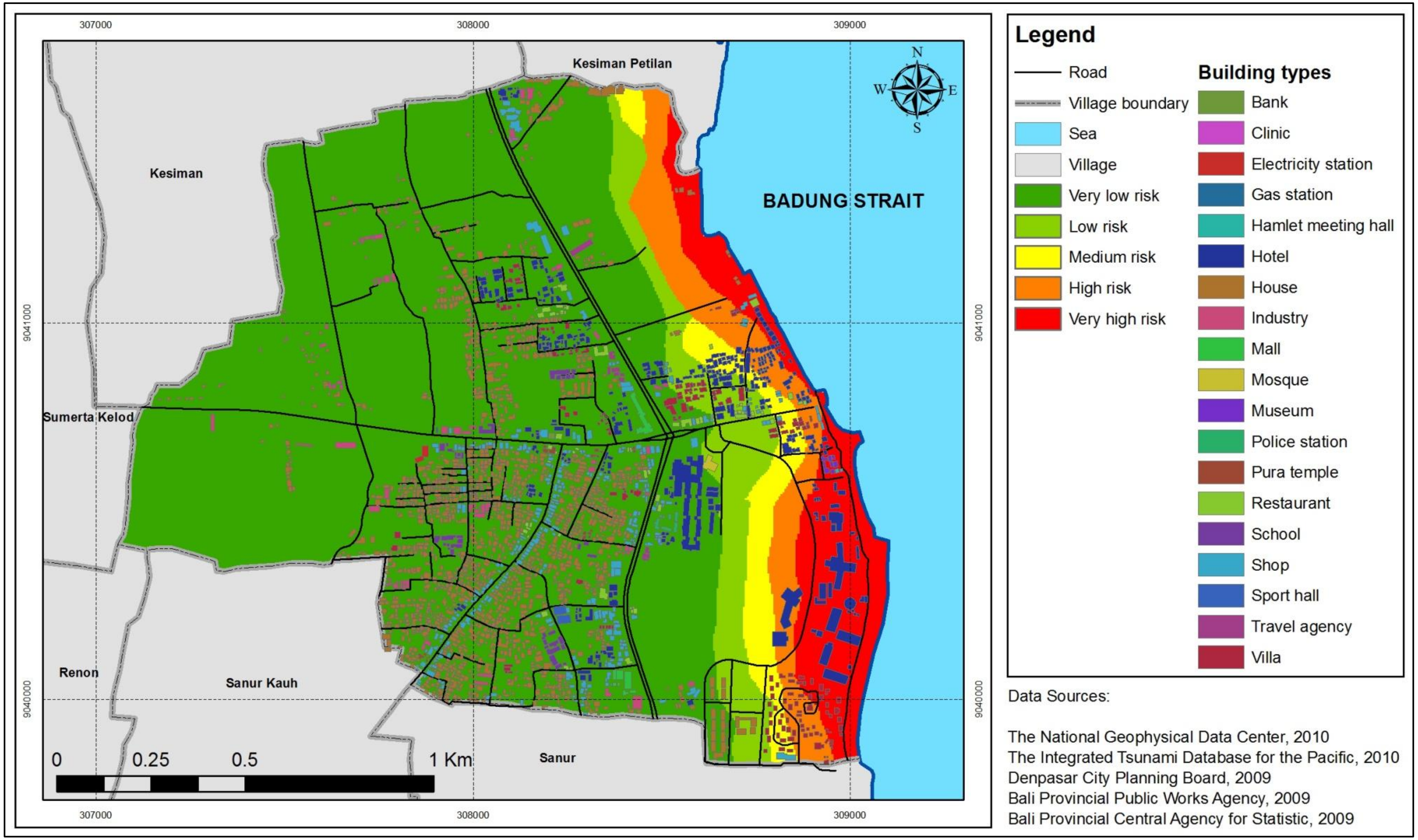


Figure 5.49. The buildings at risk in Sanur Kaja Village.

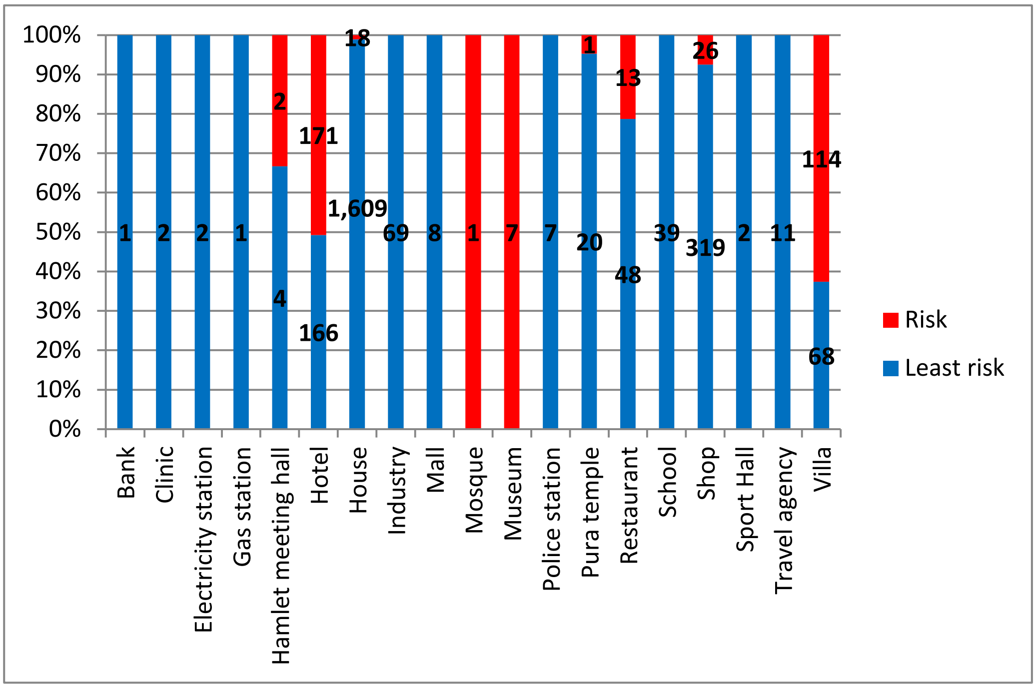


Figure 5.50. The building types at risk in Sanur Kaja Village.

All units of mosques and museums in Sanur Kaja Village are located in tsunami risk areas (see Figure 5.50). On the other hand, all units of banks, clinics, electricity stations, gas stations, industries, malls, police stations, schools, sport halls and travel agencies are potentially safe from tsunami waves. Some of these buildings could serve as recovery centres.

For the infrastructure analysis, there are 5 infrastructure types beside social and economic infrastructures that are analysed in this study, namely roads, houses, places of worship (such as church, mosque, pura and vihara temples), gas and electricity stations.

For Kuta Village, around 43% of the houses, more than 82% of the places of worship and around 50% of the total length of the roads are potentially at risk from tsunami waves. On the other hand, all units of gas stations are located in tsunami least risk areas. Furthermore, there is no electricity station in that village (see Figure 5.51).

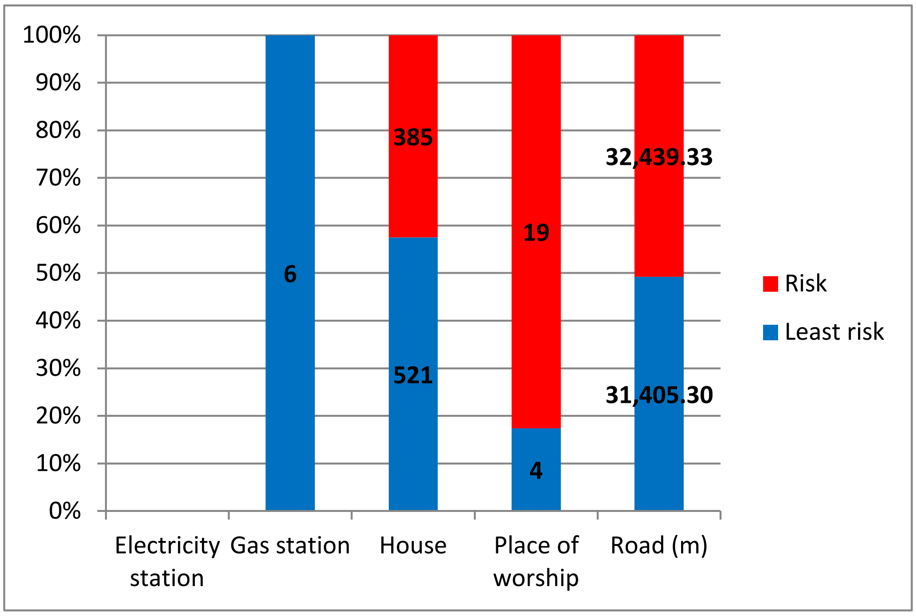


Figure 5.51. The infrastructure types at risk in Kuta Village.

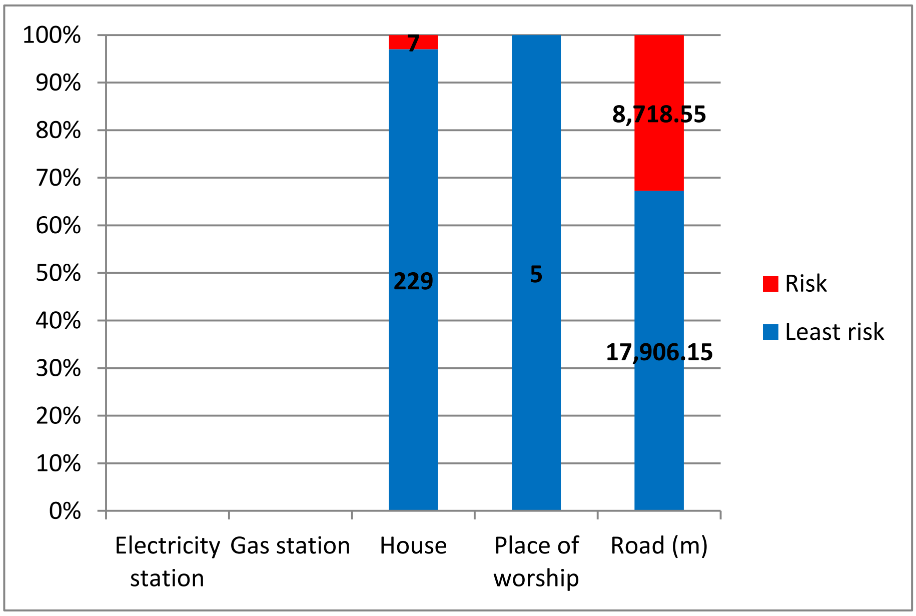


Figure 5.52. The infrastructure types at risk in Legian Village.

For Legian Village, less than 5% of the houses and around 23% of the total length of the roads are located in tsunami risk areas. All units of places of worship are located in tsunami least risk areas. There are no electricity and gas stations in that village (see Figure 5.52).

There are no electricity and gas stations in Seminyak Village. Moreover, it is only 7% of the houses and less than 16% of the total length of the roads that are at risk from tsunami waves. On the other hand, more than 90% of the places of worship are potentially in danger of tsunami impact in that village (see Figure 5.53).

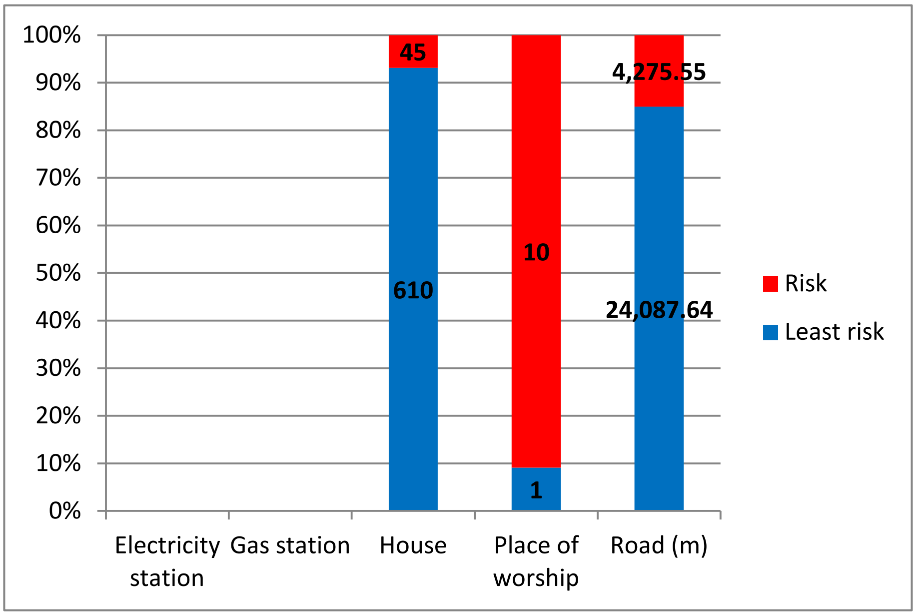


Figure 5.53. The infrastructure types at risk in Seminyak Village.

All units of electricity and gas stations in Sanur Village are located in tsunami risk areas. Furthermore, around 55% of the houses, more than 90% of the places of worship and around 74% of the total length of the roads are also at risk from tsunami waves (see Figure 5.54).

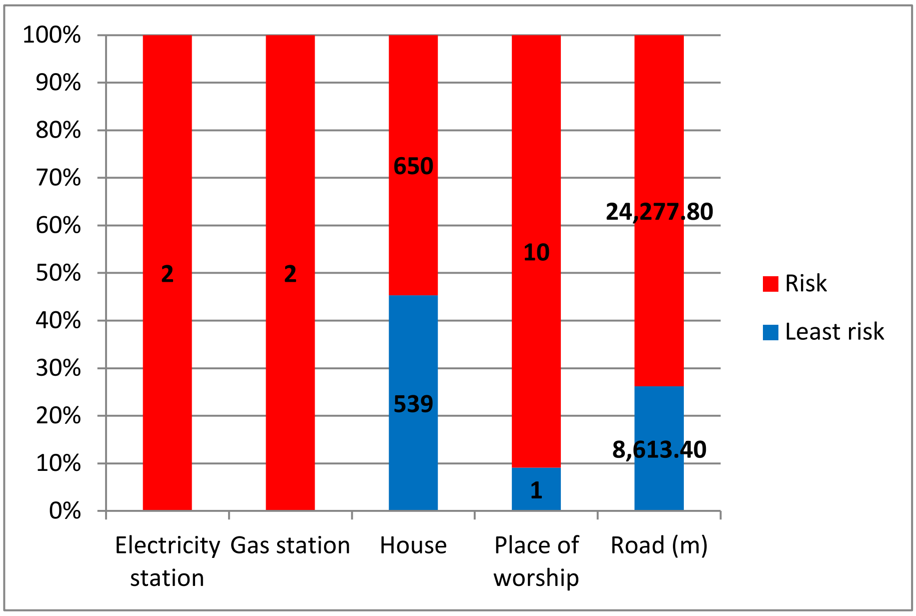


Figure 5.54. The infrastructure types at risk in Sanur Village.

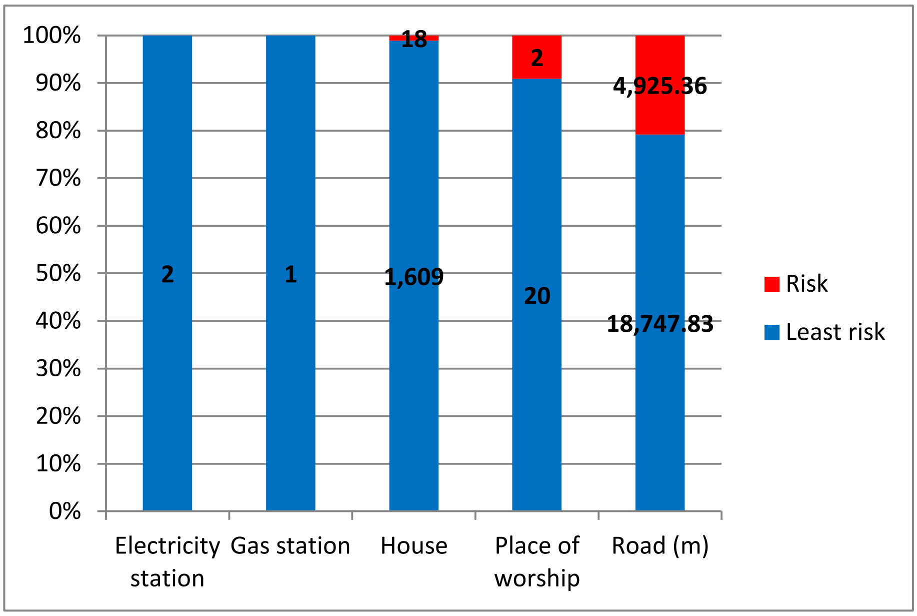


Figure 5.55. The infrastructure types at risk in Sanur Kaja Village.

For Sanur Kaja Village, around 3% of the houses, less than 10% of the places of worship and around 21% of the total length of the roads are potentially at risk from future tsunamis. On the other hand, all units of electricity and gas stations are located in tsunami least risk areas in that village (see Figure 5.55).

During evacuation, relief, and rehabilitation after a tsunami event, this infrastructure plays an important role, used to transport people, food, and materials for tsunami victims, and provide essential services or recovery locations.

5.4.1.3. Social Variables at Risk

Information about risk enables population at risk of injury or death from a tsunami event to be calculated. This calculation is based on how many people (total population, females, age groups (children and elderly) and disabled people) are located in tsunami risk and least risk areas. In this study, the definition of age groups is the total numbers of children (0 – 14 years old) and elderly (more than 60 years old).

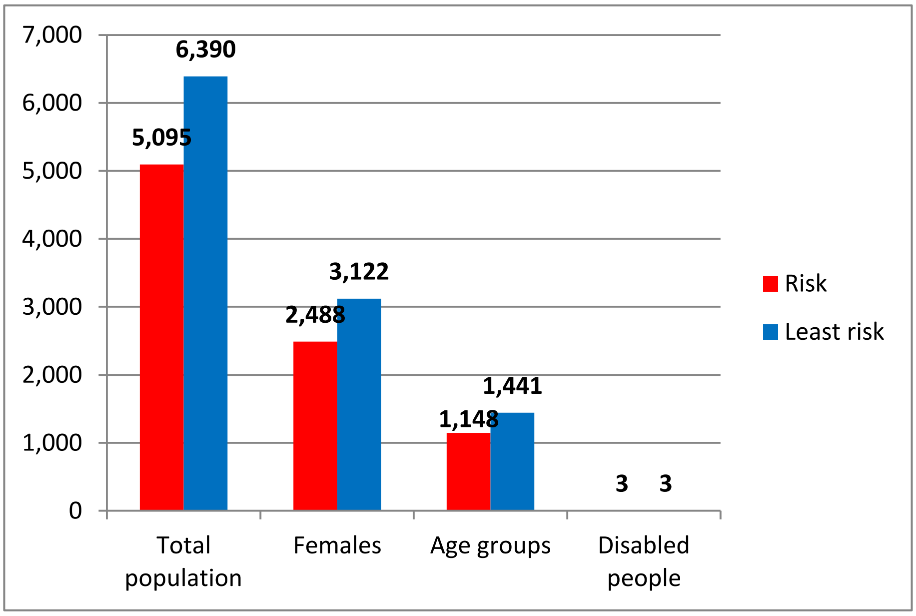


Figure 5.56. The total number of people at risk in Kuta Village.
Source: Bali Provincial Central Agency for Statistic (2009).

For Kuta Village, there are 5,095 people consisting of 2,488 females, 1,148 children and elderly, and 3 disabled people who are potentially victims from a tsunami event. On the other hand, 6,390 people are potentially located in tsunami least risk areas, consisting of 3,122 females, 1,441 children and elderly, and 3 disabled people (see Figure 5.56).

There are 1,144 people potentially in danger of future tsunamis in Legian Village. They consist of 570 females, 329 children and elderly, and 3 disabled people. On the other hand, 2,217 people potentially live in tsunami least risk areas, consisting of 1,104 females, 637 children and elderly, and 5 disabled people (see Figure 5.57).

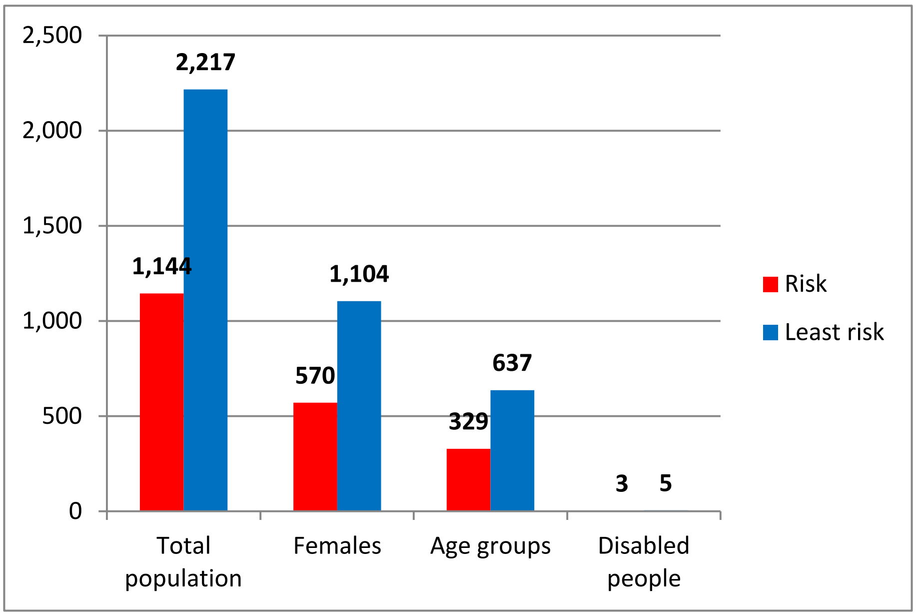


Figure 5.57. The total number of people at risk in Legian Village.
Source: Bali Provincial Central Agency for Statistic (2009).

There are only 846 people in Seminyak Village that live at risk from tsunami waves. The composition of that population consists of 425 females, 209 children and elderly, and 2 disabled people. On the other hand, around 3,304 people are potentially safe from future tsunamis because they live in tsunami least risk areas, consisting of 1,658 females, 816 children and elderly, and 7 disabled people (see Figure 5.58).

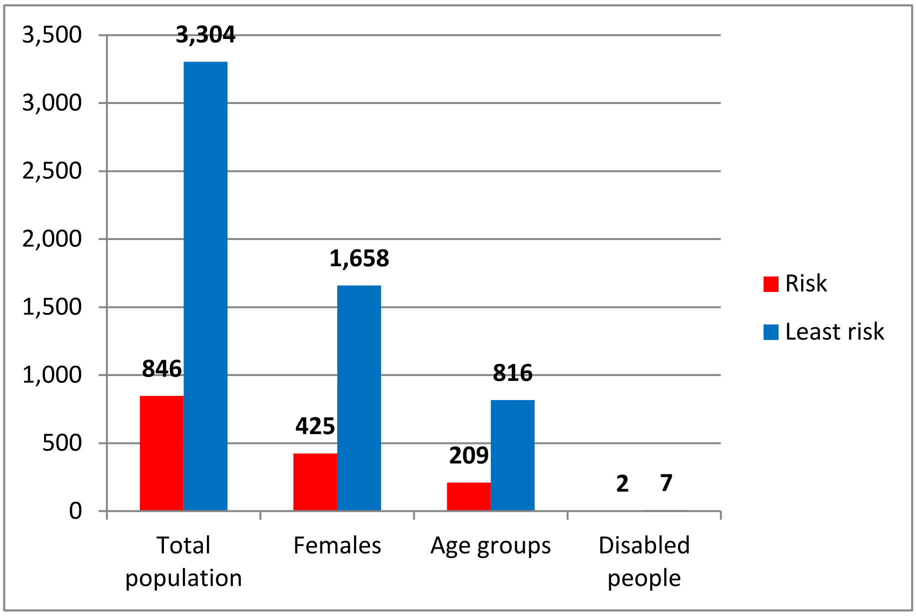


Figure 5.58. The total number of people at risk in Seminyak Village.
Source: Bali Provincial Central Agency for Statistic (2009).

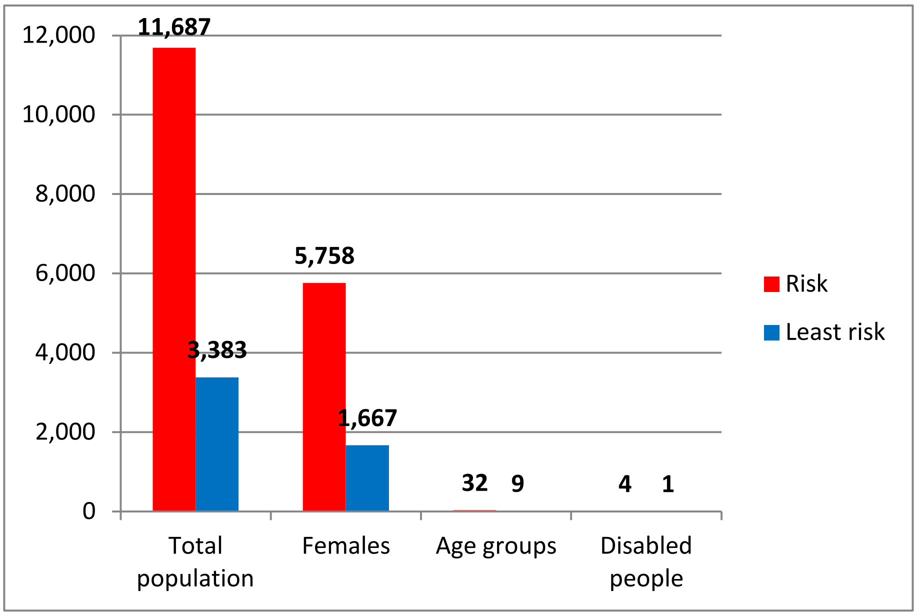


Figure 5.59. The total number of people at risk in Sanur Village.
Source: Bali Provincial Central Agency for Statistic (2009).

For Sanur Village, there are 11,687 people consisting of 5,758 females, 32 children and elderly, and 4 disabled people who are potentially victims of the tsunami hazard. On the other hand, there are only 3,383 people who are potentially safe, because they live in tsunami least risk areas far away from the coast. They consist of 1,667 females, 9 children and elderly, and 1 disabled person (see Figure 5.59).

There are 2,040 people potentially in danger of tsunami waves in Sanur Kaja Village. They consist of 1,002 females, 8 children and elderly, and 2 disabled people. Around 6,223 people are potentially safe from future tsunamis because they live in tsunami least risk areas. They consist of 3,057 females, 24 children and elderly, and 5 disabled people (see Figure 5.60).

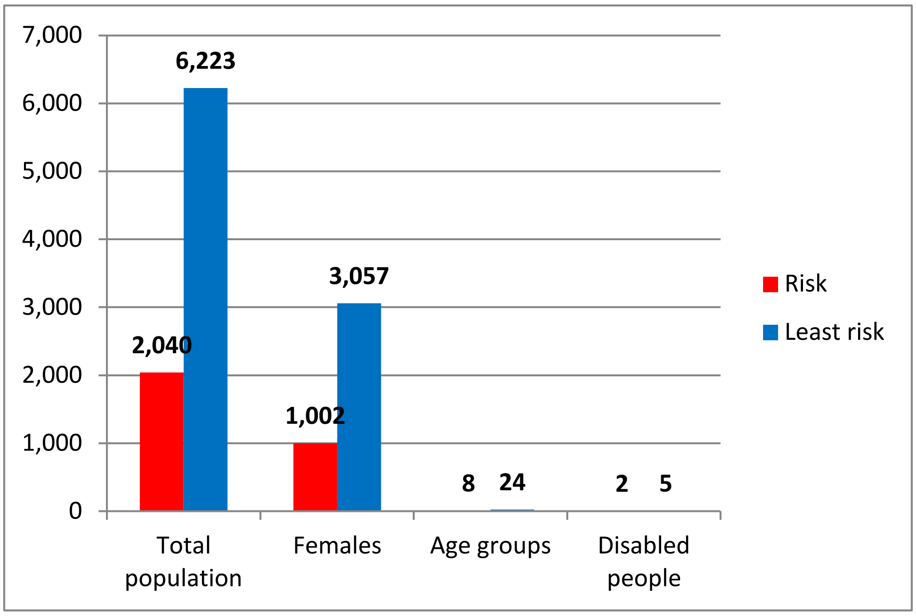


Figure 5.60. The total number of people at risk in Sanur Kaja Village.
Source: Bali Provincial Central Agency for Statistic (2009).

Furthermore, many social facilities are also at risk from tsunamis, such as schools, government offices, police stations, post offices, hamlet meeting halls, clinics and hospitals. These facilities are important for the village community.

All units of police stations and post offices are located in tsunami risk areas. More than two–third of all clinics, hamlet meeting halls and schools are also at risk from future tsunamis. Moreover, only around one–third of government offices are located in tsunami risk areas. On the other hand, all units of hospitals are located in tsunami least risk areas (see Figure 5.61).

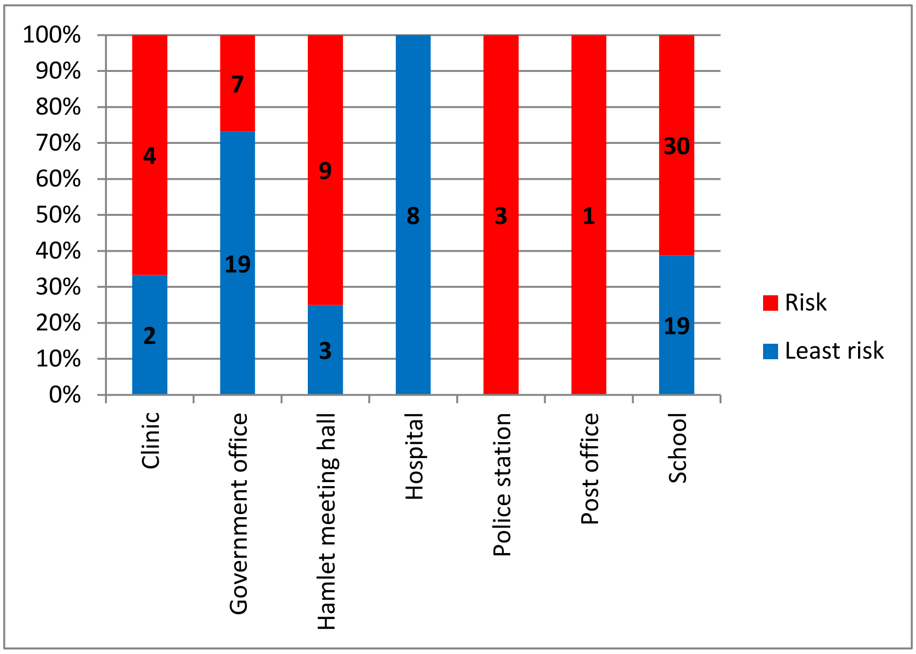


Figure 5.61. The social infrastructure at risk in Kuta Village.

For Legian Village, around 75% of the clinics are built in tsunami risk areas. On the other hand, all units of government offices, hamlet meeting halls and schools are located in tsunami least risk areas. Moreover, there are no hospitals, police stations and post offices in that village (see Figure 5.62).

All units of government offices and schools in Seminyak Village are located in tsunami least risk areas. Only 1 unit of hamlet meeting hall is located in tsunami risk areas. Other units of hamlet meeting halls are built in tsunami least risk areas. Furthermore, there are no clinics, hospitals, police stations and post offices in that village (see Figure 5.63).

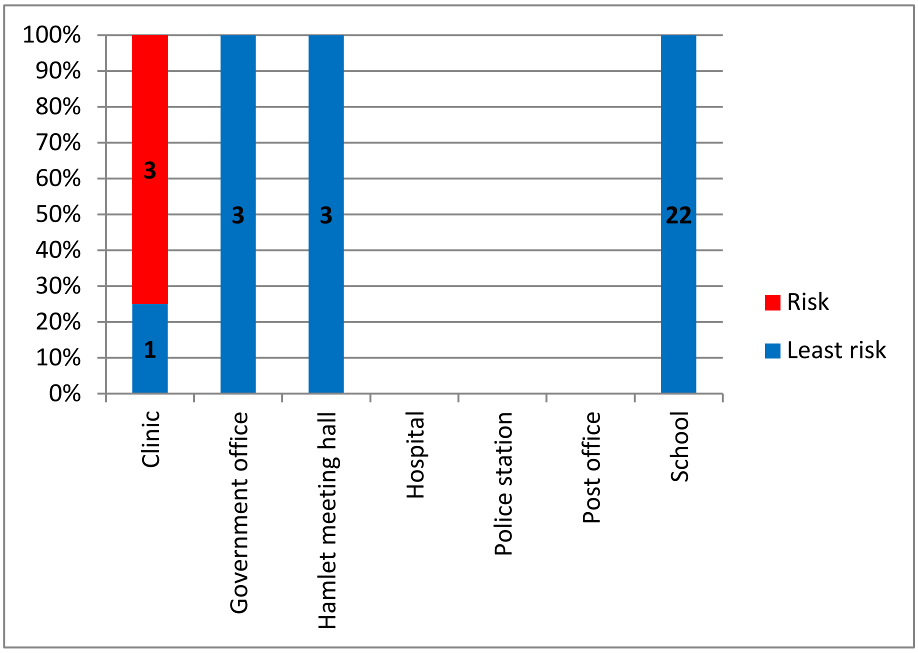


Figure 5.62. The social infrastructure at risk in Legian Village.

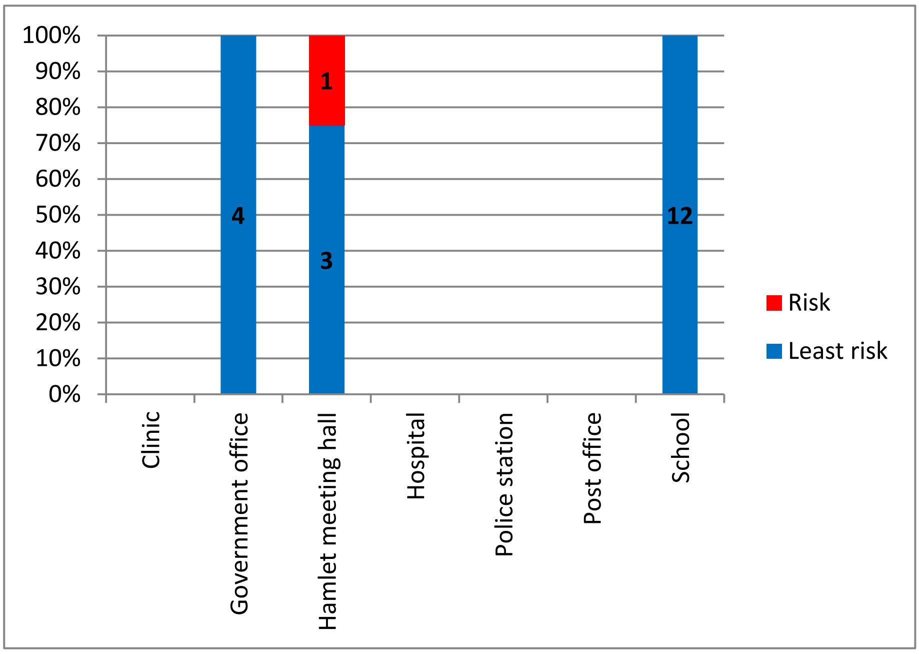


Figure 5.63. The social infrastructure at risk in Seminyak Village.

All units of government offices in Sanur Village are located in tsunami risk areas. On the other hand, all units of post offices are built in tsunami least risk areas. Around half of schools are also located in tsunami least risk areas. Around one–third of all clinics and hamlet meeting halls are built in tsunami risk areas. There are no hospitals and police stations in that village (see Figure 5.64).

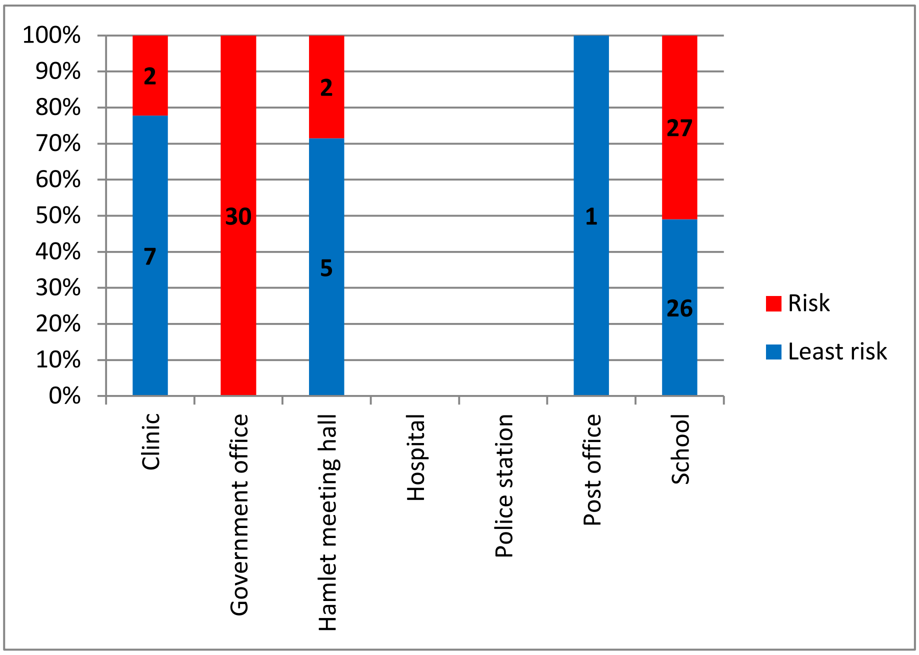


Figure 5.64. The social infrastructure at risk in Sanur Village.

For Sanur Kaja Village, all units of clinics, police stations and schools are located in tsunami least risk areas. Less than one–third of hamlet meeting halls are located in tsunami risk areas. There are no government offices, hospitals and post offices in that village (see Figure 5.65).

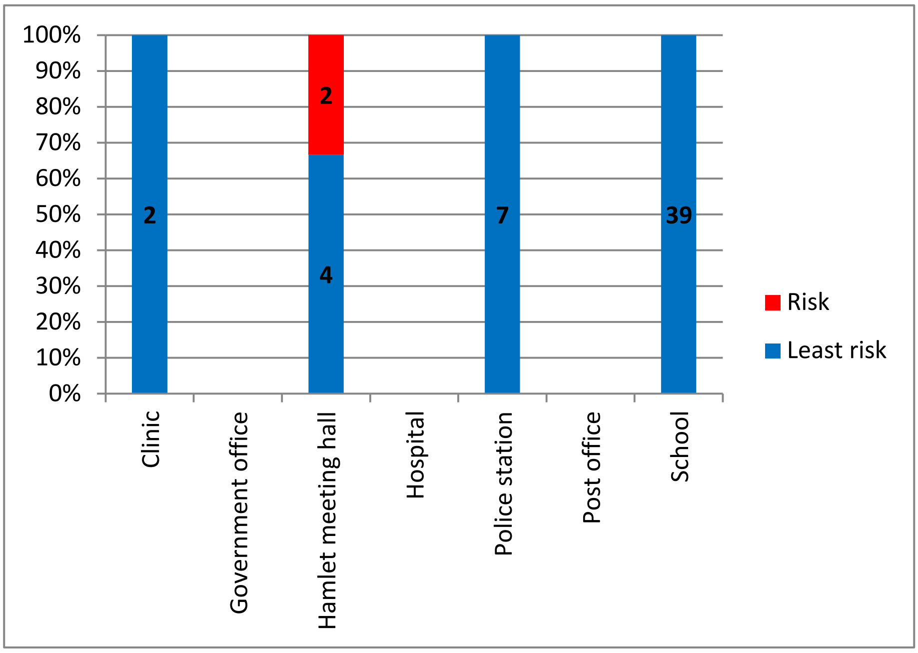


Figure 5.65. The social infrastructure at risk in Sanur Kaja Village.

5.4.1.4. Economic Variables at Risk

There are many economic facilities at risk such as agriculture, agroforestry, banks, hotels, villas, shops, malls, traditional markets, industries and restaurants. These facilities are important for the local government because they serve as the main income for people and village revenue. Tsunamis can disrupt or even destroy the economic activities.

For Kuta Village, all areas of agriculture and agroforestry are located in tsunami least risk areas. Around two–third of all banks, restaurants, hotels and villas are in danger of future tsunamis. This infrastructure will not only stop the economic activities, but it also consists of many tourists who potentially become victims if a tsunami occurs there. Half of all shops and traditional markets are also built in tsunami risk areas. Only one–third of all industries and malls are located in tsunami risk areas (see Figure 5.66).

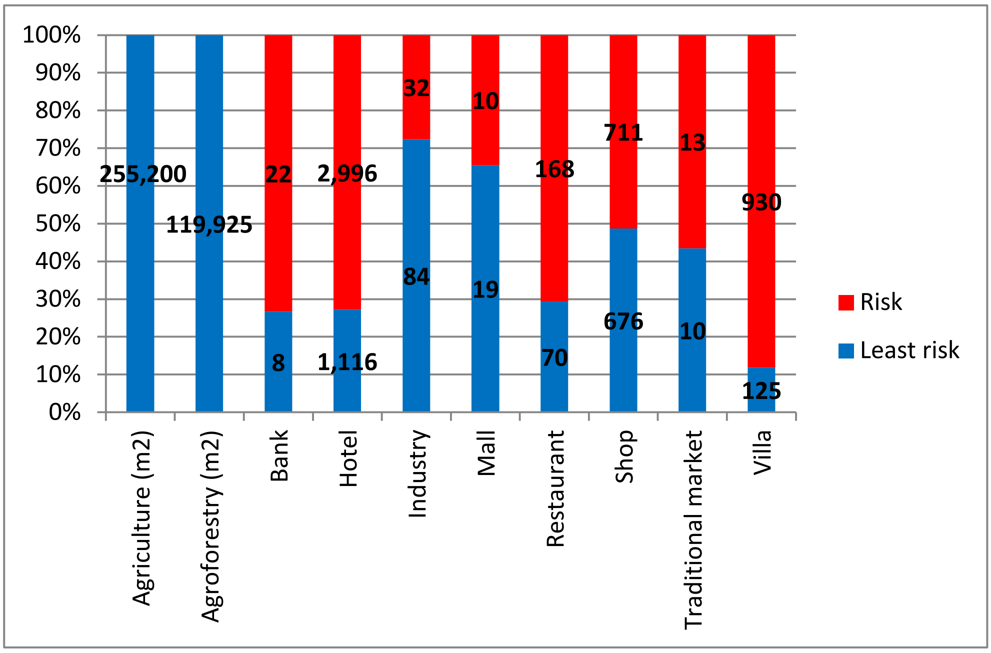


Figure 5.66. The economic infrastructure at risk in Kuta Village.

All areas of agriculture and agroforestry in Legian Village are located in tsunami least risk areas. Around two–third of all industries and villas are also located in tsunami least risk areas. On the other hand, all units of traditional market are built in tsunami risk areas. Moreover, more than half of all restaurants, banks, hotels and shops are also built in tsunami risk areas. There is no mall in that village (see Figure 5.67).

All units of industries and traditional markets in Seminyak Village are located in tsunami least risk areas. More than 95% areas of agriculture and agroforestry are also in tsunami least risk areas. Furthermore, more than 70% of the hotels, shops and villas are also built in tsunami least risk areas, but more than 60% of the restaurants are at risk from future tsunamis. There are no banks and malls in that village (see Figure 5.68).

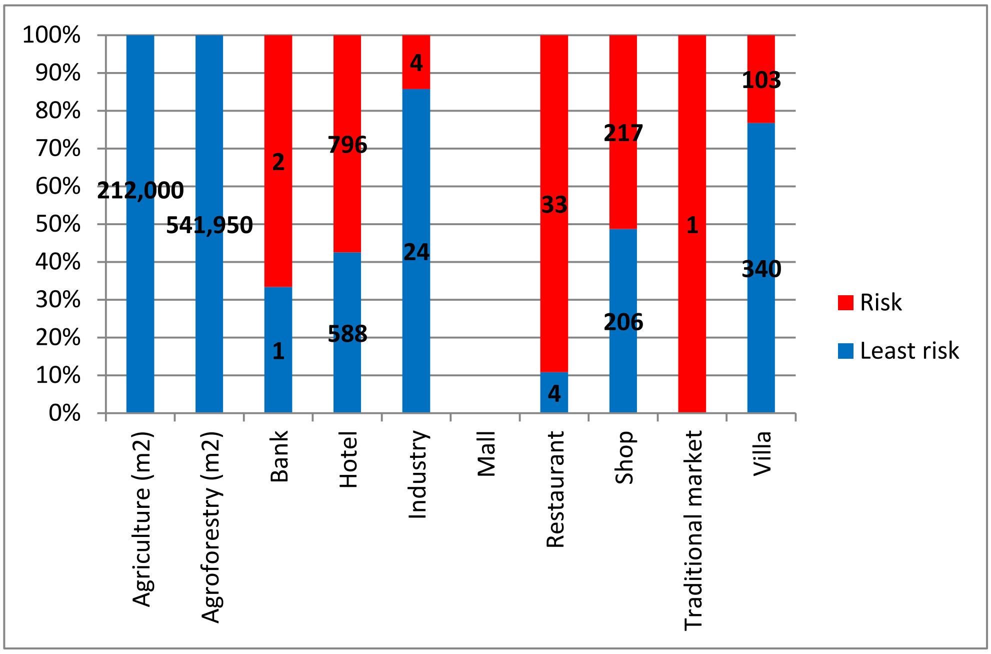


Figure 5.67. The economic infrastructure at risk in Legian Village.

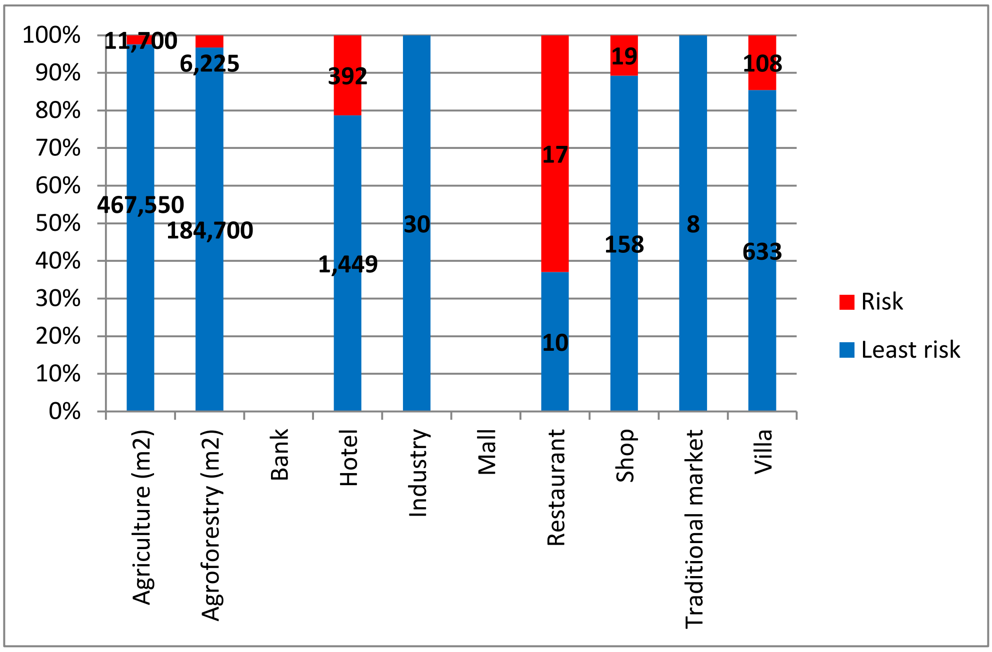


Figure 5.68. The economic infrastructure at risk in Seminyak Village.

For Sanur Village, more than 50% of the total areas or units of all economic infrastructure are located in tsunami risk areas. For example, around two–third of all hotels, malls, banks, traditional markets, restaurants and villas are potentially in danger of future tsunamis. Around half of all industries and shops are also located in risk areas. Damage to this economic infrastructure will not only reduce the economic income for this village, but also potentially trigger many victims from the tourists' side. On the other hand, there is no agriculture in that village (see Figure 5.69).

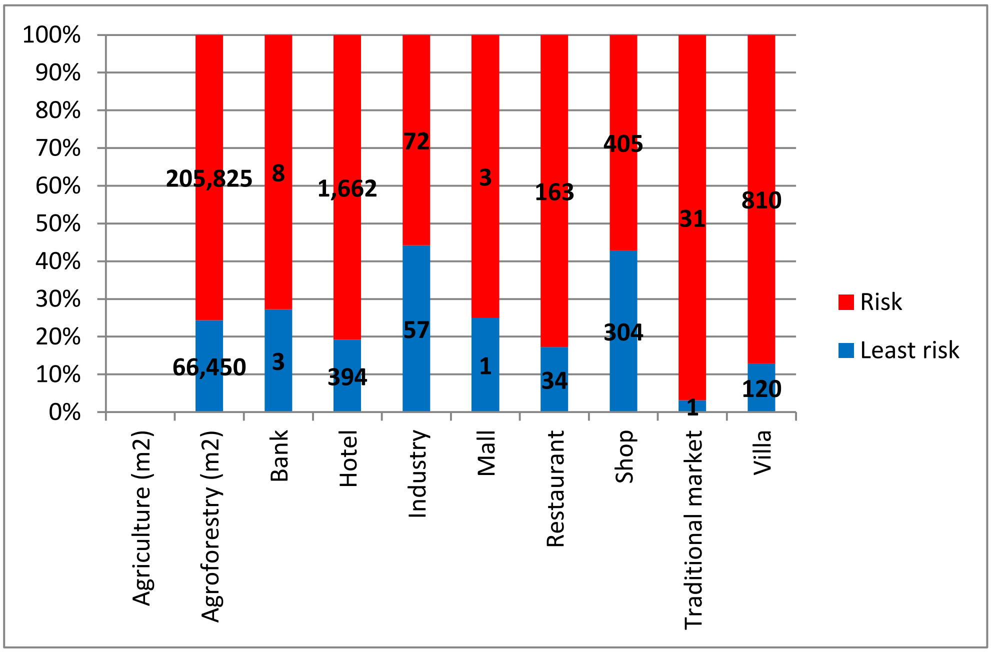


Figure 5.69. The economic infrastructure at risk in Sanur Village.

For Sanur Kaja Village, all units of banks, industries and malls are built in tsunami least risk areas. More than two–third of all agriculture, agroforestry, restaurants and shops are also located in tsunami least risk areas. On the other hand, half of all hotels and villas are at risk from future tsunamis. There is no traditional market in that village (see Figure 5.70).

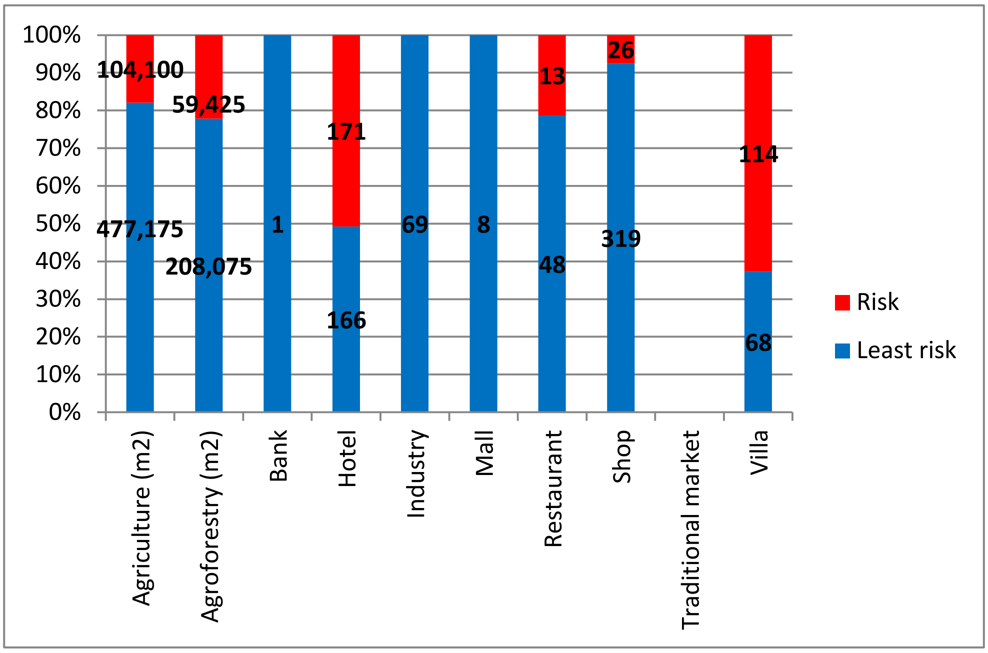


Figure 5.70. The economic infrastructure at risk in Sanur Kaja Village.

5.4.1.5. Special Sites and Lifelines at Risk

Special sites in this study include all locations that need special attention during a tsunami event because they naturally have problems to cope with the tsunami force, such as schools, clinics and hospitals. Lifelines are important facilities that are essential for community recovery, such as clinics and hospitals (these are included in both special sites and lifelines), gas and electricity stations.

For Kuta Village, there is no electricity station in that village. More than half of all clinics and schools are located in tsunami risk areas. On the other hand, all units of gas stations and hospitals are located in tsunami least risk areas (see Figure 5.71).

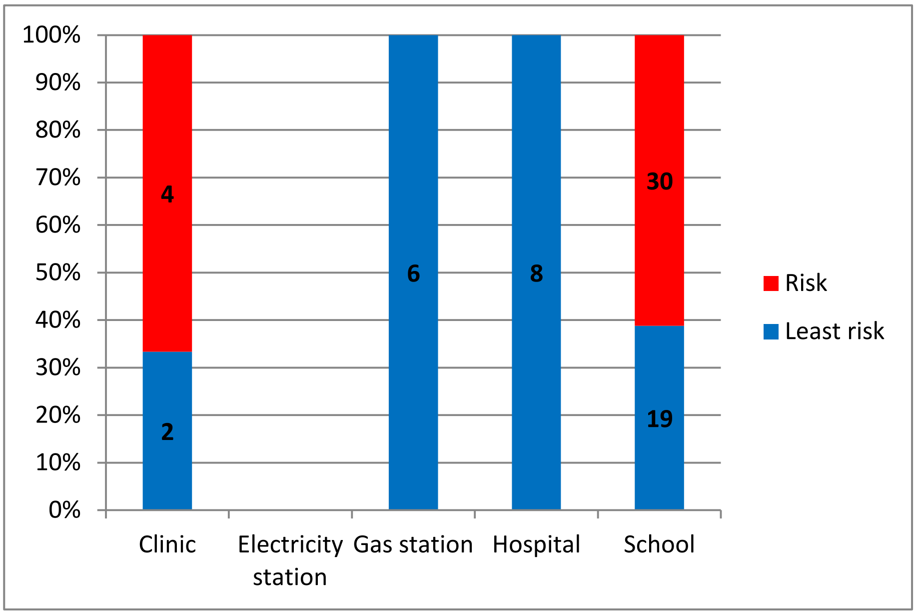


Figure 5.71. The special site and lifeline at risk in Kuta Village.

There are only two types of special sites and lifelines in Legian Village, namely clinics and schools. More than two–third of clinics are potentially at risk from future tsunamis. On the other hand, all units of schools are located in tsunami least risk areas (see Figure 5.72).

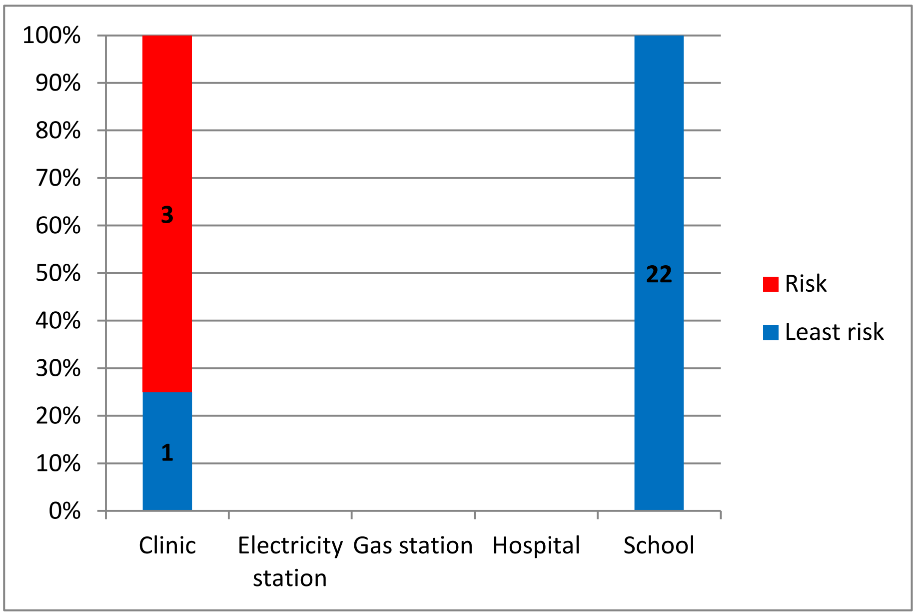


Figure 5.72. The special site and lifeline at risk in Legian Village.

There is only one type of special site in Seminyak Village, namely schools. All units of schools are located in tsunami least risk areas (see Figure 5.73).

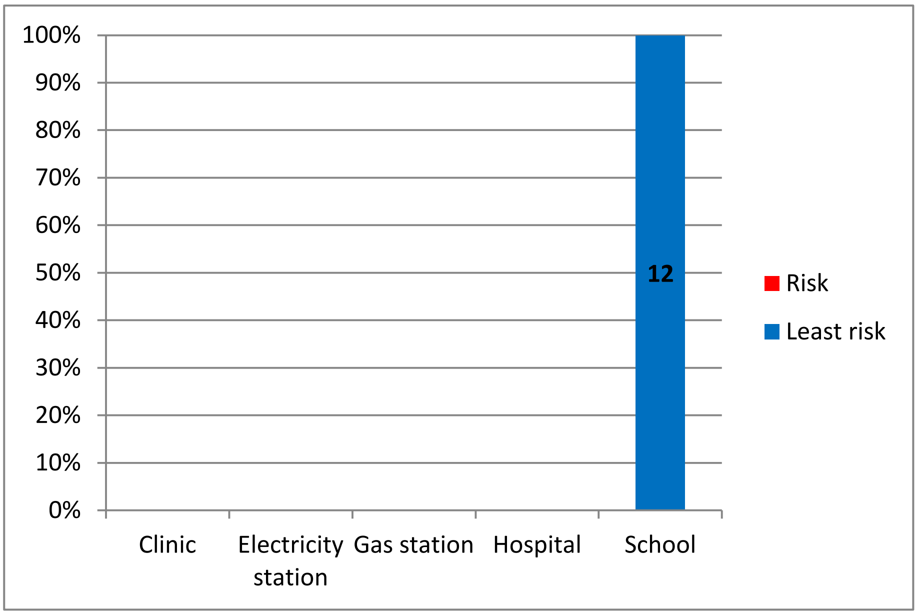


Figure 5.73. The special site and lifeline at risk in Seminyak Village.

For Sanur Village, there are four types of special sites and lifelines, namely clinics, schools, electricity and gas stations. There is no hospital in that village. All units of electricity and gas stations are located in tsunami risk areas. Furthermore, around half of the schools are also at risk from future tsunamis. On the other hand, more than two–third of the clinics are located in tsunami least risk areas (see Figure 5.74).

For Sanur Kaja Village, there are four types of special sites and lifelines, namely clinics, schools, electricity and gas stations. There is no hospital in that village. All units of clinics, electricity stations, gas stations and schools are located in tsunami least risk areas (see Figure 5.75).

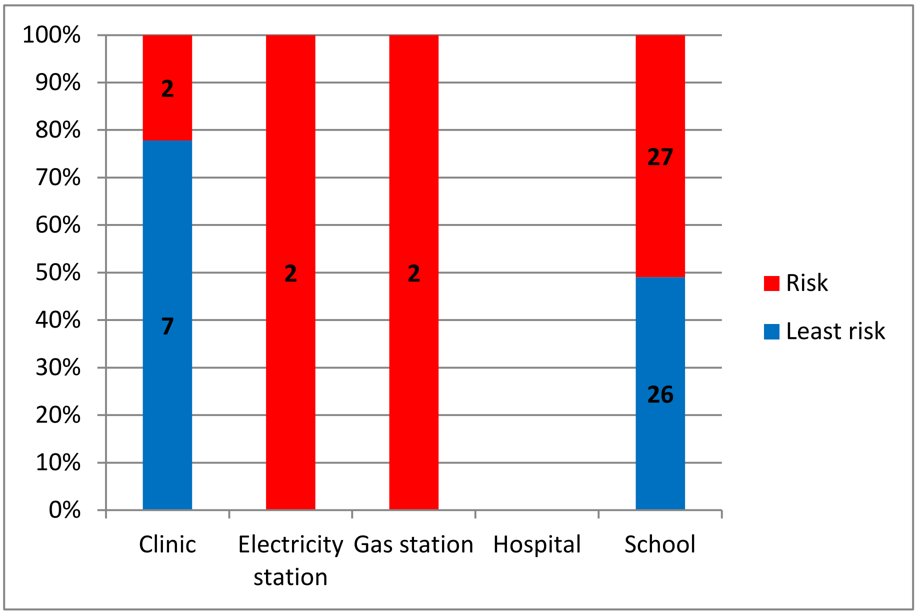


Figure 5.74. The special site and lifeline at risk in Sanur Village.

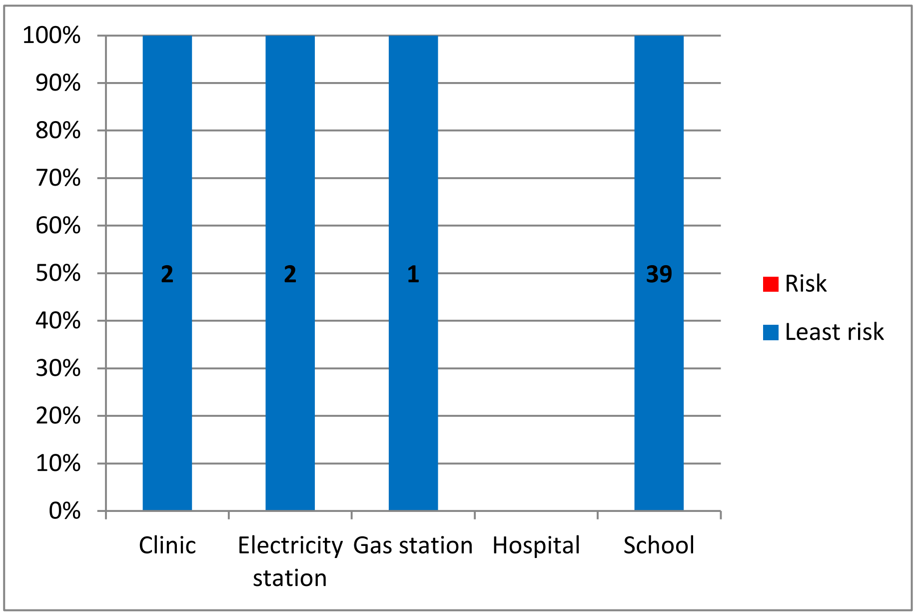


Figure 5.75. The special site and lifeline at risk in Sanur Kaja Village.

Local government has to be concerned with these areas because if a tsunami occurs during the day, there are a lot of young people and patients that will be at risk of injury or death. Villages with high numbers of schools in the tsunami risk areas, such as Kuta and Sanur Villages have to be prioritized for tsunami preparedness. Awareness and education about how to respond and rescue during tsunami event have to be conducted regularly.

5.5. Summary

This analysis has grouped all variables into all of the tsunami risk zones. Obviously GIS allows us to create multiple scenarios; for each risk zone, for each type of variable, right down to types of buildings and individual buildings. Government and community buildings and places of worship are especially important as potential recovery centres depending on the zone in which they are located. The GIS can also has many more social and economic variables added into the database and more scenarios developed. The building database can be updated regularly and risk recalculated. The risk can also be applied to new developments. Over time further information about each building can be added and mapped, such as number of storeys, building material, orientation, etc.

CHAPTER SIX – Discussion, Conclusion and Recommendations

6.1. Introduction

The primary objective of this study was to develop a model of the tsunami risk assessment that can be applied and used in other parts of coastal Indonesia, with the framework being applied to the Kuta and Sanur Regions as a case study. The results will give information to local people that live in tsunami–prone areas, and to local governments for the development of tsunami mitigation planning.

Local and provincial government officers and public servants need to be able to access readily available data in order to estimate the terrestrial impact for planning purposes. This model is fairly crude because it relies upon data that can be accessed at local levels and easily incorporated into planning schemes that can be administered by local governments.

In this study, the model from the results is a basic model for tsunami risk assessment. Moreover, it is very important to have data collection at local level so that local governments can apply and implement the results (tsunami risk maps) at the local people who live in the study area and who possibly become victims if a tsunami occurs there. Moreover, it would be useful to include local people information and knowledge because they know more about their surroundings. Community knowledge of the physical and social environment is essential for natural disaster management (Tran et al., 2009).

Although bathymetric data can enable more detailed and specific estimates of tsunami run–up to be modelled, it has been excluded here, because the complexity of the bathymetry data and its impact upon tsunami waves means that the modelling must be carried out by expert oceanographers rather than local government officers. Moreover, the bathymetry data is frequently not available in detail at the local level. Therefore this study has concentrated on that terrestrial data that is readily available to provincial and local government officers.

In this chapter, the author discusses the results separately for each assessment and creates a research framework for each assessment that can be applied and used by local government officers.

6.2. Tsunami Potential Assessment

The first goal of this study was to assess the potential of the tsunami hazard to Kuta and Sanur Regions based on historical data in order to examine whether such a study of tsunami potential needs be undertaken in this area. The historical data showed tsunami hazard to be a serious and destructive threat for coastal communities in Bali. The tsunami hazard cannot be prevented, but the damage from the tsunami can be reduced by two types of actions, namely structural and non–structural (Clague et al., 2003). Structural actions include the building of jetties, sea walls, breakwaters and tsunami resistant construction of buildings, although these actions are very expensive. Non–structural actions include land use and building zoning and relocation, emergency preparedness for coastal communities, and public education carried out in school or in coastal community meetings, so that local people and students are aware and understand this hazard.

The first action in a tsunami potential assessment is to establish the probability that a tsunami will occur in the future with estimates of probable magnitudes. A detailed catalogue of tsunamis is needed for establishing the tsunami probability, including the date of the event, the magnitude of the event, the area impacted, the causes, the highest run–up, the maximum inundation and the number of victims. The catalogue can be supplemented from newspapers, journals, internet, and libraries. There are two agencies that provide a detailed catalogue of tsunamis and other hazards that can be accessed online, namely The National Geophysical Data Center (NGDC) from NOAA Agency (2010) and The Institute of Computational Mathematics and Mathematical Geophysics (ICMMG) in Novosibirsk, Russia (2010). These information sources can be used also as a verification tool if there is inconsistency with the hazard occurrence data sets (Cutter et al., 1997). However, data prior to the 20th century, is usually less accurate because of the less sophisticated instruments used to measure it (Kulikov et al., 2005).

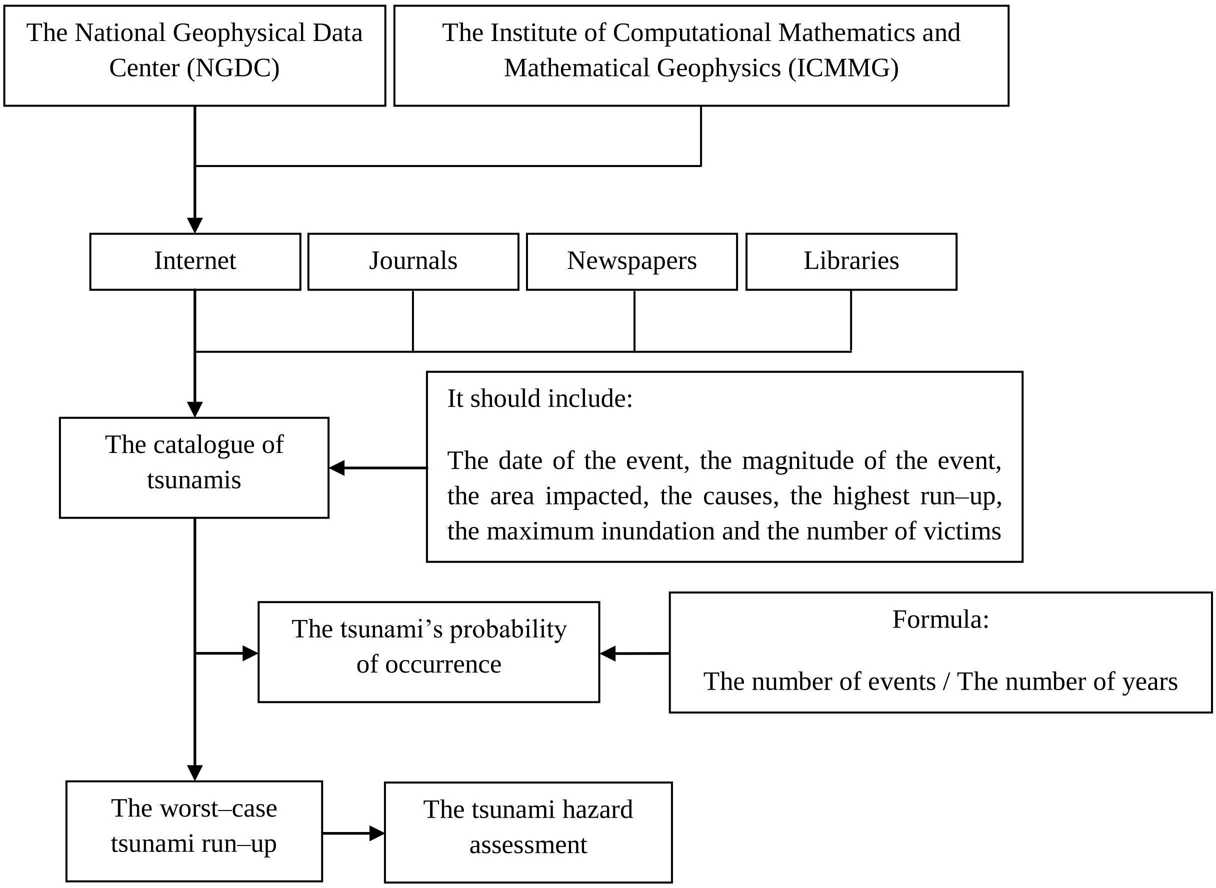


Figure 6.1. The framework for a tsunami potential assessment.

Figure 6.1 shows the framework for a tsunami potential assessment. This framework is developed based on the methodologies that have been used in this study. This framework is quite simple to understand and reflects activities that need to be carried out in the tsunami potential assessment process. The results of this framework are the tsunami's probability of occurrence based on its catalogue and the worst–case (the highest) tsunami run–up in the study area that will be used in the tsunami hazard assessment.

The information about tsunami and earthquake's probability of occurrences gives local government, disaster planners and emergency managers in Bali a perspective about mitigation programs that can be carried out in the midterm and longer term periods for coastal communities. The probability calculation may improve coastal communities' perception about the tsunami hazard because their rarity leads to a gradual lessening in peoples' awareness and preparedness over time. To make people prepare for a tsunami, they have to be concerned about it, have enough awareness, and agree with the potential magnitude and impact that is possible from a tsunami event. For example, during the Indian Ocean tsunami on 26th January 2004, mortality on Simelue Island, located near the earthquake epicentre, was low, because they knew what actions to take based on past tsunamis (Levy and Gopalakrishnan, 2005).

6.3. Hazard Assessment

The second goal of this study was to assess and map the tsunami hazard based on the worst–case tsunami run–up scenario. The worst–case scenario was used, as it will represent the highest tsunami run–up that can occur on Bali based on historical data, so it becomes a basic calculation for the inundation zones.

However, it will not rule out the possibility that a tsunami run–up could be larger or smaller in the future. Moreover, the impact and damage of future tsunamis will be larger than in the past because of the increasing numbers of buildings and coastal infrastructure development within coastal areas on Bali.

The catalogue of historical tsunami events is examined and analysed to find the highest tsunami run–up in the study area. This information is used to identify the extreme inundation zones. The definition of the extreme inundation zone is the zone or area between the shoreline and the highest contour of tsunami run–up ever recorded on Bali (Papathoma et al., 2003). In this study, the simplification of contour elevations was used to make analysis easy. This is important in creating an analysis model that can be replicated by provincial governments at the local level.

A tsunami inundation map is a powerful tool in hazard mitigation and very useful for disaster planners and emergency managers (Kumar et al., 2008). The inundation map can be used to identify and evaluate locations of important public infrastructure in coastal areas, such as restaurants, shops, villas and hotels. This might also help to determine which of these infrastructures should be relocated to safer areas or retrofitted to withstand the tsunami force and inundation. For example, hotel or restaurant buildings that only have one storey might be expanded into two or three storeys, to allow vertical evacuation. If a tsunami occurs and there is limited time to evacuate to a higher area, it would be better to run to the nearest building that has more than one storey for vertical evacuation.

The framework for a tsunami hazard assessment is developed based on the methodologies that have been used in this study and reflects activities that need to be carried out in the tsunami hazard assessment process (see Figure 6.2). The result of this framework is a tsunami inundation map based on the worst–case (the highest) tsunami run–up scenario in the study area. Furthermore, this result can be overlaid with the "administrative boundary", "land use" or "building type" layers to determine which areas, land uses or buildings might be inundated by future tsunamis within each inundation zone in the study area.

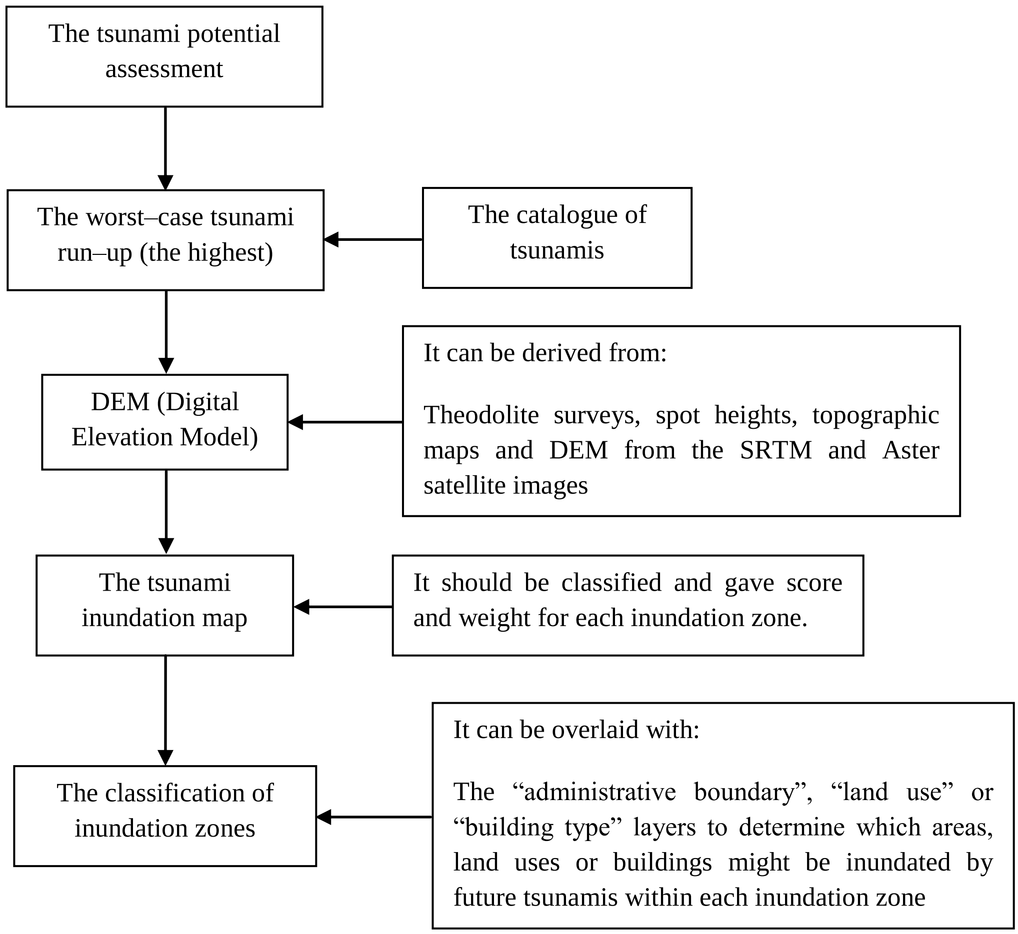


Figure 6.2. The framework for a tsunami hazard assessment.

Coastal areas are a favourite location for settlement and business. The coastal area's attractiveness continues to grow along with associated housing, coastal facilities and accommodation development. As a result, more local people and tourists, and coastal infrastructure will be threatened by the tsunami hazard.

Therefore, to manage and control new building construction in coastal areas, there should be cooperation between the planning agency and the local government related to the city spatial planning. For example, local government can create economic disincentive, such as higher taxation, to discourage people or investors from creating new developments in vulnerable coastal areas. Moreover, this map also can be used to inform local government agencies, hazard task force, local residents, investors, and visitors about preparedness and response for tsunami events. This action has been implemented in some countries, such as the USA, as part of a national program in planning for tsunami-resilient communities (Jonientz-Trisler et al., 2005).

The tsunami inundation delineation is based on the existing or available ground elevation data, such as base point for elevation reference. Therefore, it needs ground checking to verify the inundation areas and exact ground elevation. Moreover, the use of better elevation data will eventually increase the accuracy of hazard delineation. This condition can potentially discourage the application of tsunami hazard assessments in other coastal areas in Indonesia, because the detailed topographical map with high resolution of elevation is generally not available at village or sub–district level, probably due to the cost of surveys.

Local governments at village or sub–district levels that do not have any topographic maps, can use and derive the DEM (Digital Elevation Model) data from the SRTM (Shuttle Radar Topography Mission) (Jarvis et al., 2008) and ASTER GDEM (LPDAAC, 2010) images. These data are free and can be downloaded through the internet. However, the spatial resolution for these images is quite large. The spatial resolution for SRTM is 90 m and for ASTER is 30 m.

The analysis for the ground elevation can be done as a first action in tsunami mitigation, but it will not be as accurate as using detailed topographical maps because of the spatial resolution from the images. These images will be suitable for ground elevation analysis at the district or province area (larger area). If local governments cannot do this action, it would be easy to give information for local communities who live in the tsunami prone areas by public education, such as training materials, public meetings, workshops, questionnaires, pictures, etc.

6.4. Vulnerability Assessment

The third goal of this study was to utilise a model to assess, locate and map the physical, social and economic vulnerabilities to the tsunami hazards in the Kuta and Sanur Regions. This of particular importance, as the vulnerability to tsunami damage and impact is not consistent within the study area in space or time, but rather is always dynamic. Therefore, physical, social and economic factors were identified and analysed, and then used to create the primary database for GIS analysis (Papathoma et al., 2003). All parameters were selected and chosen based on tsunami impact surveys, especially the 2004 Indian Ocean tsunami (Levy and Gopalakrishnan, 2005) and the 2006 South Coast of Java tsunami (Reese et al., 2007).

Vulnerability assessment is the next step to undertake after evaluating the tsunami potential and probability of occurrence. Vulnerability assessments depend on how close the coastal communities are to the primary tsunami impact, and their social and economic characteristics (Cutter et al., 2000).

In this study, the physical vulnerability determines how both Kuta and Sanur Regions are vulnerable in relation to physical factors, such as distance from the shoreline, ground elevation and slope. Social and economic vulnerabilities, on the other hand, reflect how areas in both regions are vulnerable in terms of number of people, females, age groups (children and elderly), disabled people, poor families and fishermen. It is important to know which village has a higher vulnerability and how much the proportion of each factor contributes to the vulnerability of each village. Therefore, local government can allocate the right actions and interventions for each village in mitigation plans to mitigate the impact of future tsunamis.

Most areas around Kuta and Sanur are flat and low–lying, being below 5 m elevation and less than 6% slope. For this reason, tsunami waves can easily reach and inundate inland areas. Furthermore, coastal infrastructure, such as hotels, restaurants and shops are located near the shoreline. For example, the 2004 Indian Ocean tsunami in Aceh inundated 2 km inland and swamped coastal infrastructure, such as ports and power plants located in low–lying areas (Levy and Gopalakrishnan, 2005). The 2006 South Coast of Java tsunami had a run–up of more than 7 m in some flat areas and inundated several hundred meters inland (Reese et al., 2007). Tsunamis are more dangerous if they hit low–lying flat areas, such as Kuta and Sanur Regions because they can inundate from several hundred meters to several kilometres inland and swamp the coastal infrastructure located near the shoreline.

The distribution of vulnerability is not uniform and physically it is highly influenced by proximity to the shoreline, ground elevation and slope. By analysing the physical vulnerability map, local government has information about where a new development should be placed and built. Developments and investments by local government, coastal communities and the private sector should be minimized or strongly regulated in areas with high physical vulnerability.

Analyses at village level give an opportunity to do further investigation, such as community vulnerability mapping. Detailed and updated information can be gathered through local workshops and meetings with coastal community members to improve awareness and understanding about social and economic conditions in their villages. However, because the greater detail of the assessments requires a longer time and more money, researchers should consider time and budget availability to conduct vulnerability assessments at the village level. This is important in creating an analytical model that can be replicated by provincial governments at the local level.

The tsunami vulnerability assessment framework in Figure 6.3 is developed based on the methodologies and activities that have been carried out in this study. It is simple to understand for local government officers. The result of this assessment was a tsunami vulnerability map based on the physical, social and economic factors that influence tsunami vulnerability in the study area for each region. The outputs in a map form are more meaningful and useful, as they provide perspective to local communities and local governments. Maps can provide clear, attractive pictures of the geographic distribution of potential hazards that can be appreciated by local people with no specialist knowledge. These maps frequently provide motivation for risk management actions that would be difficult to obtain without a compelling visual. These maps also contribute to proper planning and resource allocation for disaster preparedness.

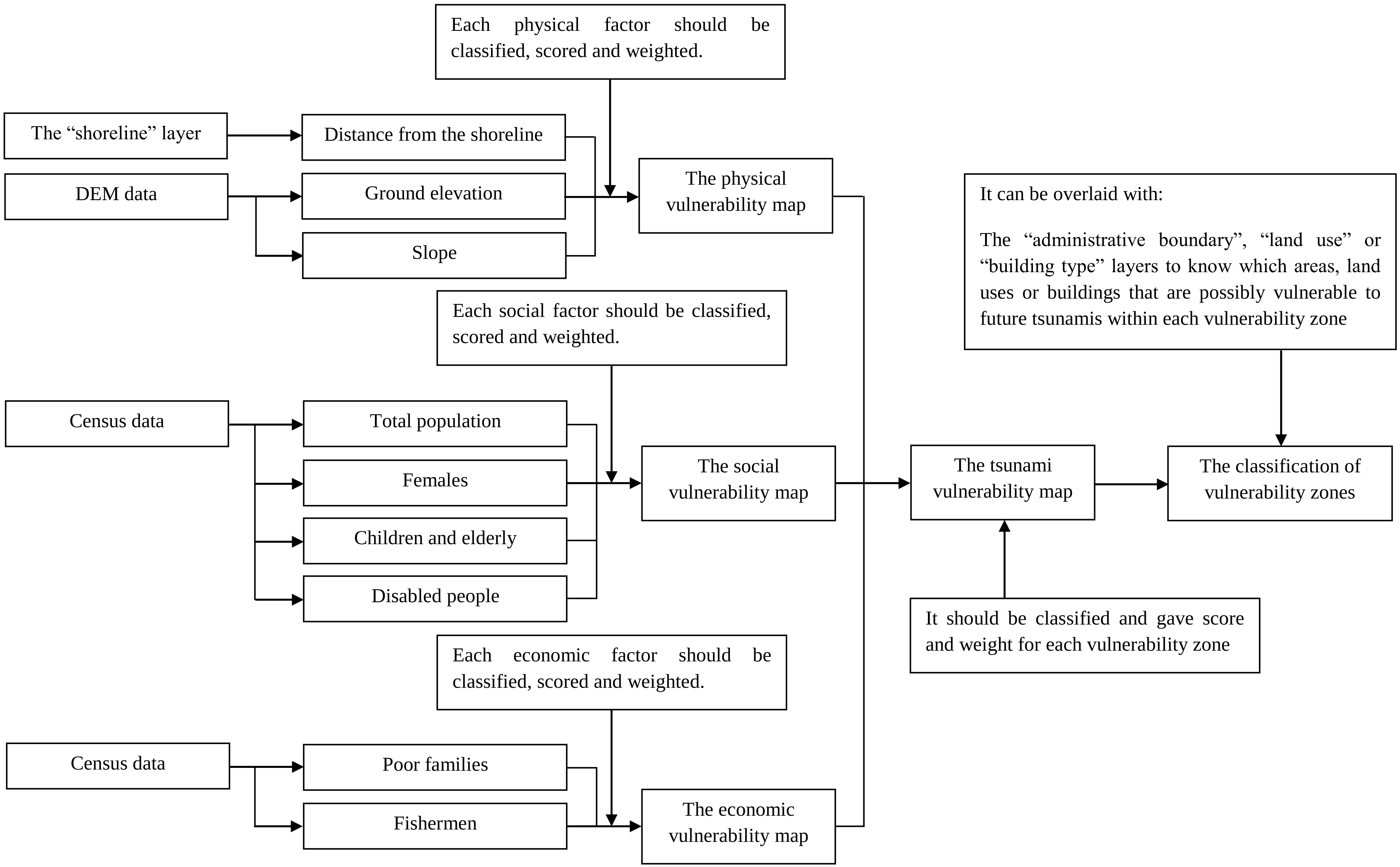


Figure 6.3. The framework for a tsunami vulnerability assessment.

The physical, social and economic factors that are used in this study are based on the available parameters that can be found in each village and generally are the basic parameters of any vulnerability study. For detailed vulnerability assessments, several parameters can be added to develop the assessment. The more parameters that are used, the more detailed is the assessment that can be developed. However, detailed assessments require a longer time, greater budget and more analysis to be done. For example, there are three physical parameters used in this study, namely distance from the shoreline, ground elevation and slope. Several parameters can be added, such as land cover, topography, geological structures, physical sea defences, coastal type and tsunami wave direction (Papathoma et al., 2003, Nugroho, 2006, Chen et al., 2003). For the social and economic parameters, several parameters can be added, such as population density, number of people per building, type of building, building environment, household income and number of tourists, houses and business centres (Papathoma et al., 2003, Cutter et al., 2000, Chen et al., 2003).

6.5. Risk Assessment

The final goal of this study was to assess and map the risk of the tsunami hazard for the physical, social, economic, and coastal infrastructure in Kuta and Sanur Regions. A risk assessment is important, as it can be used to provide information for local government, disaster planners, emergency managers and coastal communities about which areas, buildings, coastal infrastructure and groups of people are at particular risk of tsunami impact. Moreover, there will be very limited time for people to evacuate and run to higher land because the distance between the tsunami source and impact area is relatively short.

Furthermore, tsunami arrival times may vary depending on the tsunami source (Papathoma et al., 2003). For example, in the 2004 Indian Ocean tsunami, the tsunami occurred and hit Aceh and surrounding coastal area around 10 minutes after the third largest earthquake in the world occurred just north of Simeulue Island, Northern Sumatra, Indonesia at a depth of 30 km with magnitude 9.0 (Levy and Gopalakrishnan, 2005). Therefore, the effective mitigation of future tsunamis can be applied and developed by using risk maps that show the risk area of each village in each region.

The risk for each natural hazard, including a tsunami, is different from one area to another, depending on its vulnerability. The result of a risk assessment allows all parties (local government, disaster planners and emergency managers) to focus limited resources on areas with the highest priority for evacuation, recovery or rehabilitation (Wood and Good, 2004). Moreover, they should locate the risk problems and determine the significance of the risk both qualitatively and quantitatively. This is particularly important in the case of a tsunami hazard which has impact that vary spatially (Greiving et al., 2006). The ultimate goal of the hazard risk assessment is to reveal different areas with different levels of risk from the hazard by creating maps through spatial analysis (Wu et al., 2004).

As the assessment takes place prior to the actual event occurring, a certain scenario, usually a “worst–case” one, is developed as a basis for the assessment. The worst–case scenario is preferable for the tsunami risk assessment because it is very difficult to predict the scale and magnitude of a tsunami. To make tsunami risk assessment simple, realistic, easy to adopt and flexible to apply in other places, some researchers have made some simplifications, whereby off–shore bathymetry and wave run–up calculations were not included. Papathoma and Dominey–Howes (2003) did not use these parameters because of the time needed for the processing and due to data costs. Therefore they used historical data of past events to predict the worst–case scenario in a coastal area.

The tsunami risk scenario is therefore developed based on existing historical data, numerical modelling and the worst–case scenario. For example, maximum wave run–up can be expressed as vertical (elevation of water) or horizontal (distance of inundation) and any run–up more than 1 meter is considered dangerous. However, the horizontal inundation is influenced by topography, such that the vertical run–up is usually used in each scenario (Clague et al., 2003).

The risk of tsunami for Kuta and Sanur Regions cannot be interpreted directly from the inundation or hazard map and the vulnerability distribution map. An area that has a high or low vulnerability does not necessarily also has a high or low risk respectively. It is because the tsunami risk is the probability or expected losses (deaths, injuries, property, infrastructure, livelihoods, economic activity disrupted or environment damaged) resulting from interactions between the tsunami hazard and vulnerable conditions in a particular coastal area (ISDR, 2002). Therefore, the hazard and vulnerability maps should be combined to obtain risk maps that can be interpreted easily by local government, disaster planners, emergency managers and coastal communities.

Figure 6.4 shows the framework for a tsunami risk assessment that reflects activities that need to be carried out in the tsunami risk assessment process. The result of this framework is a tsunami risk map based on the combination of tsunami inundation and tsunami vulnerability maps in the study area. The tsunami risk map is the final result from a tsunami risk assessment. Furthermore, this result can be used for the tsunami risk analysis by GIS overlays with the "administrative boundary", "land use", "building type" or "social and economic parameters" layers to identify which areas, land uses, buildings, social and economic facilities are possibly at risk from future tsunamis within each risk zone in the study area. This risk analysis is very important for local governments, disaster planners and emergency managers in decide and establish mitigation programs for future tsunamis. The tsunami risk analysis framework is shown in Figure 6.5.

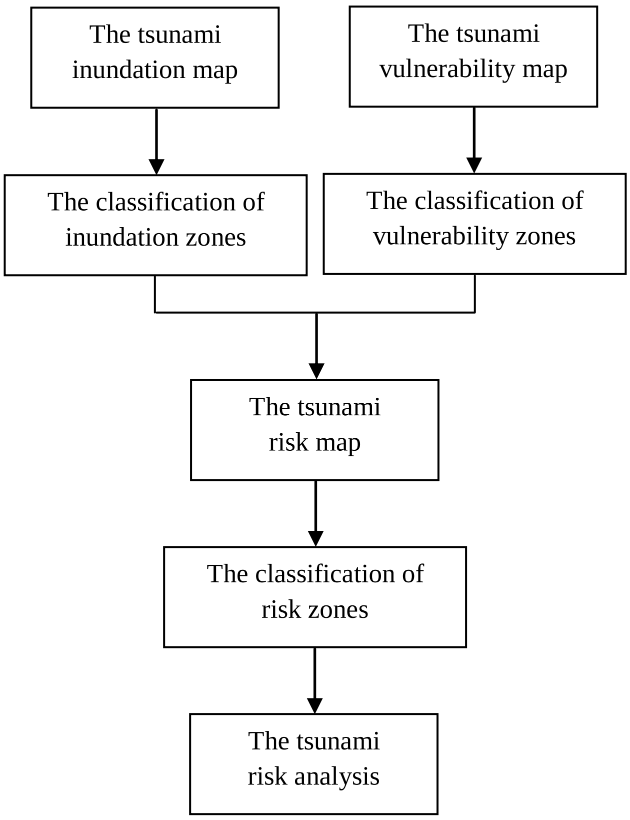


Figure 6.4. The framework for a tsunami risk assessment.

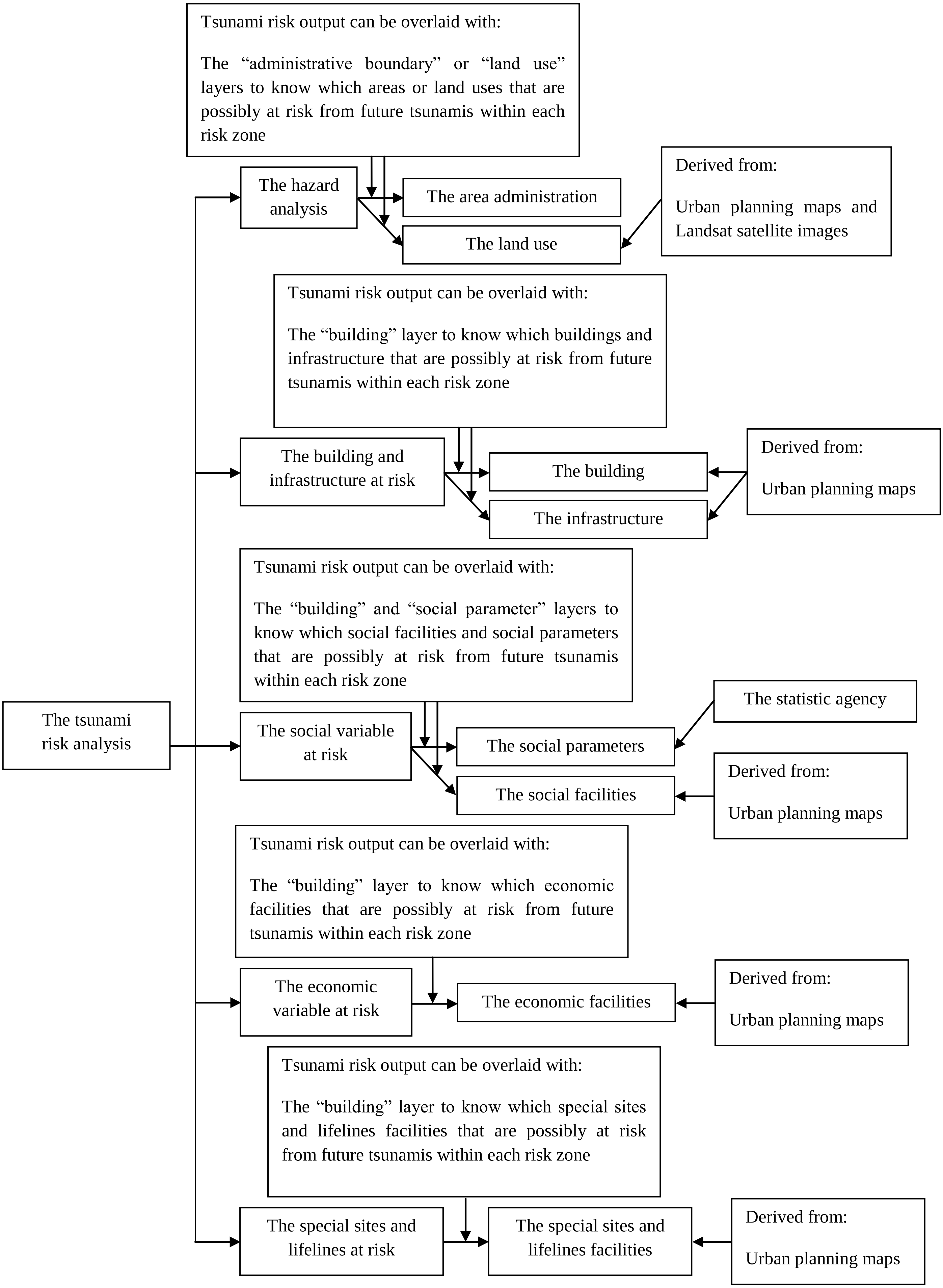


Figure 6.5. The framework for risk analysis in a tsunami risk assessment.

The risk distribution map clearly shows that some areas in "low vulnerability" villages as shown in the total vulnerability map, actually have a high risk of tsunami. It is because they are in the very high, high or medium inundation zones. By evaluating the risk distribution of each village in each region, local government, disaster planners and emergency managers have clear information of specific mitigation programs and actions that are needed for each village. They will know exactly where, which and how much area of each village is in very high, high or medium risk of tsunami hazard. They can allocate proper resources to reduce the risk by increasing the resilience and reducing the vulnerability.

It is also clear from the risk distribution that some areas in different villages are in very high or high risk of tsunami because they have higher total populations and numbers of females and some of them because they have higher numbers of poor families and fishermen. From this information, they better be able to determine what kind of actions should be implemented for future mitigation. For example, they can increase education and awareness campaigns to local communities and students in the highly populated areas, or they can increase economic incentives to reduce poverty and improve fishermen's resilience from tsunami impact in the villages highly populated by poor families and fishermen.

Constructing shelters or housing or using existing high buildings can help to cope with evacuation problems. High buildings with more than two storeys are very useful for vertical evacuation. Moreover, shelters can be built in appropriate places to increase their effectiveness and efficiency. For example, a shelter of more than two storeys in the village or near a shoreline that is always crowded with people and tourists can house evacuees immediately after the submarine earthquake.

Generating income activities is also important for villages with high economic vulnerability. Risk distribution maps can also be used as a basis for local government to allocate funds and economic stimulants that are usually very limited. For example, local government provides alternative additional income by offering part–time jobs, such as motorcycle taxi drivers or beach cleaners for poor families and fishermen. This action is very useful as part of the economic stimulant activity. Fishermen also need insurance for their boats and fishing gear, so they can recover quickly after tsunami impact.

Information on social variables that contribute to a high risk condition determines which strategy will be used during the evacuation process for disaster planners and emergency managers. Some villages may need more resources, such as vehicles, assistant officers, and shelters for evacuation. Knowing this information is also important in determining whether existing roads are sufficient for vehicles and people to evacuate during a tsunami event. Based on the resource availability and capacity, disaster planners and emergency managers also have options between providing as many vehicles and assistant officers as possible or building shelters for these areas during a tsunami event.

The tsunami impact will not only reduce the local revenue, but also disrupt or maybe arrest the entire coastal economy. For example, the fishery sector will suffer because of the damage to fishing ports, boats, and fishery facilities such as cold storage and processing equipment. Moreover, the recovery for this sector also takes a long time because fishermen have no insurance or savings to repair or replace their boats and fishing gear. Approximately 2% of the total area of agriculture in Seminyak Village and 18% of the total area of agriculture in Sanur KajaVillage may possibly be in danger of tsunami impact. In the case of Sanur Kaja, farmers may suffer substantially from future tsunamis. They will need time and money to rebuild their farmland, buy seeds and start rice and vegetable planting again in their new farmland.

Information on tsunami vulnerability and risk is essential for Kuta and Sanur Regions to develop preventative urban development planning. Vulnerability and risk maps show the weak points and elements of the areas in each village for future tsunamis. These maps will help local government, disaster planners and emergency managers to estimate the social and economic disruption, and human impact of the tsunami. It is also a part of the international program of United Nations–International Strategy for Disaster Reduction (UN–ISDR) in reducing the impact of natural hazards in term of casualties, property damage, and social and economic disruption (ISDR, 2002).

As with vulnerability, the distribution of risk in each village in each region varies between villages and depends on the contribution of each variable (physical, social, and economic) to the total risk. The contribution towards overall risk from physical, social and economic vulnerabilities also varies. These results show that the risk proportion in all villages is influenced mainly by the physical factors. Social factors contribute almost an equal value in each village. On the other hand, the economic factors only make a little contribution for the risk in Legian and Seminyak Villages. This information is important for local government, disaster planners and emergency managers because they can know exactly what is the most significant contributor for each village's risk should a tsunami occurs. Moreover, this information will help them to allocate intervention and mitigation plans, by reducing the duplication of activities in each village and optimizing the fund allocation into the right place and right activity.

For the tsunami risk analysis, the risk map can also be overlaid with the "land use" and "building type" layers in order to locate and calculate all land uses and buildings in each village that are potentially at risk from future tsunamis. Based on the results, the local government may be interested to know which type, how much area and the location of the land uses that are in danger of tsunami impact. They may also be interested to know how many buildings are at risk from future tsunamis, as well as which private or public buildings and social or economic facilities (such as schools, houses, hospitals, clinics, and traditional markets) should be relocated or protected because of the potential tsunami risk. By knowing this information, local government can create planning regulations, direct building programmes and issue construction licences for the development of coastal areas (Papathoma et al., 2003). Disaster planners and emergency managers may be interested in areas that have a high population or population density which relates to the numbers of possible victims if a tsunami occurs. Thus disaster planners and emergency managers can create and decide where emergency shelters should be located and which buildings should be used for safe evacuation (Papathoma et al., 2003).

Because every tsunami event is rare and has (on average) long recurrence times, coastal communities and local governments have time to build and develop resilience to tsunamis. However, if they fail to respond to the tsunami threat, the risk will be greater than in the past because of population growth and development and investment that has increased social vulnerability, coastal infrastructure and economic complexity in the coastal area.

Tsunamis are rare, leading some communities into a false sense of security. Education is therefore essential if coastal communities are to become more resilient to tsunamis. A public education program should provide tsunami information at regular intervals and should include instructions on how to get information during an alert, where to go, and what things to take. Educational initiatives should be entrenched into school curricula to ensure that future generations understand the hazards and potential impacts of tsunamis. Education about tsunamis should not be limited to only coastal communities, but to all communities because people from inland regions often travel to tsunami-prone areas. For example, the 2004 Indian Ocean Tsunami has caused more than 283,000 deaths with around 9,000 people being foreign tourists (Levy and Gopalakrishnan, 2005). A range of educational initiatives can be undertaken in coastal communities, such as activity sheets containing graphics, pictures, data, questions, and other relevant information can be used in schools to educate students about tsunami hazards.

The 2004 Indian Ocean tsunami and the 2006 South Coast of Java tsunami taught us that most coastal communities were not prepared for the hazard. There needs to be disaster mitigation to learn and plan how to prepare for hazards by increasing coastal community awareness. This risk map in Kuta and Sanur Regions can be used for disaster mitigation in these areas. The maps can be used to locate safe areas from tsunami for evacuation. The use of evacuation zones related to the existing early warning systems will be more effective if the coastal communities know the early signs of the coming tsunami. Through education and training programs, the coastal communities will contribute to the success of tsunami impact reduction programs.

6.6. GIS in Disaster Management

The results of this study have demonstrated that GIS can be used for disaster management, especially to manage and analyse complex spatial data sets. Each layer that contains information can be overlaid and combined to get a new layer. This task is very useful for creating and analysing the vulnerability and risk maps.

Moreover, the advantage of using GIS in disaster management is generating a dynamic database that can be used and manipulated in different ways depending on the end–user requirements. The attribute tables in this database can be updated easily, the risk scenario can be modified, the scale of the study area can be enlarged or reduced depending on the need of the end–users and the database can have new attributes added for more detailed analysis (Papathoma et al., 2003).

The GIS database will provide the coastal communities, local government, disaster planners and emergency managers with a better map of the situation and conditions in the study area. It serves as a guide to implement and run hazard risk reduction projects and programs for the local communities who live in coastal areas. Moreover, by distinguishing and classifying between safe areas and tsunami risk areas, local government, disaster planners and emergency managers can develop evacuation plans and prepare mitigation strategies (Tran et al., 2009).

GIS is an important tool in storing and managing data, analysing relationships and combining data through modelling, and therefore assisting the decision making for natural hazard mitigation (Chen et al., 2003). In natural hazard assessment, GIS can support pre–impact planning, post event response, and the mitigation process. However it needs high–quality data input and verification to make it effective. Moreover, GIS analysis also requires an understanding of how the hazards relate to each other in space and over time (Cutter et al., 1997).

In this study, there are some limitations in the GIS analysis. For example, there was limited elevation data available for creating and therefore analysing the DEM (Digital Elevation Model). The more elevation data that can be found for the study area, the more detailed and complete will be the DEM. This will be useful for creating a more accurate and detailed elevation layer to be used for deciding the inundation zones in the hazard assessment, and ground elevation and slope parameters in the physical vulnerability assessment.

Furthermore, there was no information about how many tourists visit the study area. In a tourism centre such as Bali, this information is essential for estimating and counting how many tourists could possibly become victims of future tsunamis. Even though there are some limitations in this study, the risk map of each village is easy to read and understand by the local government, disaster planners, emergency managers and coastal communities. Moreover, these maps can be displayed in different formats and illustrated with audio–visual media, such as video clips and photographs of the study area.

6.7. Conclusion

The historical data of tsunami events in Bali were used to decide the worst–case (the highest) tsunami run–up for the hazard assessment. Historical data showing that the highest recorded tsunami run–up was 4.4 m that occurred on 2nd June 1994, led this study to use a potential maximum 5 m of tsunami run–up in the hazard assessment.

The result of the vulnerability assessment is the tsunami vulnerability map based on the combination of physical, social and economic vulnerabilities. The parameters of physical, social and economic factors that are used in this study can be added to develop the assessment. However, detailed assessments require a longer time, greater budget and more analysis to be done.

The result of the risk assessment is the tsunami risk map based on the combination of hazard and vulnerability assessments. The distribution of risk in each village in each region is not the same. It varies between villages and depends on the contribution of each factor (physical, social, and economic) to the total risk. For the risk analysis, the risk map can be overlaid with the "land use" and "building type" layers in order to locate and calculate all land uses, buildings, social and economic facilities in each village that are potentially at risk from future tsunamis.

The research framework in this study consists of three main stages, namely hazard, vulnerability and risk assessments. Local government, disaster planners and emergency managers could do all three stages together or step by step depending on the availability of resources and the urgency. This research framework can also be used as a model for other coastal city managers in

Indonesia for tsunami risk assessment studies. The map plays an important role in showing the tsunami inundation zones, the tsunami vulnerability distribution and the tsunami risk pattern for each village. It completes the assessment and improves the information value.

This study has demonstrated that GIS as a tool can be used in disaster management for assessing and mapping the tsunami hazard, vulnerability and risk assessments by analysing, modelling and modifying data from the available data that can be found in the study area. The results of this study will be useful for all agencies in the study area. Local government can create planning regulations, direct building programmes and issue construction licences for the development of coastal areas. Disaster planners and emergency managers can use the maps to create tsunami preparedness and mitigation programs in the future. They also can build and decide where emergency shelters should be located and which buildings should be used for safe evacuation. Coastal communities in the study area should become prepared, knowledgeable and aware of the early signs of a potential tsunami in the future.

6.8. Recommendation

Based on the above facts and conditions, it is essential to Kuta and Sanur Regions in Bali to have tsunami preparedness and mitigation programs. It is recommended that the local government must:

- Integrate tsunami risk information in all aspects of coastal development planning, regulation, investment, community life, education, and economic activities.

- Address the very high and high risk areas of population, social and economic infrastructure and critical facilities through special tsunami mitigation programs.
- Conduct regular and systematic awareness and education about tsunami hazard to coastal community within villages in each region that have the very high and high values for social vulnerability.
- Consider the tsunami risk map to support the spatial planning and integrated coastal management for the future regulations related with the construction new buildings in coastal area, especially in Kuta and Sanur Regions.

Recommendations for future research to further develop this project include:

- Modelling of tsunami occurrence with different magnitudes for analysing risk area with different scenario.
- Integration of numerical modeling and GIS modeling to obtain better results.
- More detailed ground truthing in order to identify physical, social and economic factors that influence the vulnerability assessment.

This analytical model that has been created in this study can be applied and adapted to other coastal locations and local government jurisdictions in Indonesia and similarly tsunami vulnerable countries.

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Appendix

Appendix 1. The Tsunami Events in Indonesia from 1800 to 2010.

Year	Tsunami Source Location			Tsunami Cause		Tsunami Parameters		Tsunami Effect
	Name	Long	Lat	Earthquake Magnitude	Volcano	Maximum Water Height	Number of Run-ups	Number of Deaths
1815	TAMBORA	118	-8.2	-	Vol	3.5	4	
1815	AMBON ISLAND	128.2	-3.7	-	-	-	1	
1815	BALI SEA	115.2	-8	7	-	-	1	1200
1818	BENGKULU, SUMATRA	102.27	-3.767	7	-	-	1	
1818	BALI SEA	117	-7	8.5	-	3.5	1	
1820	FLORES SEA	119.4	-5.1	-	-	25	5	500
1833	SW. SUMATRA	102.2	-3.5	8.2	-	-	3	
1841	MOLUCCAS ISLANDS, INDONESIA	130	-5	-	-	3	1	
1841	BANDA SEA	127.5	-4	6	-	1.5	4	
1843	SW. SUMATRA	98	1.5	7.2	-	-	3	
1845	CELEBES SEA	124.85	1.48	7	Vol	-	1	
1851	LAMPUNG BAY, INDONESIA	105	-5	-	-	1.5	1	
1852	SIBOLGA, SUMATRA	98.8	1.7	6.8	-	-	1	
1852	BANDA SEA	129.9	-4.6	-	-	14.5	9	60
1856	SANGIHE ISLAND	125.5	3.67	-	Vol	-	1	
1857	BALI SEA	115.5	-8	7	-	34	2	
1857	N. MOLUCCAS ISLANDS, INDONESIA	125	1	-	-	-	1	
1858	N. MOLUCCAS ISLANDS, INDONESIA	126	1	-	-	-	7	
1859	N. MOLUCCAS ISLANDS, INDONESIA	126.5	1	7	-	10	1	
1859	N. MOLUCCAS ISLANDS, INDONESIA	125.5		7.2	-	-	1	
1859	BANDA SEA	130.5	-5.5	6.7	-	-	1	
1859	S. JAVA SEA	111	-9	-	-	-	1	2
1861	SW. SUMATRA	97.9	-1	8.5	-	7	9	1105
1861	SW. SUMATRA	98		7	-	-	4	750
1861	SW. SUMATRA	97.5	1	7	-	-	1	
1861	JAVA, INDONESIA	107.3	-6.3	-	-	-	2	
1861	SW. SUMATRA	100	-1.5	6.5	-	-	1	
1862	JAVA, INDONESIA	-	-	-	-	2.1	1	
1864	NW. IRIAN JAYA	135	-1	7.8	-	3	2	250
1871	RUANG	125.43	2.28	-	Vol	25	5	400
1876	CERAM SEA	127.25	-3	6.8	-	0.3	1	
1883	KRAKATAU	105.42	-6.102	-	Vol	35	83	36000
1885	SERAM ISLAND	127.5	-2.5	7.3	-	-	1	
1889	JAVA-S. JAVA, INDONESIA	-	-	-	-	-	1	
1889	N. MOLUCCAS ISLANDS	126.25	1	8	Vol	4	7	
1889	JAVA, INDONESIA	113.5	-7	6	-	-	1	
1892	NORTHEAST SUMATRA	99.5	2.5	-	-	-	6	
1892	SULAWESI	125.5	3.67	-	Vol	0.75	5	
1896	SW. SUMATRA	102.5	-3.5	6.8	-	-	1	
1899	BANDA SEA	128.5	-3	7.8	-	12	14	2460
1900	BISMARCK SEA	140	-4	7.8	-	-	1	5
1903	BANDA SEA	127.5	-3	6.5	-	1	2	
1904	BANDA SEA	128.7	-3.6	-	-	-	1	
1907	NW. SUMATRA	94.5	2	7.6	-	-	10	400
1907	KARAKELONG, TALAUD ISLANDS	122	3	7.3	-	4	1	

1908	SW. SUMATRA	100	-2	7.5	-	1.4	1	
1909	SUMATRA	101	-2	7.6	-	-	4	
1914	NW. IRIAN JAYA	137	-2	7.9	-	0.1	3	
1914	LAIS, SUMATRA	102	-3.5	-	-	-	1	
1915	NW. IRIAN JAYA	136	-1	6	-	-	1	
1918	SULAWESI	125.49	3.138	-	Vol	0.08	2	
1920	N. MOLUCCAS ISLANDS, INDONESIA	122.92	0.87	-	-	2	1	
1921	MAKASSAR STRAIT	117.9	0.7	6.2	-	1	1	
1921	S. JAVA SEA	111	-11	7.5	-	0.1	2	
1927	SULAWESI	119.7	-0.7	6.3	-	15	2	50
1928	FLORES SEA	121.71	-8.32	-	Vol	10	2	128
1929	TJALANG, N.W. SUMATRA	95.567	4.633	-	-	-	1	6
1930	S. JAVA SEA	114.3	-9.3	6.5	-	0.1	1	
1936	SULAWESI	126.5	4.5	7.7	-	3	2	
1938	MAKASSAR STRAIT	120	-1	7.6	-	3	6	17
1939	N. MOLUCCAS ISLANDS, INDONESIA	123	-	8	-	-	1	
1948	OFF NORTHWEST COAST	95	6	6.3	-	-	1	
1950	JAVA TRENCH, INDONESIA	128.3	-3.8	7.6	-	-	2	
1965	SANANA ISLAND	126.1	-2.4	7.6	-	-	3	71
1967	MAKASSAR STRAIT	119.3	-3.7	5.5	-	-	1	13
1967	NORTHEAST SUMATRA	97.3	5.5	6.1	-	-	1	
1968	BANDA SEA	119.8	0.2	7.8	-	10	7	200
1969	MAKASSAR STRAIT	118.9	-3.1	6.9	-	4	3	600
1977	SUNDA ISLANDS	118.46	-11.09	8	-	15	9	189
1979	LEMBATA ISLAND	123.5	-8.6	-	-	-	1	539
1979	LOMBLEN ISLAND	123.5	-8.5	-	-	-	1	
1979	IRIAN JAYA	136.04	-1.679	7.9	-	2	2	100
1983	BANDA SEA	127.92	-4.056	6.9	-	3	1	
1984	SULAWESI	118.81	-2.823	6.8	-	0.1	1	
1985	BALI ISLAND, INDONESIA	114.19	-9.245	6.2	-	2	1	
1987	TIMOR SEA	124.16	-8.247	6.6	-	0.1	1	
1992	FLORES SEA	121.9	-8.48	7.8	-	26.2	24	2500
1994	HALMAHERA	127.73	1.015	7	-	2	3	
1994	JAVA, INDONESIA	112.84	-10.48	7.8	-	13.9	25	250
1994	JAVA, INDONESIA	112.89	-10.36	6.6	-	3.7	1	
1994	HALMAHERA	127.98	-1.258	6.8	-	3	1	1
1995	TIMOR SEA	125.13	-8.378	6.9	-	4	1	11
1996	SULAWESI	119.93	0.729	7.9	-	3.43	15	9
1996	IRIAN JAYA	136.95	-0.891	8.2	-	7.68	108	110
1998	TALIABU ISLAND, INDONESIA	124.89	-2.071	7.7	-	2.75	1	
2000	SULAWESI	123.57	-1.105	7.6	-	6	2	
2002	IRIAN JAYA	134.3	-1.757	7.6	-	5	3	
2004	SERAM ISLAND	127.4	-3.12	6.7	-	-	1	
2004	OFF W. COAST OF SUMATRA	95.982	3.295	9	-	50.9	997	227898
2005	INDONESIA	97.108	2.085	8.7	-	3	16	10
2005	KEPULAUAN MENTAWAI	99.607	-1.644	6.7	-	0.4	1	
2006	SERAM ISLAND	127.21	-3.595	6.7	-	3.5	1	4
2006	JAVA	107.41	-9.254	7.7	-	10	20	664
2007	SUMATRA	101.37	-4.438	8.4	-	0.98	20	
2008	SUMATRA	99.972	-2.486	6.5	-	0.12	1	
2008	SULAWESI	122.09	1.271	7.3	-	-	3	
2009	SUMATRA	99.49	-1.479	6.7	-	0.18	1	
2009	SUMATRA	99.867	-0.72	7.5	-	0.27	1	
2010	SUMATRA	97.132	2.3	7.7	-	-	6	

Source: National Geophysical Data Center, NOAA USA, July 2010.

Appendix 2. The Tsunami Intensity Scale According to Soloviev (1978).

Tsunami Intensity (K_0)	**Run – up Height (m)**	**Description of Tsunami**
I	0.5	Very slight. Wave so weak as to be perceptible only on tide gauge records.
II	1.0	Slight. Waves noticed by people living along the shore and familiar with the sea. On very flat shores waves generally noticed.
III	2.0	Rather large. Generally noticed. Flooding of gently sloping coasts. Light sailing vessels carried away on shore. Slight damage to light structures situated near the coast. In estuaries, reversal of river flow for some distance upstream.
IV	4.0	Large. Flooding of the shore to some depth. Light scouring on made ground. Embankments and dykes damaged. Light structures near the coast damaged. Solid structures on the coast lightly damaged. Large sailing vessels and small ships swept inland or carried out to sea. Coasts littered with floating debris.
V	8.0	Very large. General flooding of the shore to some depth. Quays and other heavy structures near the sea damaged. Light structures destroyed. Severe scouring of cultivated land and littering of the coast with floating objects, fish and other sea animals. With the exception of large ships, all vessels carried inland or out to sea. Large bores in estuaries. Harbour works damaged. People drowned, waves accompanied by a strong roar.
VI	16.0	Disastrous. Partial or complete destruction of man-made structures for some distance from the shore. Flooding of coasts to great depths. Large ships severely damaged. Trees uprooted or broken by the waves. Many casualties.

Source : http://www.riskfrontiers.com/scales/scalespage16.htm

Appendix 3. The Project Documentations.

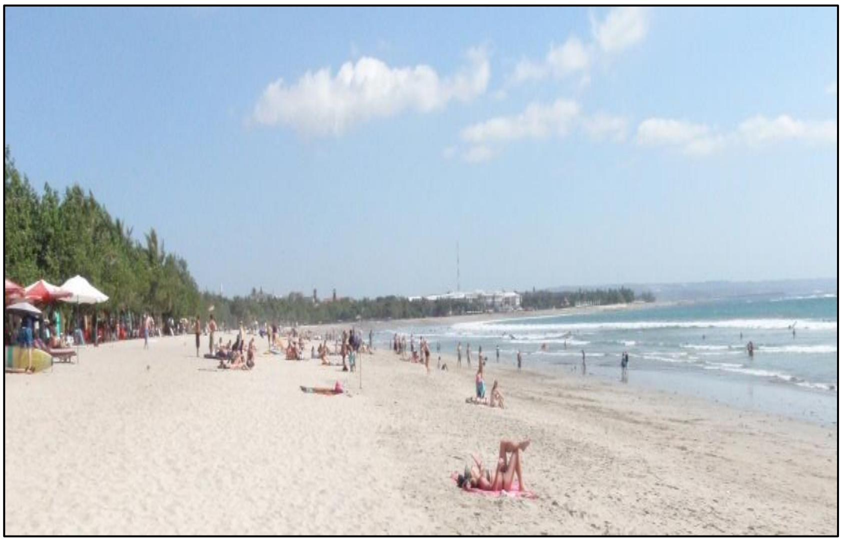

Figure 8.1. The condition of Kuta Beach. There are many tourists and small kiosks who could possibly become potential victims if tsunamis occur there.

Source: The author (2009).

Figure 8.2. The gas station "Pertamina" in Kuta Village: One of the lifeline facilities that is essential for community recovery.

Source: The author (2009).

Figure 8.3. The Catholic Church in Kuta Village. It is only around 200 m from the Kuta Beach.

Source: The author (2009).

Figure 8.4. The front gate of the hotel "Ramada Bintang Bali" in Kuta Village: One of the hotels which is located in tsunami risk areas that could potentially be inundated by future tsunamis.

Source: The author (2009).

Figure 8.5. The front gate of the government elementary school "Sekolah Dasar No.3 Legian" in Legian Village. Schools are one of the special sites that need special attention during a tsunami event.

Source: The author (2009).

Figure 8.6. The "Kuta Clinic" in Kuta Village. Clinics and hospitals are lifeline facilities that are essential for community recovery.

Source: The author (2009).

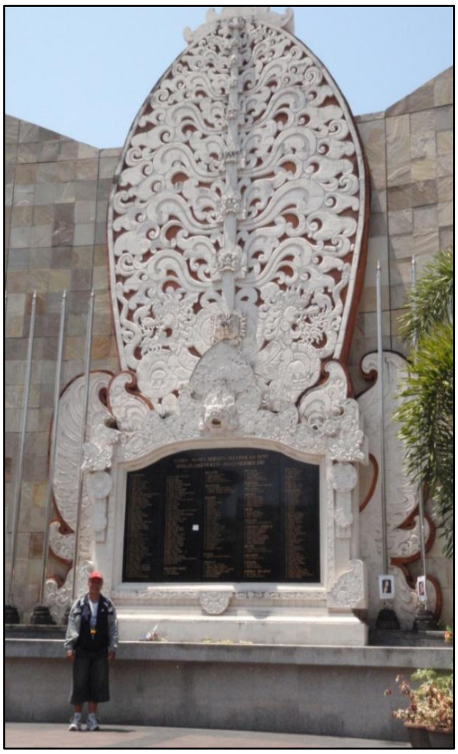

Figure 8.7. The "Bali Bombing Monument" in Kuta Village. This monument is around 1 km from the Kuta Beach.

Source: The author (2009).

Figure 8.8. The front gate of the Pura Temple "Dalem Penataran" in Seminyak Village. It is one of the places that can be used as a shelter in tsunami mitigation.

Source: The author (2009).

Figure 8.9. The condition of Sanur Beach. Boats can become floating debris in future tsunamis.

Source: The author (2009).

Figure 8.10. The open space area in Sanur Village. It is one of the places that can be used as an evacuation place in tsunami mitigation because it is located in the tsunami least risk areas.

Source: The author (2009).

Figure 8.11. Children can potentially become victims if a tsunami occurs in Sanur Kaja Village. Children and elderly are people who need assistance during a tsunami event.

Source: The author (2009).

Figure 8.12. The front gate of the traditional market "Pasar Senggol Sanur" in Sanur Village. Traditional markets are one of the economic facilities which serve as the main income for people and village revenue that can be disrupted by future tsunamis.

Source: The author (2009).

Figure 8.13. The front gate of the hotel "La Taverna" in Sanur Village. This hotel can be used for vertical evacuation because several buildings in there have more than one storey.

Source: The author (2009).

Figure 8.14. The small kiosks that sell snacks and drinks in Sanur Beach. These kiosks can become dangerous floating debris that can potentially harm or injure coastal communities during a tsunami event.

Source: The author (2009).

Figure 8.15. The front gate of the government junior high school “SMPN 9 Denpasar” in Sanur Kaja Village. Large schools are very useful for evacuation centres during a tsunami event.

Source: The author (2009).

Figure 8.16. The agriculture areas in Sanur Kaja Village. Future tsunamis can destroy these agriculture areas. Farmers require much money and longer time to rebuild these areas.

Source: The author (2009).