INSTITUT FÜR GEOGRAPHIE AN DER UNIVERSITÄT REGENSBURG

Tsunami Evacuation Modelling

Development and application of a spatial information system supporting tsunami evacuation planning in South-West Bali

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Summary

This research aims at developing a spatial information system supporting tsunami evacuation planning using geo- information technology. A case study was conducted in a tsunami- prone area in the South- West of Bali.

Because of the great earthquake in the northwest of Sumatra island, Indonesia, the devastating tsunami of December 26, 2004 has become the most important research topic in tsunami research and disaster mitigation efforts today. The main effort in minimising casualties in tsunami disaster is to evacuate people from the hazard area before tsunami strikes by means of either horizontal or vertical evacuation.

Within the thesis an assessment of people's ability to evacuate is presented. This assessment requires knowledge of probable tsunami sources and impact characteristics along the coast. To address the spatial and temporal component of the population at risk, a population disaggregation concept was developed to identify people's movements between different functional urban sectors for day and night- times. This includes people commuting into the study area and tourists.

Accessibility analysis on the basis of a Cost Weighted Distance (CWD) approach is utilised to identify optimized evacuation routes from a defined initial location to the nearest evacuation shelter. Robust multi-storey buildings which meet the general requirements of an evacuation shelter building (ESB) as well as safe areas based on a tsunami inundation scenario were identified in the study area. In addition, a criteria set for ESB's has been worked out.

A final evacuation modelling is combining the accessibility modelling with the exposed population in order to give a statement about the evacuation ability of the population at risk for different evacuation times. Results of the modelling include evacuation bottlenecks based on shelter capacities, population hotspots and available evacuation routes.

Based on one inundation scenario, the application of the evacuation modelling in the study area shows that a wide majority of the exposed population is able to access an evacuation shelter within an evacuation time of 25 min. However, a multi- scenario approach is required in order to improve the identification of areas affected by tsunami impact. Central research expertises are the requirement of detailed population data to ensure effective evacuation planning and the need to allocate additional evacuation shelters particularly at locations with high population density. A crucial point is the limited capacity of some evacuation shelter buildings in the study area, which leads to an insufficient evacuation ability in some shelter catchment areas. Based on these results, additional ESB planning can be recommended to decision makers.

By addressing the above- mentioned issues that greatly influence the evacuation process, the research provides essential spatial information for local decision makers in tsunami- prone areas based on a modelling approach transferable to other coastal areas. .

Ringkasan

Penelitian ini bertujuan untuk mengembangkan sebuah sistem informasi spasial yang mendukung perencanaan evakusi dengan menggunakan tehnologi geoinformasi. Daerah rawan bencana tsunami di Barat Daya Bali merupakan wilayah yang dipilih untuk studi kasus.

Sejak kejadian gempa besar di Barat Laut kepulauan Sumatera dan mengakibatkan tsunami 26 Desember 2004, topik penelitian di bidang tsunami dan pengurangan dampak bencana menjadi suatu penelitian yang sangat penting. Upaya utama untuk meminimalkan korban dalam bencana tsunami adalah evakusi orang di wilayah bencana sebelum tsunami terjadi baik secara horisontal maupun vertikal. Penilaian kemampuan masyarakat untuk evakuasi telah disajikan dalam thesis ini. Dalam penilaian ini membutuhkan informasi tentang peluang kejadian tsunami dan karakteristik dampaknya di sepanjang pantai. Untuk menunjukkan komponen populasi orang yang memiliki resiko secara spasial dan waktu, konsep penyebaran populasi orang dibangun dengan mengidentifikasi pergerakan orang di dalam wilayah fungsional yang berbeda di sektor perkotaan siang dan malam. Dalam konsep ini, orang yang masuk dan keluar di area studi seperti turis dan kaum pendatang diperhitungkan.

Pendekatan analisis aksesibilitas dengan basis Cost Weighted Distance (CWD) digunakan untuk mengidentifikasi rute evakuasi yang optimal dari suatu lokasi yang telah ditentukan ke tempat evakuasi terdekat. Gedung bertingkat yang kuat sebagai salah satu syarat umum untuk gedung sebagai tempat evakuasi dan daerah yang aman berbasiskan skenario tsunami inundasi diidentifikasi dalam studi area dan penentuan kriteria untuk gedung sebagai tempat evakuasi telah dikerjakan dengan baik.

Hasil akhir model evakuasi adalah mengkombinasikan model aksesibiltas dengan orang yang terekspos untuk memberikan suatu pernyataan tentang kemampuan evakuasi dari suatu populasi orang yang beresiko untuk waktu evakuasi yang berbeda. Hasil dalam model ini termasuk juga evakuasi „bottleneck" yang berdasarkan kapasitas tempat evakuasi, tempat orang berkumpul, dan ketersediaan jalur evakuasi.

Berdasarkan pada satu skenario inundasi, model aplikasi di area studi menunjukkan secara umum bahwa mayoritas orang yang terekspos dapat mencapai tempat evakuasi dengan waktu evakuasi sekitar 25 menit. Bagaimanapun juga, pendekatan multi skenario dibutuhkan untuk menentukan secara tepat daerah yang terkena dampak tsunami. Penelitian ini membutuhkan informasi orang secara detail untuk menjamin perencanaan evakuasi yang efektif dan memerlukan tambahan tempat evakuasi secara khusus untuk daerah populasi tinggi. Masalah penting adalah keterbatasan kemampuan gedung sebagai tempat evakuasi di area studi, yang menyebabkan kemampuan evakuasi yang tidak cukup di daerah-daerah tangkapan sebagai tempat evakuasi. Berdasarkan hasil ini, penambahan perencanaan gedung sebagai tempat evakuasi dapat direkomendasikan untuk para pengambil kebijakan. Dengan menunjukkan hal yang tersebut di atas, isu yang telah di ungkap akan sangat mempengaruhi proses evakuasi. Penelitian ini telah menyediakan informasi spasial yang penting untuk para pengambil keputusan lokal di daerah rawan tsunami berdasarkan model yang dapat di transfer ke daerah pantai yang lain.

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List of abbreviations

ADPC	Asian Disaster Preparedness Centre
AWI	Alfred Wegener Institute
BAKOSURTANAL	Badan Koordinasi Survei dan Pemetaan Nasional (National Coordinating Agency for Surveys and Mapping)
BAPPEDA	Badan Perencanaan Pembangunan (Regional Development Planning Board)
BMG	Badan Meteorologi dan Geofisika (Meteorological and Geophysical Agency)
BPS	Badan Pusat Statistik (Statistics Indonesia)
CWD	Cost Weighted Distance
DLR	German Aerospace Center
DSM	Digital Surface Model
DTM	Digital Terrain Model
ESB	Evacuation Shelter Building
FEMA	Federal Emergency Management Agency
GITEWS	German-Indonesian Tsunami Early Warning System
GTZ- IS	German Technical Cooperation – International Services
IHRA	International Hotel and Restaurant Association
IOC	Intergovernmental Oceanographic Commission
KESBANGLINMAS	Kesatuan Bangsa dan Perlindungan Masyarakat (Office of National Unity and Community Protection)
LAPAN	Lembaga Penerbangan dan Antariksa National (National Institute of Aeronautics and Space)
LIPI	Lembaga Ilmu Pengetahuan Indonesia (Indonesian Institute of Sciences)
NGDC	National Geophysical Data Centre
NGO	Non- Governmental Organisation
NOAA	National Oceanic and Atmospheric Administration
PMI	Palang Merah Indonesia
	(Indonesian Red Cross)
SDSS	Spatial Decision Support System
SOP	Standard Operating Procedure
TNI	Armed Forces of Indonesia
UN- ISDR	International Strategy for Disaster Reduction

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1 Introduction

The devastating tsunami of December 26, 2004 caused 230 000 deaths and about $ 4.5 billion damages. This tremendous disaster initiated – besides major relief efforts – intensive tsunami research and the apparent need for tsunami early warning systems. As a key element for tsunami hazard mitigation, a tsunami early warning system (GITEWS) will be developed for the Indian Ocean in the scope of a German- Indonesian cooperation. A fundamental aspect of the project is capacity building in the area of disaster management for decision makers, experts and the general public at risk. The administrative bodies and the affected population have to be prepared in case of a disaster, have to understand the warnings and react appropriately.

Evacuation of people in risk areas is the first priority once a tsunami early warning is received or natural warning signs indicate the immediate arrival of a tsunami wave. As the available time span between a warning and the impact of a tsunami wave in Indonesia generally is very short, all necessary preparations should have been made in advance. An official evacuation plan is essential to provide the community with the necessary reference, guidance and information by describing activities and measures taken to ensure temporary evacuation of people and property from threatened locations before the disaster strikes. During a tsunami event, the primary task of the emergency planner is to ensure the safety and rapid evacuation of people. The decision to evacuate very much depends on the severity of the immediate effects of the disaster on the vulnerable population.

Spatial analyses in a geo information system are a widely used approach in emergency planning by providing features to centralize and visually display spatial information. Evacuation planning should be based on a hazard assessment by analysing possible hazard scenarios affecting a certain area and should develop procedures for safe transfer from the affected area into safe areas. A spatial information system will be developed for the study area providing possibilities to visualize activities and measures taken to ensure temporary evacuation of people from threatened locations before the disaster strikes.

Extensive spatial information is needed to provide a suitable data base for dealing with the dynamic and uncertain nature of an evacuation process. Static evacuation plans are not always suitable when an actual disaster happens. Instructions that do not consider the evolution of a tsunami threat over time can result in suboptimal decisions that can lead to unnecessarily imposed risk and lost lives. In addition, people's evacuation behaviours such as evacuation time and walking speed also have effect on the optimal strategy. Therefore, in determining the evacuation route, it is important to explicitly consider the time-varying nature of node and people's reaction to evacuation in such circumstances. It is necessary to provide dynamic information and instructions to help people to make the right decision.

1.1 Objectives and structure of the thesis

The aim of this thesis is to implement a pre- operating study for a spatial information system for tsunami evacuation planning in South- West Bali in cooperation with local authorities using geo information system and earth observation analyses. The research will be conducted under the premise of transferability to other coastal areas with similar environmental properties especially for the coastal areas in Indonesia exposed to tsunami impacts. The research mainly focuses on the objectives shown in *Table 1* below.

No.	Research objectives
1.	Definition of requirements for evacuation planning
2.	Development of a transferable and applicable spatial information system for tsunami evacuation planning
3.	Giving a statement about the endangerment of the study area
4.	Giving a decision support for evacuation in case of a tsunami event
5.	Cooperation with the local administration and decision makers

Table 1 Research objectives of the thesis (Source: own composition)

The work will consider three major parts:

Part 1 is the acquisition and implementation of geobasisdata into a Geo Information System (GIS). Beside this, a tsunami hazard assessment has to be conducted determining the exposed areas. This includes historical tsunami impact information and tsunami inundation modelling results. Based on these results, spatial analyses in respect to evacuation planning considering spatial properties of the urban and rural structure and visualization of structures potentially suitable for evacuation are presented. The existence of adequate reachable higher ground outside inundation areas for horizontal evacuation as well as characteristics of buildings potentially suitable for vertical evacuation are significant information for evacuation planning and therefore are particularly featured.

Part 2 incorporates population characteristics in the analysis. The vulnerability of population in areas under the effect of tsunami hazards is a major reason of concern. Information on population, required for evacuation planning, has an essential spatial component and, particularly in urban areas, is changing continuously. Therefore available population data are disaggregated into smaller units considering day and night distribution.

Part 3 is based on the previous results. Tsunami evacuation is simulated using both accessibility modelling, since the modelling demonstrates the effort of people to move themselves from their initial location to the nearest (in terms of cost) evacuation shelter (horizontal and vertical), and a modelling of the evacuation ability considering the certain shelter capacities.

Research questions

In order to achieve the research objectives, the following research questions shown in *Table 2* will be addressed.

No.	Research Objectives	Research Questions (RQ)
1.	Definition of requirements for evacuation planning	a) What spatial data are needed for evacuation planning? b) What are the most important needs for the end users (local stakeholders, exposed population)?
2.	Development of a transferable and applicable spatial information system for tsunami evacuation planning	a) Which spatial information tools are suitable for evacuation modelling? b) What has to be considered in developing a spatial information tool to ensure its transferability to other coastal areas? c) Which spatial parameters have to be considered for tsunami evacuation modelling?
3.	Giving a statement about the endangerment of the study area	a) How is the intensity of tsunami hazard locally distributed? b) How many people are exposed? c) In the context of evacuation planning, where are critical facilities? d) Where are evacuation bottlenecks?
4.	Giving a decision support for evacuation in case of a tsunami event	a) Where are potential evacuation shelters? b) Where are potential evacuation routes? c) Are the people in risk areas able to evacuate in a given period of time? d) Which spatial information products are useful for the local decision makers?
5.	Cooperation with the local administration and decision makers	a) Which stakeholders should be incorporated in the research process? b) How to transfer the gained knowledge and create acceptance for the local population?

Table 2 Research Objectives and research questions of the thesis (Source: own composition)

1.2 State of research

With a view to the research objectives, two main topics take centre stage in this thesis. (1) Population disaggregation methods and (2) evacuation modelling approaches including evacuation shelter properties will be discussed in this chapter regarding the current state of research.

Population disaggregation

Awareness and preparedness to natural hazards is the critical issue for local populations who are potentially vulnerable to a tsunami hazard. Essential to evacuation planning is determining where people are likely to be located, which varies temporally (e.g. day and night).

The census district is the common basis for collecting population data, also for the study area in this thesis. Population data from censuses are commonly made available per administrative or political unit whereby the populations seem to be homogeneously distributed over the whole area, despite possibly significant variations in real population densities (SCHNEIDERBAUER 2007). However, evacuation planning requires detailed information on spatial and temporal population distribution, such that the idea to safe all the people in the tsunami hazard area can be achieved (BUDIARJO 2006).

Two methods for disaggregating population data are generally available. A top- down approach interpolates the total population on a local scale based on physical structures mapped from remote sensing data. A bottom- up approach extrapolates punctual information onto the district level (TAUBENBÖCK ET AL. 2007). The basic idea behind spatial disaggregation using remote sensing data is based on a correlation between the structural characteristics of the urban or rural environment and its population.

With spatial knowledge about the physical urban morphology, regionalization can be performed. Regionalization or localization stands in social research for an area that is subdivided into homogeneous sectors based on economic, structural, demographic and/or social criteria. General rules for a spatial definition of homogeneous urban sectors are:

(1) the characterization of the land use
(2) the exclusion of other land cover types such as bare soil or water, and
(3) the classification of large units with respect to the image resolution and to boundaries along relevant natural and anthropogenic features

The result generates functionally or structurally zoned spatial sectors, subdividing the whole area by certain homogeneous characteristics (TAUBENBÖCK ET AL. 2007). These static physical urban elements allow a linkage to the dynamic urban element: population. The hypothesis is based on the assumption that populations living in areas showing nearly similar housing conditions will have homogeneous social and demographic characteristics. Thus, spatial disaggregation is based on a correlation of spatial structural characteristics and population (TAUBENBÖCK ET AL. 2007). Remote sensing can provide criteria to generate homogeneous spatial sectors within the heterogeneous urban environment. The basic product of remote sensing is an urban land cover classification for identification of the housing areas and their respective spatial reference. Thus, the capabilities of remote sensing provide physical parameters to describe regularities and irregularities for regionalization. Value-added remote sensing products provide physical criteria like 'built-up density', 'building height', 'land use' and 'location' to classify urban morphology. Based on the hypothesis that homogeneous structural urban sectors show homogeneous demographic characteristics, the local population distribution is indirectly derived.

Evacuation modelling

Traditional evacuation research has primarily focused on analyses of static evacuation plans or maps and the use of performance- based tests to determine disaster impacts on transportation infrastructure, property, population behaviour and survivability. The use of static evacuation plans has not yielded a convenient means to conduct experimental designs for determining the plans' ability to accommodate population growth, urban growth, or aging populations. In addition, static evacuation plans do not provide the best means for optimizing emergency procedures and evacuation personnel requirements (PITTMANN ET AL. 2006).

The potential role for GIS in evacuation research has been noted by a number of authors (GATRELL AND VINCENT 1991, DANGERMOND 1991, JOHNSON 1992, REJESKI 1993). GIS have been applied in generating alternative evacuation routes out of a given zone and in managing the spatial data associated with an evacuation decision support system (DE SILVA ET AL. 1993). In general, the wider application of GIS in hazards research has focused on modelling the physical aspects of hazards and not on potential evacuation difficulties. Although evacuation vulnerability modelling is clearly related to GIS natural hazards research, it's more closely aligned with GIS research on modelling human vulnerability and risk (BURKE 1993). However, these capabilities propose GIS technologies as a natural framework to deal with much of the complexity embedded into the evacuation research and decision-making processes.

Simulation models represent another category of tools, which may be used for planning or decision support. Several GIS packages offer simulation capabilities for simple processes, but specialized models will be required to refine the level of analysis, or may represent consolidated tools that are pre-existing to GIS in a given context (COVA ET AL. 1997). At the heart of any network evacuation simulator is a traffic simulation model. The approaches to the design of traffic models in general depend on the area of their intended application and the detail required in modelling the behaviour of the entities within the system. Network- based traffic simulation models can be categorized into three basic groups: micro, macro and meso, based on how they attempt to model the behaviour of evacuation entities. Micro- simulators track the movement of individuals as the simulation proceeds while macro- simulators are driven by a model analogous with fluid dynamic flows. Meso-simulators attempt to gain the best of both micro- and macro- simulation by simulating "platoons" of individuals throughout the network (DE SILVA ET AL. 2000).

The question how to combine the enormous potential of GIS in evacuation modelling with the technical specialized and dynamic simulation models is obvious.

BATTY (1994) discusses the possible contribution GIS can make to visualize simulation. To extremes can be identified: (1) one where the various components of GIS can be drawn into the modelling process and (2) where modelling can take place within the GIS.

A combination of the two is often used for the design of Spatial Decision Support Systems (SDSS) whereby using the analytical tools within GIS, some sort of analytical modelling of the data take place. In contrast, decision models within the SDSS are likely to draw on the display and data analyses facilities of the GIS. It is therefore evident that the union of these technologies offers attractive modelling and analytical resources to develop a decision aid tool for evacuation planning (DE SILVA ET AL. 2000).

For this reason, GIS and simulation models are often proposed to the decision-maker as an "integrated tool." This relation is presented in *Figure 1*.

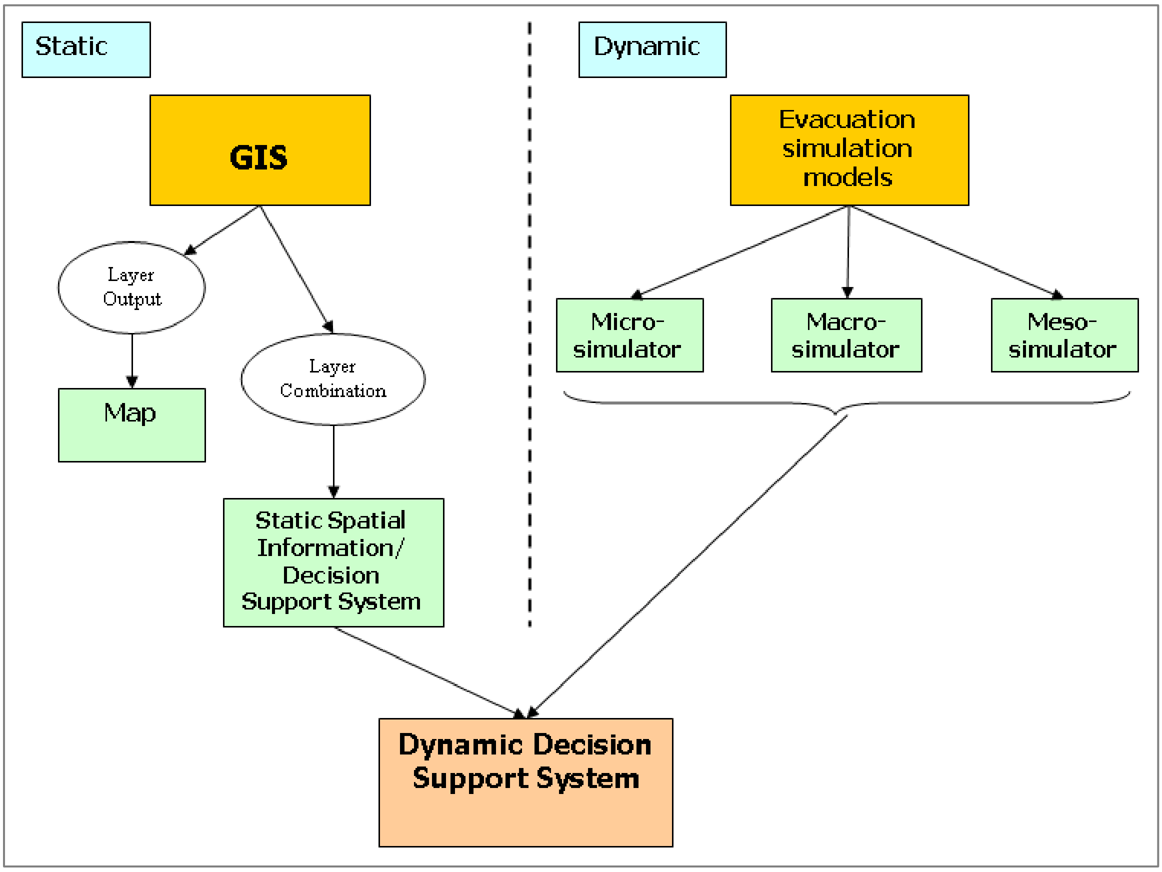


Figure 1 Combination of GIS and dynamic simulation models (Source: own illustration)

1.3 Approach

1.3.1 GIS for Natural Disaster Management

Natural disasters are inevitable and it is almost impossible to fully recoup the damage caused by disasters. But it is possible to minimise the potential risk by developing disaster early warning strategies, prepare and implement developmental plans to provide resilience to such disasters and to help in rehabilitation and post disaster reduction.

The use of GIS has become an integrated, well developed and successful tool in disaster management as it allows the combination of the different kinds of spatial data, with non- spatial data, attribute data and use them as important information in the various stages of disaster management. A complete strategy is required to effectively reduce the impact of natural disasters, which can be split into six phases: Disaster prevention and disaster preparedness take place before a disaster occur, the response phase during a disaster, the disaster relief, rehabilitation and reconstruction after the occurrence of a disaster. In the disaster prevention phase, GIS is used to manage the large volume of data needed for the hazard and risk assessment, in the disaster preparedness phase it is a tool for evacuation planning and the integration of satellite data with other relevant data in the design of a disaster warning system. During a disaster, GIS can provide essential spatial information for evacuation coordination, e.g. by calculating suitable shelter accessibility. In the disaster relief phase, a GIS is very useful for rapid acquisition, processing and analyses of satellite data and the provision of satellite based information products on natural and environmental disasters, for human relief activities. In the disaster rehabilitation phase, GIS is used to organise the damage information (BANGER 2002).

The importance of GIS for Natural Disaster Management is therefore relevant in two major aspects: 1) the analytical capability for decision making and 2) the data integration capacity. Both aspects allow the integrated analyses of large amounts of different data in each disaster phase (CASTELLANOS- ABELLA 2002).

1.3.2 Tsunami evacuation planning and spatial decision support

In case of a tsunami event, the primary task of the emergency planner is to ensure the safety and rapid evacuation of the people at risk. The decision to evacuate very much depends on the estimated degree of the immediate impact of the tsunami on the exposed population. Planning for a tsunami evacuation therefore involves addressing both the ability to evacuate (age, gender, etc.) and logistical issues that greatly influence the evacuation operation (DE SILVA ET AL. 2000).

A spatial information system in a GIS environment can provide a decision support by answering questions like, what evacuation routes should be selected based on the location of the hazard, how many people have to be evacuated, and where they should go to reach the nearest shelter. Testing a variety of inundation scenarios, for example under simulated emergency conditions can also be greatly aided by GIS data and techniques. During a tsunami event, GIS can be an important aid to emergency evacuation. By overlaying and analyzing a variety of maps, emergency planners can quickly estimate populations needing to be evacuated (COLE ET AL. 2005). If the tsunami hazard effects new areas, alternative evacuation plans or inundation scenarios can also be implemented. The results of the GIS- generated analyses, whether as a map or report, can be distributed instantaneously to relevant authorities over the internet for fast public information delivery.

2 Study area – Case study Kuta

2.1 Geographical position and political structuring

Bali, as the westernmost island of the Small Sunda islands, is located between 0°30’40” - 8°50’48’” southern latitude and 114°25’53” - 115°42’40” eastern longitude with an island expanse of 5 561 km². The largest east- west expansion amounts 144 km and that in north- south direction 87 km. In the West, Bali is separated from the Java island by the small Selat Bali (Bali- street) and in the East the 40 km wide Selat Lombok (Lombok- Street) is the parting line to the neighbour island Lombok. The island is washed round by the Bali Sea in the North and the Indian Ocean in the South (BAKOSURTANAL 2003).

The province of Bali is subdivided into nine administrative districts (Kabupaten), 51 sub- districts (Kecamatan) and 570 villages (Desa/ Kelurahan) and urban districts. The villages are subdivided again into 1 480 smaller villages (Desa adat) and about 3 630 village districts (Banjar). The smallest official administrative unit is the village with a mayor at the top. However, the village districts have a great importance as a mutually supportive group and local self- administration. The capital and administration centre of the island is Denpasar with a current population of 340 000 people. Since 1992, the city is the ninth administrative district of Bali (NADLER 2005). The study area is located in the South of the island between 8°42’36” – 8°44’29” southern latitude and 115°9’38” – 115°10’48” eastern longitude and belongs to the district of Badung. The area contains the villages of Kuta and Legian as well as parts of Seminyak and Tuban. The common superior administration unit is the sub- district (Kecamatan) of Kuta.

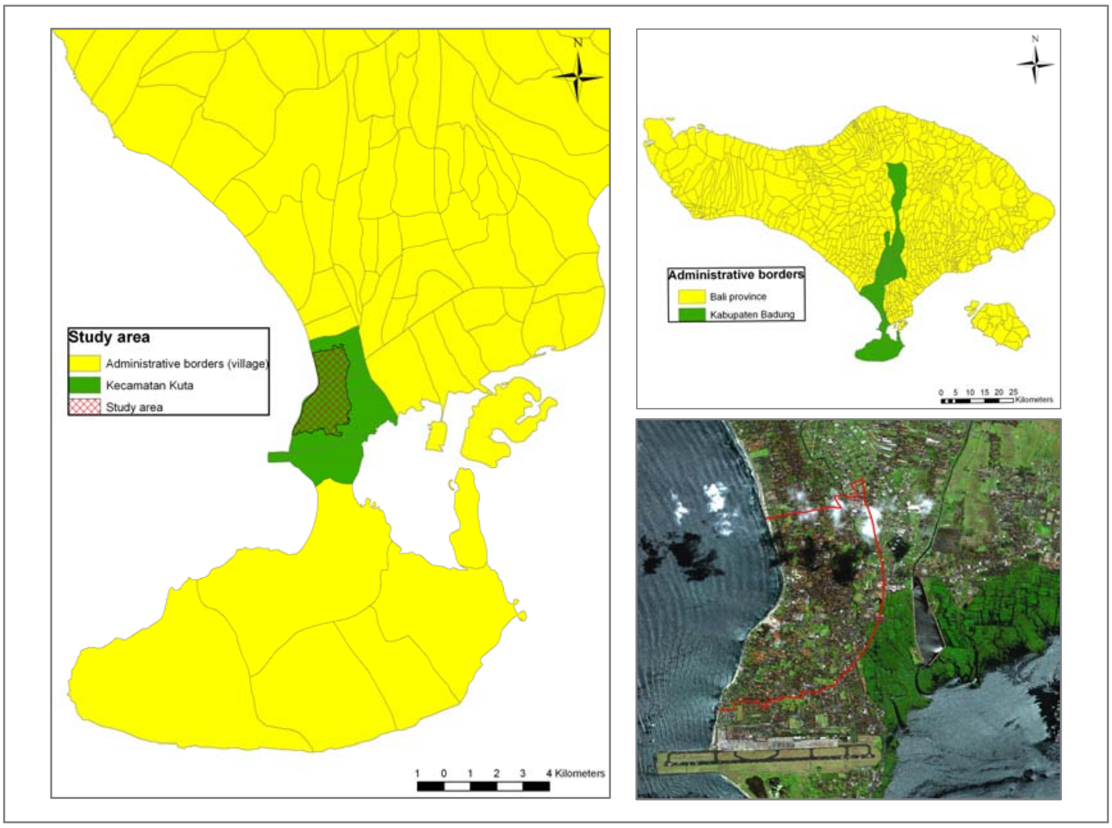


Figure 2 Geographical position of the study area (Source: own illustration - Data basis: BPS CENSUS 2000; Map basis: Quickbird satellite image)

2.2 Economic factor tourism

Bali is characterized by agriculture and tourism. About 50% of the population are working in the tourism industry, the rest almost without exception in the agricultural sector. 65% of the island area is used agriculturally, but the share of the agriculture in the Balinese gross national product sank from about 55% in 1979 to 30% in 2005. This is mainly a result of the high growth in population and changed land claims. In the last decades, tourism has emerged to the most important economic factor. Considering other industries which directly depend on the touristic demand like souvenir trade, tourist guides and transport industry, about one-third of the gross national product is obtained directly from tourism. As a result of the multiplier factors of the tourist expenses, growth impulses overlap to other economic sectors. The agriculture and fishery sector cover a high proportion of the food demand from the hotels. The local beverage industry is an important hotel supplier and the local building material production benefit from the fact that many hotels are built in a Balinese style and with local building materials.

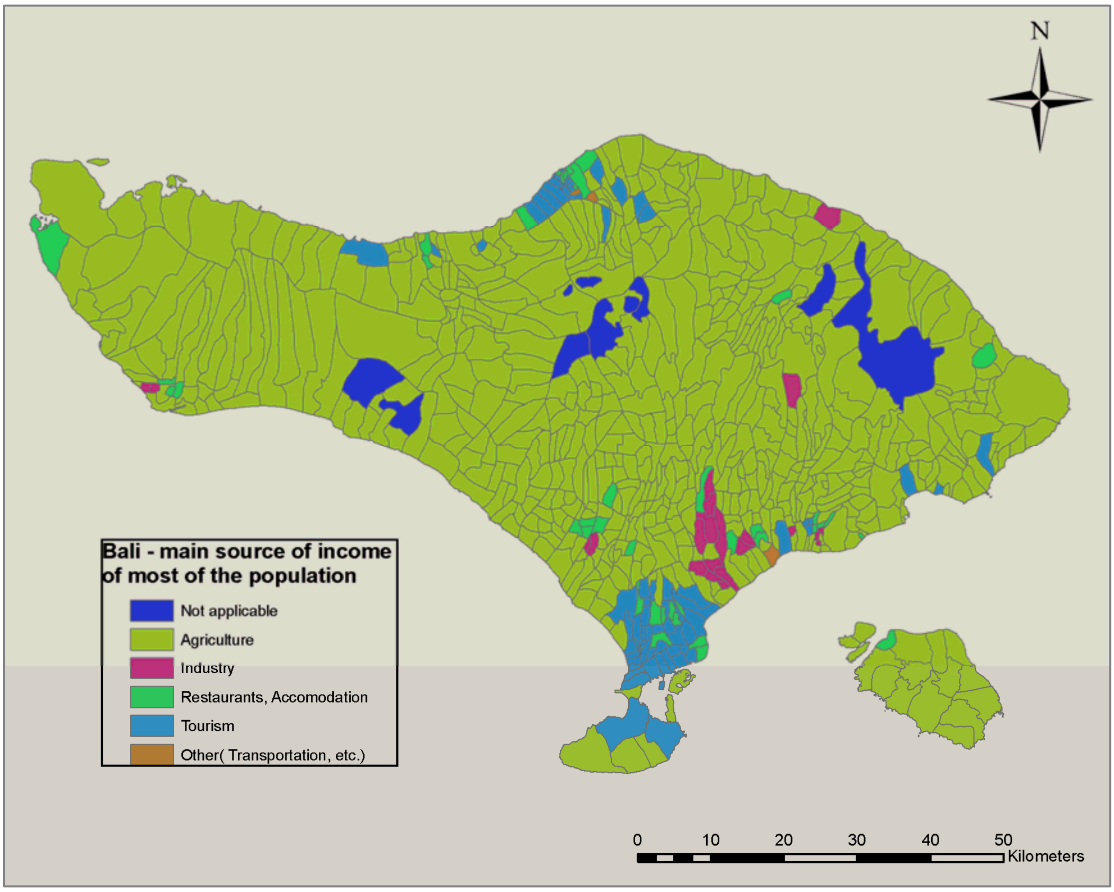


Figure 3 Bali – Main source of income of most of the population (Source: own illustration - Data basis: BPS PODES 2005; Map basis: BPS census 2000)

Nearly 20% of all touristic demands in the last years felt upon the souvenir purchase. The production and the sale of local handicraft is vitally important, because the products belong to the most preferred articles of tourists. The auxiliary incomes from these jobs show a wide social and spatial spread, also villages apart from the tourist centres benefit from this business. Many villages live on this sector and many crofters depend on this auxiliary income, because of the decreasing income from the agriculture. However, Bali shows distinctive spatial disparities. The differences between the districts regarding the per capita gross national product are substantially. The tourism industry expanded in the economical advantaged and cultural rich areas in the South, whereas the periphery was little attended. Despite a bigger spatial spread of tourist attractions in the last decade, the touristic demand is still very concentrated to South- Bali. About 80% of the employees in the hospitality industry are working in the district of Badung and the "tourist triangle" Kuta- Sanur- Nusa Dua by now is mainly a complete urbanized area that merges seamlessly in the urban agglomeration of the capital Denpasar. Therefore from one perspective the tourism sector contributes to the reduction of regional and social disparities in Bali but considered differently the sectorial and spatial concentration in the South will further increase because of the economic and cultural supremacy (VORLAUFER 1999).

2.3 Tectonic structures

The Indonesian archipelago is located along a complex convergence of the Eurasian, India-Australian, Caroline and Philippine sea plate and several minor ones. These plates are moving relative to each other in a complicated manner. Typical plate motion can be summarized as follows: The relative motion of the Eurasian plate to the India- Australian one is approximately northward, whereas that of the Philippine sea plate is west by northwest. The Philippine sea plate relative to the Caroline one is moving east by southeast near the Aru trench and west by northwest near the Yap trench. The Indonesian archipelago consists of five active island arcs: The Sunda, Banda, Sangihe, Halmahera and North Sulawesi arc. The Sunda arc, as a result of the convergence of the Indian Ocean and the Eurasian plate, extends westward from Sumba through Java, Sumatra and the Andaman islands. The Banda arc resulted from the collision of the south-eastern part of the Eurasian and Australian plate and extends eastward from Sumba. To the northern part of this arc, the Sangihe and Halmahera arcs in the Molluca Sea region were caused by the activities of two opposing subductions of the Molluca sea plate. Taking into consideration the above tectonics, the Indonesian region is divisible into 6 zones (LATIEF ET AL. 2000):

Zone A: The West Sunda arc includes the northwest Sunda Strait (Sumatra and the Andaman Islands)

Zone B: The East Sunda arc includes the area in the region of the East Sunda Strait to Sumba (Java, Bali, Lombok, Sumbawa and Sumba)

Zone C: The Banda arc covers the area of the Banda sea (Flores, the Timor and Banda islands, the Tanimbar islands, Ceram and Buru)

Zone D: The Makassar Strait

Zone E: The Molucca sea, Sangihe and Halmaher

Zone F: The North Irian Jaya

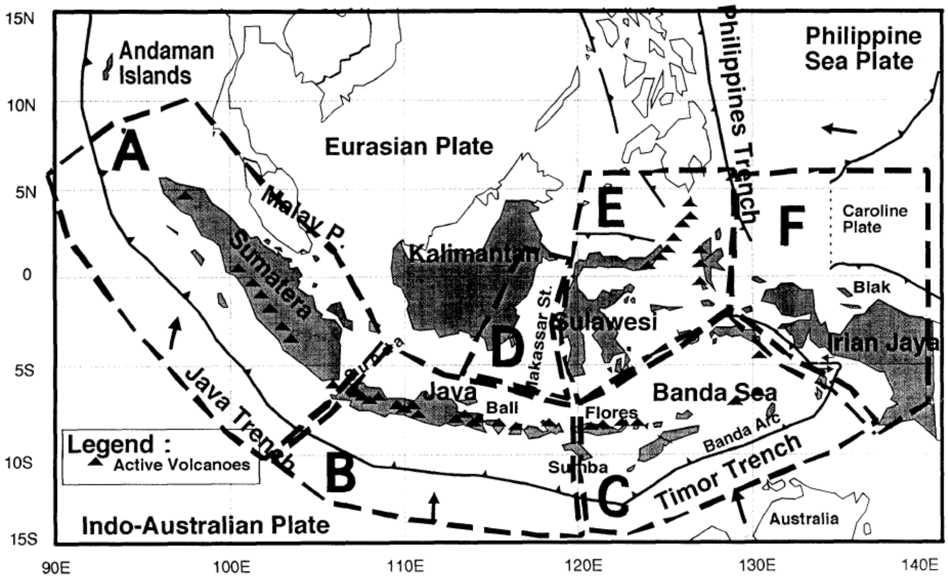
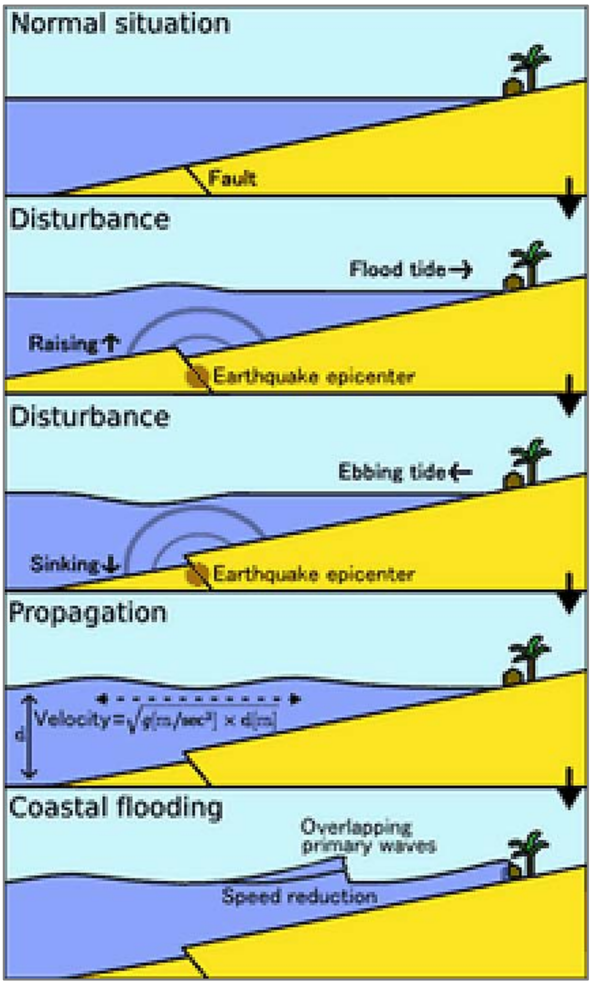


Figure 4 Seismotectonics of 6 Indonesian zones (A- F) (Source: LATIEF ET AL. (2000), p.28)

2.4 Tsunami generation and zonal activities in the region of Bali



Tsunamis are generated by several kinds of geo-physical phenomena; earthquakes, volcanoes, landslides and debris flows. In Indonesia, earth-quakes are the primary source of tsunami generation. When the earthquake occurs, it causes a vertical movement of the sea floor over a large area. As the land mass shifts, the waves become broader and move outwards. The most destructive tsunamis are generated by large, shallow earth-quakes that have an epicentre near or on the ocean floor usually along subduction boundaries where tectonic plates collide in regions of high seismic activity. The amount of vertical and hori-zontal motion of the sea floor and the efficiency with which energy is transferred from the earth's crust to the ocean water to create destructive waves, are all part of the tsunami generation mechanism. In deep water, a tsunami travels over great distances at high speed and with limited energy loss. As the wave approaches land, its height increases while its speed decreases.

Figure 5 Tsunami generation and propagation (Source: http://www.important.ca/tsunami_causes.html)

As a result of the complicated plate- convergence presented in *Chapter 2.3*, the Indonesian region has a very high seismic activity and will continue to experience big earthquakes in the centuries to come, some of which could generate tsunamis.

Bali is located in the area of the East Sunda arc (see Zone B in *Chapter 2.3*). In the following, the occurrence of historical tsunamis caused by earthquakes and affecting Bali is presented. The seismicity in the East Sunda arc is mainly controlled by the action of the Indian Ocean plate subducting beneath the Eurasian plate. The seismicity depth reaches about 650 km with a gap in seismicity between 300 to 500 km. 82 destructive earthquakes which have the potential to generate a tsunami have been reported in this zone, about 45% of the total number of destructive earthquakes reported in Indonesia. *Figure 6* shows the tsunami events in the East Sunda arc from 1600 to 1998. About 10% of the total number of tsunamis reported in Indonesia occurred in this zone. Nine tsunamis were generated by earthquakes and one by volcanic eruption. The last tsunami was the East Java tsunami in 1994 (Moment Magnitude M = 7.6) that killed 238 people. The average interval between tsunami events is estimated to be about 10-15 years (LATIEF ET AL. 2000).

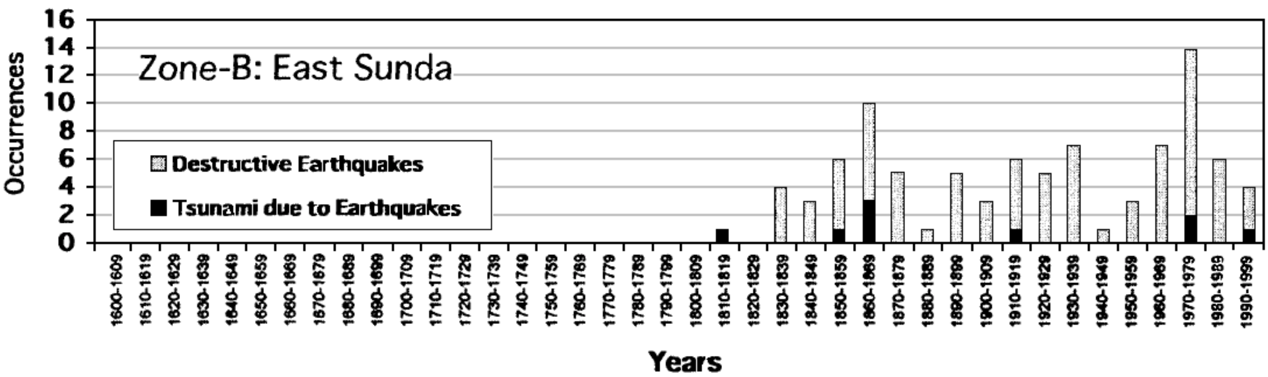


Figure 6 Histogram of destructive earthquakes (1800 – 1999) and tsunamis caused by earthquakes (1600 – 1999) by zone and by decade (Source: LATIEF ET AL. (2000), p. 33, modified)

3 Methods

3.1 Data collection

The data research was conducted during a five month stay in Bali. A cooperation with GTZ-IS Indonesia, a German stakeholder in the course of the GITEWS project, was agreed in advance. In the context of capacity building, GTZ- IS is responsible for the strengthening of the local organisation related to tsunami warning and disaster management in Indonesia. The close collaboration on site was important for the first contacting with local stakeholders and the official legitimation of the research process.

3.1.1 Data requirement and data acquisition methods

The data collection process was conducted before and during the fieldwork period. Before the field work, the data were obtained from literatures and internet sources. During the fieldwork period, data acquisition methods included interviews and field observation as well as data acquisition for secondary sources. *Table 3* provides the list of data requirement and data acquisition methods in relation to the research questions.

No.	Research Question (RQ)	Data requirement	Source	Acquisition method
1.	RQ 1a, 1b Required spatial information for an evacuation planning process	- Reference on tsunami evacuation - Reference on existing institutions with experience in dealing with tsunami evacuation planning	- FEMA/NOAA –IOC, UN-ISDR - PMI - BUDIARJO (2006) - Herryal Z. Anwar (LIPI)	- Literature study - Internet browsing - Expert interviews
2.	RQ 2a, 2b, 2c Spatial information systems for evacuation planning	- Information about evacuation modelling using GIS - Reference on institutions dealing with spatial information and GIS - Availability of suitable software products	- ADPC (2007), (2007a) - BUDIARJO (2006) - JONG ET AL. (1996) - Oak Ridge National Laboratory - BAPPEDA	- Literature study - Internet browsing - Expert interviews

3.	RQ 3a, 3b, 3c, 3d Components of risk assessment	- Tsunami hazard parameter - Information about population distribution - Critical facilities locations	- DLR - LIPI - Field observation - H.Spahn (GTZ) - Khomarudin et al. (2008)	- Internet browsing - Expert interviews - Facility identification - Functional urban zone identification
4.	RQ 4a, 4b, 4c, 4d Evacuation modelling	- Evacuation routes - Evacuation shelter locations - Evacuation shelter capacity	- BAKOSURTANAL - Field observation - AWI - POST ET AL. (2007) - BUDIARJO (2006)	- Internet browsing - Expert interviews - Road and facility identification
5.	RQ 5a, 5b Cooperation process in the context of capacity building	- Reference on local stakeholders - Results of cooperation process	- Kelurahan Kuta - BMG - PMI - GTZ - IHRA - KESBANGLINMAS Kabupaten Badung	- Expert interviews - Workshop participation - Internet browsing

Table 3 Data requirement and data acquisition methods in relation to the research questions (Source: own composition)

3.1.2 Data acquisition and field work preparation

Before the fieldwork, data collection mainly focused on the secondary data, collecting information about existing knowledge on tsunami evacuation, socio- economic, socio- demographic and spatial data of the study area and the touristic infrastructure of whole Bali. Based on these acquired data, an initial analysis was conducted to prepare the data acquisition in the field. The preparation included:

Developing interview guidelines

Referring to the RQ – block 3 in *Table 3*, the locations of critical facilities and potential safe areas in the context of evacuation planning had to be determined and valuated concerning their critical characteristics. As critical facilities, schools and hospitals were considered because of their strong concentration of people at certain times during the day.
Due to the dominating touristic infrastructure in the study area, hotels are of particular importance for vertical evacuation. Their locations could be determined by the information from statistical data, but specific characteristics had to be gained by interviews. Necessary information and knowledge to obtain were formulated in an interview guideline and translated into interview questions.

Preparation for workshops on evacuation planning

Referring to the RQ- block 1, cooperation processes with local administration and local decision makers in the form of technical workshops on evacuation planning were very important for the exchange of experiences and information. Main components of the field work process, especially methods for the disaggregation of population data and the identification of potential evacuation shelters, had to be discussed. A key topic was the implementation of technical evacuation components in a general evacuation planning concept as well as the clear and understandable presentation of evacuation procedures which have to be disseminated to the local population.

Functional zonation of the study area

Referring to the RQ –block 3, detailed information about the population distribution in the study area had to be gained by fieldwork. An own population distribution concept, considering information about population movements between different functional urban sectors was developed to disaggregate population data gained from census data on village level. This concept is explained more detailed in *Chapter 3.3*. On the basis of a Quickbird satellite image, different functional urban sectors were signed out in the study area to identify homogeneous zones with similar urban characteristics (*cp. Chapter 1.3)*. The considered parameters for this zonal predefinition were building density, building type, building size and roof colour. However, due to a lack of time and technical expertises, this identification process is not based on a methodological but only on a visual approach.

In this preparing step, five different sectorial uses could be determined and signed out accordingly:

Tourism sector	**Local sector**
Commercial area	Commercial area
Residential area	Residential area
Mixed tourism and local sector	

Table 4 Preliminary functional sectors in the study area (Source: own composition - Data basis: Quickbird satellite image)

The pre-zonation was cross- checked and corrected during the fieldwork process. Relevant secondary input data could be gained from the "Central Bureau of Statistics Indonesia (BPS)" and the mayor of the village of Kuta.

Preparing working sheets for the fieldwork

Referring to the RQ- block 3 and 4, a comprehensive fieldwork had to be conducted. To ensure a consistent research, a detailed working sheet was developed. During the preparation, useful data from the "Indonesian Red Cross (PMI)", which already conducted similar fieldworks, could be used as helpful examples and proposals for the detailed development of the sheet. The main contents are stated below.

A	Functional Zoning	Verification of predefined sectors Subzonation if necessary
B	Road network	Numbering of road segments Number of lanes Traffic volume
C	Potential safe areas for vertical evacuation	Building function Number of storeys Potential capacity
D	Potential safe areas for horizontal evacuation	Type of location Potential capacity
E	Critical facilities	Facilities name Facilities function Number of storeys Potential capacity

Table 5 Main contents of the working sheet for the fieldwork (Source: own composition)

3.1.3 Field work

The field work was conducted in the study area of the Kecamatan (Sub- district) Kuta. The main objective of the survey was the verification of the predefined functional urban sectors, the identification of the road network, potential safe areas and critical facilities in the sense of tsunami evacuation.

Identification of the road network

For the identification of the road network, detailed road maps as well as street layers, digitized from satellite images, were already available. The idea of this activity was to complete the available road dataset and to valuate certain road segments regarding their important function as evacuation route. Therefore all roads in the study area were evaluated considering their width, which is described with the number of lanes, and the traffic volume during day and night. The evaluation criteria and the considered attributes are presented in *Table 6*.

Road Network			
Width	*ID*	*Traffic volume*	*ID*
One lane small	1	Very much	1
One lane wide	2	Much	2
Two lanes small	3	Not much	3
Two lanes wide	4		
Four lanes	5		

Table 6 Valuation criteria for the road network in the study area (Source: own composition - Data basis: Field work in the study area)

Identification of functional urban sectors

Information on population, required for evacuation planning, has an essential spatial component and, particularly in urban areas, is changing continuously. The census data on village level are the most detailed available information, but for evacuation planning at local level these data are too coarse to provide a good insight into the spatial distribution of the population at risk. The sub-division of the study area into functional urban sectors was necessary to get a more detailed impression of the population movement within one day (HOFSTEE AND ISLAM 2004). As explained in *Chapter 3.1.2.*, the predefined sectors in the satellite image had to be verified in the fieldwork. For the most part the predefined sectors had to be subdivided again. Unclear referable sectors were defined by interviewing local people on site. The sector identification process is shown in *Figure 7.*

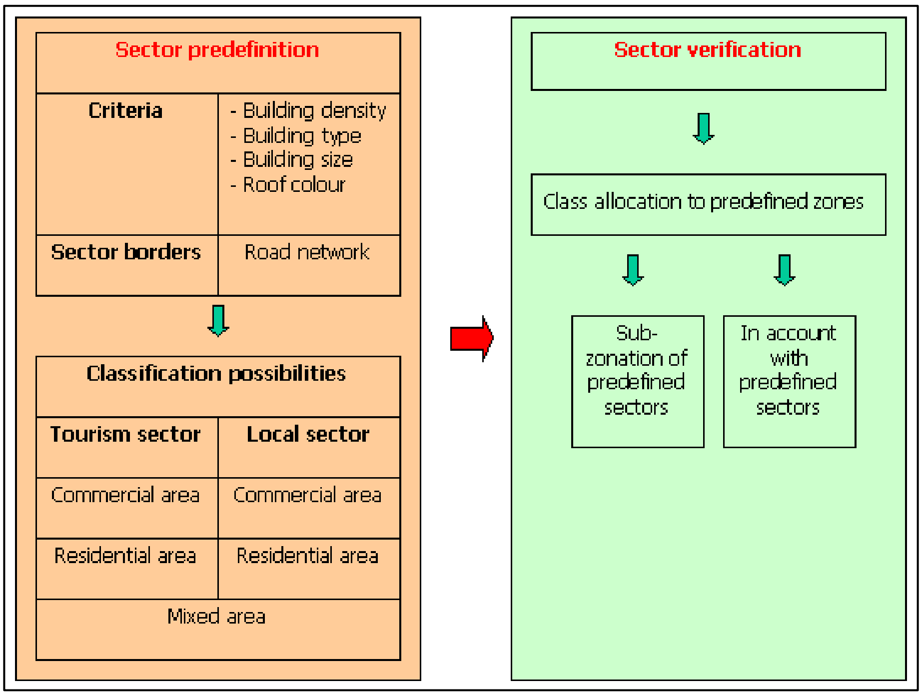


Figure 7 Identification of functional urban sectors in the study area, gained by field work (Source: own illustration)

Identification of evacuation shelters

a) Building functions potentially suitable as evacuation shelter building (ESB)

The observation aimed at identifying building and location functions that can be assigned as evacuation shelter. In case of a tsunami event, two methods to evacuate people from the hazard area are generally available (EISNER AND NTHMP 2001):

1. Horizontal evacuation - moving people to more distant locations or higher ground outside the inundated area

2. Vertical evacuation - moving people to higher floors in buildings.

Referring to general characteristics of suitable shelters gained from literature (BUDIARJO 2006, EISNER AND NTHMP 2001), the criteria of observation are:

=> for horizontal evacuation: public locations with an adequate capacity

=> for vertical evacuation: public facilities, multi-storey buildings, available reserve space for temporary evacuation and good construction quality.

However, these general characteristics for evacuation shelters which are considered for the field work indeed are correct, but a professional technical expertise is necessary for an official definition of a building as evacuation shelter. An overview of facilities and locations in the study area which meet these basic demands for evacuation shelters is presented in *Table 7* and *Table 8.*

No.	**Building function**	**Suitability for vertical evacuation**	**Public-oriented function**	**Building design and construction**	**Critical issue**
1.	Hotel	Suitable	Limited access to public	- Hall, foyer and function room can be occupied for evacuation - Generally well planned and good construction; has to be proved!	Security and privacy issues should be arranged together with owner and disaster authority
2.	School	Suitable	Accommodate education activity for students living in surrounding area	- Hall and classes can be occupied for evacuation - Generally well-planned and good construction; has to be proved!	During teaching time the building can only accommodate the people in it
3.	Government office	Suitable	Civil building, oriented to serve the people	- Hall, foyer and function room can be occupied for evacuation	

4.	Sport hall	Suitable	Accommodate sport activities of the users	- Open lay-out suitable for accommodating huge numbers of evacuees - Generally well-planned and good construction; has to be proved!	
5.	Market building	Suitable only for people within the building	Public facilities, accessible to everybody in the certain operating hours	- Commercial oriented, lack of empty space, full of merchandise and storage	During evacuation, the building can only accommodate the people in it
6.	Mosque	Suitable	Accommodate prayer activities for Moslems	- Open lay-out suitable for accommodating huge numbers of evacuees - Generally well planed and good construction; has to be proved!	
7.	Shopping centre	Suitable only for people within the building	Public facilities, accessible to everybody in a certain operating hours	- Commercial oriented, lack of empty space, full of merchandise and storage - Generally well planned and good construction; has to be proved!	Vulnerable to robbery and thievery in emergency situation. During evacuation, the building can only accommodate the people in it
8.	Billiard centre	Suitable	Public facilities, accessible to everybody in the certain operating hours	- Open lay-out suitable for accommodating huge numbers of evacuees	

Table 7 Overview of potentially suitable facilities for vertical evacuation in the study area (Source: own composition)

No.	Location function	Suitability for horizontal evacuation	Public- oriented function	Location property	Critical issue
1.	Parking place	Suitable	Public location, accessible to everybody at any time	- Flat area - Asphaltic ground	
2.	Sports field	Suitable	Public location, accessible to everybody at any time	- Flat area - Flat gras vegetation	
3.	Public places	Suitable	Public location, accessible to everybody at any time	- Flat area - Usually asphaltic ground	
4.	Field/ Acre	Suitable	Private property but mostly accessible to everybody at any time	- Rough area	

Table 8 Overview of potentially suitable facilities for horizontal evacuation in the study area (Source: own composition)

b) Potential evacuation shelter identification

After identifying general characteristics of suitable shelters, the criteria used to determine which building or location is a potential evacuation shelter, have to be completed. Referring to expert interviews and technical literature (BUDIARJO 2006, EISNER AND NTHMP 2001), the additional criteria of observation are:

for safe areas (horizontal evacuation)	for evacuation shelter buildings (ESB) (vertical evacuation)
- outside maximum inundation zone - good accessibility - Slope < 20° (cp. Chapter 3.2.2) - suitable land use classes	- good building accessibility - good accessibility to space for temporary evacuation inside the building - located at a distance of more than 200m from the shore (BUDIARJO 2006, P.61) - good and proved stability

Table 9 Additional criteria for evacuation shelters (Source: own composition - Data basis: Budiarjo 2006, Eisner and NTHMP 2001)

During the field work, suitable evacuation shelters were identified and valuated considering the mentioned criteria *(see Chapter 4.1).* But also in this case, a professional technical expertise is required to assign evacuation shelter buildings.

c) Hotel survey

Due to the fact that the hotel sector in the study area is part of the private commercial sector, there is no responsible public administration which can provide detail building and socio- economic information. To identify a hotel as a potential evacuation shelter, a lot of data apart from the location and general accessibility of the building are necessary. A detailed building inspection, like for the public facilities, was not possible due to a lack of time. Therefore the "Indonesia Hotel and Restaurant Association Badung Regency of Bali", an umbrella organisation of star hotels in Bali, was contacted to conduct a written survey for the topic "Hotels as evacuation shelter buildings". The questionnaire was developed together and is given in *Appendix 1*.

Identification of critical facilities

In case of a tsunami evacuation, special attention should be paid to the more vulnerable people and groups. Particularly the very young ones as well as old and handicapped people are among the victims of a tsunami disaster (BIRKMANN ET AL. 2007). These groups are not separately mentioned in statistical data in the required spatial resolution, therefore statements about their spatial distribution can only be made in relation to some known facilities. Schools and hospitals are important institutions that house people who are not able to be responsible for their own evacuation. As described in *Chapter 3.1.2.,* a questionnaire for the fieldwork was developed in advance to evaluate the facilities concerning their critical characteristics. During the fieldwork, responsible authorities were contacted in order to get information about the geographical position and relevant evacuation properties of the facilities. Therefore an own questionnaire only for hospitals and schools were developed as presented in *Appendix 2 and 3*.

3.2 Hazard impact & exposed area

3.2.1 Tsunami hazard assessment

An assessment of the tsunami hazard is needed to identify people and assets at risk, and the level of that risk. This assessment requires knowledge of probable tsunami sources (such as earthquakes, landslides, volcanic eruption), their probability of occurrence, and the characteristics of tsunamis from those sources at different places along the coast. Data of earlier (historical and paleotsunamis) tsunamis may help quantifying these factors. In case that only very limited or no past data exist, numerical models of tsunami inundation can provide estimates of areas that will be flooded in the event of a local or distant tsunamigenic earthquake (UNESCO- IOC 2006).

An evacuation resulting from a tsunami hazard impact forces immediate action because of little warning and limited preparation time. Detailed knowledge for early warning (expected arrival time and extend of tsunami), the potential tsunami impact at coastline (expected wave heights at coastline) as well as the potential tsunami impact on land (expected intensities on land, hazard zones) is required for an applicable evacuation planning (POST ET AL. 2007)

Four methods are generally available to conduct a hazard assessment.

(1) Based on historical records of tsunami impact observations

(2) Based on one numerical inundation scenario

(3) Based on many numerical inundation scenarios

(4) Based on a combination of historical data and modelling results

For this research one tsunami inundation scenario is the basis for the evacuation modelling. However, an assessment from historical data was conducted in advance due to a lack of inundation scenarios at the beginning of the research. A multi- scenario approach was also taken into consideration as a basis for further analysis. All three approaches are shortly presented in the following.

I. Using historical records of tsunami impact observation

The National Geophysical Data Centre (NGDC) provides a global tsunami database with information on tsunami source events and locations where effects from tsunamis were observed. These data include the maximum water heights above sea level (in meters) and the maximum horizontal distance of inland flooding (in meters). Based on these information and knowledge about protective measures in the affected area, the degree of hazard impact on land can be quantified as presented in *Figure 8* below (POST ET AL. 2007).

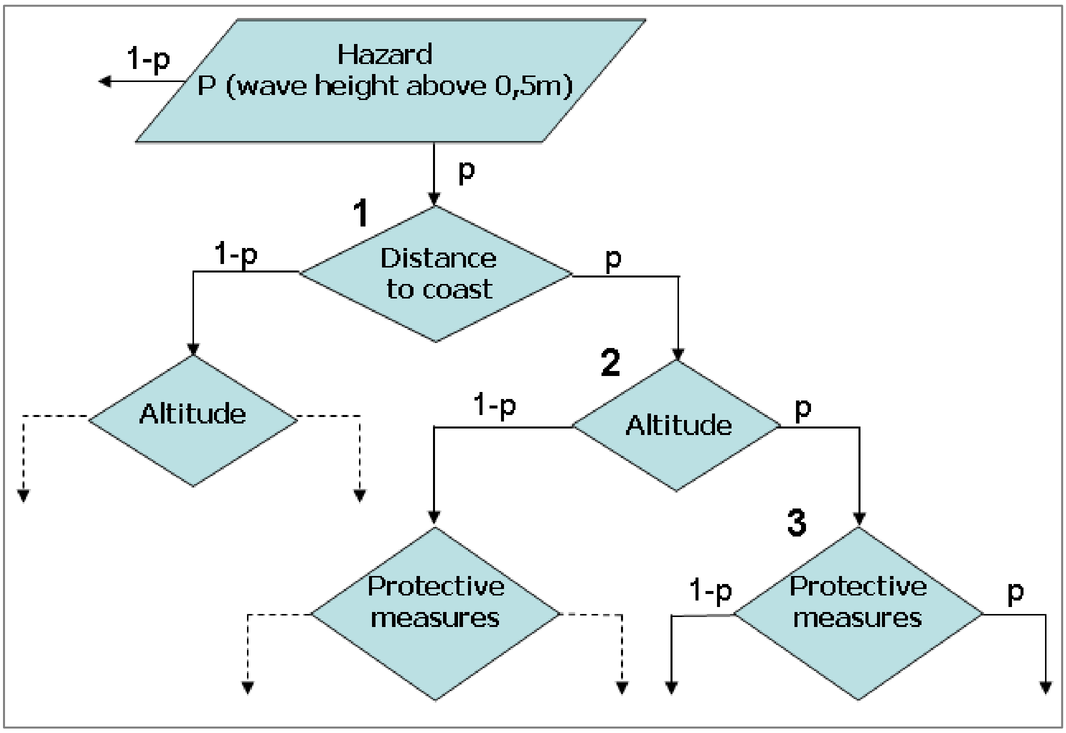


Figure 8 Decision tree to approximate the degree of hazard impact on land (Source: Post et al. (2007), modified)

It is quite trivial that there is a correlation between the distance to the coast and the degree of impact. The NGDC database can be used for a classification into distance zones with different probabilities to be affected by a tsunami. From the results one can derive zones with a different frequency of an event.

The influence of the altitude is obviously also an important factor. The spatial distribution of the altitude (topography) along the coast can be derived from Digital Surface Models (DSM's) or Digital Terrain Models (DTM's). This classification is strongly depending on the resolution of the surface or terrain model.

The protective measures include all aspects (indicators) which can mitigate the tsunami intensity. These can be structural measures like dams, but also the vegetation can have a protective effect, such as mangrove forests. To quantify the relevance of protective measures it is necessary to define their relative qualitative differences. This accounts especially for the vegetation, where the spatial differences in the area of interest need to be incorporated as well as the assessment scale of the risk assessment. For example, the existence of many or highly efficient protective measures in a given area can lead to the estimation of "no risk" in the decision tree for a given scenario. By the combination of these gained parameters, the degree of a tsunami impact on land can be represent spatially distributed. (POST ET AL. 2007)

II. Using inundation modelling results

For estimating tsunami impacts on land, the hazard assessment is often conducted by using numerical inundation modelling results. This analysis requires high resolution topography and bathymetry data (elevation data on land and underwater), and information about potential regional tsunami sources. The outcomes of tsunami inundation modelling are to identify areas that could be flooded and to estimate water depths, current strengths, wave heights, and wave arrival times. The calculated results yield the spatial distribution of the maximum inundation area depending on the location of the source (STRUNZ ET AL. 2008A).

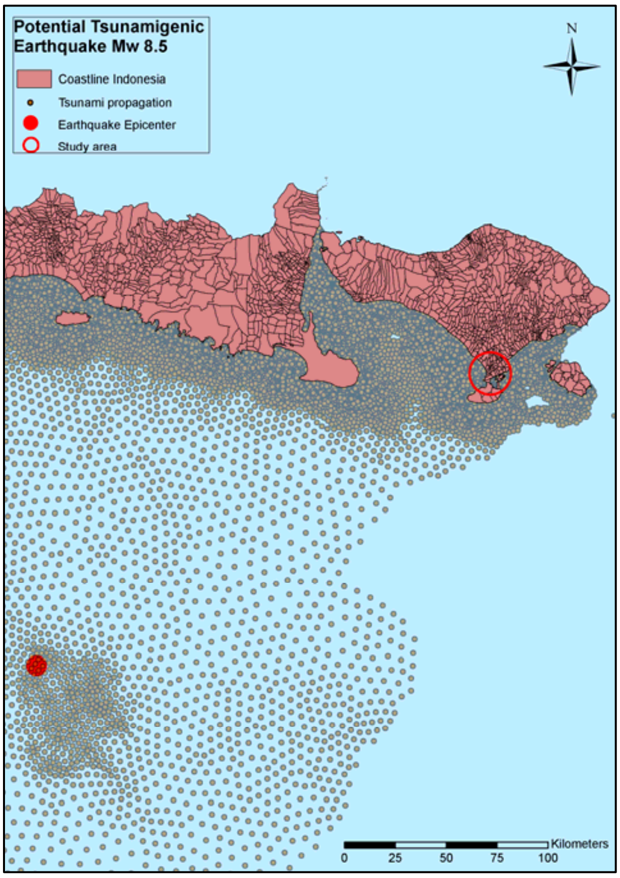
Based on one scenario

In order to identify the potential tsunami impact of a "worst case" event for a certain region, a scenario with an epicentre relatively near the coast and a high moment magnitude can be used to derive hazard impact zones expected.

This research was conducted using an inundation scenario calculated by the Alfred Wegener Institute (AWI) for Polar and Marine Research within the GITEWS tsunami early warning project. The underlying tsunami simulation system is based on the current knowledge on the possible ocean bottom deformations due to seismic activity in the Sunda Trench region.

However, the decision to take only one scenario was not made in order to show a worst case scenario, but because the small study area is completely affected by a majority of the available scenarios. For the evacuation modelling an artificial scenario was selected showing both affected and safe areas. The scenario is based on the assumption of a tsunamigenic earthquake in the South- West of Bali with a moment magnitude of 8.5. Inundation heights in the study area lower than 0.5m are not considered, because a life- threatening situation usually not emerges at this level. The estimated tsunami arrival time at coastline is about 30minutes.

The used scenario is visualized in *Figure 9* and *Figure10*.



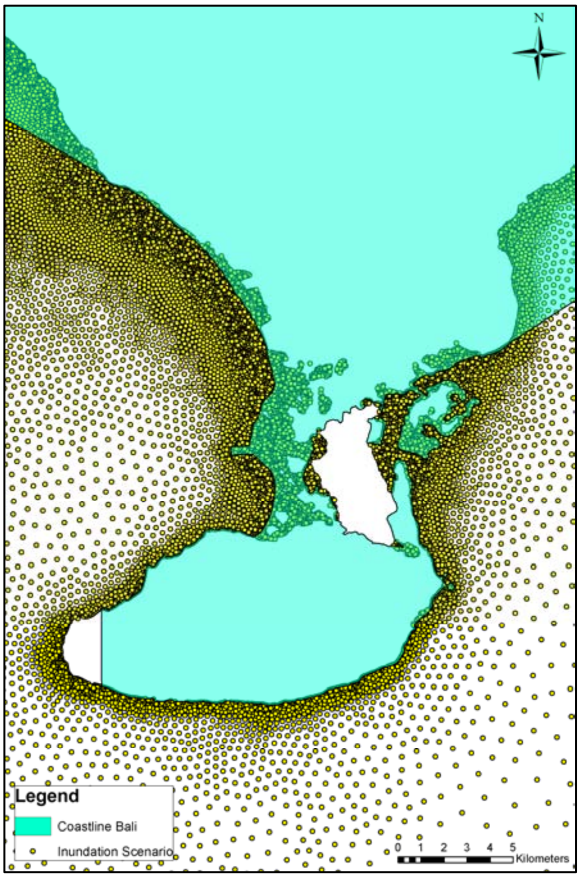


Figure 9 (left) / 10 (right) Inundation scenario used for the evacuation modelling in the study area (Source: own illustration - Data basis: Alfred Wegener Institute (AWI), modified; Map basis: Indonesia overview, DLR)

Based on many scenarios

A multi- scenario approach analyses the likelihood of tsunamis of various sizes (based on many scenarios) that can then be simplified into tsunami hazard zones.

An efficient way to establish tsunami hazard zones using multiple scenario results is by counting on each point on the land if this location is inundated or not. Incorporating all available scenarios - which should be representative for all possible tsunami events in the considered region - leads to a frequency distribution of each location on land being exposed to a tsunami or not. Although not directly indicating an expected intensity, the resulting information may serve decision makers to characterise zones by the fact of frequency being exposed:

(1) High impact zone, which is hit by every potential tsunami

(2) Medium impact zone, which is hit by many potential tsunamis

(3) Low impact zone , which is only hit by very few, extreme tsunami intensities

Tsunami hazard zones can also be defined by relating the impact areas to tsunami warning categories. Tsunami Early Warning Systems currently relate the level of warning (e.g. minor, major warning) to the expected wave height at the coastline. By deriving the inundation zone for each warning level (wave height), one can relate the warning levels to hazard impact zones and safe areas within the hazard map (STRUNZ ET AL. 2008A).

3.2.2 Degree of exposure and potential safe areas

Based on the above presented hazard assessment results, areas which are not affected by a tsunami wave and hence outside the inundation zone, can be regarded as potential safe areas.

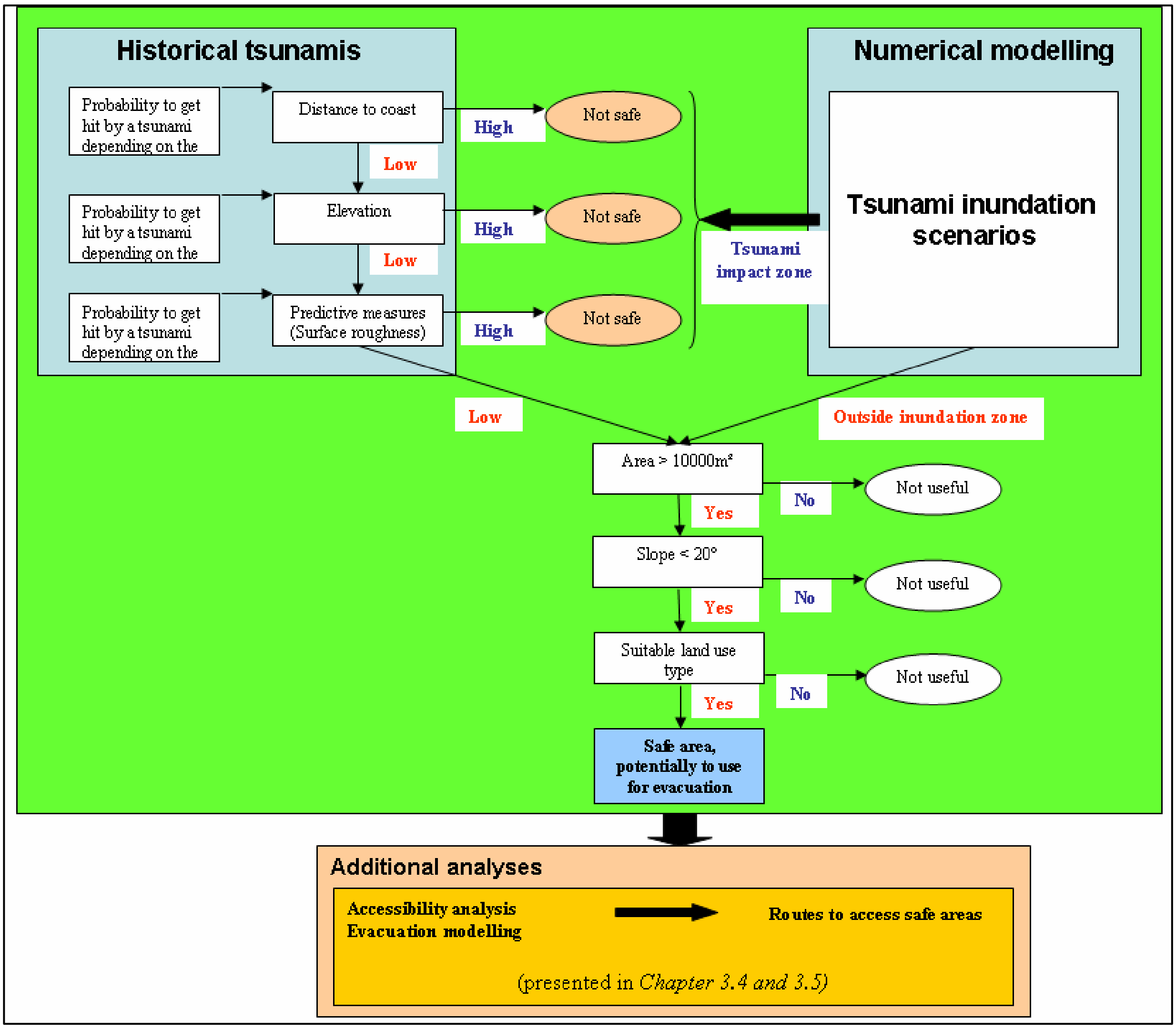


Figure 11 Requirements for safe areas (horizontal evacuation) (Source: own illustration - Data basis: expert interview with Dr. Joachim Post, 15.04.2008)

Considering evacuation planning aspects, these not-affected zones have to meet further conditions to be classified as safe area. To ensure a good accessibility and a sufficient capacity for a huge amount of evacuees, the zones have to be larger than 10 000m² and a slope around the areas smaller than 20° (EXPERT INTERVIEW DR. JOACHIM POST, 15.04.2008). An overview of the requirements for safe areas is presented in Figure 11 considering hazard assessment components both from historical records of tsunami impact observations and from numerical inundation modelling.

3.3 Population modelling

As presented in *Chapter 3.1.3.*, for evacuation planning it is essential to have a good insight into the spatial distribution of the population at risk. The available census data on village level are too coarse for a planning process at local level. The question then is: how can population data in census districts be disaggregated to smaller geographical or mapping sectors, that better satisfy the demands for information for emergency actions and disaster mitigation management. (HOFSTEE AND ISLAM 2004)

It is quite difficult to localize population more precisely by disaggregating census data and only to be undertaken when adequate information of the location of dwellers are available (from high-resolution satellite images, land use maps, etc.) as there can be a high variation in area, number and characteristics of the population. A Quickbird satellite image was available for the study area and therefore a concept of spatial disaggregation using remote sensing data was initially applied. An object- oriented urban land cover classification can serve as a basis to structure the complex urban environment in homogeneous zones.

Based on two different ancillary input data – total population for the study area and punctual population data collected from fieldwork – two methods for population disaggregation are generally applicable. A top-down approach interpolates the total population on a local scale based on physical urban structures mapped from remote sensing data. A bottom-up approach extrapolates the punctual information (houses) onto the district level.

Due to a lack of time, the latter method was not practicable and therefore only a top- down approach was reasonable. The focus was to establish a correlation between the spatial physical characteristics of an urban area and the total population of the study area. The first step of this approach is the spatial quantification of homogeneous units based on physical criteria to classify urban morphology. However, to identify these elements in a GIS, a comprehensive preliminary work is required, while an object- oriented classification methodology of built- up areas for the detection of house units have to be conducted in advance (TAUBENBÖCK ET AL. 2007). This effort was not applicable for the research and therefore only a visual interpretation of some physical criteria in the satellite image was useful, as presented in Point II in this Chapter.

The common physical parameters which can be derived by an object- oriented classification methodology are presented in *Table 10* below considering the application and use for this research.

Method	Goal	Application	Use
<u>Built- up density</u> Calculation and classification of the proportion of the built- up density to a defined area	Giving a statement about population density depending on built- up density	- Building mask for the study area not available - The study area is a mixed touristic area, population density diverge widely	Visual interpretation on the basis of a QUICKBIRD image
<u>Building size</u> Building classification regarding building size	Giving a statement about building use and respectively about population distribution	- Building mask for the study area not available - Building height not available	Visual interpretation on the basis of a QUICKBIRD image
<u>Building shape and roof structure</u> Building classification regarding building shape and roof structure	Deriving information about the building function and respectively about population distribution	- Very time- consuming - The validation of classifications for other areas showed only moderate results	Visual interpretation on the basis of a QUICKBIRD image
<u>Land use</u> Proportion of settlement areas inside a defined area	Deriving more detailed information about population distribution as from census data	- The study area is nearly complete settlement area and to small for useful information gained through land use data	Visual interpretation on the basis of a QUICKBIRD image

Table 10 Methods for population disaggregation (Source: own composition - Data basis: Taubenböck et al. 2007)

For the study area, two alternative disaggregation methods using a top- down approach were tested:

I. METHOD A: Combination of land use and census data

The population distribution can be modelled combining a land use dataset with a scale 1 : 50 000 and BPS (Central Bureau of Statistics Indonesia) census data from 2000 providing population figures on the level of the administrative unit *desa/ kelurahan* (village). Weighting factors concerning the presence of people in areas of different types of land use are the critical value in this analysis. The factors were derived from BPS PODES data (KHOMARUDIN ET AL. 2008). The percentages of weighting indicate the number of people who perform an activity in the certain land use classes. Therefore the weighting between rural, urban, coastal and non- coastal areas is different, because the people activity in these areas is different. The main sources of income indicate the percentage of people performing activities in certain regions and on the basis of these information the different weighting factors were developed. The method is visualized in *Figure 12.*

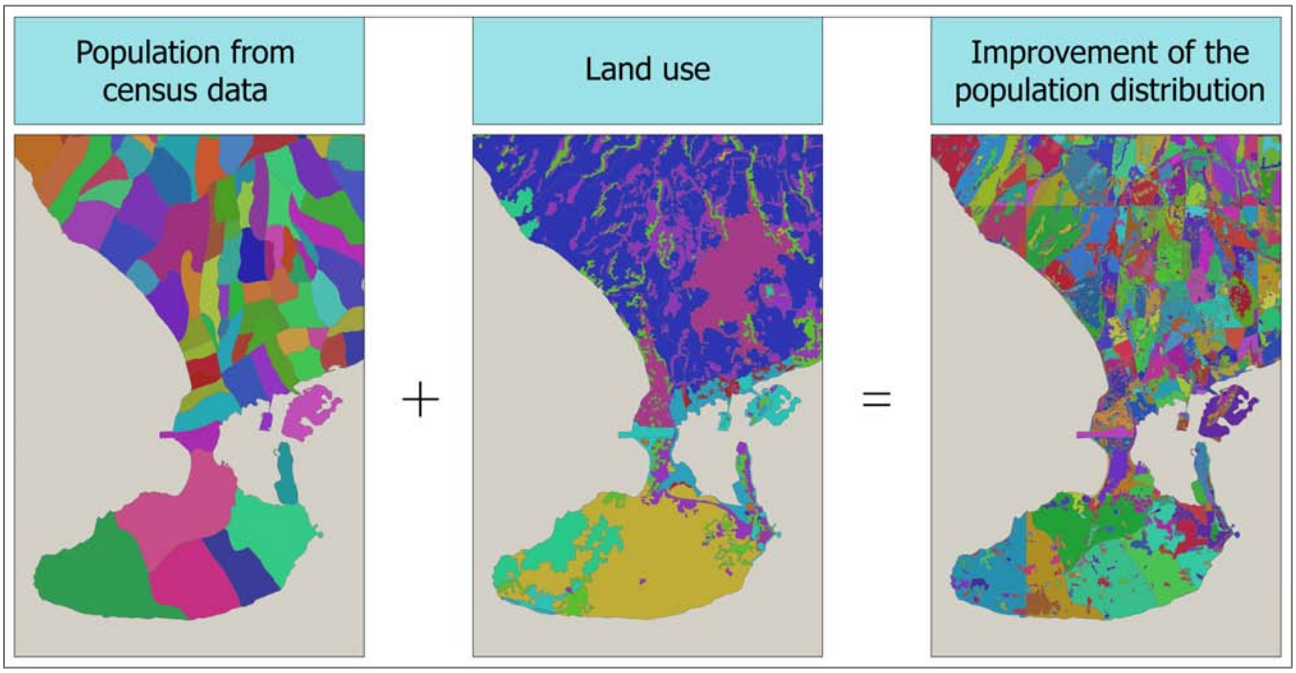


Figure 12 Population disaggregation with a combination of land use and census data (Source: own illustration - Data basis: BPS CENSUS 2000 and LAPAN; Map basis: BPS CENSUS 2000)

II. METHOD B: Combination of remote sensing data and field work results

Another method to derive more detailed information about the population distribution is to consider population movements between functional urban sectors during day- and night-time. As shown in *Chapter 3.1.3.*, different homogeneous sectors were assigned on the basis of a Quickbird image and cross- checked during the field work regarding their main function inside the settlement area. To quantify the population movements between these sectors, an own distribution concept was developed. Therefore the people's activities in the defined zones during day- and night-time were of particular interest.

BPS census data from 2000 providing population figures on village level are the basis of this concept. To calculate the actual population, the touristic population had to be quantified in addition. Due to the fact that the study area is an intersection of different administrative units (cp. *Chapter 2.1*), the touristic population had to be estimated considering several data sources as presented in *Table 11* below.

The actual population has to be separated in a day and night population. While the night population conform to this calculation, for the day population the daily commuters have to be considered. Due to the lack of dependable data for these people movements, figures were estimated on the basis of information gained by interviews. The distribution and quantification of the day and night population to the certain functional sectors was the result of field observations and experts interviews with *I Gede Suparta (Major of Kuta village)* and *Rokhis Khomarudin (LAPAN)*.

DATA	SOURCE
Average of guests per day in accommodation establishments in Bali 2005	Ministry of Culture and Tourism, Indonesia
Room occupancy rate in classified hotels in Bali 2004	Ministry of Culture and Tourism, Indonesia
Bed occupancy rate in classified hotels in Bali 2003-2004	Ministry of Culture and Tourism, Indonesia
Average room occupancy in hotels in Bali from January 2001 – September 2007	Bali Tourism Development Corporation
Direct tourist arrivals to Bali from 2002 – September 2007	Bali Tourism Development Corporation
Number of foreign visitors in Kuta village 2007	Police department, Sector Kuta
Bali accommodation directory 2006	Bali Government Tourism Office

Table 11 Considered data for the calculation of the tourist population in the study area (Source: own composition)

Figure 13 shows the estimated population distribution in the study area during day- and night-time considering the cross- checked functional zonation.

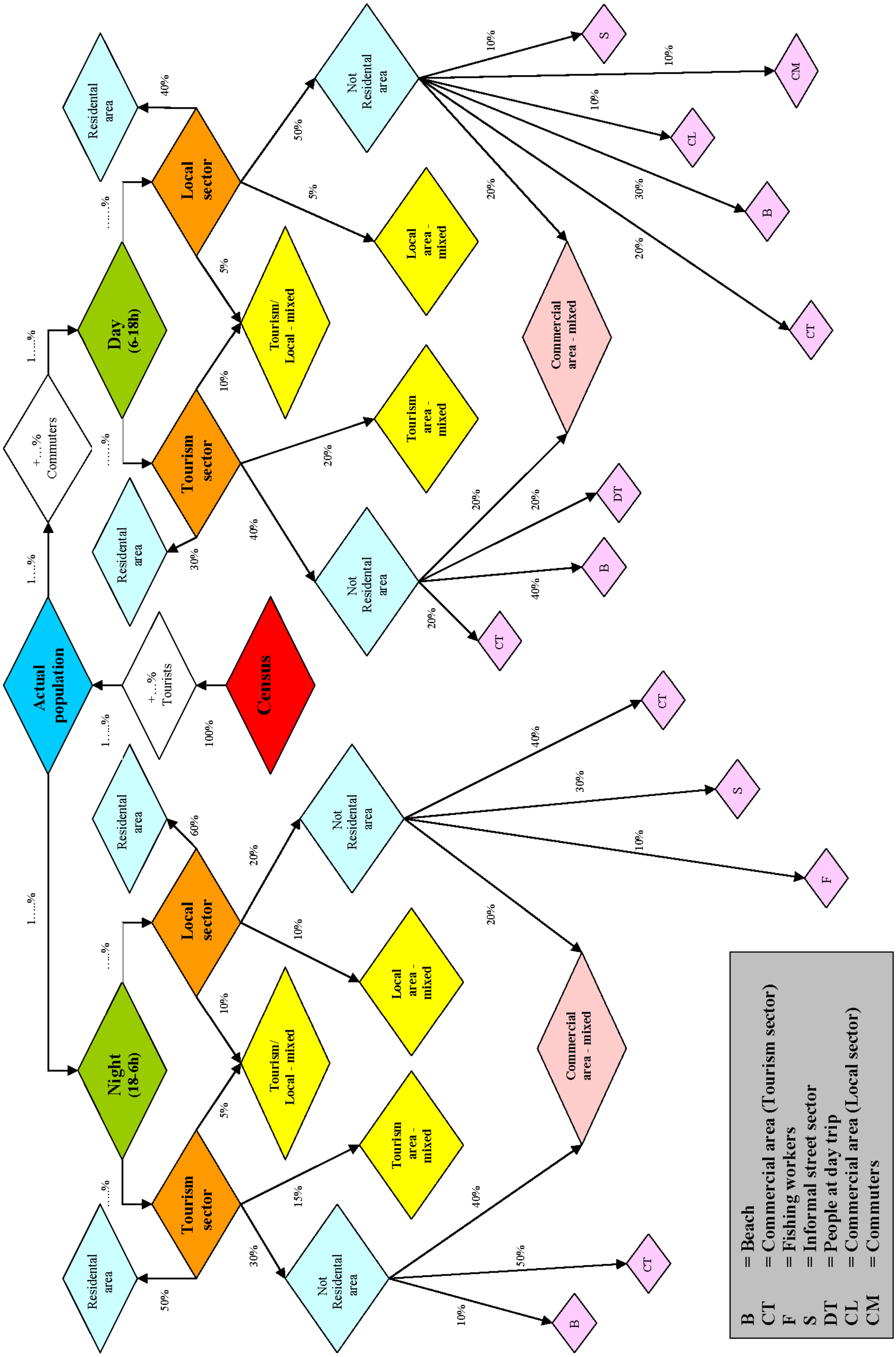


Figure 13 Population distribution concept for the study area considering functional urban sectors (Source: own illustration - Data basis: own data collection)

The effect of the different reference parameters of both methods is presented in *Figure 14* below. Crucial for the population modelling result of Method A is the strong representation of the census population and the neglect of the tourist population. Method B is based on a much more detailed approach and the gained results differ widely from the census data by considering tourist and commuter data. The calculated results of both methods are presented in *Chapter 4.3*.

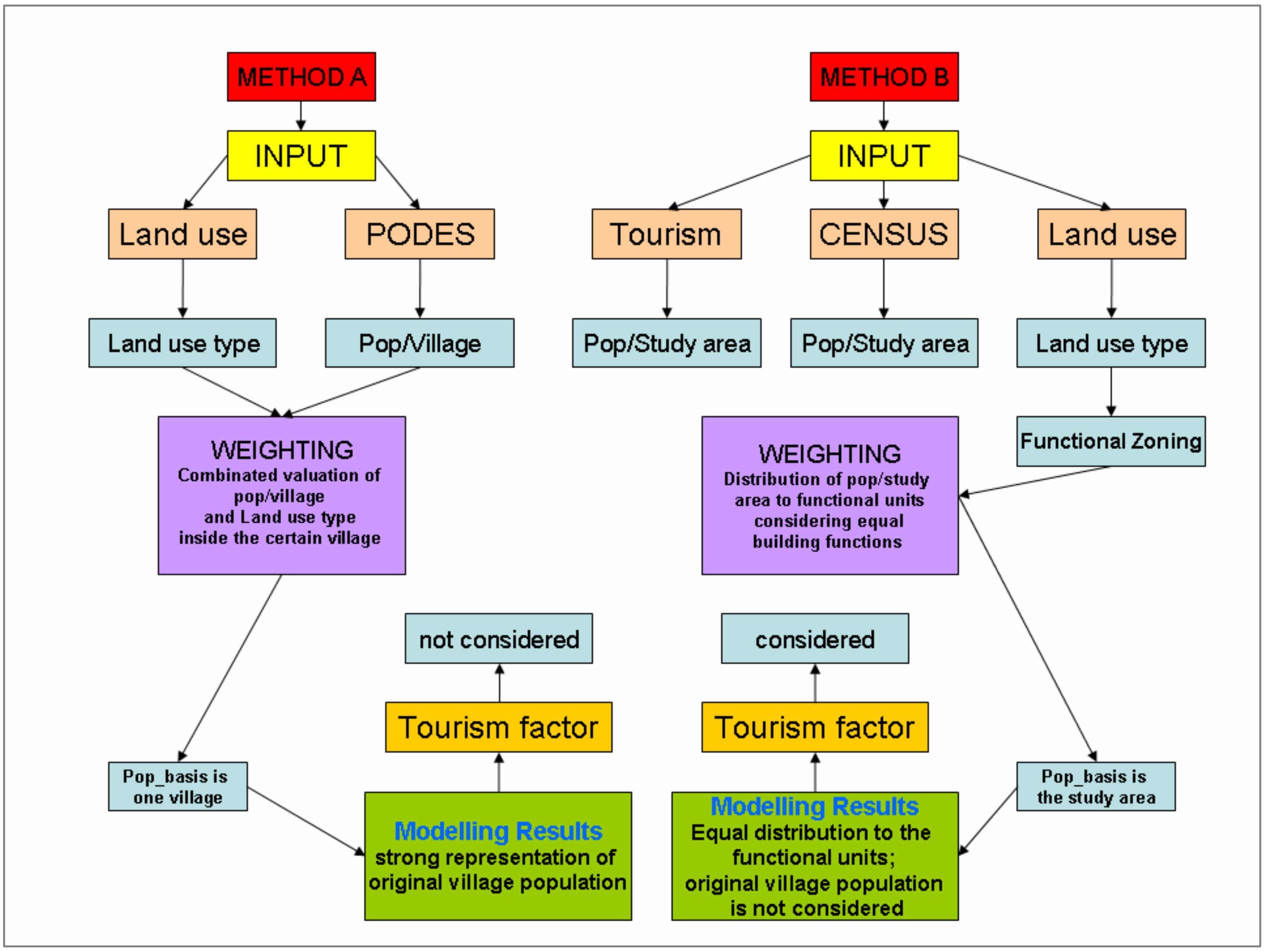
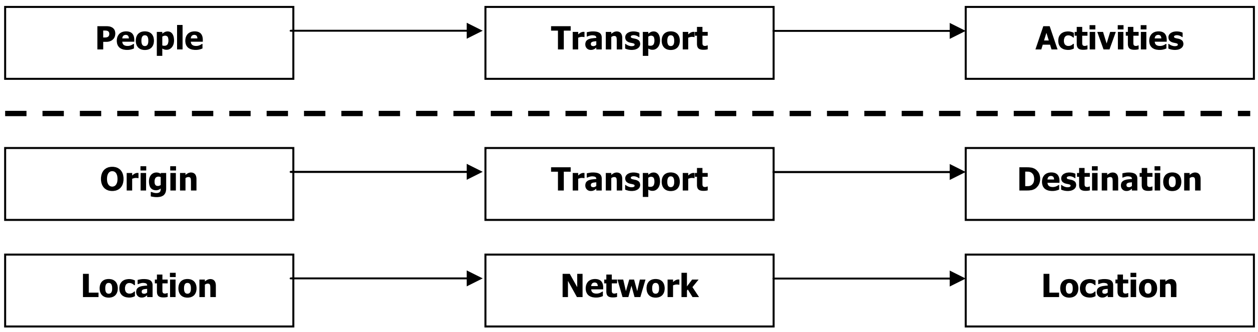


Figure 14 Effect of different reference parameters for the population modelling results in the study area (Source: own illustration)

3.4 Accessibility modelling

Accessibility can be defined as the ability for interaction or contact with sites of economic and social opportunity (FARROW AND NELSON 2001). However, there are a multitude of ways in which this intuitive concept has been expressed in literature. MOSLEY (1979) conceptualised the basic components of accessibility into: (1) the people, (2) the activities or services which people require, and (3) the transport that links between those two. The actual accessibility depends on each of the components of the following scheme.

In this scheme, people in the figure represent the population. The size and the composition of the population affect the accessibility, because they determine the scale of the demand for services or activities. The transport links reflect the travel time, costs and effort to travel between origin and destination location. The activities reflect the spatial distribution of activities at destinations and the demand for those activities. At Moseley's scheme, accessibility analyses can be applied to both ends. JONG AND ECK (1996) rewrote this schema in Geographic Information System (GIS) terms as follows.



Here, which origins located within destination's reach can be calculated, and vice versa, depending on the specific demand of the user.

In this research, accessibility modelling is the preparing process for evacuation modelling by providing the movement surface for the evacuees. Referring to point 4 of the research objectives (cp. *Table 2*), the following questions have to be answered to give a decision support for evacuation in case of a tsunami event:

a) Where are potential evacuation shelters?
b) Where are potential evacuation routes?
c) Are the people in risk areas able to evacuate in a given period of time?

An overview of available and required data for evacuation modelling is presented below in *Table 12*.

Research Question	**Available data**	**Required information**
a)	Potential evacuation shelters gained from historical data, inundation modelling and field work	No additional data required
b)	Road network	Other passable paths (off-road)
c)	Population distribution calculated with two different methods	Ability to evacuate

Table 12 Available and required data for the evacuation modelling in the study area (Source: own composition)

Research question a) and b) will be answered in this chapter, question c) in the subsequent *Chapter 3.5* ("Evacuation modelling")

The following *Chapter 3.4.1* describes a simple but flexible GIS method and tool for deriving verifiable accessibility models in the context of evacuation modelling.

3.4.1 Concept of Cost Weighted Distance (CWD)

To define the best evacuation route from a given point, the fastest path from that point to the arrival point has to be found. The fastest path is not always the shortest path (which is the direct line between point and the arrival point).

In this concept the accessibility is calculated on a *cost surface* which consists of a regular two-dimensional grid where each cell represents either passable routes such us roads, vegetation and beach or relatively inaccessible land and water bodies. Different types of evacuation routes have different characteristics. A flat road, for example, allows faster travel speed than dense vegetation. Therefore it is not enough to measure the *distance* between two points. Instead, a measure of travel *cost* is preferable, which can be considered as *travel time* (ADPC 2007A).

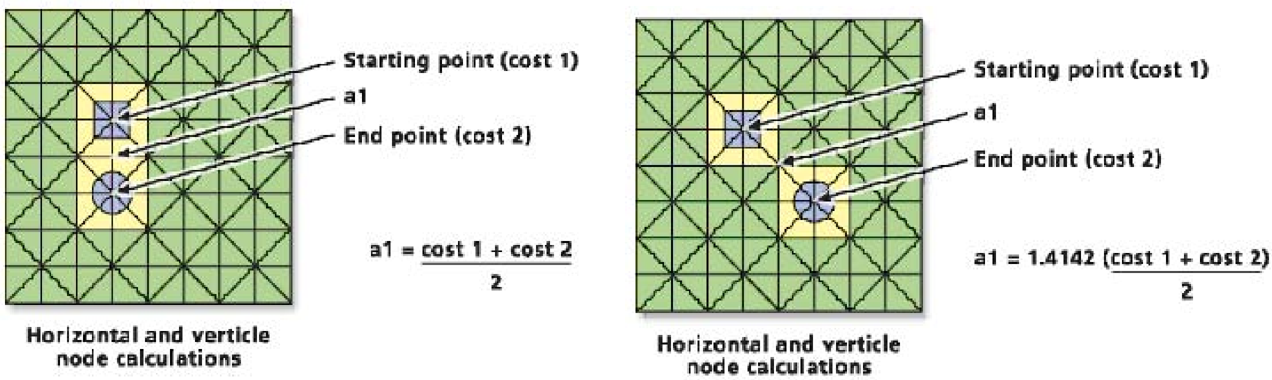


Figure 15 Computation of CWD between two adjacent cells (Source: ADPC 2007a, p.6)

3.4.2 Evacuation shelter accessibility

Instead of defining the cost surface as the distance between starting point and each cell in the domain, it is possible to define it as the distance between each cell and the "Evacuation shelter points" (which are more than one). The value of each cell is the Cost Weighted Distance (CWD) between cell and the closest evacuation shelter point.

The process steps for the accessibility modelling will be explained as follows:

1. The Cost surface was created on the basis of land use information of the study area. Land use data for Bali were available in a vector- format with a scale of 1 : 50 000 and had to be converted to raster format in a first step.

2. Reclassification of the land use was a basic step of the analyses. Each class of the dataset got a new value, describing their capability to modify the speed of walking person (ADPC 2007A). The new values represent how much the average speed will be conserved on the different land use classes. Based on a value of 100 (100% speed conservation), for example, a value of 80 means that the speed will be reduced by 20%. Due to the fact that not every class of the dataset is a passable one, like water bodies or mangroves, a suitable filter had to be set. For further analyses all classes had to be retained, therefore relatively inaccessible classes got the value 1 or 5.

As presented in *Chapter 3.1.3.*, the road network was evaluated considering the width, which was described with number of lanes, and the traffic volume during day and night. For the accessibility modelling, a further evaluation regarding the speed conservation had to be conducted and combined with the land use data. The following *Table 13* shows the estimated speed conservation values of the roads in the study area.

Road_classification					
Width_ID	1	1	1	2	2
Traffic volume_ID	1	2	3	1	2
Limitation value	50	65	80	55	70
Land use_name	Road_lim50	Road_lim65	Road_lim80	Road_lim55	Road_lim70
Width_ID	2	3	3	3	4
Traffic volume_ID	3	1	2	3	1
Limitation value	85	60	75	90	75
Land use_name	Road_lim85	Road_lim60	Road_lim75	Road_lim90	Road_lim75
Width_ID	4	4	5	5	5
Traffic volume_ID	2	3	1	2	3
Limitation value	80	95	85	90	100
Land use_name	Road_lim80	Road_lim95	Road_lim85	Road_lim90	Road_lim100

LEGEND (ID_name)						
Width	**1**	One lane small		**Traffic volume**	**1**	Very much
	2	One lane wide			**2**	Much
	3	Two lanes small			**3**	Not much
	4	Two lanes wide				
	5	Four lanes				

Table 13 Estimated speed conservation values for the road network in the study area (Source: own composition - Data basis: own estimation)

The reclassified land use classes are presented in *Table 14* below.

VALUE	COUNT	CLASS_EVAC
1	3643251	Mangrove/Lake
5	17150714	Building/River/Pond
40	5057466	Rice field
50	2008964	Dense Vegetation
65	1236	Road_lim65
70	4237	Road_lim70
75	62162	Road_lim75/Bridge_lim75
80	1376979	Open Vegetation/Road_lim80
85	301173	Road_lim85/Bridge_lim85
90	363356	Beach/Road_lim90
95	4064524	Small Vegetation/Open Field/Road_lim95
100	1086264	Bridge_lim100/Road_lim100

Table 14 Reclassified land use classes for the definition of speed conservation values (Source: own composition - Data basis: ADPC (2007a), modified)

3. The cost that must be spent to walk through each cell will be computed combining the average speed of evacuation with the reclassified value of land use. As a statement in sec/m is more useful for the analyses, the inverse value of this combination was calculated for the speed map. In this research, the slowest speed of evacuees' movement during evacuation is assigned for the evacuation modelling. According to the Institute of Fire Safety and Disaster Preparedness Japan (SUGIMOTO ET AL. 2003), the slowest evacuees' speed is 0,751 m/sec that occurs on a group of elderly walking people. The Asian Disaster Preparedness Centre (ADPC 2007A) emanate from a value of 1,2 m/sec, which seems to be more realistic for the majority of evacuees. Therefore this value is used for the accessibility modelling.

4. Evacuation shelter points are the basis for an evacuation time map. In this surface the value of each cell represents the cost (in terms of time) necessary to go from there to the costless shelter following the fastest path. For horizontal evacuation, the shelter points were placed along the border to potential safe areas gained from inundation modelling results considering accessibility bottlenecks (mostly big roads). Evacuation shelter points for vertical evacuation were placed considering the evacuation shelter buildings which were identified during the field work.

The evacuation time map was calculated using the *Cost allocation* tool in ArcGIS on the basis of the speed map and starting from each of the placed shelter points.

A further output of this calculation is a map with catchment areas which allows dividing the whole space of the area into shelter sectors. The raster identifies which cells will be allocated to which source, that means it represents the portions of the area referring to each of the shelter points.

The whole accessibility modelling process is presented in *Figure 16*.

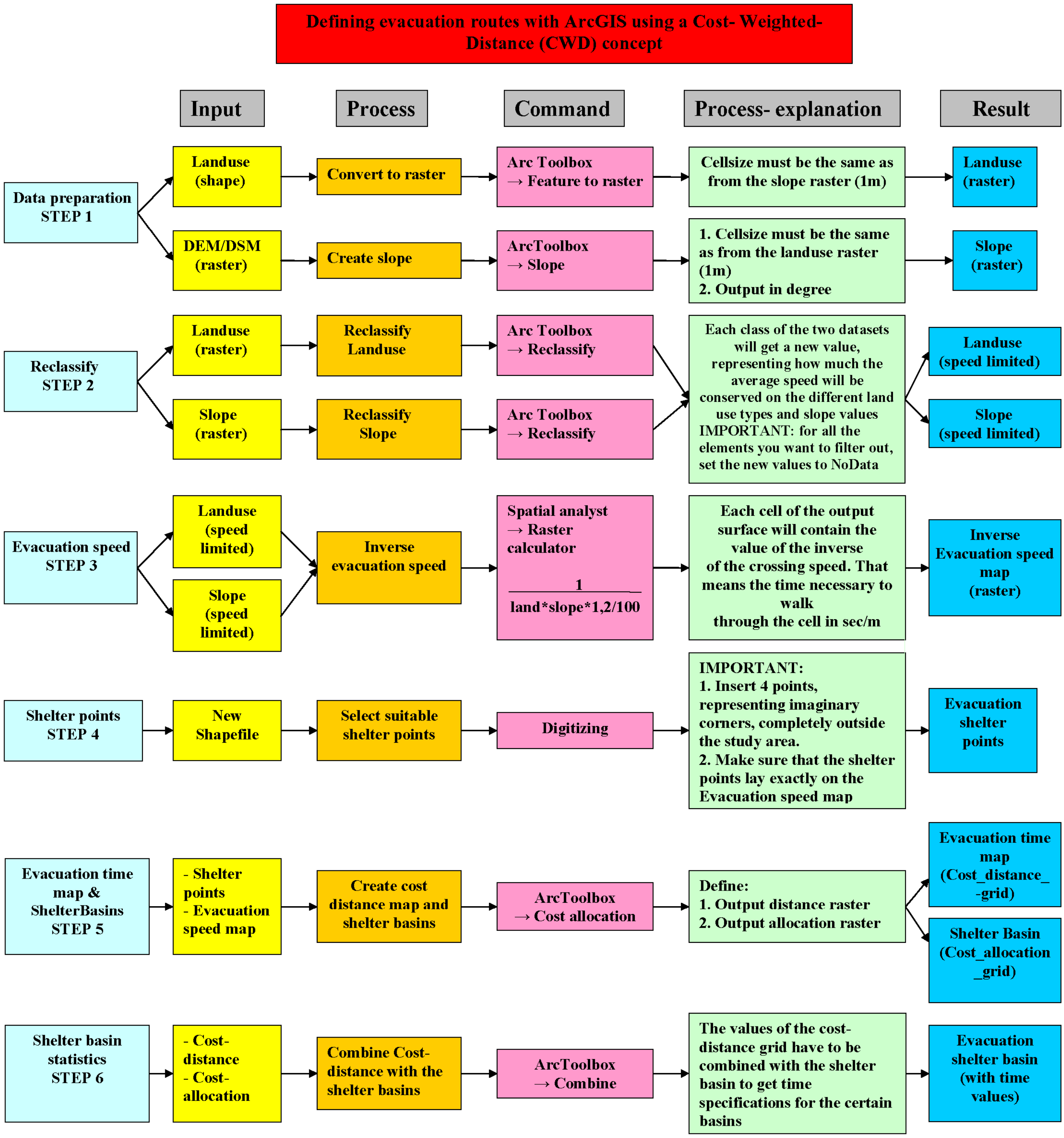


Figure 16 Process steps for the accessibility modelling approach (Source: own illustration – Data basis: ADPC (2007a)

3.5 Evacuation modelling

As presented in *Table 2* in the previous chapter, the ability to evacuate has to be calculated in order to give a decision support for evacuation in case of a tsunami event. Therefore some further information is needed as shown in the *Figure 17* below.

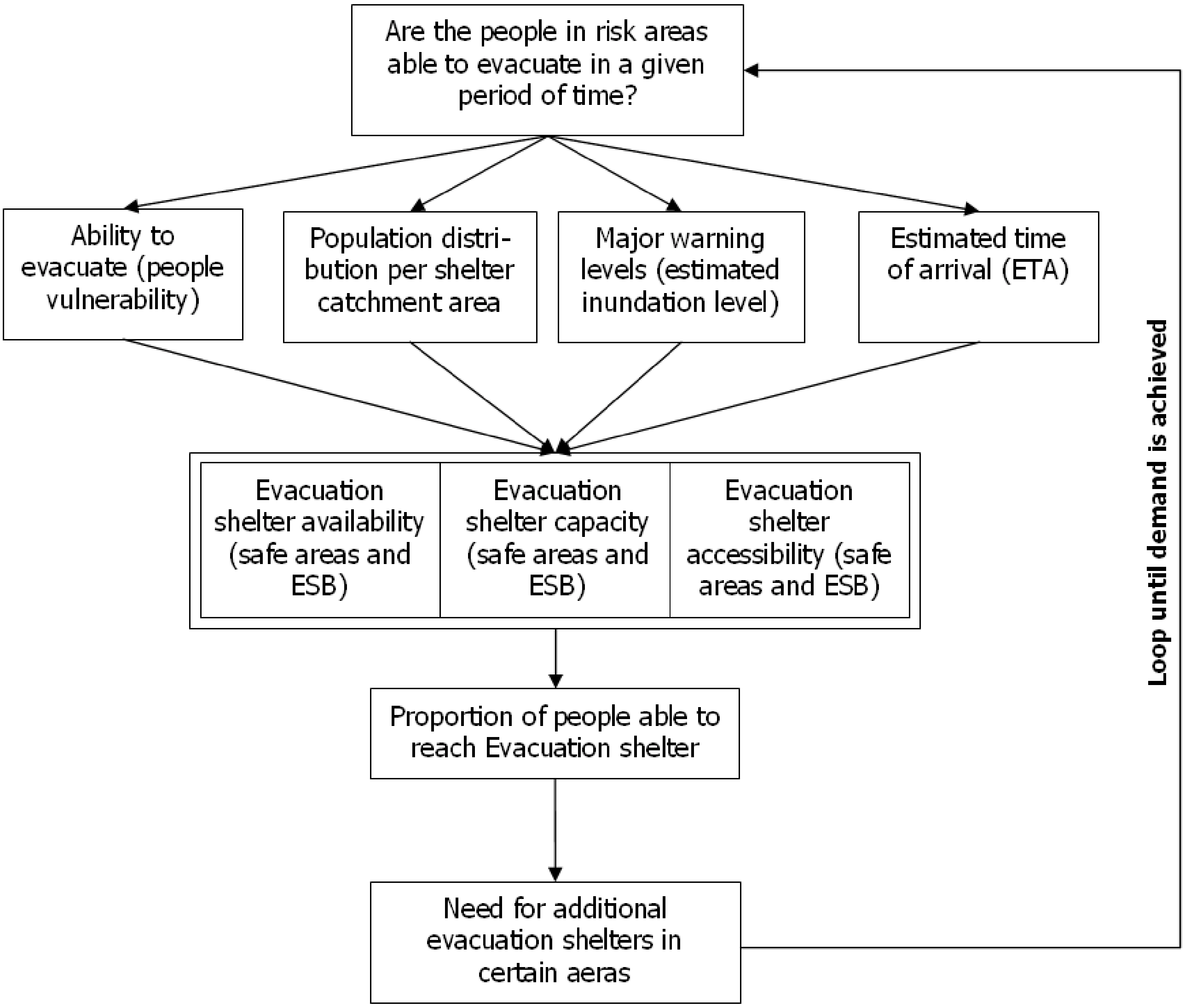


Figure 17 Relevant information to calculate people's ability to evacuate (Source: own illustration)

3.5.1 Shelter area accessibility for day and night population scenario

In *Chapter 3.3*, two methods (A and B) for a disaggregation of population data were presented. The evacuation modelling was conducted using the results of these two methods (for day and night population) and also with raw census data, to contrast differences between the certain results.

The first modelling process step was to calculate how many people in each catchment area are able to reach the evacuation shelter in a given time. The estimated arrival time of the used scenario is about 30min until a tsunami wave will reach the coast of the study area. While it is assumed that it will take about 5-10 minutes until the tsunami warning message will reach the exposed population (GTZ- IS 2007), time limits of 15 and 25min were set by an appropriate classification of the evacuation time map. That means that the share of the population within a certain time zone have enough time to access the nearest evacuation shelter, outside the time zone it is not possible.

First of all, the disaggregated population data had to be intersected with the evacuation shelter catchment areas to calculate the particular population density and amount of people in every potential catchment area for the identified shelters. By using the *Union* tool in ArcGIS, shelter catchment area, time map and the certain population data were combined.

The population per square meter from every disaggregated dataset was multiplied with the new areas gained from the *Union*- process and the sum for every catchment area was calculated. The percentage of the population inside a defined time zone (15 or 25min) around a shelter, to the population inside the whole catchment area, shows the particular ability to access the nearest shelter within the stated time on the basis of the used population distribution. An example is given in *Figure 18* below.

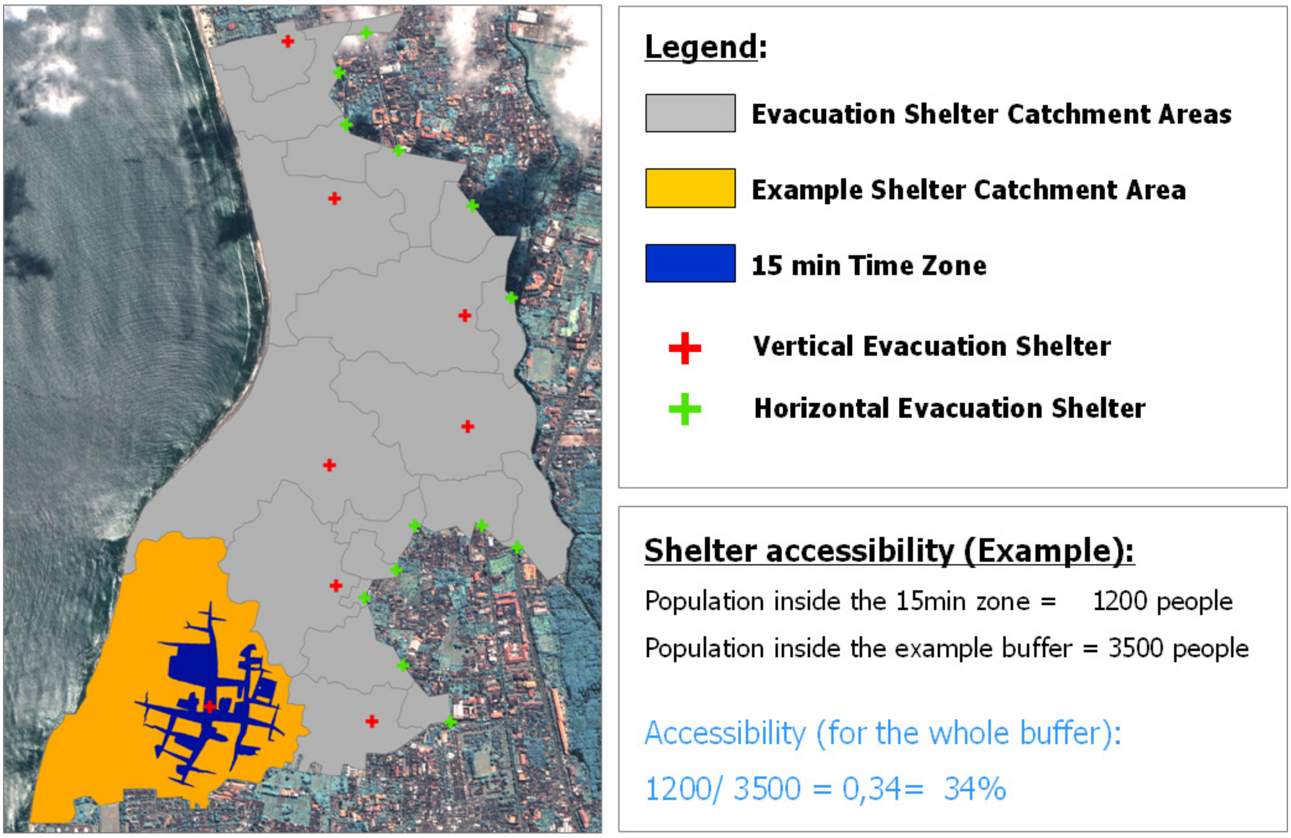


Figure 18 Example for the shelter accessibility within 15 minutes (Source: own illustration - Data basis: own calculation; Map basis: Quickbird satellite image)

The conducted calculations in all combinations are presented in *Table 15* below.

Population data	**Temporal distribution**	**Combined Evacuation time zone**
Method A	Day	15min
Method A	Night	15min
Method A	Day	25min
Method A	Night	25min
Method B	Day	15min
Method B	Night	15min
Method B	Day	25min
Method B	Night	25min
CENSUS Data	Not available	15min
CENSUS Data	Not available	25min

Table 15 Conducted calculations for the shelter accessibility in the study area (Source: own composition)

3.5.2 Evacuation ability for day and night population scenarios

Values for the shelter accessibility only show that a certain number of people is able to reach the nearest shelter within a given time. However, the real ability to evacuate depends on the accessibility **and capacity** of a shelter area.

The capacities of the defined evacuation shelter buildings (ESB) for **vertical evacuation** in the study area could not be calculated exactly because of problems with permit procedures. Therefore the potential evacuation space was estimated using literature results. BUDIARJO (2006) estimated the available evacuation space of evacuation shelters by a calculation based on architectural design space requirement. The space required for accommodating evacuees is 1m² per person. It can be described as 0,8m² per person for stay and 0,2m² per person for circulation. Hence, the capacity (in person unit) can be calculated as:

Available evacuation space * building area / 1

where:

Available space	=	available reserve space for evacuation in existing potential ESB (m²)
Building area	=	evacuation floor(s) area of existing potential ESB (m²)
1	=	space requirement for accommodating evacuees (m²/person)

The building area was roughly estimated based on information from a satellite image and photographs. BUDIARJO(2006) explained the assumptions and formula to calculate the capacity for evacuation of some building functions which are potentially suitable for vertical evacuation:

1. Market building

*Capacity for evacuation: 23% * building area / 1*

Space requirement for market building design is 5.2m² per person comprises: 1m² per person for buyer; 0.2m² per person for circulation; 2m² per person for seller and merchant display; and 2m² per person for storage. From this space requirement, the spaces that can be occupied for evacuation purpose are the buyer area (1/5.2 = 19.2% area) and circulation area (0.2/5.2 = 3.8% area). Hence, the total available space for evacuation is 19.2%+3.8% = 23% of the total building area. Regarding the crowd in this building, in evacuation situation the building can only accommodate the people located in it.

2. Hotel

*Capacity for evacuation: 26.3% * building area / 1*

Space requirement for hotel design is 16m² per person comprises: 12m² per person for staying and 1.5 m² per person for circulation; 0.5m² per person for utilities; 1.5 m² per person for hall, lobby, and restaurant (public function); 0.3m² per person for employees' room; and 0.2m² per person for office function. From this space requirement, the spaces that can be occupied for evacuation are the area (1.5/16= 9.4% area); public function area (1.5/16 = 9.4% area); and assumed 10% non-occupied rooms (0.1*12/16 = 7.5% area). Hence, the total available space for evacuation is 9.4%+9.4%+7.5% = 26.3% of the total building area.

For the study area some other building functions were suitable for vertical evacuation. The potential evacuation space was estimated based on information from interviews and the inspection of similar buildings.

3. Storehouse

*Capacity for evacuation: 25% * building area / 1*

Space requirement for storehouse is estimated based on a building observation during the field work.

4. Billiard Centre

*Capacity for evacuation: 50% * building area / 1*

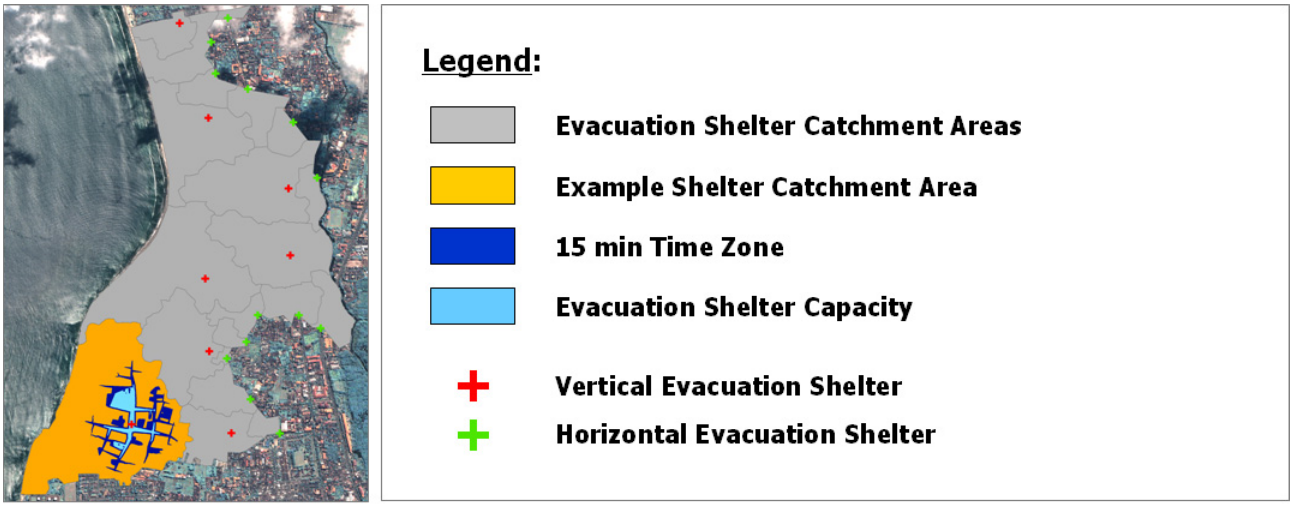
Space requirement for storehouse is estimated based on a building observation during the field work.

The evacuation space within safe areas for **horizontal evacuation** was calculated on the basis of suitable (passable) land use classes. The following classes were selected:

(1) Small Vegetation
(2) Open Vegetation
(3) Open field

The calculation for the evacuation ability for day and night population scenarios is based on the same principle as for the shelter area accessibility in *Chapter 3.5.1.*

The difference is that the population inside a defined time zone (15 or 25min) around a shelter has to be compared with the shelter capacity. If the shelter capacity is smaller than the number of people which are potentially able to evacuate, the value for the real *Evacuation ability* is smaller than the value of the *Accessibility*. If the shelter capacity is bigger than the population within the evacuation time buffer, the value for the *Evacuation ability* equates to the value of the *Accessibility.* An example is given in *Figure 19*.



Evacuation ability (Case 1):

Evacuation Shelter Capacity = 1500 people

Population inside the 15min zone = 1200 people

Population inside the example buffer = 3500 people

Accessibility (for the whole buffer):
1200/ 3500 = 0,34= 34%

Evacuation ability (Case 2):

Evacuation Shelter Capacity = 800 people

Population inside the 15min zone = 1200 people

Population inside the example buffer = 3500 people

Accessibility (for the whole buffer):
800/ 3500 = 0,23= 23%

Figure 19 Example for the evacuation ability within 15 minutes (Source: own illustration - Data basis: own calculation; Map basis: Quickbird satellite image)

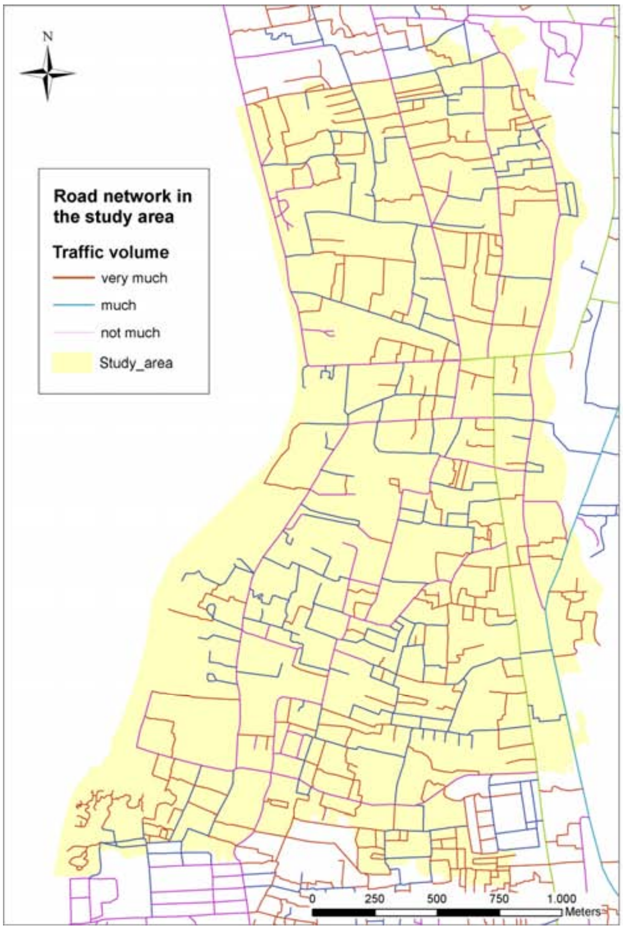
4 Result

4.1 Data collection

Identification of the road network

As described in Chapter 3.1.3, all roads in the study area were evaluated considering their width and the traffic volume. The results are presented in *Figure 20* and *21*. It becomes evident that most of the roads are single- lane and only a few main road axis cross the area. Regarding the traffic volume it is obvious that there is a strong dependence on the road width. The bigger the road, the more traffic can be noticed. Exceptions are touristic and commercial areas, where smaller roads are also highly frequented (*cp. Figure 22*).

An important observation, especially for pedestrian evacuation, is the bad road infrastructure near the coast. Only a few roads in the North and in the centre of the study area lead directly to the beach, whereas in the South only some small ones connect the beach area with the main road infrastructure. Main traffic junctions are located in the eastern centre and in the South of the study area.



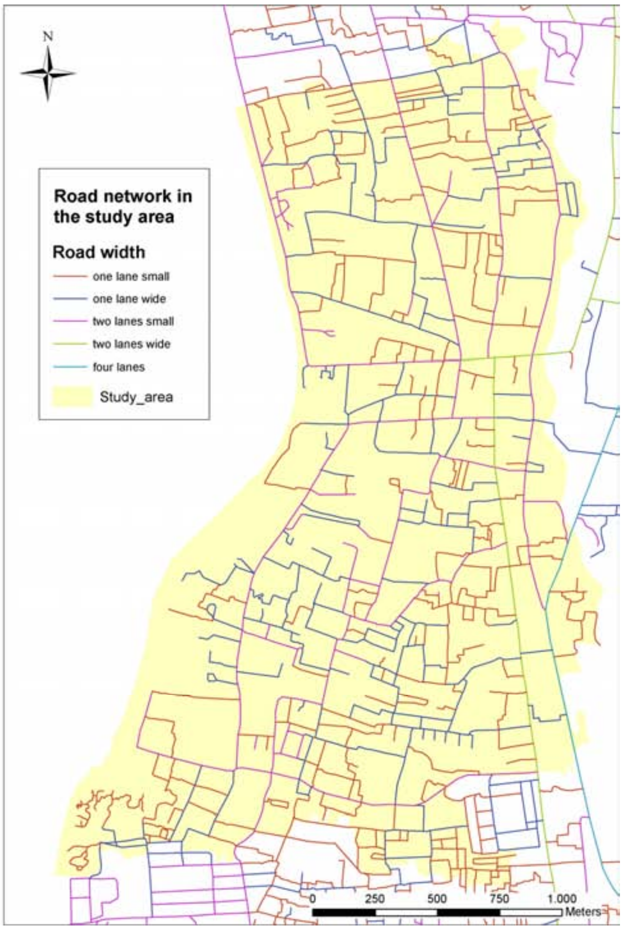


Figure 20 (left) /21 (right) Traffic volume (left) and road width (right) in the study area (Source: own illustration – Data basis: own data collection; Map basis: Quickbird satellite image)

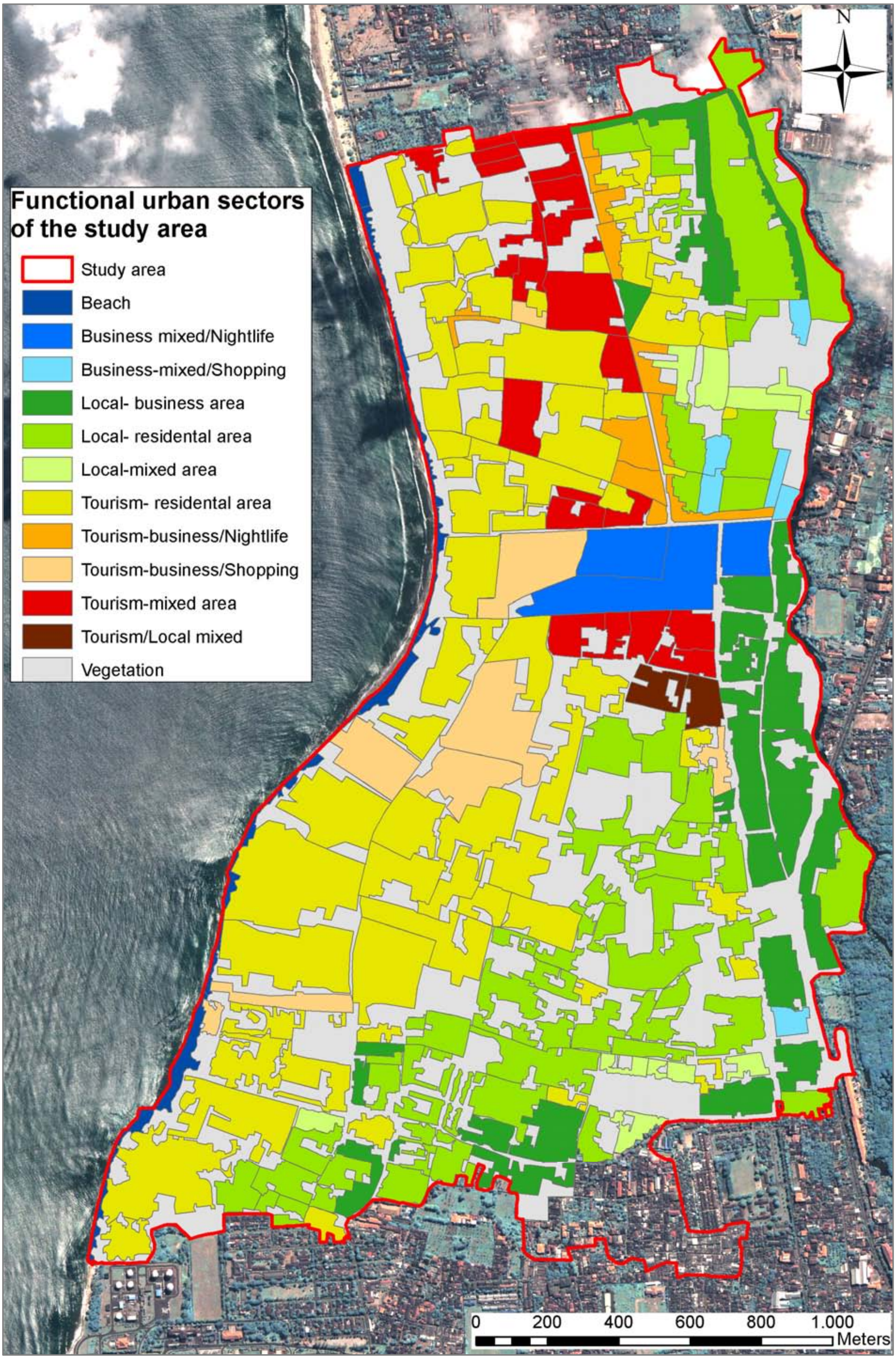


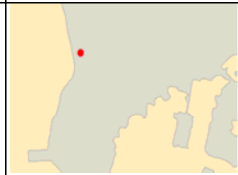
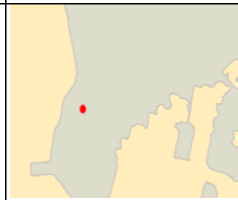
Figure 22 Functional urban sectors in the study area (Source: own illustration - Data basis: own data collection; Map basis: Quickbird satellite image)

Identification of functional urban sectors

The sectors were identified according to the process presented in *Chapter 3.1.3*. *Figure 22* shows the gained zonation of the study area. The functional structure defines a very clear separation between the local and the touristic population. Residential areas of the tourism sector (Hotels, Bungalows, etc.) are mostly located near the coast, touristic commercial areas along the main roads in the northern part of the study area. The areas of the local population are located further inland, business areas mostly along the main roads in the southern part. Nightlife districts are concentrated in the centre of the study area and along the main road in the tourism sector. Common functional sectors of the touristic and the local population are visible in the centre of the area, mostly commercial districts, like shopping centres, supermarkets and food stores.

Identification of evacuation shelters and critical facilities

Evacuation shelters were identified considering building functions potentially suitable as evacuation shelter building, general characteristics of suitable shelters from literatures and required additional criteria which were find out by expert interviews and technical literature (BUDIARJO 2006, EISNER AND NTHMP 2001) (*cp. Chapter 3.1.3*). The buildings are presented in *Table 16* below.

No	Name, location, Function	Shore distance Evacuation type	Shelter accessibility	Number of Storeys, Evacuation space capa-city, Space accessibility	Map	Image	Image
1	Hotel Arena, Kelurahan Legian, Hotel	350m Vertical evacuation	Good	2 storeys Big Good			
2	Paradiso Billard, Kelurahan Kuta, Billard Centre	400m Vertical Evacuation	Good	2 storeys Big Good			
3	Hotel Kuta Royal, Kelurahan Kuta, Shopping Centre	900m Vertical Evacuation	Good	1 storey Big Good			
4	Supernova, Kelurahan Kuta, Shopping Center	1100m Vertical evacuation	Good	1 storey, Big Good			Not available

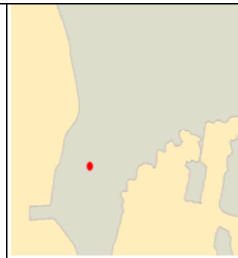
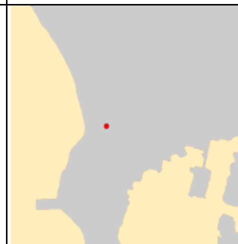
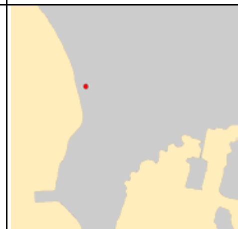
5	Pepito storehouse, Kelurahan Kuta, Storehouse	1200m Vertical Evacuation	Good	1 storey Big Good			Not available
6	Hotel Jatra, Kelurahan Kuta, Hotel	500m Vertical Evacuation	Good	2 storeys Big Good			
7	Pasar Kuta, Kelurahan Kuta, Market building	800m Vertical Evacuation	Good	1 storey Big Good			Not available
8	Hotel Baru, Kelurahan Seminyak Hotel	300m Vertical Evacuation	Good	1 storey Big Good			Not available

Table 16 Potential ESB's in the study area, identified during the field work (Source: own composition)

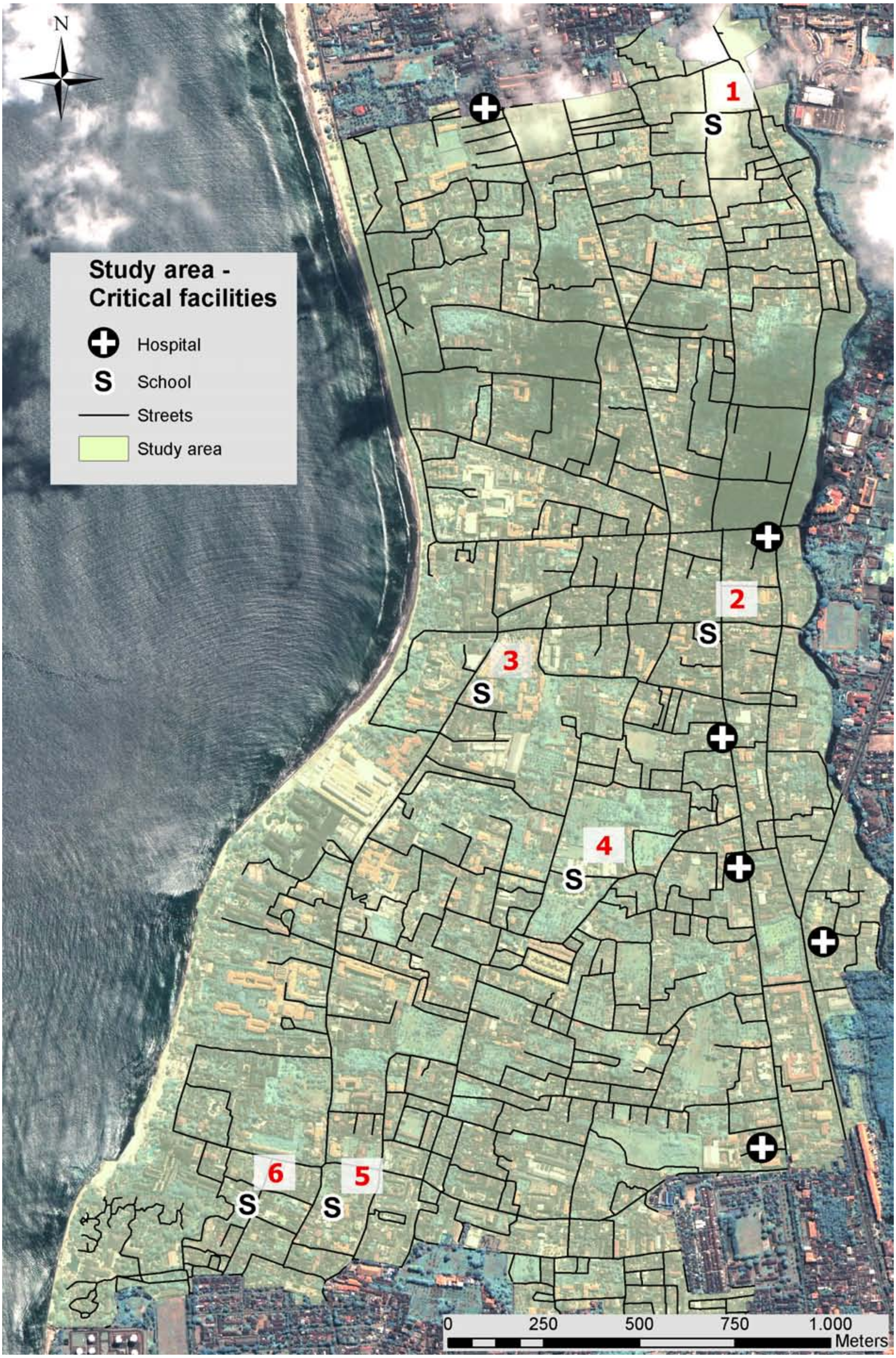


Figure 23 Critical facilities in the study area (Source: own illustration - Data basis: own data collection; Map basis: Quickbird satellite image)

Critical facilities were also located during the field work. Number and position of hospitals and schools could be found out from the Department of Health and Education in the district of Badung. Further relevant information, like number of students or patients, building size, etc., were not available and had to be asked in the certain facilities. However, a questioning of hospitals in the study area was not successful, since the rate of return of the questionnaires was very bad until the end of the field work. As shown in *Figure 23* most of the hospitals are located in the eastern part of the study area and more than 1 kilometre away from the coast. A good accessibility to main evacuation routes is ensured since nearly all facilities are located along main roads. All buildings are at least two- storeyed and therefore the basic potential to evacuate people to higher floors is given.

Further information relevant for evacuation planning could not be gained during the field work. The schools are widespread in the study area. Most of the facilities are located within a distance of less than 1 km from the coast and are only accessible by smaller roads. The questioning of the schools in the study area was more successful and the following additional information could be gained during the field work:

No.	**Number of storeys**	**Number of students**	**Schooltime**
1	1	261	7.30 - 12.00h
2	1	536	7.30 - 12.00h
3	2	2124	7.30 – 12.00h 13.00 – 18.00h
4	2	1183	7.30 – 12.00h 13.00 – 18.00h
5	1	346	7.30 – 12.00h 13.00 – 18.00h
6	1	85	7.30 – 12.00h

Table 17 Questioning results from the school sector (Source: own composition)

4.2 Hazard impact and exposed area

As described in *Chapter 3.2.1,* both historical records of tsunami impact observations and tsunami inundation modeling results were the basis to conduct a hazard assessment for the study area. In the following the results of both methods are presented.

Using historical records of tsunami impact observation

A first tsunami impact zone classification can be mapped based on distance zones and their probability to be affected by a tsunami. The result map (*see Figure 24, left*) shows different frequency rates of an event. The zonation is mapped in 100m steps until a distance of 1 km and further in 1 km steps until a distance of 10000m from the coast. Although, the inundation zones of more than 60 % of all tsunami events were less than 100 m inland (own calculation), it is obvious that the probability to be affected by a tsunami wave is very high for the study area. The next important parameter is terrain elevation above sea level, because the influence of altitude on tsunami inundation is obviously an important factor (POST ET AL. 2007). The altitude zonation also takes into account river valleys, where the tsunami can run further inland. These valleys are highly exposed areas. The classification of elevation classes strongly depend on the resolution of the respective elevation data used. Because of the high resolution of the Digital Surface Model (DSM), the zones are mapped in 1m steps until an elevation of 15m, in 5m steps until 50m and in 10m steps until an elevation of 80m (*see Figure 24, middle*). The zone with a very high probability of being affected by a tsunami reaches from 0 to 10m above sea level. The study area is a very flat area and therefore, with a high probability, completely affected by a possible tsunami event. Beside historical information on tsunami events, elevation and distance relationships, "protective measures" have to be considered as well (POST ET AL. 2007). Hence, a distance- elevation relationship in combination with surface roughness (land cover data) can be applied to develop tsunami impact zones. The results of these zonations are presented in *Figure 24 (right)*. It becomes evident, that protective measures in the study area mitigate the tsunami intensity. Due to the urban structure it is assumed that mainly buildings cause the mitigation effect.

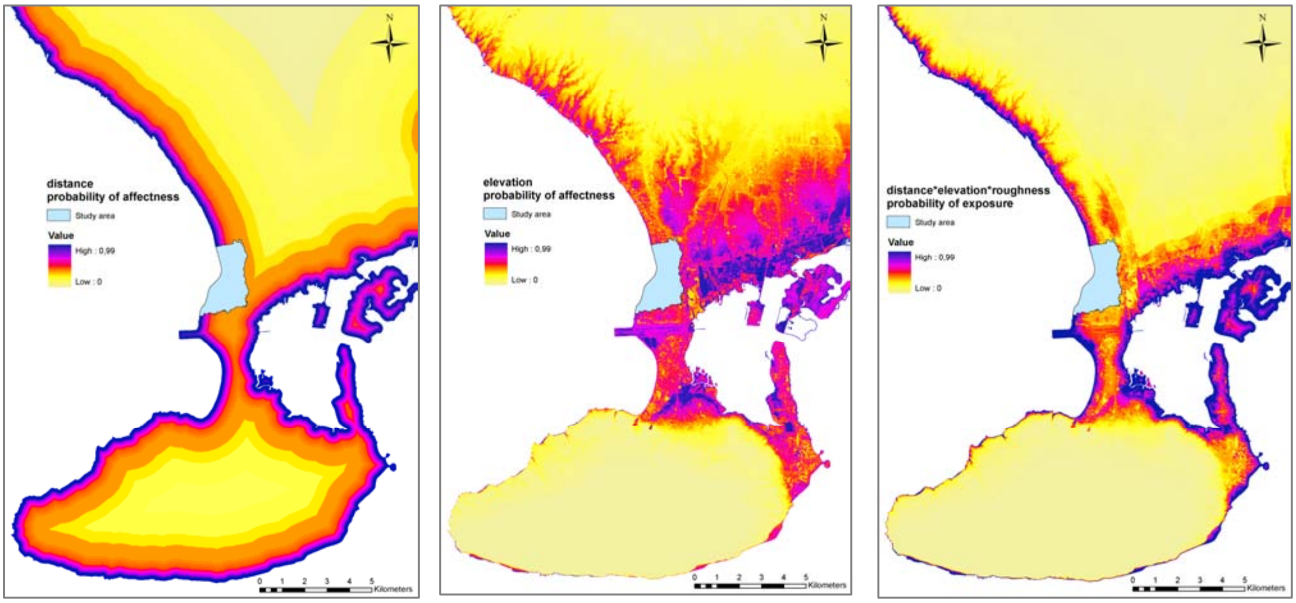


Figure 24 Tsunami hazard zonation of South Bali, based on historical records of tsunami impact observation. From left: (a) probability of affectness regarding the horizontal distance, (b) probability of affectness regarding elevation, (c) probability of exposure as a combination of distance, elevation and surface roughness (Source: own illustration - Data basis: NGDC; Map basis: Quickbird satellite image)

Using inundation modelling results

As described in *Chapter 3.2.1*, a multi- scenario approach analysis the likelihood of tsunamis of various sizes that can then be simplified into tsunami hazard zones. Altogether 372 Scenarios were considered in the analyses for the South of Bali in *Figure 25*. The scenarios are distributed equally within the tsunamigenic sources in the Sunda Trench region (impacting coastline of Sumatra, Java, Bali), where seismic activities may introduce ocean bottom deformations and consequently tsunamis. The scenarios reflect several possible tsunamigenic earthquakes with moment magnitudes of 8.0, 8.5 and 9.0. The hazard impact zones reflect the percentage of all scenarios which inundate a particular land area. Hence for the red zone, between 70% and 95% of all scenarios impact the coastland. The yellow zone (moderate impact) denotes up to 10% to 70%, the green zone 3% to 10% impact of all scenarios. Looking at the results in *Figure 25*, it becomes evident that the study area is completely affected by 10% to 70% of all available scenarios.

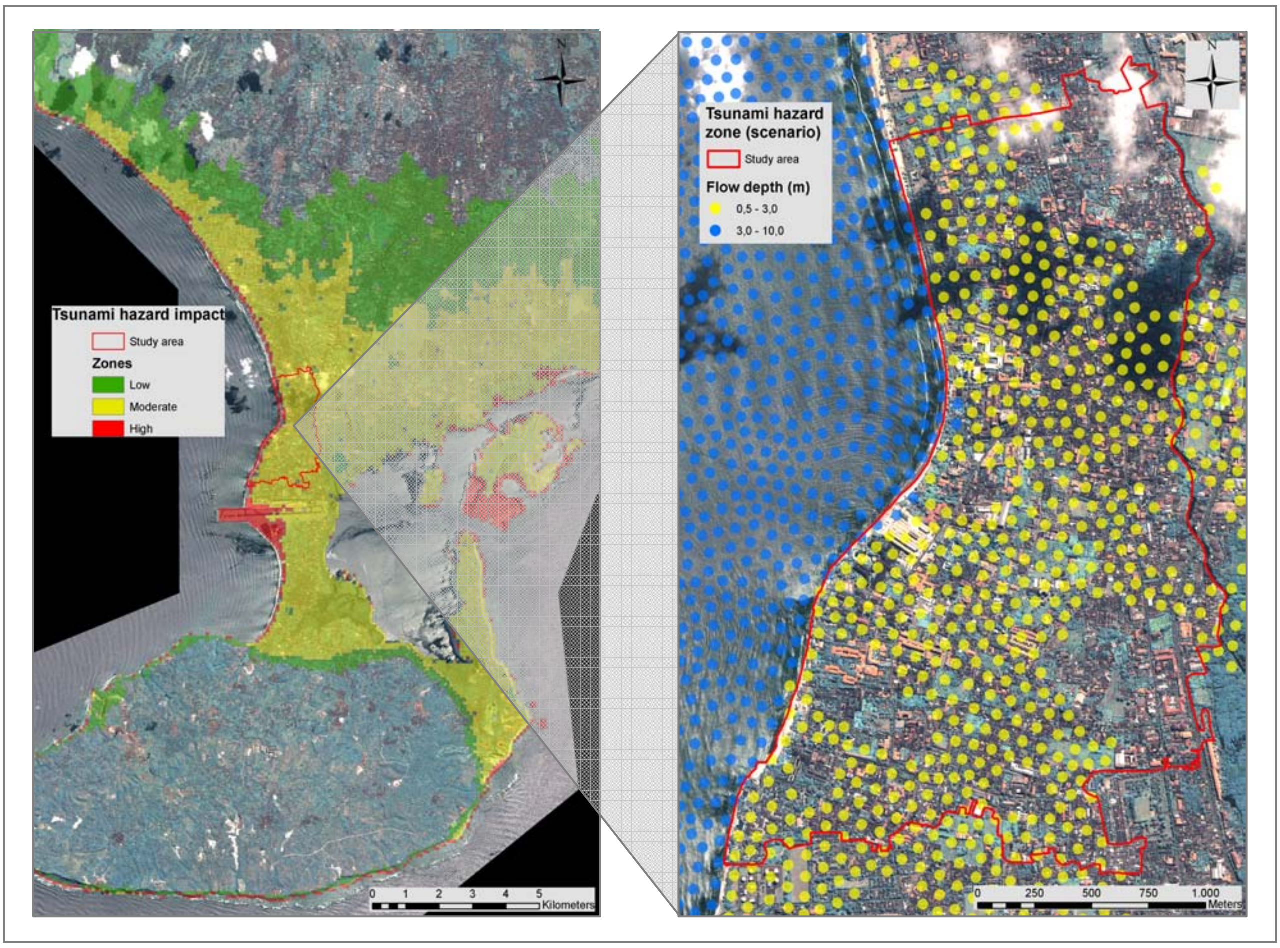


Figure 25 (left) / 26 (right) Hazard impact zones in the South of Bali, based on a multi- scenario approach (left) and on one inundation scenario (right) (Source: own illustration – Data basis: AWI; Map basis: Quickbird satellite image

However, the identification of potential safe areas within the study area is essential for further analysis regarding accessibility and evacuation modelling. Therefore, for the study area only one scenario is considered as a basis for the modelling process in this research as presented in *Figure 26*. The scenario shows that flow depth values between 3.0 and 10.0 m only occur as run- up at the coastline while the smaller depths until 3.0m show the impact at the coastland. Most of the study area is affected except some smaller areas in the North and in the South.

4.2.1 Potential safe areas

As presented in *Chapter 3.2.2*, areas which are not affected by a tsunami wave and hence outside the inundation zone, can be regarded as potential safe area.

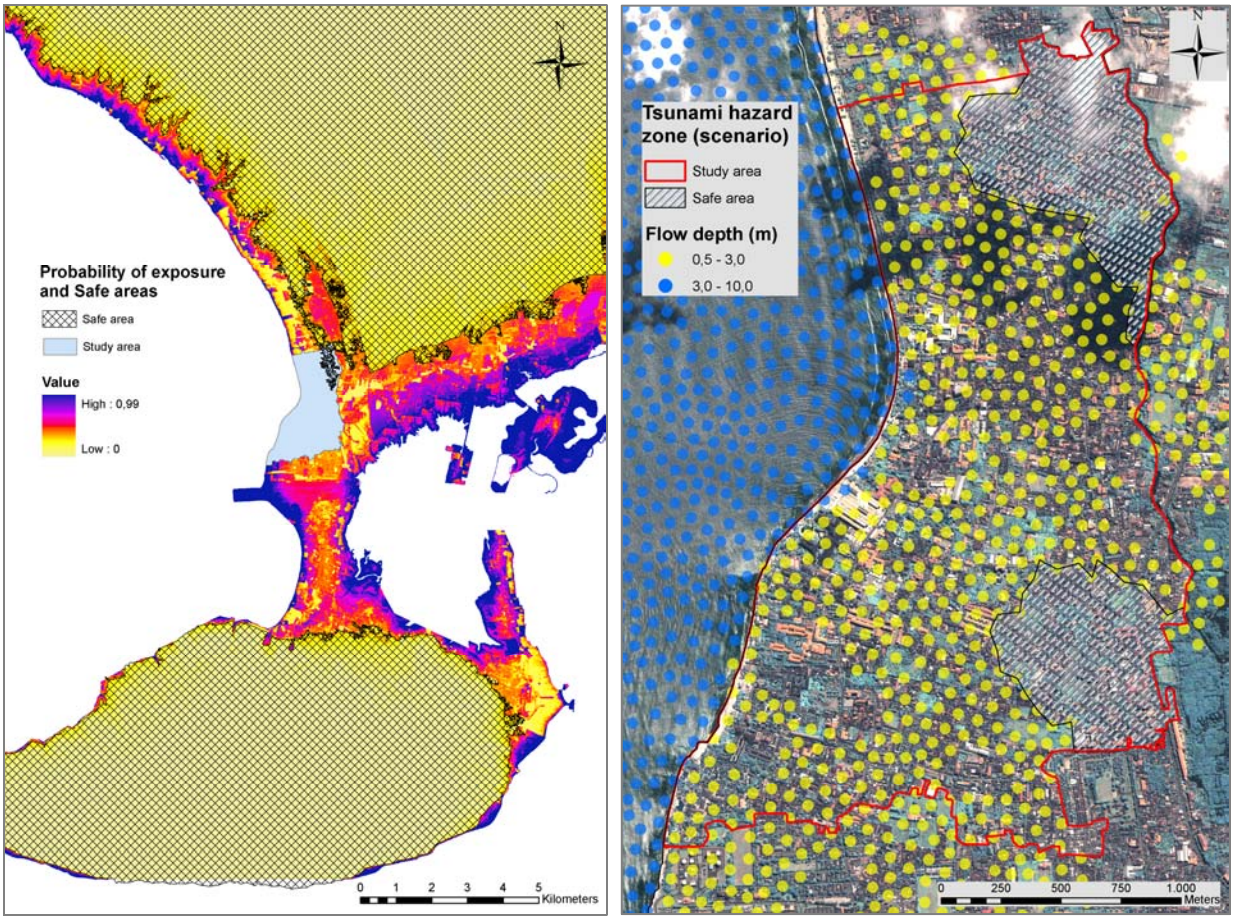


Figure 27 (left) / 28 (right) Safe areas in the study area based on historical tsunami data (left) and on one inundation scenario (right) (Source: own illustration – Data basis: NGDC; Map basis: Quickbird satellite image)

The exposed areas gained from historical data are based on the probability of affectedness relating to the historical records of tsunami impact information. To derive safe areas, a very low probability value has to be defined. Therefore a minimum value of 10% is defined to identify areas as safe respectively outside potential inundation zones (EXPERT INTERVIEW DR. KAI ZOßEDER, 23.04.2008). Considering the further requirements for safe areas to ensure a good accessibility and a sufficient capacity for a huge amount of evacuees (Area > 10000m² and Slope < 20°) as presented in *Chapter 3.2.2*, safe areas for the study area were derived accordingly (*see Figure 27*). It becomes evident, that except some small parts in the North, the whole study area is located within the calculated hazard impact zone. Therefore this result is not suitable for further analysis where safe areas within the study area are essential.

Regarding the multi- scenario approach it is already mentioned that up to 70% of all available inundation scenarios completely affect the study area and no safe areas can be derived. Therefore it is necessary to use the artificial scenario for further accessibility and evacuation modelling. As shown in *Figure 28*, the two areas in the South and in the North of the study area are outside inundation zone and meet the additional requirements for safe areas (*cp. Chapter 3.2.2*).

4.3 Population modelling

As described in *Chapter 3.3,* it is quite difficult to disaggregate population census data because adequate knowledge of the location of the dwellers is necessary, as there can be a high variation in area, number and characteristics of the population.

The conducted population disaggregation in the study area using two different methods is based on different disaggregation units and spatial resolutions.

Method A: With the combination of land use and census data, population data can be disaggregated to assigned land use types as the smallest unit (KHOMARUDIN ET AL. 2008). Land use data were available in a scale of 1 : 50000.

Method B: Population data can be disaggregated to one functional urban sector with the combination of remote sensing data and field work results.

The *Figures 29/30 and 31/32* below show the day and night population in the study area calculated by Method A and B. As it can be seen in the *Figures 29/30*, the population data are represented by larger spatial disaggregation units as in *Figure 31/32,* which is a result of the lower spatial resolution of the input data.

Weighting factors considering the degree of people activity in every land use class as well as the number of people in the input census data, represent the disaggregated population distribution. The land use class which covers the study area is mostly settlement area and it is assumed that this class represents a very high activity (KHOMARUDIN ET AL. 2008). Two main results can be derived for Method A:

→ Both for the day and the night population, the study area is divided into four zones with a different number of people. This is only a consequence of the used input data (Land use classes and census districts) and cannot be related to the real population distribution in the urban agglomeration of the study area.

→ Regarding the differences between the day and night population it can be seen that during the night there are more people in every zone than during the day. Due to this common increase, it becomes evident that no population movements between the different zones are considered, but only an increase of people from outside the study area.

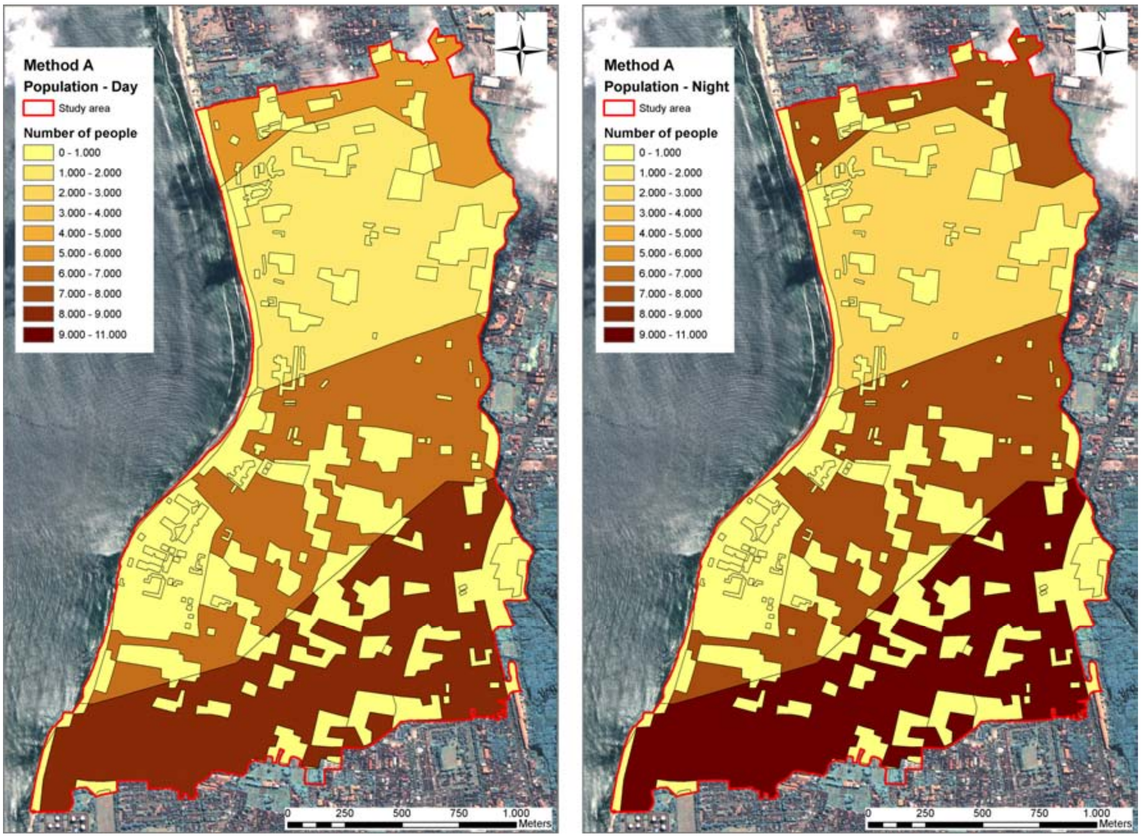


Figure 29 (left) / 30 (right) Distribution of the day and night population in the study area, calculated with Method A (Source: own illustration - Data basis: Khomarudin et al. 2008; Map basis: Quickbird satellite image)

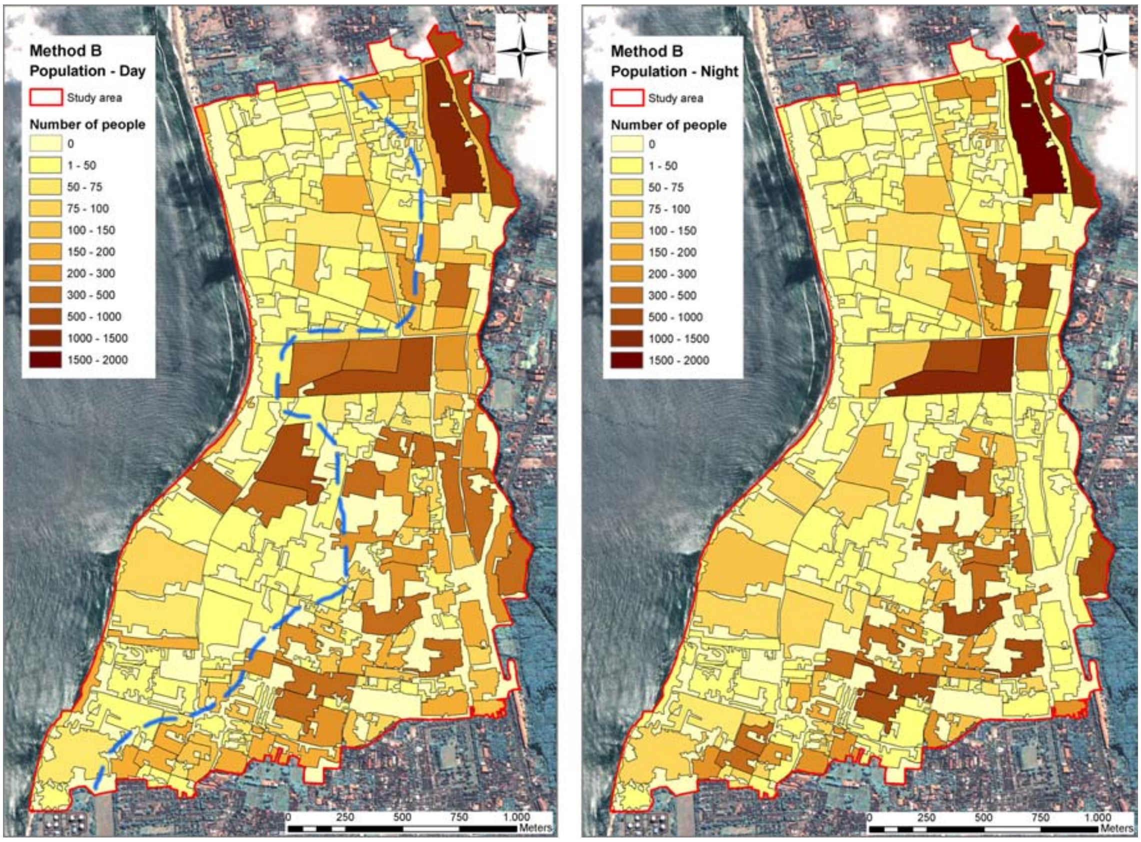


Figure 31 (left) / 32 (right) Distribution of the day and night population in the study area, calculated with Method B (Source: own illustration - Data basis: own data collection; Map basis: Quickbird satellite image)

Method B in *Figure31/32* is based on functional sectors gained by field work. Sectors of interest are city districts which show a similar structure of building functions and from which people activities during different times of day and night can be derived. In this context, the tourist population plays an important role because of the strong dominance of touristic infrastructure in the study area. Regarding the results, population hotspots become evident on a first view. A clear difference between the areas near the coast and the hinterland are visible as marked with a line for the day population in *Figure 31*. To a large extent, the hinterland is more populated both regarding the day and night population. The most densely populated sectors are located in the North- West and in the centre of the study area.

In comparison with Method A, the results provide a more differentiated insight into the population distribution of the study area. The spatial disaggregation units are much smaller and independent from based input data, as the census districts in Method A. In *Figure 33* and *34,* a sample area is separated to compare the number of people calculated with Method A and B and to get an idea how far both methods are suitable for further analysis in this research. The population values differ widely from each other and the limited significance of the disaggregation approach with Method A becomes evident. Therefore this Method is unaccounted for the next modelling steps as more detailed population data are required for evacuation planning.

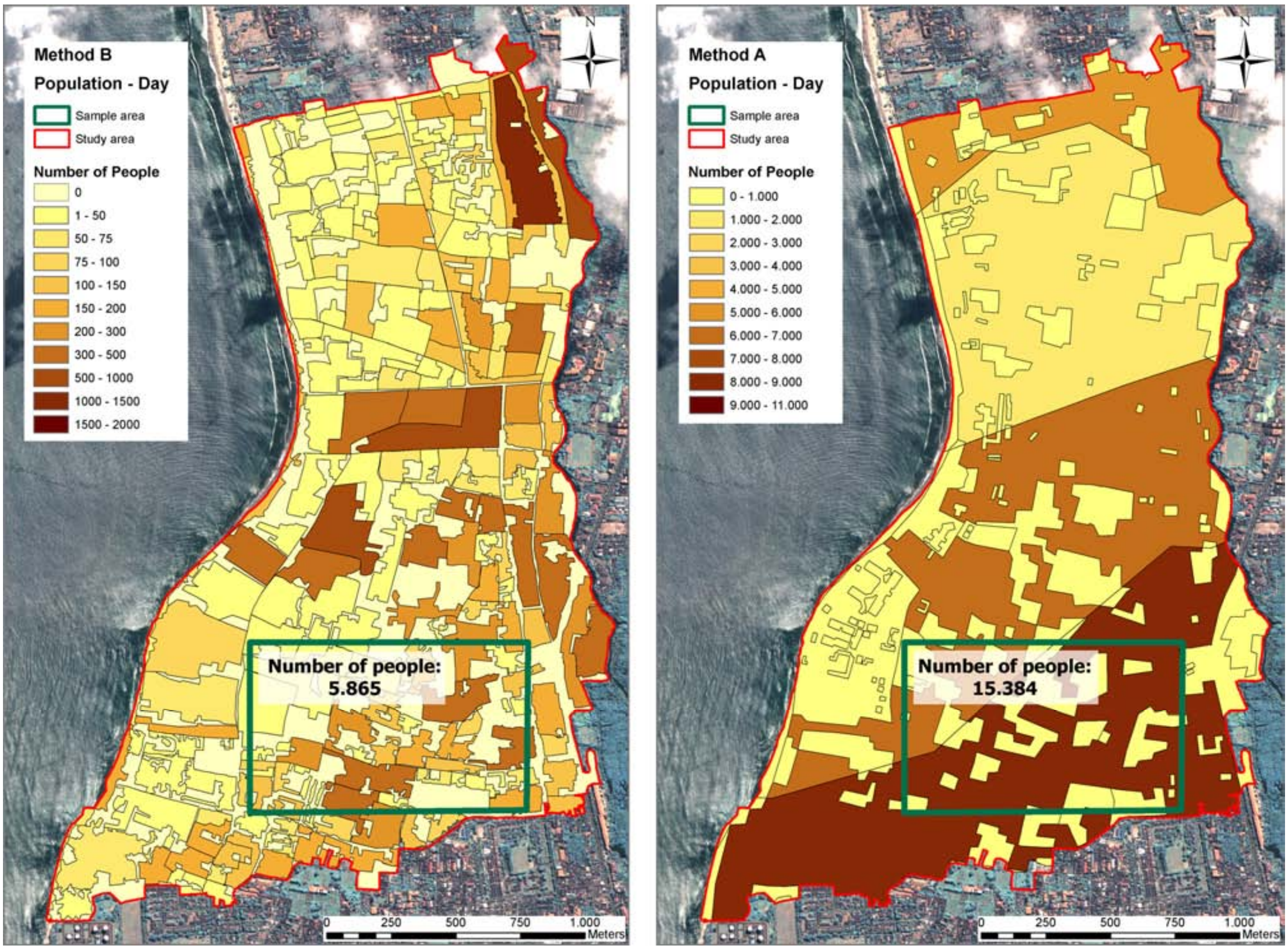


Figure 33 (left) / 34 (right) Comparison of the population number in two sample areas based on the calculations with Method A and B (Source: own illustration - Data basis: own calculation; Map basis: Quickbird satellite image)

In the following, the results from Method B will be analysed regarding population movements between the functional urban sectors (*cp. Figure 35*).

Basically, the population distributions show considerable differences between day and night. During the day, commuter movements to the workplaces in the study area are considered which leads to increasing values in the business areas for the local and tourist population. Generally the population activity is more concentrated on commercial areas and beach areas both for local people and tourists, while the activities in the residential areas are weighted less. The highest population concentration can be stated in areas where local and touristic population have common activities, as can be seen in the mixed commercial areas.

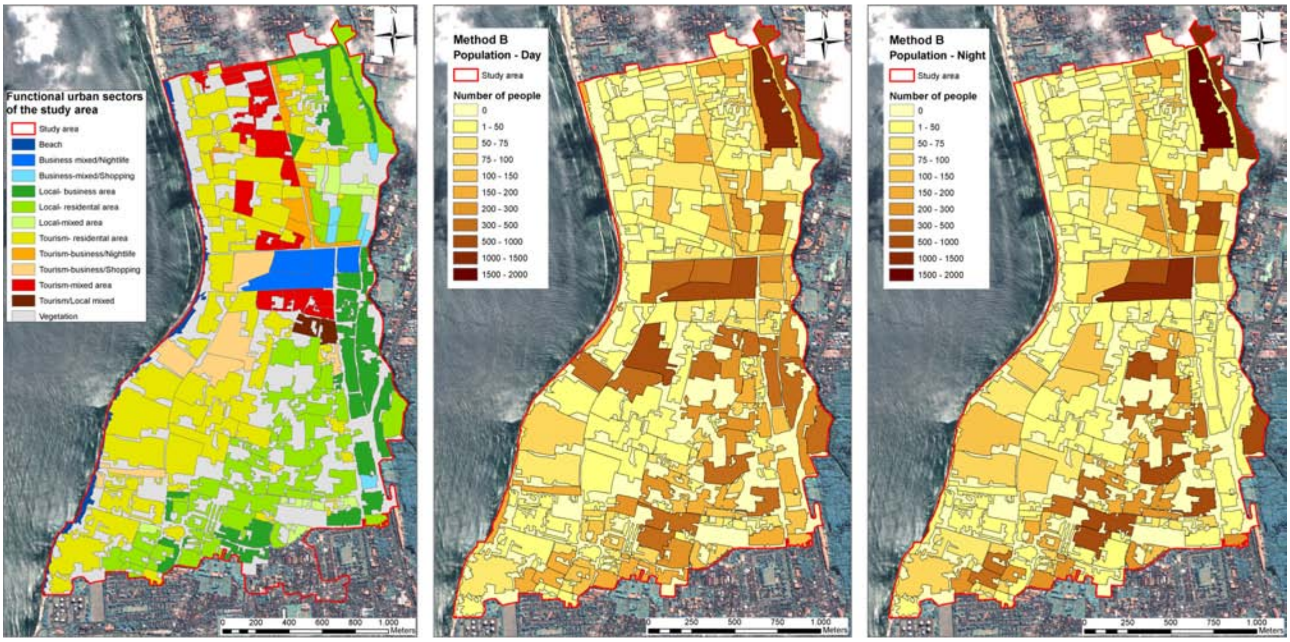


Figure 35 (left) / 36 (middle) / 37 (right) Functional urban sectors in the study area (left); distribution of day (middle) and night (right) population in the study area, calculated with Method B (Source: own illustration - Data basis: own data collection; Map basis: Quickbird satellite image)

The night population is more concentrated on residential areas both for the tourists and the local population, as well as in the nightlife districts, where the highest activity is assumed. The lowest concentration can be stated again in the vegetation areas and also in the commercial areas for local people, because there is no activity assumed outside the working time.

In *Table 18* the calculated day and night population of each functional sector is presented. The values confirm the visual interpretation of the maps. During the day the beach and the commercial areas both for the tourism and the local sector are highly frequented. At night, most of the people stay in the residential or in the nightlife areas.

Functional type	Number of people - Day	Number of people - Night
Beach	922	82
Business mixed/Nightlife	1303	2018
Business mixed/Shopping	400	71
Local- business area	3749	209
Local- residential area	11354	18225
Local- mixed area	809	1039
Tourism- residential area	1179	1967
Tourism- business/Nightlife	886	1343
Tourism- business/Shopping	2135	536
Tourism- mixed area	1117	758
Tourism/Local- mixed	620	300

Table 18 Differences between the day and night population calculated with Method B (Source: own composition – Data basis: own population disaggregation concept)

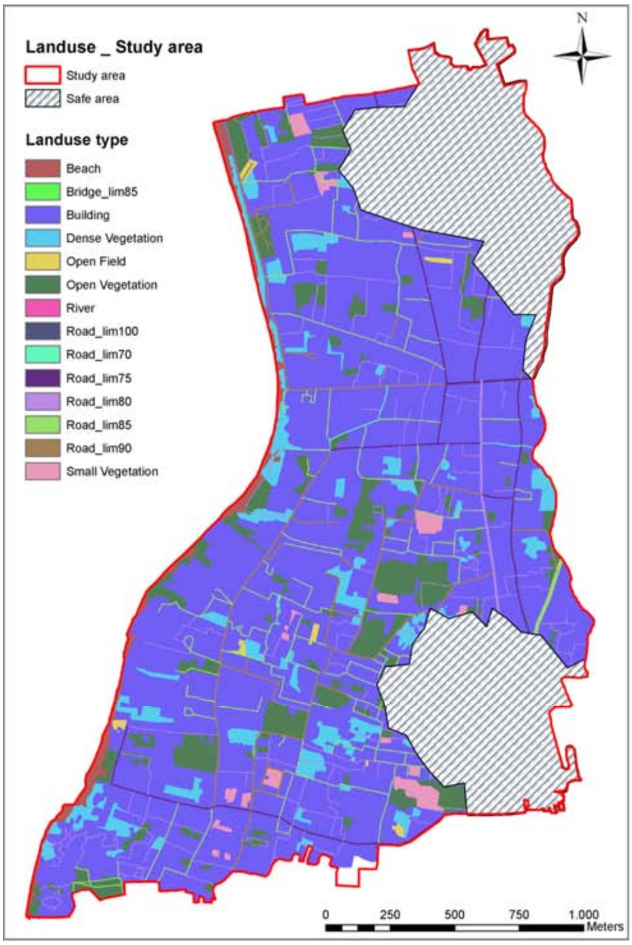
4.4 Accessibility modelling

The estimated evacuation speed depending on the characteristics of all passable paths is the basis of the shelter accessibility modelling. As described in *Chapter 3.4.2*, appropriate values were assigned to the land use classes considering the particular speed impedance of each class. In *Table 19,* the time required to walk through one cell (1m) of each land use class is presented.

Land use class	sec/m	Land use class	sec/m
Beach	0,93	Road_lim60	1,39
Building	16,67	Road_lim65	1,28
Dense Vegetation	1,67	Road_lim70	1,19
Lake	83,33	Road_lim75	1,11
Mangrove	83,33	Road_lim80	1,04
Open Field	0,88	Road_lim85	0,98
Open Vegetation	1,04	Road_lim90	0,93
Pond	16,67	Road_lim100	0,83
Rice Field	2,08	Bridge_lim75	1,11
River	16,67	Bridge_lim85	0,98
Small Vegetation	0,88	Bridge_lim100	0,83
Road_lim55	1,52		

Table 19 Time required walking through one cell (1m) of each land use class (Source: own composition)

Most of the values range between 0,8 and 1,5 sec/m, which is a realistic variation from the based average speed of 1,2 sec/m for pedestrian evacuation (ADPC 2007A). The very high values (e.g. for Lake and Mangrove) are the result of the estimated high impedance values. Actually, these land use classes are not passable but had to be considered in the calculation to provide an are-wide cost surface for the study area. In *Figure 38 and 39*, the land use classes in the study area and the inverse evacuation speed per cell are contrasted. The dark areas show land use classes with a high speed impedance, mostly buildings. It is assumed, that it is possible to go through a building, for example using the front and the back door, but it takes a lot of time. The road network has obviously low impedance values and seems to be the best evacuation path because of its dense network. But it becomes apparent that also other land use classes show very low speed values. They often don't have connections to each other but they function as important interfaces between the road networks as the preferred evacuation routes. For example, the marking A in *Figure 39* shows open field areas which are important connections between the safe area in the South and the surrounding road network. Marking B also shows an important connection between the beach area and the safe area in the North, consisting of small and open vegetation. All well-passable land use classes are an important improvement of the common evacuation road network.



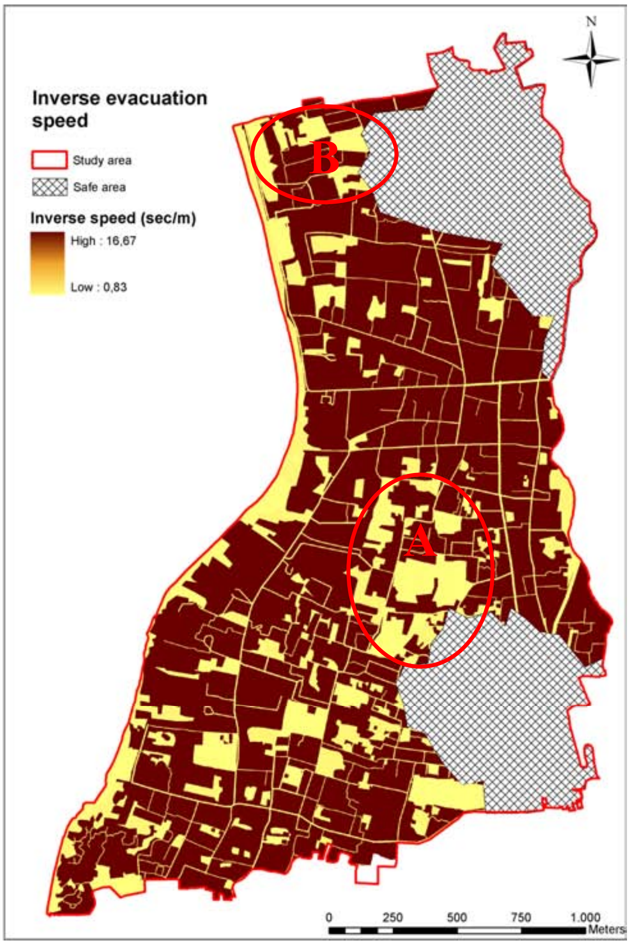
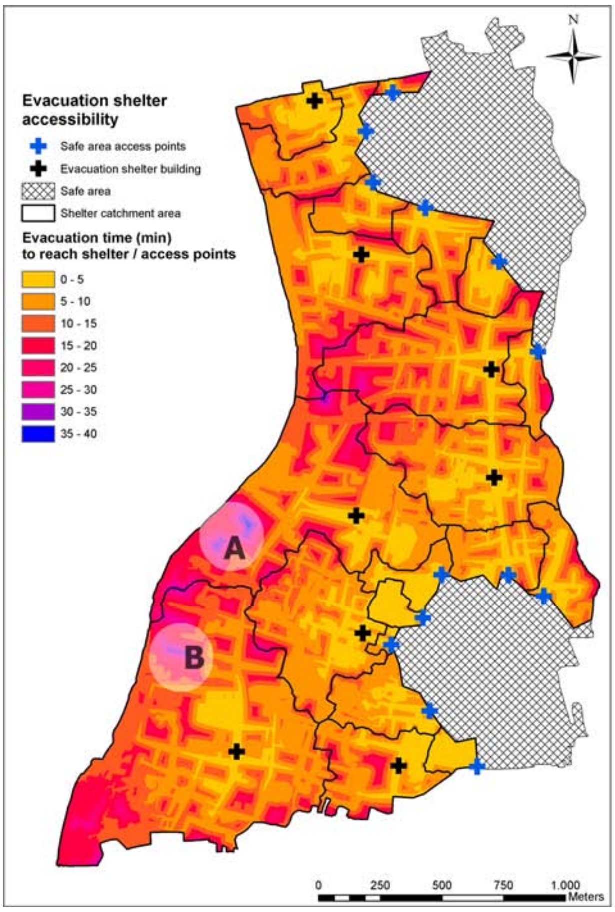


Figure 38 (left) / 39 (right) Left: Land use classes in the study area (Source: own illustration – Data basis: LAPAN; Map basis: Quickbird satellite image; Right: Evacuation speed per cell in second per meter (Source: own illustration – Data basis: own calculation; Map basis: LAPAN land use classes

Based on the evacuation speed map, the shelter accessibility is calculated. Figure 40 shows the evacuation time (in min) from every point (cell) in the study area to the nearest (in terms of cost) evacuation shelter. The shelter catchment areas mark the accessibility borders to the several shelters.

The road network is in evidence and mark mostly short access times. Other areas, although they are near an evacuation shelter, have higher time values because of a relatively high impedance of the underlying land use class. The map shows that all people are able to evacuate within 40min, based on the estimated cost values for each cell. Looking at the markings A and B in *Figure 40*, it becomes evident that there are some critical areas along the coast with very high evacuation times. For evacuation planning it is of great importance to identify such evacuation hotspots with bad evacuation shelter accessibility options, especially in areas where population density is high. The accessibility modelling approach in this research provides a tool to define the fastest evacuation route from a source point to the nearest shelter in order to clearly identify the evacuation possibilities of critical areas.



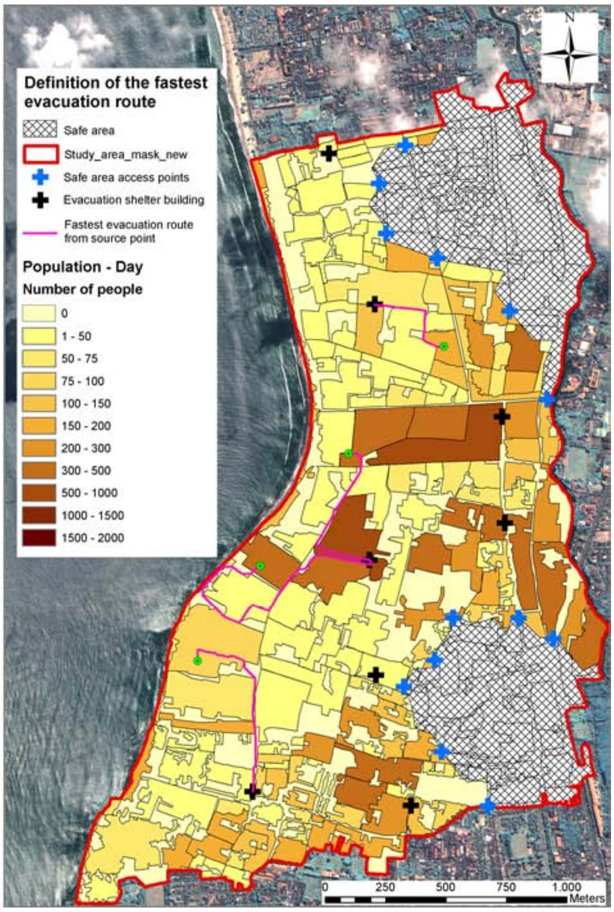


Figure 40 (left) / 41 (right) Left: Evacuation shelter accessibility based on a CWD approach (Source: own illustration – Data basis: own calculation; Map basis: inverse evacuation speed map); Right: Example for the definition of "fastest evacuation routes" (Source: own illustration – Data basis: CWD surface; Map basis: population distribution, calculated with Method B)

In *Figure 41* the fastest evacuation routes from some source points to the nearest evacuation shelter are presented exemplarily. The example routes show that the fastest path is not always the shortest path (which is the direct line between the source point and evacuation shelter).

The accessibility modelling, as presented in *Figure 40*, is based on defined evacuation shelter points: (1) Shelter access points for horizontal evacuation and (2) evacuation shelter buildings for vertical evacuation. While the horizontal access points are only based on **one** potential inundation scenario and the vertical shelters are defined in one's sole discretion, it have to be made clear that the modelling is only a pre-operating approach. The buildings were defined based on known criteria (*cp. Chapter 3.1.3*) gained from literature (BUDIARJO 2006, EISNER AND NTHMP 2001) and new expertises during the field work process. The inundation scenario, as the basis for the assigned safe areas for horizontal evacuation, was chosen because of the good representation of relevant characteristics of a possible tsunami event which could occur the study area. Generally, the great importance of vertical evacuation within the study area is beyond all questions. In a coastal urban area where population and building densities are high, vertical evacuation to a reachable evacuation shelter can be considered as the most appropriate action. In these circumstances, evacuating people to the second or third floor of robust buildings which withstand the earthquake and tsunami waves is the most effective way to save lives (BUDIARJO 2006). In *Chapter 3.1.3*, general and specific requirements for evacuation shelter buildings are presented with the advice to a necessary professional technical expertise for an official assignment of buildings as evacuation shelters. Due to a lack of time and technical knowledge, such an inspection was not feasible in this study. Regarding all general, specific and technical requirements for an evacuation shelter building, a criteria check list presented in *Figure 42* was developed and can be used for further studies.

Criteria Check List for Tsunami Evacuation Shelter Buildings (ESB)

General requirements

Stucture	**1.** Design and construction should meet the requirement of earthquake- resistant standards and codes **2.** Substantially built buildings of concrete, masonry, and heavy steel frames are required regarding material and construction
Evacuation floor	**1.** Multi- storey buildings (evacuation floor must be higher than the estimated wave height). Flat concrete roofs can also be used as an evacuation area
Function	ESB is defined by an additional function for available buildings with a specific function. The existing function should be public function or public service oriented function

Additional criteria (based on a survey of tsunami-survived buildings in Aceh and literature review)

Location and orientation	**1. Location** ESB should be located at a distance of more than 200m from the shore **2. Orientation** Building mass that situated in the same direction with the waves is more resistant than the one blocked by the wave flows.
Facade and openings	Many openings like doors and windows in the façade of buildings can prevent destruction caused by a tsunami wave. Corridors, opening arch, terrace or porch can also support the building resistance
Building shape	The shape of a building, like simple, long span or complex meet a similar function than the orientation of a building. The bigger the contact surface for a wave flow, the less resistant is the building

Building functions that can be assigned as ESB regarding main criteria

Building	Public- orientated function	Building characteristics
Mosque	Accommodate prayer, education, socio cultural activities for Moslems and surrounding communities. Accessible for almost the whole day and night	Open lay-out suitable for accommodating huge number of evacuee
School	Accommodate education activity for students living in surrounding area.	Hall and classes can be occupied for evacuation.
Government office	Civil building, oriented to serve the people.	Hall, foyer, and function room can be occupied for evacuation
Sport hall	Accommodate sport activities of the users/customers as well as public	Open lay-out suitable for accommodating huge number of evacuees

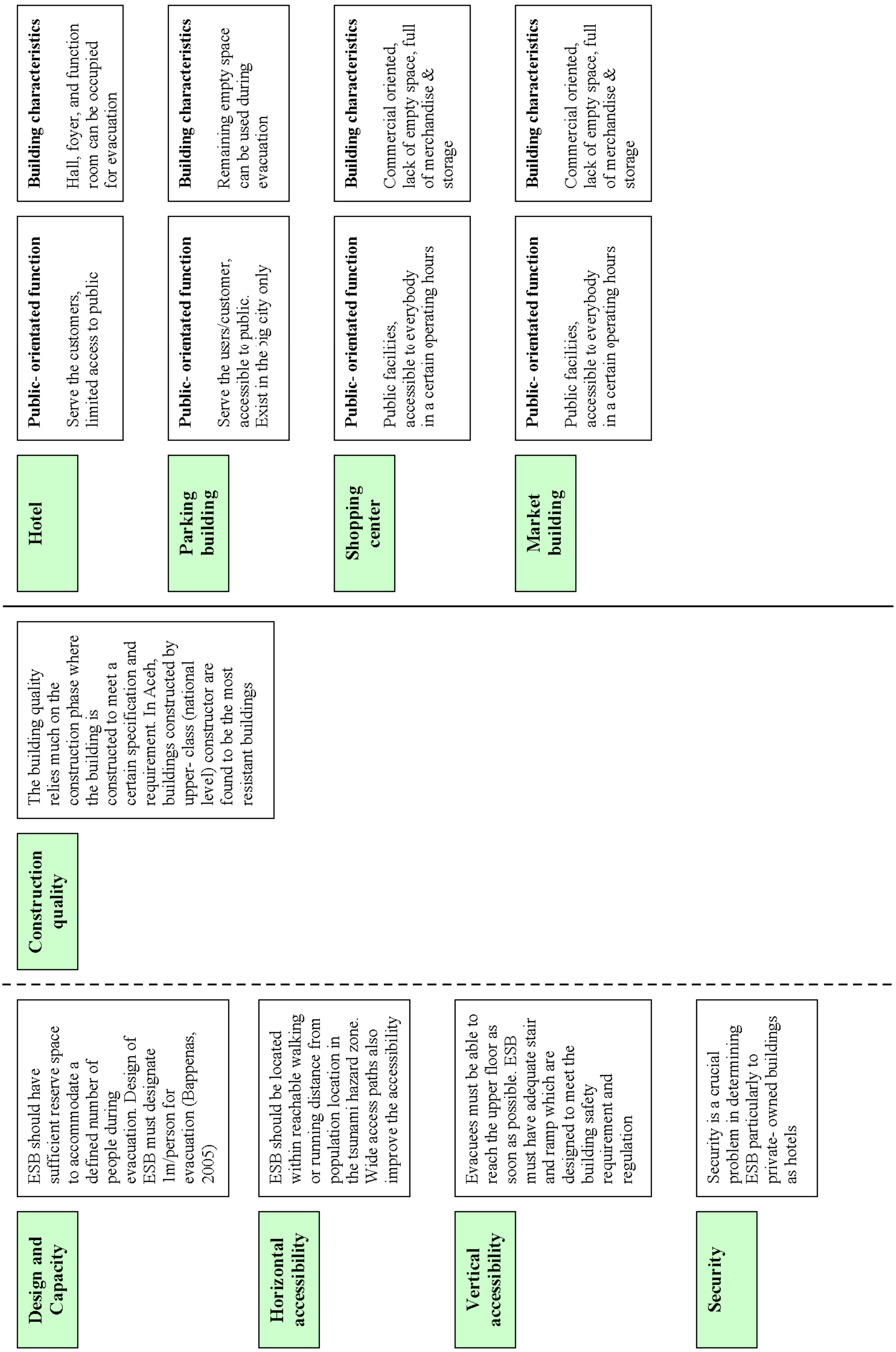
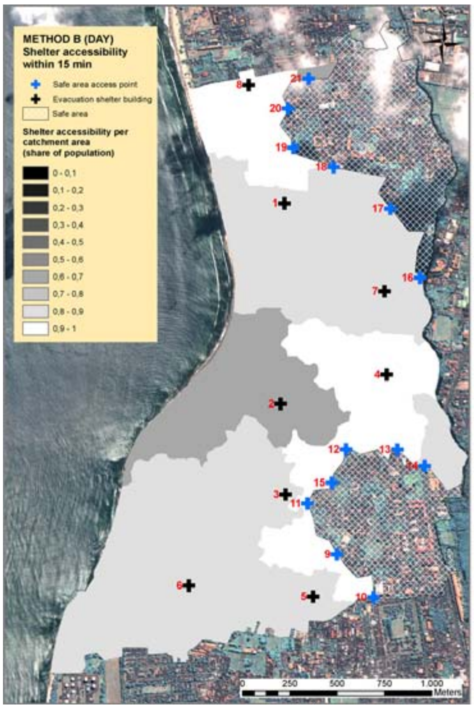


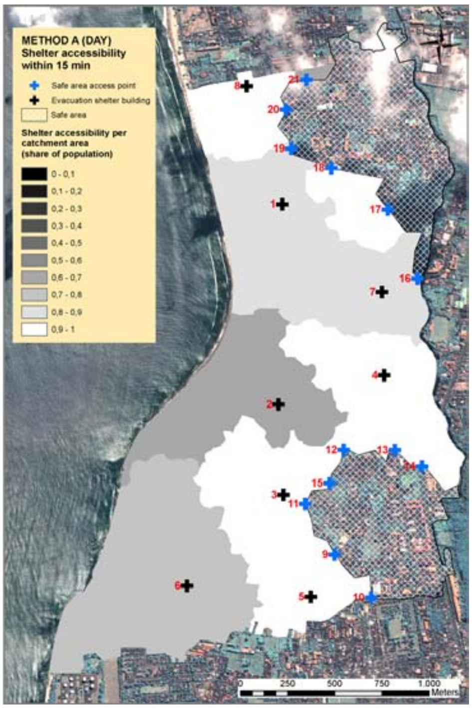
Figure 42 Criteria check list for tsunami evacuation shelter buildings (ESB) (Source: own illustration – Data basis: BUDIARJO 2006, EISNER AND NTHMP 2001)

4.5 Evacuation modelling

4.5.1 Shelter accessibility for day and night population scenario

As described in *Chapter 3.5.1*, the first step of the evacuation modelling process is to calculate how many people in each catchment area are able to reach the evacuation shelter in a given time considering three different population distributions (Method A and B, census population) and two different time limits (15 and 25min). In *Figure 43, 44 and 45*, the shelter accessibility within a time limit of 15min is presented for all population distributions (day situation).





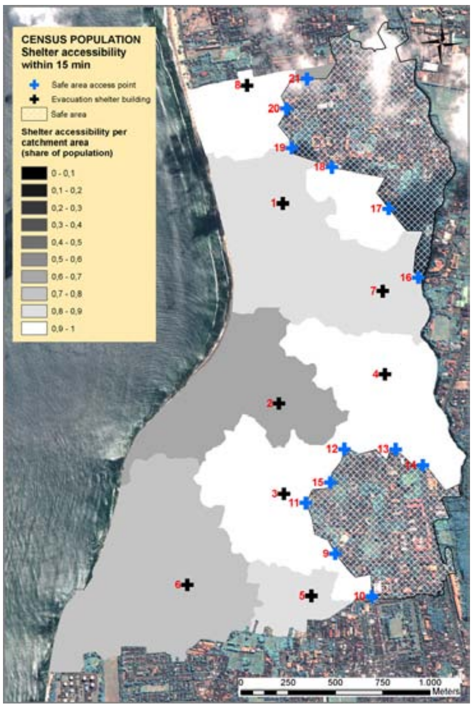


Figure 43 (UL) / 44 (UR) / 45 (LL) Evacuation shelter accessibility for the day population (calculated with Method A, B and the census population) within 15 min – (Source: own illustration - Data basis: CWD surface; Map basis: catchment areas of the evacuation shelters, Figure 29, 31 and census population map)

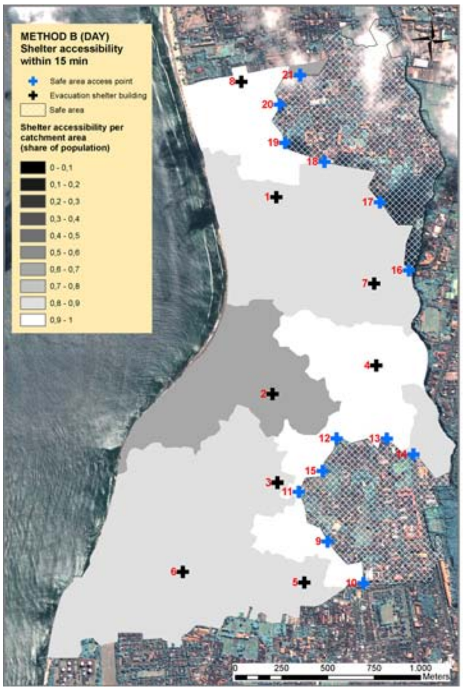
The value 0 shows the worst, the value 1 the best evacuation shelter accessibility. By a first visual interpretation of the results, it becomes evident that the accessibility values for the calculation with Method B considerably differ from Method A and the census population. The latters show a better accessibility for many catchment areas, whereby the results among each other are very similar. For all different population distributions the accessibility values generally are very high. *Figure 40* can explain this circumstance, because the map shows that nearly all shelters are reachable within 15min. The results of the calculations with a time limit of 25 show nearly the same differences and are presented in *Appendix 4 and 5*.

Table 20 itemizes the calculated results regarding the shelter accessibility of each catchment area, to offer a more detailed interpretation. Comparing the different accessibility values, the statement of the visual interpretation can be confirmed but the differences between the three Methods are marginal. The percentage of the people who are able to evacuate within 15 minutes to the total population in each catchment area is similar for each method, although the population values are very different. Evacuation shelter number 2 shows the worst accessibility values in all calculations while the access points to safe areas for horizontal evacuation are reachable for most of the people.

Basin_No.	Pop_ complete			Pop_ 15min			Accessibility value		
	Method A	Method B	CENSUS	Method A	Method B	CENSUS	Method A	Method B	CENSUS
1	627	596	808	559	531	693	0,89	0,89	0,86
2	1711	2179	4298	1162	1467	2969	0,68	0,67	0,69
3	997	643	1869	922	577	1722	0,93	0,90	0,92
4	1431	1991	2425	1320	1891	2262	0,92	0,95	0,93
5	447	1222	325	412	1067	291	0,92	0,87	0,90
6	2882	3502	3813	2245	2988	2719	0,78	0,85	0,71
7	1258	2569	1758	1062	2061	1481	0,84	0,80	0,84
8	415	141	215	414	141	214	1,00	1,00	1,00
9	348	840	213	347	838	212	1,00	1,00	1,00
10	44	58	63	44	58	63	1,00	1,00	1,00
11	8	28	19	8	28	19	1,00	1,00	1,00
12	171	214	315	171	214	315	1,00	1,00	1,00
13	358	778	256	355	773	255	0,99	0,99	0,99
14	267	727	202	252	656	189	0,94	0,90	0,93
15	62	118	162	62	118	162	1,00	1,00	1,00
16	307	434	439	265	369	378	0,86	0,85	0,86
17	113	522	153	104	459	140	0,92	0,88	0,92
18	174	443	249	161	397	231	0,93	0,90	0,93
19	128	190	185	113	179	163	0,88	0,94	0,88
20	504	252	342	487	241	322	0,97	0,96	0,94
21	76	115	34	50	75	23	0,66	0,66	0,68

Table 20 Calculation results for the shelter accessibility of each catchment area (Source: own composition – Data basis: own calculation)

The *Figures 46/47 and 48/49* show the shelter accessibility for the day and night population of Method A and B within a time limit of 15min. According to the population distribution in *Chapter 3.3*, only the calculation with Method B show obvious differences for the day and night accessibility, while for Method A the values are very similar. In general, both calculations show that a majority of the population in each catchment area is able to access the nearest evacuation shelter both during day and night.



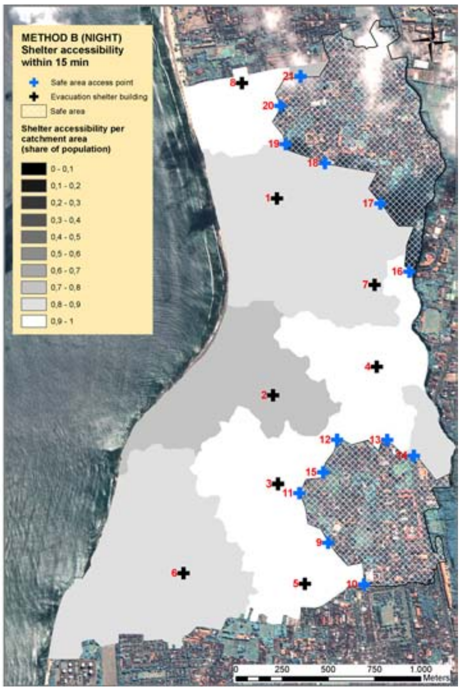
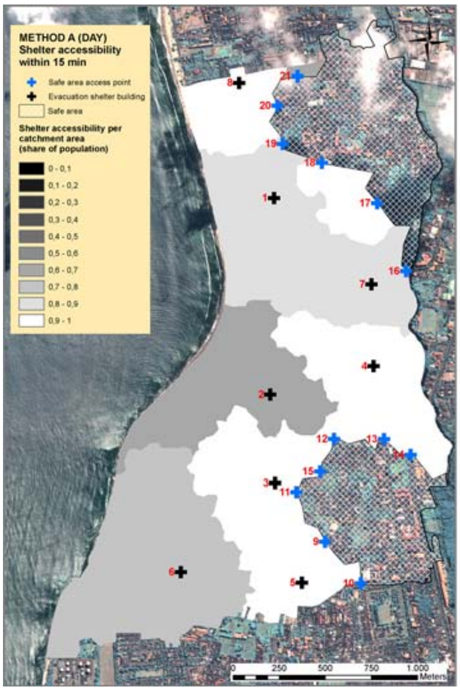


Figure 46 (left) /47 (right) Evacuation shelter accessibility within 15 min for day/night population, calc. with Method B (Source: own illustration - Data basis: CWD surface; Map basis: catchment areas of evacuation shelters, Fig. 31 and 32)



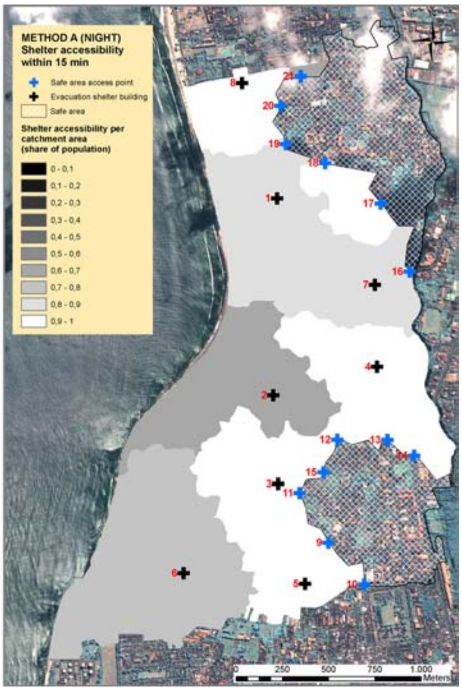


Figure 48 (left) /49 (right) Evacuation shelter accessibility within 15 min for day/night population, calc. with Method A (Source: own illustration - Data basis: CWD surface; Map basis: catchment areas of evacuation shelters, Fig. 29 and 30)

Table 21 and 22 confirm these visual impressions. Looking at Method B, the evacuation shelters 1, 2, 5 and 21 show the biggest differences between day and night while for the shelters 8 , 9, 10, 11, 12 and 15 no differences are statable. Regarding the accessibility values of Method A, only shelter 1, 19 and 20 shows very small difference values, for all other calculations no differences are identifiable.

The results will be further discussed in *Chapter 5.4.*

Catchment _area_No.	Accessibility values		Difference values
	Method A_day	Method A_night	
1	0,89	0,88	0,02
2	0,68	0,68	0,00
3	0,93	0,92	0,00
4	0,92	0,92	0,00
5	0,92	0,92	0,00
6	0,78	0,78	0,00
7	0,84	0,85	0,00
8	1,00	1,00	0,00
9	1,00	1,00	0,00
10	1,00	1,00	0,00
11	1,00	1,00	0,00
12	1,00	1,00	0,00
13	0,99	0,99	0,00
14	0,94	0,95	0,00
15	1,00	1,00	0,00
16	0,86	0,86	0,00
17	0,92	0,92	0,00
18	0,93	0,93	0,00
19	0,88	0,88	0,01
20	0,97	0,96	0,01
21	0,66	0,66	0,00

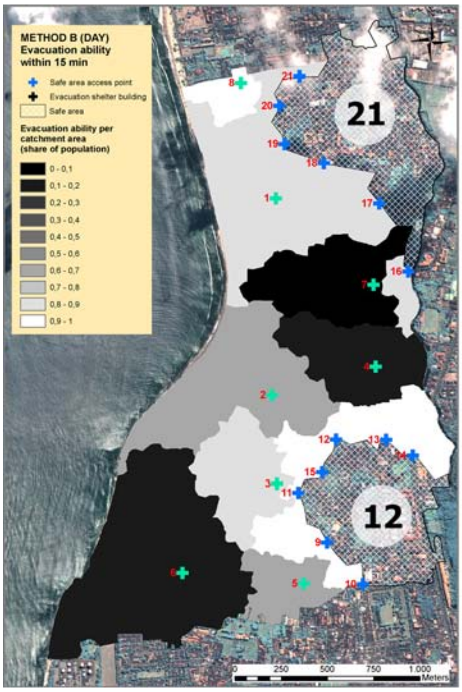
Catchment _area_No.	Accessibility values		Difference values
	Method B_day	Method B_night	
1	0,89	0,81	0,08
2	0,67	0,76	-0,08
3	0,90	0,94	-0,04
4	0,95	0,93	0,02
5	0,87	0,94	-0,07
6	0,85	0,84	0,02
7	0,80	0,83	-0,03
8	1,00	1,00	0,00
9	1,00	1,00	0,00
10	1,00	1,00	0,00
11	1,00	1,00	0,00
12	1,00	1,00	0,00
13	0,99	1,00	-0,01
14	0,90	0,88	0,03
15	1,00	1,00	0,00
16	0,85	0,91	-0,06
17	0,88	0,86	0,02
18	0,90	0,87	0,02
19	0,94	0,90	0,04
20	0,96	0,92	0,04
21	0,66	0,79	-0,13

Table 21 (left) / 22 (right) Difference between day and night accessibility values, calculated with Method A (left) and B (right) (Source: own composition – Data basis: own calculation)

4.5.2 Evacuation ability for day and night population scenario

The evacuation ability is a result of the accessibility considering the capacities of the certain evacuation shelters. Hence, the number of people who is able to evacuate is limited to the certain capacity of the evacuation shelters.

For the calculation, the blue safe area access points are treated as one shelter point for each safe area. That means that the six access points for the upper safe area and the seven access points for the lower safe area are considered in each case as only **one** shelter point in the calculation for the evacuation ability map (as signed with number 12 and 21 in the *Figures 50/51 and 52/53*). This modification of the input parameter was conducted because for the calculation of the evacuation ability, the shelter capacity is of importance. The mentioned access points are related to only two safe areas and therefore were combined accordingly. The results show again that the day and night results calculated with Method B differ more from each other than the results of Method A. It is also obvious that the evacuation ability of most of the catchment areas differ widely from the related accessibility values which do not consider shelter capacities.



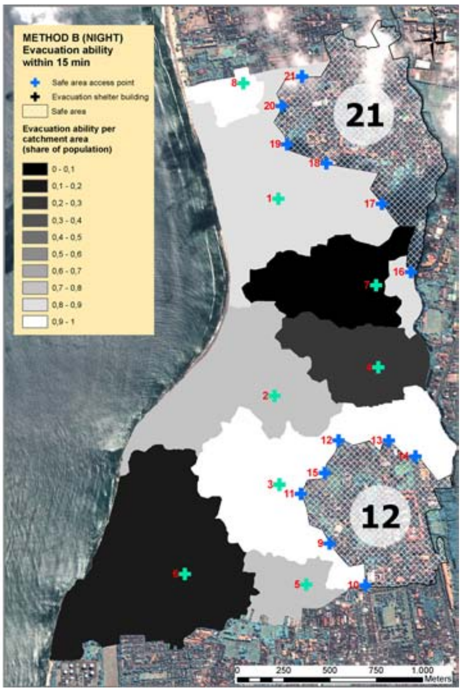
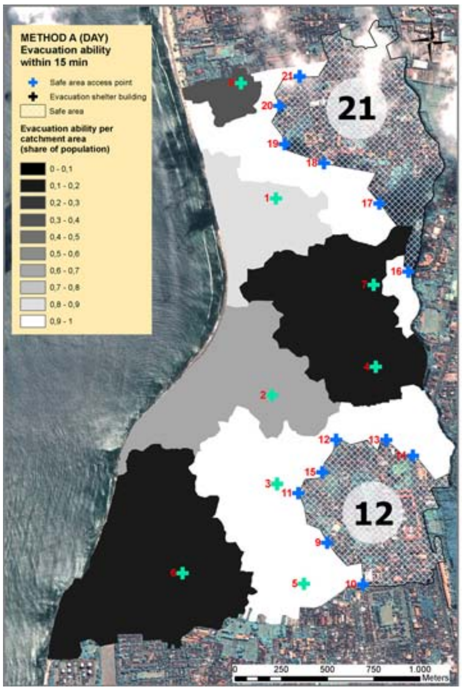


Figure 50 (left) /51 (right) Evacuation ability within 15 min for the day and night population, calculated with Method B (Source: own illustration - Data basis: CWD surface; Map basis: catchment areas of the evacuation shelters)



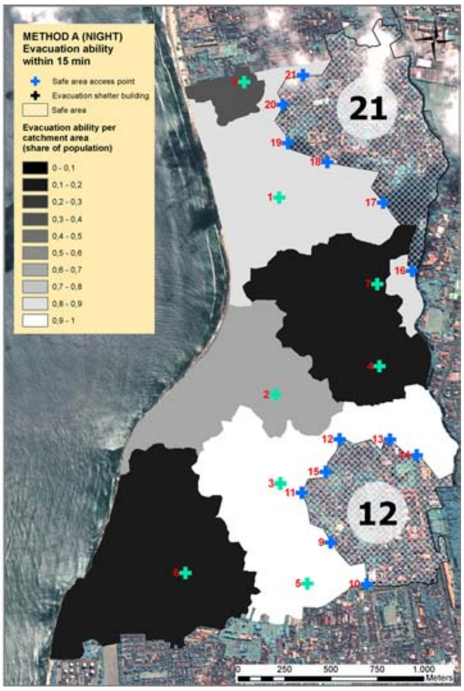


Figure 52 (left) /53 (right) Evacuation ability within 15 min for the day and night population, calculated with Method B (Source: own illustration - Data basis: CWD surface; Map basis: catchment areas of the evacuation shelters)

Generally, the *Figures 50/51 and 52/53* show very different values. *Table 23 and 24* itemize the calculated results regarding the evacuation ability of each catchment area. Especially shelter 5 and 8 show considerable different evacuation ability values in Method A and B. Regarding the day situation for shelter 8, Method A calculates a value of 0,36 and Method B a value of 1,0.

Also the calculations for shelter 5 show different results, while the values range between 0,67 (Method B) and 0,92 (Method A) for the day population. This is a consequence of the different population values. While the particular evacuation shelter capacities are the same for both calculations, the population values differ widely from each other. In Method A, for example, 414 people are able to reach Shelter 8 within 15 minutes, but due to the shelter capacity of 151 people only 36% of the people can be evacuated. In Method B, only 141 people are estimated within a time buffer of 15 minutes around the shelter and therefore all people are able to evacuate. The good values for the catchment areas of the safe area access points, both in Method A and B, are a result of the sufficient capacities of these areas.

The results will be further discussed in *Chapter 5.5*.

Catchment_area_No.	Pop_15min		Shelter capacity	Accessibility value	
	Method A_day	Method A_night		Method A_day	Method A_night
1	559	559	776	0,89	0,88
2	1162	1327	2000	0,68	0,68
3	922	1091	1125	0,93	0,92
4	1320	1608	226	0,16	0,13
5	412	488	824	0,92	0,92
6	2245	2664	526	0,18	0,15
7	1062	1315	214	0,17	0,14
8	414	440	151	0,36	0,34
12	1238	1462	97375	0,99	0,99
21	1180	1346	77320	0,91	0,90

Table 23 Difference between the evacuation ability of the day and night population, calculated with Method A (Source: own composition – Data basis: own calculation)

Catchment_area_No.	Pop_15min		Shelter capacity	Accessibility value	
	Method B_day	Method B_night		Method B_day	Method B_night
1	531	409	776	0,89	0,81
2	1467	842	2000	0,67	0,76
3	577	849	1125	0,9	0,94
4	1891	1059	226	0,11	0,2
5	1067	1049	824	0,67	0,74
6	2988	3409	526	0,15	0,13
7	2061	2434	214	0,08	0,07
8	141	99	151	1	1
12	2685	3077	97375	0,97	0,98
21	1721	1753	77320	0,88	0,87

Table 24 Difference between the evacuation ability of the day and night population, calculated with Method B (Source: own composition – Data basis: own calculation)

5 Discussion

5.1 Data collection

The availability of suitable data is the basis of evacuation modelling. The data research in Bali was a difficult process due to different factors: (1) To get statistical data and to interview experts, the support of responsible administrations was essential. However, the willingness to cooperate was often not high and therefore very time- consuming. (2) Another point was the unclear responsibilities between the local administration among each other and between the local and regional administration. Due to these problems, the data research had to be restricted in some cases. In the following, all data which were essential for this study are presented in *Table 25* regarding their availability. In addition, further data which could be used to broaden and to improve this approach are attached. These attached data were not considered in this thesis because of the limited frame of the research approach or because of a lack of time as a result of the above mentioned problems.

No.	Data requirement	Availability and data source	Additional useful data
1.	*Tsunami Hazard Parameter:* a) Historical data (horizontal distance of inland flooding and flow depth) b) Numerical inundation models	a) available, derived from NDGC b) available, provided by AWI	- Complete historical data base for Indonesia (NDGC data are incomplete) - High- resolution DEM to derive detailed slope values
2.	*Street network* a) Street width b) Traffic volume	Digital street data provided by (BAKOSURTANAL) a) available, gained by field work b) available, gained by field work	- Street surface (pavement, condition)
3.	*Land use data*	Available, provided by LAPAN	- Digital building mask
4.	*Evacuation shelter locations* a) for vertical evacuation b) for horizontal evacuation	a) available, gained by field work b) available, derived from inundation modelling	a) detailed building data of potential ESB (Structure, design, capacity, accessibility)
5.	*Location of critical facilities*	Partly available, gained by field work (schools, hospitals)	- Detailed data of critical facilities (Number of people, storeys, accessibility, capacity)
6.	*Detailed population data*	Available, gained by field work	- Building- based population data - Socio- economic data - Detailed tourist data - Commuters data

Table 25 Data requirement and additional useful data for the thesis (Source: own composition)

Tsunami hazard parameter

Tsunami hazard maps show areas that could be inundated by a tsunami. The hazard maps and information mainly serve to educate and prepare the public and assist emergency responders to plan evacuations (EMERGENCY MANAGEMENT AUSTRALIA 2005). For the study area both historical data and numerical inundation models were available. While results obtained by numerical inundation modelling possess a certain degree of uncertainty (due to incomplete knowledge on model parameter, input data assumptions, etc.), historical event data can be used for validation. As presented in *Chapter 3.2.1*, a hazard assessment was conducted, based on data from the NDGC. However, this historical data base is incomplete. By a comparison with other sources for historical data, it became obvious that some tsunami events are missing. A complete data base would provide a more suitable validation possibility.

A further useful parameter for a hazard assessment would be the consideration of slope values. On the one hand depressions and elevations which strongly influence the propagation of a tsunami wave could be highlighted. On the other side, extreme slope values can influence the evacuation speed. A DSM (Digital Surface Model) was available for Bali, but because of the completely flat study area, slope values were not considered.

Street network

The street network, as the most important evacuation route in case of a tsunami, is a main component in evacuation modelling (CHURCH AND SEXTON 2002). A digital dataset was provided from BAKOSURTANAL and, as presented in *Chapter 3.1.3*, was valuated during the field work considering the width, which was described with number of lanes, and the traffic volume during day and night. Since the quality of an evacuation route is a main factor during mass evacuation, a lot more street characteristics could be taken into consideration for evacuation modelling. The street surface plays an important role, while, for example, a bad pavement as well as a bad condition, can influence the evacuation speed. The better and extensive the input data, the better the evacuation modelling results.

Land use data

The available land use data were initially the basis of the calculation for the Cost Weighted Distance (CWD) as presented in C*hapter 3.4.1.* Therefore the available data were sufficient, because the cost surface was only differentiated regarding different land use types. More detailed data were necessary to disaggregate census population data. In *Chapter 3.3* a method for population disaggregation combining land use and census data is presented. The gained results show only a low level of detail at the considered scale (*see Chapter 4.3*). A digital building mask would provide more possibilities to downscale population data. An accordant dataset was provided by BAPPEDA in the course of the field work, but the data were incorrect regarding topology and geometry. An adoption of available data or the generation of new one’s, was not possible due to a lack of time.

Evacuation shelter locations

As presented in *Chapter 3.1.3*, potential evacuation shelter buildings (ESB) were identified during the field work and evaluated regarding the public function, number of storeys and potential capacity. Safe areas for horizontal evacuation were assigned according to the inundated areas based on the used tsunami inundation scenario. A central part of the shelter identification was the effort to integrate the hotel sector in this process. Due to a bad response rate of the questionnaires, many relevant data for vertical evacuation had to be estimated. The role of the hotel sector in evacuation planning will be discussed more detailed in *Chapter 5.4*. However, for a professional identification of ESB, more detailed building information (building structure, design, capacity, accessibility, etc.) are required as shown in the criteria check list for ESB presented in *Chapter 4.4*. For the study approach used in this work, the available data gained by field work were sufficient.

Location of critical facilities

As presented in *Chapter 3.1.3* , schools and hospitals in the study area were identified during the field work to highlight facilities of vulnerable groups, which need special attention in case of an evacuation. Due to a lack of necessary secondary data for a detailed evaluation of the facilities, a survey was conducted based on standardized questionnaires. Thereby, a decisive point was the difference between public and private institutions, both in the school and in the health sector. The public institutions were willing to provide information after presenting a recommendation from the superior authority. From the private sector only a few information could be received. Therefore, a detailed examination of the critical facilities was not possible.

Although, the gained results during the field work allow some basic statements regarding evacuation planning. Four schools are one- storied and accommodate up to 500 people during the school hours, mainly elementary school students which need special guidance in case of an evacuation. Only two schools are multi- storied (*cp. Table 17*) and can potentially use the upper floor for vertical evacuation. However, more detailed information is required to provide special evacuation guidance for such facilities. Of great importance is to know whether the buildings meet the general requirements for ESB. Evacuation planers have to know if the students are able to evacuate themselves to an upper floor or if they have to move from this place to reach an evacuation shelter. Critical facilities are mostly population hotspots (e.g. schools during school hours or big hospitals) and therefore have to be considered in ESB location planning to ensure an optimized shelter distribution. In case of an evacuation, it plays an important role if about 2000 students (*cp. Table 17*) have to move or not. Furthermore it is essential to know if, especially elementary schools students are sensitized for the tsunami danger and if special evacuation plans are available. It is essential to provide special evacuation guidance for such facilities. Otherwise, a tsunami warning will cause panic and respectively uncontrolled evacuation behaviour.

Regarding the hospitals in the study area, the situation is more complicated. Comparing the location of the facilities with the potential inundation zone based on the used inundation scenario (*cp. Figure 23 and 26*), it is obvious that some of them are located within the identified tsunami hazard zone. An important required information is once more if the facilities can accommodate the people inside in an upper floor and if a special evacuation plan is available. Disabled people mostly are not able to evacuate themselves and therefore the response time in case of a tsunami warning is much lower than, for example, for schools. Detailed evacuation guidelines are required to ensure the evacuation of the patients in a very short time.

While the consideration of critical facilities is such an important factor in evacuation planning, it must be point out that in reality a lot more facilities should be implemented in an evacuation planning process. Following a definition issued by the German Federal Ministry of the Interior (BUNDESMINISTERIUM DES INNEREN 2005), critical infrastructures are organizations and facilities having high relevance for the national community whose disturbance or failure would have lasting effects on supply, considerable disruptions of public safety, or other significant adverse impacts (e.g. high rate of loss of life).

All critical facilities are characterized by their importance for an efficient society and by their high exposure to a tsunami. Among other things, they are further sub- divided to so called "essential facilities" (STRUNZ ET AL. 2008B) featuring particularly endangered people (young, old, ill, disabled) including schools, hospitals, kindergartens, residential homes for elderly or disabled people.

While the evacuation of people in risk areas within a certain time is the main concern in evacuation planning, these facilities are considered in this pre- operating study. However, other types of facilities are also relevant. "Supply facilities" like airport, harbor, police stations, fire brigade and military, are important in providing general supply functions. "High loss facilities" like industry, power plants and oil tanks, are facilities with high danger in causing negative effects for people and environment (secondary hazards like fire, oil spill). All these facilities have different demands for evacuation planning. Providing information about this infrastructure is important for official evacuation planning in order to be able to define local "hotspots" for early warning and special evacuation requirements.

Population data

As presented in *Chapter 3.1.3*, the sub-division of the study area into functional urban sectors was necessary to get a more detailed impression of the population movement within one day. Population data were gained by disaggregating an estimated total population consisting of census data, tourist population and commuters. Functional urban sectors were defined and population movements between these sectors were assigned considering day and night population. A main concern of this approach was to show the different spatial behavior patterns of the tourist population during one day. However, due to insufficient data, the tourist population had to be estimated. A main problem was the administrative border of the study area (*cp. Chapter 2.1*). Due to the intersection of three village borders, the allocation of statistical data to the study area was difficult. Detailed attendances, accommodation occupancy rates and the average length of stay are required data to improve the population data.

From the local administration responsible for tourism, no detailed data were available. As already mentioned in *Chapter 3.1.3*, a hotel questionnaire was developed in cooperation with the "Indonesia Hotel and Restaurant Association Badung Regency of Bali" to gain information about criteria for evacuation shelters. In this framework it was also asked for tourist data, but the response rate of this questionnaire was under 1%. Due to the dense hotel structure (including bungalow resorts) of the study area, building based data could provide more detailed information regarding population movements between the different functional sectors.

Also data about the number of commuters in the study area during one day would be helpful to get a better picture of the population distribution or rather density hotspots at a particular time. It is difficult to measure these population streams because a lot of people are working in the informal sector and data about the residence of people working officially in the study area are not available. The used estimation (for the commuters) is only a result of some interviews and field observation.

Altogether, the estimated total population number is disaggregated to functional sectors as the smallest unit. Detailed building- based data would provide much better information (TAUBENBÖCK ET AL. 2007). Area- wide data about building functions could highly improve the functional zoning. Socio- economic data could be used to highlight vulnerable groups which need special attention during an evacuation (*see Chapter 3.1.3*).

5.2 Hazard impact & exposed area

Aim of the hazard assessment is to achieve a better understanding of tsunami hazard and the possible impacts on society in order to enable local and national decision makers and other stakeholders to get better prepared for future tsunami events (GONZÀLEZ ET AL. 2005)

As described in the *Chapters 3.2.1 and 4.2*, three basic approaches are generally available to conduct such an assessment: (1) using observations of historical tsunami events which occurred in the respective area, (2) by using numerical inundation modelling results (one or many scenarios) and (3) by using a combination of historical data and inundation modelling results.

For the study area the first method was used at the beginning of the research because of absent inundation modelling results in order to create a basis for the evacuation modelling process. The historical data for the study area are taken from the National Geophysical Data Centre (NGDC) where historical observations are available. However, this data base is incomplete. An examination showed that many known tsunami events are not mentioned. A further limiting factor of this approach is the consideration of worldwide events in the analysis and not only the tsunami events which affected Indonesia. The intention of an analysis of historical tsunami events is to find out which magnitude led to what situation at the coast in the historical context, regarding horizontal and vertical inundation and the certain occurrence probabilities. However, this approach does not consider the different regional conditions for tsunami generation and propagation. A decisive point is the bathymetry of the seafloor because the speed, and ultimately the direction, of the tsunami are controlled by the depth of water. Therefore the tsunami impact on land strongly depends on particular regional circumstances (GTZ- IS 2007).

Numerical modelling of tsunami inundation on land delivers information on intensities of possible tsunami inundation events for a certain location. For the study area only one inundation scenario could be used for the evacuation modelling process because the results of the multi- scenario approach did not provide safe areas within the study area (*cp. Chapter 4.2.1*). According to a main objective of this thesis, giving a statement about the endangerment of the study area, using a multi- scenario approach would provide a comprehensive data basis. An first efficient way to establish tsunami hazard zones using multiple scenario results is by counting on each point on the land if this location is inundated or not. Incorporating all scenarios - which should be representative for all possible tsunami events in the considered region - leads to a frequency distribution of each location on land being exposed to a tsunami or not. Although not directly indicating an expected intensity, the resulting information may serve decision makers to characterise zones by the fact of frequency being exposed. This means that information are provided based on the frequency being hit rather than on expected intensities for a single case event (STRUNZ ET AL. 2008A).

In a further step of analysis the gained impact zones can be modified by relating the impact areas to tsunami warning categories which are derived from tsunami wave height at the coast. Tsunami Early Warning Systems currently relate the level of warning (e.g. minor, major warning) to the expected wave height at the coastline. By deriving the inundation zone for each warning level (wave height), one can relate the warning levels to hazard impact zones and safe areas within the hazard map. This enables to plan and prepare disaster management and evacuation planning strategies for different tsunami intensity classes (STRUNZ ET AL. 2008A). As a further step, guidance for evacuation can be related to the warning levels. Different warning levels and hence different estimated tsunami intensities lead to differentiated evacuation demands. For example, in case of an "Advisory" warning with a related wave height from 0 to 0.5m, it is not necessary to evacuate a whole city or a bigger area, because only the areas near the coast are affected. A simple guidance like "move away from beaches and rivers" (GTZ-IS 2008) is sufficient in this case. Apart from the general necessary relation between warning level and evacuation guidance, it is of prime importance that people at risk have to know exactly **how to react on which information.** Therefore standardized evacuation guidelines for each case are necessary to implement fixed evacuation procedures for the population and for the local decision makers. In case of a warning the population have to know if, depending on the warning level, they are located in potential inundation area and how they have to cope with the situation. The responsible decision makers need clear and easy understandable information of the correlation between a special warning level, the related tsunami impact zone and the related evacuation guidance. *Figure 54* below clarifies this combination.

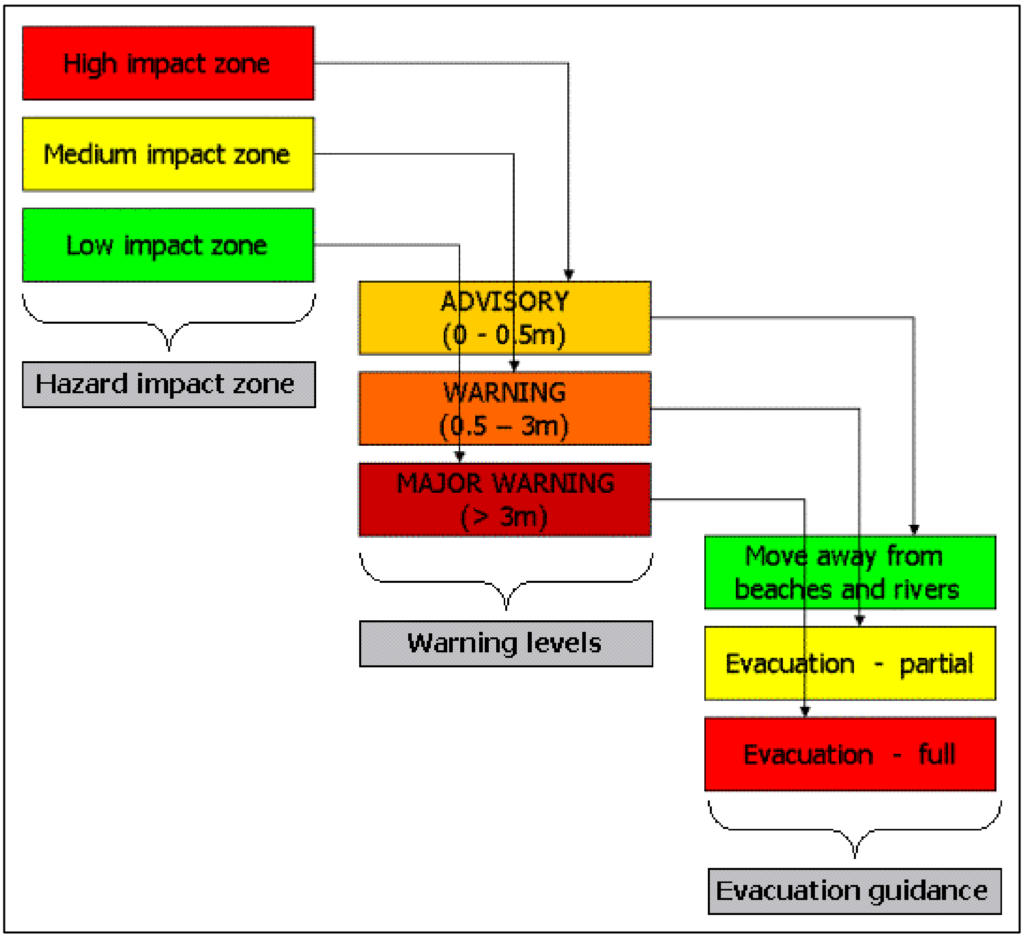


Figure 54 Useful combination between hazard impact zones, warning levels and evacuation guidance (Source: own illustration - Data basis: GTZ- IS (2008), modified)

Results obtained by numerical modelling possess a certain degree of uncertainty (due to incomplete knowledge on model parameters, input data assumptions, spatial resolution of input data as e.g. bathymetry and consequent error propagation) (STRUNZ ET AL. 2008A). These uncertainties in modelling results have to be considered when establishing the tsunami affected area for further analysis regarding evacuation planning. This can be done either by incorporating model uncertainty assessment results (e.g. uncertainty margins for each respective model output) or as a first approximation to assign a buffer value to simulation results based on expert knowledge or by validating on historical event data.

These described technical uncertainties refer to an important fact which concerns the whole discussion about tsunami hazard assessment and evacuation planning. Evacuation procedures based on hazard maps need to be disseminated to the local population. It should not be ignored that the underlying data for all procedures are only based on scenarios, estimations of experts or historical experiences. However, the exact process of a tsunami event is not predictable and therefore all recommended evacuation procedures, especially calculated inundation and safe areas, have an uncertainty factor that have to be considered. Evacuation plans have to be designed in a way that allows a flexible adaptation to changing situations. Scenario- based hazard information are only a decision support which have to be used for a fast calculation of a situation in order to provide an easy and standardized evacuation guidance for an expected tsunami event. The population have to be sensitized to the dynamic process of tsunami events as well as to the appropriate evacuation procedures which have to be handled in case of a changing warning message.

5.3 Population modelling

The general importance of detailed population data for evacuation planning on local level and population disaggregation methods are already described in *Chapter 3.1.3 and Chapter 3.3*. An aim of this research was to develop an accurate representation of population distribution in the study area, estimating daytime versus nighttime fluctuations in the event of a tsunami. The implementation of a micro scale map of population density in the daytime and nighttime provides a realistic snapshot of who is on the ground when the tsunami event occurs, highlighting higher risk areas during response and evacuation efforts (SLEETER AND WOOD 2006).

Many methods to disaggregate population have been practiced in the GIS and Remote Sensing fields. TAUBENBÖCK (2007) raise the crucial questions, (1) how many people live where (within an urban agglomeration) and (2) how does population concentration change spatially within one day. With an object- oriented classification methodology, structural criteria like built- up density, building height and land use can be derived and, based on the hypothesis that homogeneous structural urban sectors show homogeneous demographic characteristics, the local population distribution can be indirectly derived. Hence, the first question can be answered. Considering structural characteristics of housing units, like particular roof types, building size and location, different land use classes, like residential and commercial areas can be assessed. Assuming that commercial areas are predominantly populated during normal working hours and residential areas during the night, a weighting factor can be used to consider spatial population dynamics within one day. This approach was not goal- oriented for this research because of more detailed demands concerning spatial behaviour patterns of the extremely mixed tourist and local population in the study area. Furthermore the process of an object- orientated urban land cover classification is very time- consuming and could not be conducted in this research.

The division of the study area into functional urban sectors is an important prerequisite to visualize population movements during day and night regarding their activities in the particular sectors in a certain time flow. The main objective was to sign out general "activity- areas" which **mainly** show one certain function. Therefore it is not necessary to know each building function but only to conceive a particular character of an urban sector. Thereby the main challenge was to quantify the tourist population. While the local population is moving predominantly between residential areas and commercial areas, the tourist population show very heterogeneous moving patterns. Tourist movements are the spatial changes of activity locations of tourists and are motivated and affected by the attractions and activities available at the destination (LAU AND MCKERCHER 2006). Another very dynamic population group which play an important role in the study area are the daily commuters. The area of Kuta is one of the most touristic places in Bali and therefore offers good opportunities to earn money, mainly in the informal sector within the tourist centres. This fact leads to massive population movements during the day and have to be considered.

This mixture of local and tourist population in a relative small area was reflected in the effort of a functional pre- zonating on the basis of a high- resolution satellite image. The only functional sector which showed very clear structures were the residential areas for the tourists , because of the regular formation of Hotels and Bungalows. Apart from some small commercial units, the area could not be assigned to homogeneous functions. A field work was essential to assign functional urban sectors to the particular population group and to quantify the population movements within one day. As presented in *Figure 22*, the study area shows a very complex structure of functional units and seems to be very unclear at first view. But regarding the assigned quantifications of the particular sectors, it becomes apparent that the differences between the day and night population are considerable and play an essential role in the process of evacuation planning. It is of great importance where concentration spots of people are at a particular time to meet the requirements of evacuation planning at local level. In *Chapter 5.2,* the need of standardized evacuation guidelines for different tsunami warning levels is described. Related evacuation plans identify affected and safe areas, evacuation routes and options for vertical evacuation, but the real evacuation process stands and falls with the availability of suitable population data. If the real population distribution in an affected area differs widely from the estimated distribution as the basis for an evacuation plan, the evacuation process during a tsunami event will not achieve the planning objectives. Displayed evacuation routes could be blocked because they are overcrowded with people, capacities of evacuation shelters could be insufficient because wrong evacuees numbers are calculated and the accessibility times from source points to the nearest evacuation shelter could be extended by a reduced evacuation speed. In return, a wrong estimated population distribution could lead to a neglect of resources like little frequented evacuation routes and half-empty evacuation shelters.

The results of the two applied disaggregation methods in *Chapter 4.3* demonstrate the wide variations between different approaches both regarding the general distribution and regarding the day and night values. Looking at Method A, it becomes apparent that a simple weighting factor for the differentiation of a day and night distribution does not meet the demands for local evacuation planning within urban agglomerations. Furthermore the disaggregation shows too spacious results to supply information regarding evacuation modelling. On the one hand, this method is generally more concentrated to weighting factors concerning the presence of people in areas of **different** types of land use. On the other hand this static approach does not consider dynamic processes like touristic behaviour patterns and commuter streams.

Regarding the demands for evacuation planning on a local level on the one site and the different approaches for population distribution in combination with the appropriate efforts on the other site, it can be stated that for this thesis the development of a new method for disaggregating population was necessary. Neither a bottom- up approach (building- based population data collected by fieldwork; see *Table 10*) nor a known top- down approach (population distribution according to urban structural characteristics derived from remote sensing data, see *Table 10*) was a suitable method to achieve positive results as a basis for evacuation modelling. The conducted field work was a very time- consuming process but indispensable to display the dynamic population distributions in a touristic urban agglomeration within one day. The gained outcomes provided a stabile base for the subsequent accessibility and evacuation modelling.

Regarding the important objective of population modelling, highlighting higher risk areas during response and evacuation efforts, a further parameter could be included the study: the different vulnerability of social groups. In order to estimate the current susceptibility and coping capacities of different social groups and households to tsunami hazard, a UNU-EHS study (BIRKMANN ET AL. 2007) tested different indicators in order to explain the revealed vulnerability, and also to estimate the present vulnerability and coping capacities. The following indicators were selected and tested, in terms of their relevance to visualise different revealed vulnerabilities:

- Amount of young and elderly people in the total population
- Gender
- Income
- Employment
- Land ownership
- Social networks and membership of organisations
- Loans and savings
- Potential recovery time (index)

The analysis of the distribution of the dead and missing people after a tsunami event according to the different social indicators initially shows that in two of the most affected cities (Galle and Batticaloa) gender played an important role with regard to the dead and missing, while the number of females is significantly higher than for males. Many reasons have been given for this from the observations of rescue teams and comments by survivors:

(1) more women were at home looking after routine domestic activities

(2) when the tsunami hit, women caught by the waves got their dresses (sarees) and hair entangled with objects in their path (fences, trees, etc) causing death

(3) women were trying to look after children and were delayed at home after being warned, while others were fleeing

(4) women tried to lock up houses and collect precious items, which delayed them moving out

The analysis also shows that young, elderly and disabled people are highly vulnerable mainly because of limited mobility, strength and balance. Therefore it is important to target these most vulnerable groups first and as a priority in evacuation situations (BIRKMANN ET AL. 2007).

Due to the lack of time, for the study area vulnerable groups are only defined by allocating building functions to certain social groups: (1) Schools are localized to show a great number of children during a particular time and (2) the location of hospitals represent a great number of people who need special help during an evacuation. Using questionnaires as a data- gathering tool, the vulnerability of different social groups could be highlighted much better and implemented into an evacuation modelling process.

Regarding the gained results in *Chapter 4.4*, the advantage of Method B over Method A is already described since the results of the field work provide a detailed insight into the population movements of the study area. Looking at *Figure 22,* a functional dichotomy of the area is in evident. The tourist population is located along the coast while the local inhabitants are living further inland. The majority of the population are local people; the tourists come up to about one-fifth of the total population in the study area. This leads to the following statements regarding evacuation planning:

(1) The tourists are the most vulnerable population group to tsunami impact in the study area at any time of the day. Due to the functional mix of residential and business sectors near the coast (*cp. Figure 22*), the whole area is highly frequented both during the day and the night.

(2) The majority of the population in the study area live further inland but even so within the estimated tsunami hazard zone (*cp. Figure 31, 32 and 28*).

(3) The most vulnerable areas are the tourist business sectors during the day because of the short distance to the coast and because local inhabitants and commuters stay in these areas during the working hours.

However, these statements are only based on the developed population distribution concept used in Method B. A validation of this concept is required, since the weighting values for the functional sectors are only based on field observation and expert interviews. A literature research was not successful since no comparable functional zonation for coastal areas could be found.

5.4 Accessibility modelling

Accessibility modelling is the core of the evacuation modelling process while it provides the evaluated surface for all evacuation procedures. While evacuation plans are commonly created by choosing main roads as suggested evacuation routes, the most important additional benefit of this approach is the consideration of alternative evacuation routes beside the road network. In a real evacuation situation the road network will be the most frequented route, but if other land use surfaces seem to provide a shorter path to the next evacuation shelter these routes will also be used. While different types of evacuation infrastructure have different characteristics, it is not enough to consider only the distance values. Instead, a measure of travel cost (Cost Weighted Distance) is preferable. A further benefit of this approach is that the cost is measured as travel time and the cost to travel across different land use classes is estimated considering speed impedance values. For the study area impedance values were assigned only considering the surface of each passable land use class. Based on a surface with no impedance, for the road network the width and the traffic volume are the speed limiting factors. The selection of the certain values for each land use class was based on a study from the Asian Disaster Preparedness Centre (ADPC) (ADPC 2007B). To test the effect on the evacuation time for a defined distance, the values for each land use class were changed a few times and assigned according to an own estimation. A possible validation of these estimations could be empirical investigations of people movements over different land surfaces or a further literature research.

The CWD approach offers the possibility to use a lot more parameter improving the simulation of evacuee's movement. Slope of terrain is one of the factors that most influence the evacuation speed; walking or running on a steep area would be more expensive in terms of physical exertion than doing the same on a flat zone. For this reason it is an important input in evaluation of Cost Weighted Distance and can easily combined with the speed conserving values for the different land use classes. For the study area slope values are not considered because the area is very flat and therefore an appropriate calculation would not be useful. As described in *Chapter 3.4.2*, the evacuation speed from a source point to the nearest evacuation shelter is defined as the average speed of evacuation (1,2m/sec) combined with the reclassified (speed limited) land use value and, if meaningful, the reclassified (speed limited) slope value. Regarding the average speed of evacuation, it is emanated that **one** person can walk 1,2m/sec in average (ADPC 2007A). Other speed values could found in literature during the data research. *Table 26* shows some estimations from other data sources.

Walking condition	**Average walking speed (m/s)**	**Source**
A person pushing a perambulator	1.07	Institute for Fire safety & Disaster preparedness (SUGIMOTO ET AL. 2003)
A person with a child	1.02	Institute for Fire safety & Disaster preparedness (SUGIMOTO ET AL. 2003)
An independent walking elderly person	0.948	Institute for Fire safety & Disaster preparedness (SUGIMOTO ET AL. 2003)
One person (not specified)	1.38	KLÜPFEL ET AL. 2004

Table 26 Average evacuation speed values from literature (Source: own composition)

An important aspect during an evacuation is the dependence of the walking speed on the group size, which is not considered in this analysis. The Traffgo GmbH (KLÜPFEL ET AL. 2004) tested this dependence with different group sizes. The results showed that different group sizes greatly influence the particular velocity, while bigger groups moved slower than smaller ones. This parameter could also be considered in the analyses by establishing a relationship between the population density per raster cell and the related time necessary to walk through the cell. A cell grid with the gained velocities could replace the fix average speed of 1,2m/sec. *Figure 55* below shows this relationship.

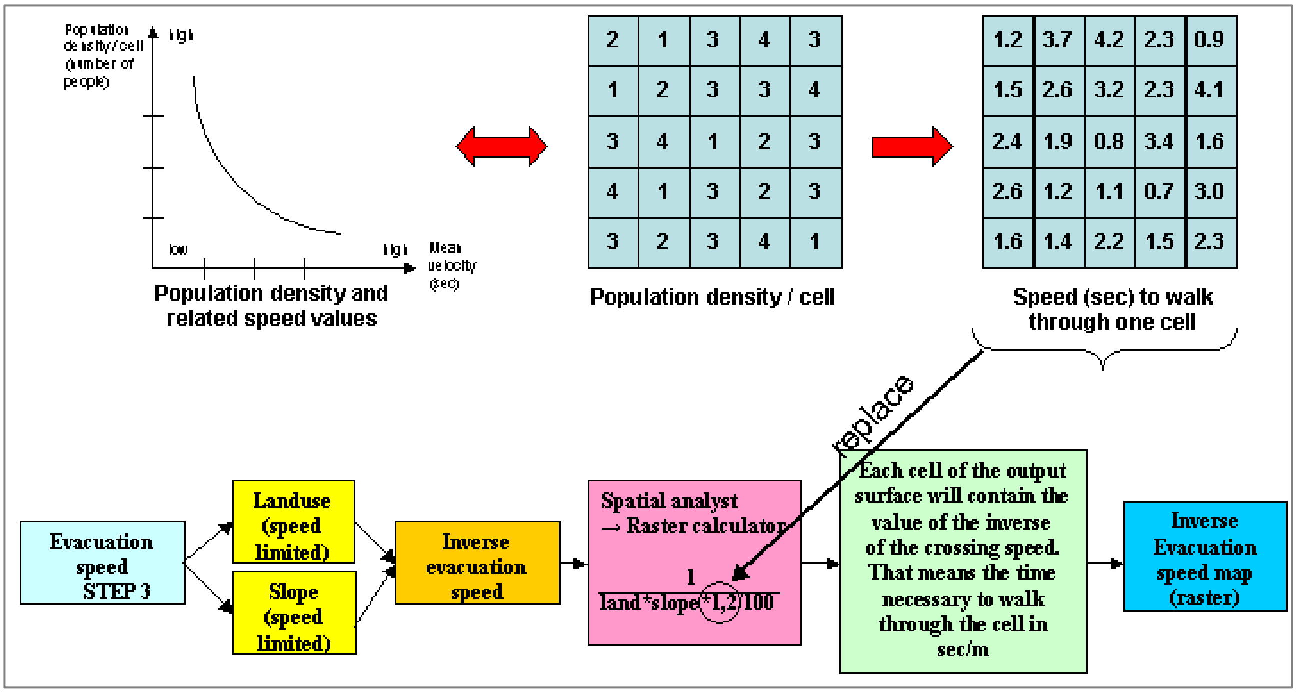


Figure 55 Potential improvement of the CWD method (Source: own illustration - Data basis: CWD approach)

Regarding the defined evacuation shelters as the basis for accessibility modelling, it has been already referred to the pre- operating character of this study, while shelter points are only based on a scenario and own assessments. All results of this study are only meant to serve as spatial information and recommendations for official evacuation planning. The official definition of evacuation shelters in the study area can only be a political decision and is therefore a very sensitive topic. In the study area no evacuation shelters were defined officially during the research process. Due to the fact that the topic of evacuation planning is just at the outset in the province of Bali, the related official decision structures are currently not clearly defined.

Local decision makers were sensitized to this topic during the field work by workshops on evacuation planning supervised by GTZ- IS. Thereby central discussion points on the part of the local representatives were the nescience about potential affected areas in case of a tsunami as well as questions to location and requirements of evacuation shelter buildings. These uncertainties and doubts are a result of the insistent note that, on the one side, all assigned risk areas are only based on numerical inundation models or historical data, but, on the other side, that it is of great importance to define fix buildings which meet the requirements for evacuation shelters. A more specific problem are the different structures of ownership in Bali. Due to the wide touristic infrastructure, hotels are the most important potential evacuation shelters. The hotel industry in Bali is predominantly private sector and the public influence capability is limited. For economical reasons, the owners are often not interested to broach the issue of tsunami too much, to avoid a relation between the real touristic product and a potential tsunami hazard. However, the tsunami issue is more and more in people's mind and the issue tsunami safety plays more and more an important role, especially in coastal areas. Hence, hotels are increasingly interested to mark their facilities as "tsunami safe". Thereby a central point will be, how far the hotel owners are poised to accommodate not only their own hotel guests but also evacuees from outside in case of a tsunami event. These discussions have to be led between the local decision makers for evacuation planning and the local hotel industry.

The concept of vertical evacuation and ESB should also be enforced and supported with the implementation of building codes and regulation for land use planning and rehabilitation. The implementation will rely much on local government's role rather than national-wide authority (BUDIARJO 2006). On the one hand, known building functions that can be assigned as evacuation shelter building, like mosques, schools, offices or shopping centres can be implemented in the facility planning process regarding general requirements for evacuation shelters. On the other hand, in case of vertical evacuation, people actually can also evacuate themselves to the upper floor in their own houses (if the houses fulfil basic ESB requirements). In this case, the construction strength is questionable because it may not be able to withstand tsunami waves. Therefore the current inadequate enforcement of building regulation and construction quality control has to be improved.

5.5 Evacuation modelling

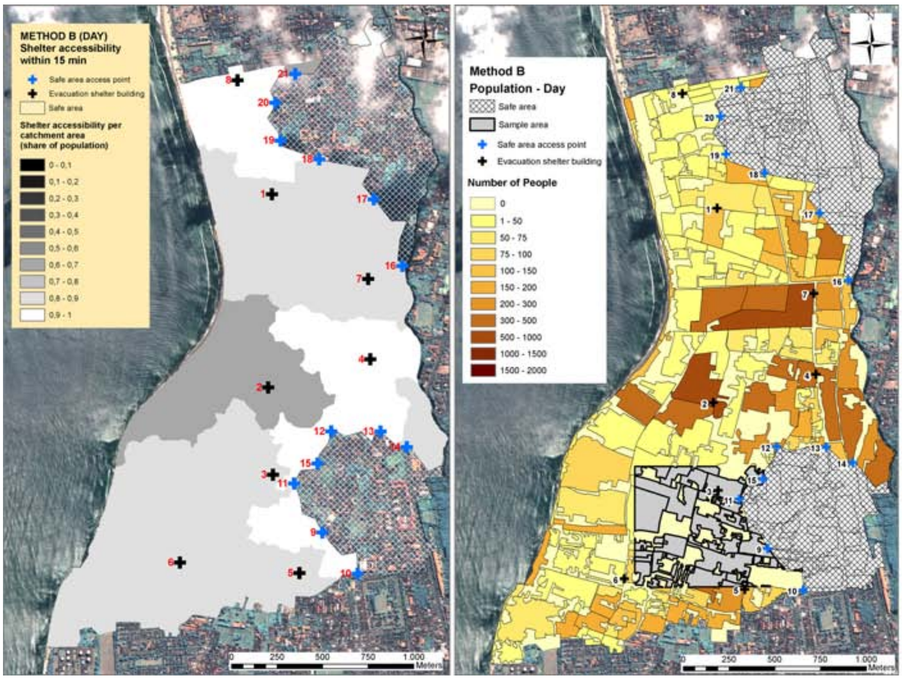
The great challenge of the evacuation modelling is to combine the results of the accessibility modelling with the disaggregated population data. Thereby the temporal dynamic of an evacuation process has to be represented as best as possible. The relevant information which are needed to calculate people's ability to evacuate, presented in *Figure 17*, were the basis for this process and will be discussed regarding the gained results in *Chapter 4.5*.

First of all, the calculation results for the study area can only be evaluated with some limitations.
(1) The evacuation modelling is based on different population distributions considering census data from 2000, estimated tourist and commuter data (*cp. Chapter 3.3*) and two population disaggregation concepts which are not validated.
(2) The identified hazard impact zones are only based on one potential inundation scenario. A multi- scenario approach would provide a better data base (*cp. Chapter 3.2*).

(3) The identified evacuation shelters (safe areas and ESB) are not approved officially and the shelter capacities are partly estimated (*cp. Chapter 4.1 and 4.2.1*).

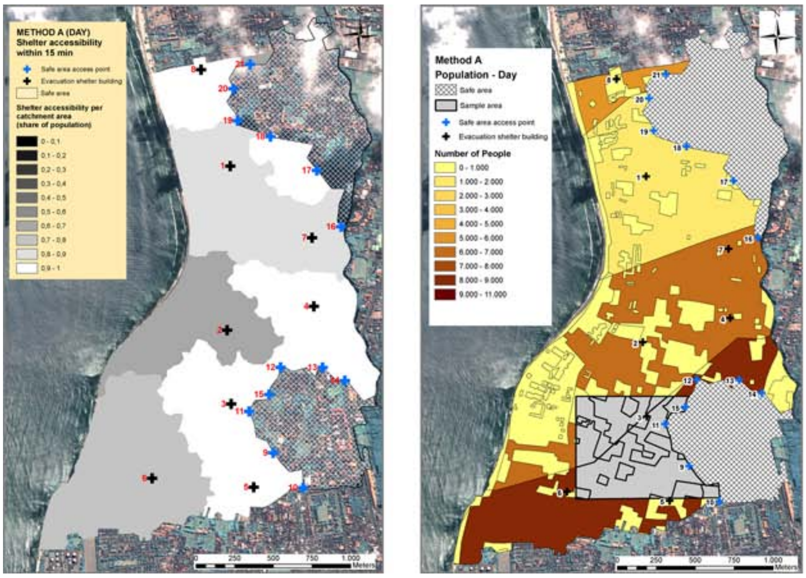
(4) The accessibility modelling and accordingly the evacuation time values are based on an estimated cost surface (*cp. Chapter 3.4.2*).

The modelling results deliver very important information. The different values of the shelter accessibility for day and night population as presented in *Chapter 4.5.1* are a result of the different population distributions. Thereby a crucial information is the relative good accessibility for the major part of the population, independent from the based population data. While the location of safe areas for horizontal evacuation is based on an inundation scenario and therefore predetermined, it is possible to improve the evacuation of a large area within a short time (15min in the study area) by a reasonable distribution of potential evacuation shelter buildings. This information is only based on the Cost Weighted Distance (CWD) approach as estimated parameter. As discussed in *Chapter 5.3*, this approach can be improved by considering further parameters like group size or by an evaluation of the defined speed values for different land use classes. The method for the shelter accessibility can be an important and transferable spatial information for official evacuation planning, since areas with bad evacuation ability are in evidence and all necessary action can be initiated. An indispensable basis for such information is an appropriate population distribution to ensure a correct identification of required evacuation shelters. The maps presented in *Chapter 4.5.1* only show the shelter accessibility for each shelter catchment area on the basis of different population distributions. A decisive additional information is, if the based population data are sufficient to describe the evacuation situation of areas with different population densities. In *Figure 56 and 57* the results of the shelter accessibility for the day population calculated with Method A and B are contrasted with the based population data. Looking at Method B, detailed statements regarding the emptying of areas with different population densities are possible. It is evident that very densely populated areas in the centre of the study area show good accessibility values, while a large number of people near the coast is not able to reach the nearest evacuation shelter within 15min.



Number of population disaggregation units	Number of people per unit
1	15
2	23
3	22
4	47
5	37
6	11
7	25
8	117
9	52
10	83
11	4
12	186
13	128
14	57
15	24
16	45
17	2
18	127
19	98
20	68
21	77
22	128
23	265
24	113
25	47
26	451
27	28
28	18
29	18
30	12
31	20
32	329
33	5
34	230
35	27
36	205
37	87
38	27
39	101
40	121
41	38
42	90
43	5
	3613

Figure 56 Analysis of the evacuation shelter accessibility within 15 min regarding the population distribution (Method B) in the study area (Source: own illustration - Data basis: CWD surface and population data calculated with Method B; Map basis: Figure 31 and 46)



Number of population disaggregation units	Number of people per unit
1	6
2	3
3	2
4	0
5	1
6	7
7	59
8	18
9	1
10	8824
11	15
12	7
13	7
14	10
15	10
16	45
17	6236
	15251

Figure 57 Analysis of the evacuation shelter accessibility within 15 min regarding the population distribution (Method A) in the study area (Source: own illustration - Data basis: CWD surface and population data calculated with Method A; Map basis: Figure 29 and 48)

Comparing the population distribution of Method A with the related shelter accessibility calculation, no specific statements regarding population hotspots and their ability to access a certain shelter are possible, because the population map is too coarse.

The two sample areas show the number of population disaggregation units calculated with Method A and B and the related number of population per unit. The different population values are a result of the disaggregation approaches and are already discussed in *Chapter 5.3*. Important for the evacuation modelling is also the spatial resolution of the population distribution. Sample area A is subdivided into 17 sectors, sample area B into 43 sectors. In case of a tsunami event, the temporal evacuation process within sample area B can be monitored more detailed since the allocation of people to the evacuation shelters can be planned exactly (particularly regarding shelter capacity) and the evacuation situation of a spatial sector at a particular time is easy to determine. The highlightning of sensitive areas with a weak potential to access evacuation shelters is an important spatial information for evacuation planning, but can only come into value by a detailed based population distribution.

Further important information are the locations of central evacuation bottlenecks within the study area. That means, (1) where converges a high population density and potentially high frequented evacuation routes and (2) where are coastal areas with a bad ability to evacuate.

In *Figure 58*, the main evacuation bottlenecks in the study area are identified and will be discussed in the following regarding the functional sectors in *Figure 59*.

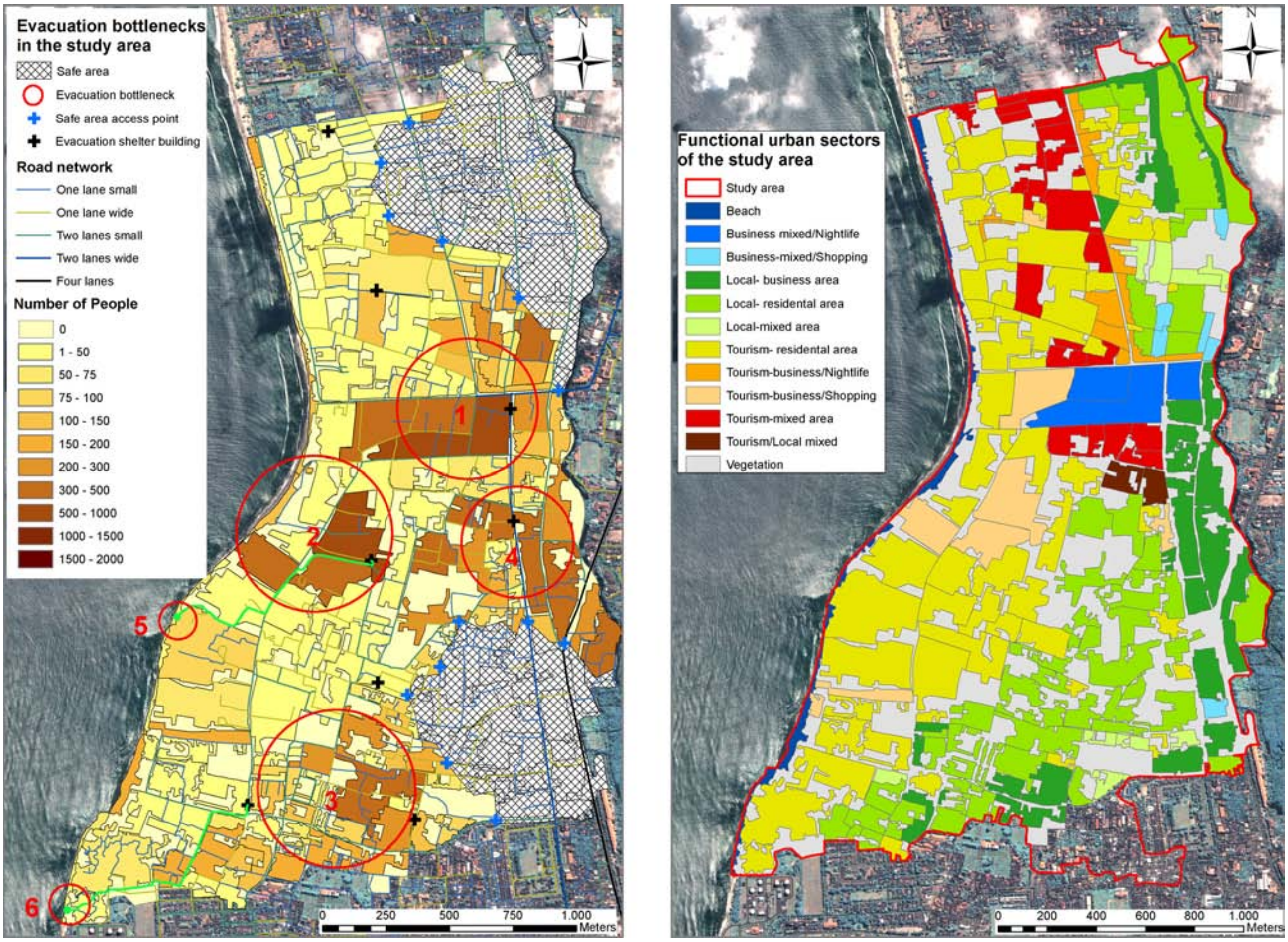


Figure 58 (left) / 59 (right) Left: Evacuation bottlenecks in the study area (Source: own illustration - Data basis: population distribution calculated with Method B and the evaluated road network; Map basis: Figure 31); Right: Functional urban sectors in the study area (Source: own illustration - Data basis: own data collection; Map basis: Quickbird satellite image)

Bottleneck 1 shows a mixed commercial district for the local population and the tourists which is densely populated both during the day and the night. The area is located at an important traffic junction in the study area and therefore a main evacuation bottleneck. People within the commercial area and also people from the beach will use these roads to evacuate and therefore a traffic jam and a slow evacuation speed can be expected in case of an evacuation. **Bottleneck 2** shows a touristic commercial area near the coast which is densely populated during the day. The main road from the South to the centre is an important communication road to the main hotels districts and beach areas in the study area. In case of an evacuation, mainly tourists will use this road. **Bottleneck 3 and 4** show residential and commercial areas of the local population. Both during the day and the night these areas show the most activity of the local population. Hence, the main roads along these areas will be highly frequented during an evacuation. **Bottlenecks 5 and 6** exemplarily show two beach areas in the South of the study area. The green routes identify the fastest evacuation route to the nearest evacuation shelter. *Figure 40* reveal that many areas along the coast show high evacuation times and respectively the worst evacuation shelter accessibility in the study area.

These statements are only based on estimated values (speed impedance, population density) and are only useful to sum up the potential situation during an evacuation and to get an overview of potential bottlenecks.

The evacuation modelling was conducted to give a decision support for evacuation in case of a tsunami event. Thereby a decisive parameter is the temporal and spatial dynamic of an evacuation process (DE SILVA AND EGLESE 2000). While this study is based on a static approach, dynamic components were tried to compensate with static parameters. The based cost surface can simulate the emptying of an evacuation area by stating values which show how many people are able to evacuate within a certain time and within a defined area. Considering day and night population distribution, changing situations during one day can also be showed. *Figure 17*, presented in *Chapter 3.5*, shows a further important factor for evacuation modelling: the need for additional evacuation shelters in certain areas. This point is based on the results of the previous accessibility and evacuation modelling where it can be stated if there is a need or not. However, more detailed information are required. The following questions have to be answered to deal with this problem:

(1) How much time does it take until an evacuation shelter has reached the maximum capacity?
(2) How many people have to be evacuated to another shelter in the remaining time?
(3) Are additional capacities available in surrounding shelters?
(4) Is there a need for an identification of additional evacuation shelters and what capacity is required?

These questions can also be answered with a static approach. The evacuation modelling in *Chapter 4.5* calculates the shelter accessibility in the study area within 15 minutes. By an application of the modelling approach with different time frames (e.g. 5, 10, 15, 20 minutes) it is possible to calculate the required time until an evacuation shelter has reached the maximum capacity. The number of remaining people which have to be evacuated to another shelter can be calculated by the difference of the people in the catchment areas which are potentially able to reach the nearest shelter within a given time, and the people who already reached the assigned shelter. *Table 27* provide a rough exemplarily calculation for additional required evacuation shelters in the study area based on population data gained by Method B. Column two and three show the number of people who are able to evacuate to the nearest shelter within 15 minutes (*cp. Table 24*). For some shelter catchment areas the capacity is not sufficient. By comparing the maximum number of people in each catchment area with the shelter capacities, the required additional capacity can be easily calculated. The gained results also provide information about the required building type. While for catchment area number five a small building with a low capacity is sufficient (e.g. a market building), the areas four, six and seven need one or more bigger buildings which meet the general requirements for ESB (e.g. hotel, sport hall).

Basin_No.	**Pop_15min**		**Shelter capacity (number of people)**	**Additional shelter (Yes/No)**	**Required shelter capacity (max. number of people)**
	Method B_day	Method B_night			
1	531	409	776	NO	----
2	1467	842	2000	NO	----
3	577	849	1125	NO	----
4	1891	1059	226	YES	1665
5	1067	1049	824	YES	243
6	2988	3409	526	YES	2883
7	2061	2434	214	YES	2218
8	141	99	151	NO	----
12	2685	3077	97375	NO	----
21	1721	1753	77320	NO	----

Table 27 Exemplarily calculation for additional required evacuation shelters in the study area (Source: own composition – Data basis: population distribution concept (cp. Fig. 13)

Regarding point (3), available capacities of surrounding shelters can be calculated simultaneously in the same way and can be compared with the number of people from other catchment areas which still have to be evacuated. In case there are still evacuees who are not able to evacuate because of insufficient capacities, additional shelters have to be identified.

The main disadvantage of the static approach in this research is that the evacuation modelling cannot be showed in a dynamic process. To improve the modelling accordingly, dynamic models dedicated to analyzing and displaying interaction of flow data are required. The Flowmap software (BUDIARJO 2006) can be mentioned as a suitable tool for dynamic processes regarding evacuation modelling by providing useful measures for accessibility analyses. The *catchment area analyses* feature provides a possibility to allocate disaggregated population units to the nearest evacuation shelter. Flowmap allows two bounds to be set: a destination (evacuation shelter) can have a maximum capacity, or destination can have a maximum reach (distance, travel time) (ZWAN ET AL. 2005). In the former, if the maximum capacity is reached, the destination is not taken into account any longer in the remainder of the allocation procedure. While in the latter, origins that fall outside this reach cannot be allocated to this destination. The maximum reach must be set and is equal for all destinations. The result from catchment area analysis include: the number of allocated population to a destination, the catchment area of each destination, the distance or travel time from each origin (cell) to its destination, and the remaining non-allocated population number can be obtained. The *Service location planning modelling* is a further Flowmap tool that can find the location of new additional evacuation shelters required to population that is not covered by the existing potential shelters. The tool attempts to allocate additional evacuation shelters particularly at the location which contains high population number (high density area). The option is useful because the shelters should be located at high-density areas where the population is high rather than at the low-density areas. To combine or incorporate the existing potential shelters with the proposed additional ones, *catchment area analysis* is conducted to get the location, shelter catchment area and capacity of each allocated shelter as well as evacuees' travel time from each cell to its allocated evacuation shelter.

5.6 General discussion

In the following, the particular results of the previous process steps will be discussed in the overall context considering the gained findings for the study area and the transferability of the used approach.

Due to the good initial data basis for Bali, the possibility to conduct a detailed pre- operating research in the study area was given. Available numerical inundation models, land use and street data as well as rough population data were important input data for a first estimation of the tsunami risk for the study area. But for all that, the high demands on evacuation planning necessitate a comprehensive field work. The critical points in very dense urban areas like the study area are detailed population data integrating tourists and commuters as well as applicable evacuation shelters. Looking at the results of the accessibility modelling, it becomes apparent that vertical evacuation plays an important role in urban evacuation planning (BUDIARJO 2006). Especially the hotel sector has to be integrated in the planning process due to the huge amount of adequate buildings in the study area. Although the modelling is based on a subject to the shelter selection, it becomes apparent that it is necessary to select an applicable spatial structure of these buildings to ensure a complete coverage of the area. Important criteria are the consideration of population hotspots and evacuation bottlenecks, because in case of an evacuation many different-sized population streams using the few evacuation routes, will evacuate to the next evacuation shelter. Defining population hotspots also requires a dynamic regard of the affected population to respond to changing situations. The disaggregation of the available census data to identify spatial and temporal population movements within one day is an adequate methodology to meet these demands. Thereby, the functional zonation of the study areas shaped up as a suitable approach.

Apart from the general evacuation infrastructure, the evacuation time respectively the number of people which is able to evacuate on the basis of an estimated cost surface is a main concern in this research. The analyses show that most of the affected people can reach an evacuation shelter within an estimated time span of 40min (*cp. Figure 40*), but regarding the assumed values a subsequent sensitivity analyses is necessary to validate these results. For models involving many input variables this CWD method is an essential ingredient of model building and quality assurance. Thereby the influence of different input factors to certain output quantities will be analysed. Relating to the study approach, the influence of the speed impedance factor for the evacuation time map based on different land use classes as well as further relevant input parameter like slope or mass evacuation values can be analyzed regarding the particular evacuation time.

Regarding the transferability of the research results, the concept of Cost Weighted Distance (CWD) was proved to be a suitable approach mainly by considering alternative evacuation routes beside roads. Their important function in the study area, as interface between roads as the main evacuation routes become evident. Especially for evacuation planning in high- populated urban areas the concept is very useful to relieve the high frequented road network. The technical implementation of the concept on a small scale is without any difficulty and well transferable to other coastal areas. However, the point- based access to evacuation shelters is a critical factor. While for the vertical evacuation to ESB's this approach is correct, the punctual accessibility to safe areas outside inundation zones is a limitating factor. For the study area, wide streets as the most important evacuation bottlenecks were chosen as access points. For an analysis on a small scale this method is suitable to simulate an evacuation situation, but on a broad- scale level some problems can occur. To ensure a realistic accessibility, the access points have to be set very dense and regular along the border of an inundation zone. However, this entails a big manual effort and processing power. A further profit of this concept is the raster- based approach which allows an adaptation to different levels of detail. While for the small study area a 1m cell size was chosen to ensure a detail analyses, this resolution is not applicable for larger areas. By considering the defined cell size in the formula for the accessibility modelling, different scales are possible.

A crucial point of this research is to keep in mind the link to the local administration and decision makers in the study area. According to the research objectives of this thesis, the requirements for evacuation planning are defined, the potential tsunami threat in the study area is analysed and by the development of a spatial information system, a useful decision support is provided. Based on the gained expertises during this research it is possible to define some important stakeholders which should be incorporated in the research process. Each mandated institution ideally has a Standard Operating Procedure (SOP) as the guidelines and the procedures to deliver its services.

(1) A hazard assessment has to provide scientifically information products as well as simplified maps for the local communities. Therefore it is of great importance that the development integrates knowledge from research or technical institutions, e.g. LIPI, BAPPEDA, BMG and Bakosurtanal.

(2) Population modelling is a crucial topic in evacuation planning as described in detail in the previous chapters. BPS can provide the necessary base data for further analysis or can conduct field surveys to gain more detailed population data. The neighbourhood communities play an important role in the Indonesian society and should be involved to get more detailed information on the socio- economic structure of communities.

(3) For the identification of suitable evacuation routes it is essential to know the location of population hotspots, evacuation bottlenecks and have information about the traffic volume in the course of the day. Community leaders or local NGO’s (Non- governmental organisations) can help to identify these parameters. PMI has much experience in emergency planning and should also be involved in the planning process.

(4) The assignment of evacuation shelters is of great importance. The identification process of suitable shelters should involve structural engineers, TNI (Armed forces of Indonesia), research institutions as well as the local and regional administration.

(5) The identification of vulnerable groups (elder people, children, women and handicapped people) which need special attention during an evacuation is essential. Specific evacuation measures are mainly related to transport facilities. TNI, police and maybe private sectors will be the responsible institutions for transportation and have to be involved in the planning process.

(6) Traffic control and security is also task of the police.

(7) Evacuation procedures need to be disseminated to the local population. Information materials, maps and signs will help to inform general public about evacuation procedures. This process requires the cooperation of local governments, community leaders, private sector, local academic institutions and NGO’s.

6 Conclusion & Recommendations

Conclusion

Generally, the thesis research can satisfy the research objectives and answer the research questions addressed in *Table 2*. The research aims to develop and apply a spatial information system supporting tsunami evacuation planning.

In relation to each research objective, the research can be concluded as follows:

Definition of requirements for evacuation planning

The requirements for evacuation planning are derived from the related evacuation planning objectives, determining exactly what tasks need to be carried out once the decision to evacuate has been made. A community risk assessment can be seen as the starting point for evacuation planning by providing the basis for an appropriate evacuation strategy (EMERGENY MANAGEMENT AUSTRALIA 2005). To define the degree of tsunami impact on land, a hazard assessment provides information about the nature, location, intensity and probability of a tsunami threat. Numerical modelling of ocean tsunami wave propagation delivers estimated arrival times at the coastline, time duration of the tsunami event as well as inundation and wave heights above land surface. Using these information tsunami impact zones along the coast can be estimated. Historical records of tsunami impact observations are also important sources to gain information on probabilities of tsunami events with a certain magnitude and to derive relationships of hazard impact zones on land when tsunami modelling results are not available (POST ET AL. 2007).

In case of a tsunami the decision whether a region should be evacuated requires information on the spatial distribution of exposed population and critical facilities (schools, hospitals, etc.) in order to provide information about local evacuation "hotspots" and "uncritical" areas. Due to the fact that population data on a smaller scale better satisfy the demands for local evacuation planning, methods to disaggregate population data should be applied while providing more detailed information. Regarding different concentrations of people over the day, a dynamic parameter considering temporal and spatial population movements can improve the information quality.

For evacuation two methods are generally available: horizontal evacuation, moving people to more distant locations or higher ground outside the inundation area (safe areas), or vertical evacuation, moving people to higher floors in buildings (ESB). Safe areas can be derived from numerical inundation models. Adequate accommodation criteria like sufficient capacity, adequate ground surface and low slope values have to be determined in addition. Robust multi- storey buildings assigned as the destination in vertical evacuation have to meet specific requirements of structure, evacuation floor, function, design, capacity, accessibility and security (BUDIARJO 2006). Evacuation routes have to be defined considering main streets and other passable land surfaces like small vegetation or agricultural crop land. Roadways and intersections that could be evacuation bottlenecks should be highlighted to show main emptying structures.

Development of a transferable and applicable spatial information system for tsunami evacuation planning

First of all, the developed spatial information system should meet the technical demands to implement the most common input data required for evacuation planning. Big amounts of input data, like satellite images and spatial base data have to be processed. Shapefiles and raster data are the main used data types because of the area- wide availability. A spatial information system based on ArcGIS seemed to be the most stabile solution for this research. Special software packages for evacuation modelling were tested but not used due to problems with data types and size. The methodical composition of the developed information tool is clearly structured and documented both regarding the technical process and the required input data. The methodical approach leaves room for further improvement like additional input data and technical extensions and can easily adapted to changing demands in other tsunami- prone areas.

Giving a statement about the endangerment of the study area

Substantiated statements about the endangerment of an area are based on different components. As a process in risk assessment it is generally agreed that it includes (1) the determination of the potentially endangered coastal regions by conducting a tsunami hazard assessment, (2) the estimation of the vulnerability of the people and the environment in the affected areas and (3) the identification of capacities and resources available to address or manage a tsunami threat (coping). (TAUBENBÖCK ET AL. 2008)

Based on the results of one potential inundation scenario, the affected coastal regions of the study area are mapped, excluding the various spatial intensity and probability of the tsunami occurrence. The scenario is based on the current knowledge on the possible ocean bottom deformations due to seismic activity in the Sunda trench region and was calculated for a moment magnitude of 8.5. To provide a good insight into the spatial distribution of the population at risk, available input data were disaggregated to smaller sectors considering day and nighttime fluctuations. The identification of facilities featuring particularly endangered people improves the quality of information. Coping is the mechanism by which people are able to reduce effectively the impacts of the disaster and facilitate their lives as far as possible (BIRKMANN ET AL. 2007). The capability to evacuate, regarding physical infrastructure and available evacuation time, is determined in this research by the accessibility and evacuation modelling results.

Giving a decision support for evacuation in case of a tsunami event

The decision to evacuate highly depends on the severity of the expected effects of the disaster on the exposed population and the ability to evacuate. Planning for an emergency evacuation therefore involves addressing both behavioural and logistical issues that greatly influence the evacuation operation (DE SILVA AND EGLESE 2000).

Logistical problems in evacuation can arise during the warning process, when transporting and providing accommodation for large numbers of evacuees or while administering protective measures. The behavioural issues encompass the complications that arise due to the process of mass evacuation while survival instincts overcome rational knowledge. An evacuation can therefore end up to a chaotic situation which the emergency planners must be prepared to manage in order to avoid danger, confusion and death. Local responsibilities can therefore greatly benefit from a GIS- based spatial information tool which can provide products to examine the effects of different assumptions or different plans.

Local decision makers have to know the locations of hotspots which are of vital importance during an evacuation. This can be areas with high population density at a particular time, critical facilities (schools, hospitals) in affected areas or evacuation bottlenecks which will be strongly frequented during an evacuation. Changing population distributions during day and night lead to different evacuation demands. A population distribution concept considering day and night values which was developed in this thesis (*see Chapter 3.3*) can provide useful information for temporally differentiated decision processes. Facilities featuring particularly endangered people were identified during the field work (*see Chapter 4.1*) and therewith population groups which need special help during an evacuation are highlighted. Central bottlenecks of the study area are illustrated in *Figure 58* to demonstrate the main frequented evacuation routes.

Both the emergency planners and the exposed population have to know the fastest evacuation route to the nearest evacuation shelter from every point in the affected area and the estimated time to go there. The CWD concept (*see Chapter 3.4*) provides various information like accessibility modelling, evacuation modelling and the visualization of "best evacuation routes" from each point of the study area.

Cooperation with the local administration and decision makers

From a very early stage of this research, local administration and decision makers were contacted and every process step was agreed accordingly. Different workshops and meetings in Bali were essential to intensify the cooperation with local stakeholders and to legitimate the field work on site. The exchange of experiences and information regarding evacuation planning was an important basis for the composition of this thesis. Based on the gained expertises during this work, important stakeholders for evacuation planning could be identified.

The reference of achievements obtained in answering the research questions is presented in *Table 28*.

No	Research questions	Reference
1.	**Research Objective:** Definition of requirements for evacuation planning	
	What spatial data are needed for evacuation planning?	Chapter 3
	What are the most important needs for the end users (local stakeholders, exposed population)?	Chapter 3
2.	**Research Objective:** Development and application of a spatial information system for tsunami evacuation planning	
	Based on literatures and expert interviews, which spatial information tools are suitable for evacuation modelling?	Chapter 3.4 and 5.5
	What has to be considered in developing a spatial information tool to ensure its transferability to other coastal areas?	Chapter 6 and Chapter 5.6
	Which spatial parameters have to be considered for tsunami evacuation modelling?	Chapter 3.1, 3.2 and 3.3
3.	**Research Objective:** Giving a statement about the endangerment of the study area	
	How is the tsunami hazard locally distributed?	Chapter 3.2 and 4.2
	How many people are exposed?	Chapter 3.3 and 4.3
	In the context of evacuation planning, where are critical facilities?	Chapter 3.1.3 and 4.1
	Where are evacuation bottlenecks?	Chapter 5.5
4.	**Research Objective:** Giving a decision support for evacuation in case of a tsunami event	
	Where are potential evacuation shelters?	Chapter 3.1.3, 3.2.2, 4.1 and 4.2
	Where are potential evacuation routes?	Chapter 3.1.3, 3.4, 4.1, 4.4
	Are the people in risk areas able to evacuate in a given period of time?	Chapter 3.5 and 4.5
	Which spatial information products are useful for the local decision makers?	Chapter 4 and Chapter 5.5
5.	**Research Objective:** Cooperation with the local administration and decision makers	
	Which stakeholders should be incorporated in the research process?	Chapter 5.6
	How to transfer the gained knowledge and create acceptance for the local population?	Chapter 6

Table 28 Reference of achievements obtained in answering the research questions (Source: own composition)

Recommendations

The thesis has illustrated several fields were further research is recommended.

The great importance of vertical evacuation in urban areas is frequently mentioned. The results of the evacuation modelling process presented in *Chapter 4.5.2* show that the current defined ESB' s are not sufficient to cover the whole area. The "Service location planning" approach as discussed in *Chapter 5.5* can be used to optimize the current building distribution. While the designation of an existing building as an ESB is strongly related with certain criteria, a technical inspection is required. Therefore, the developed criteria check list for ESB (*see Figure 42*) provides extensive information and recommendations both regarding general building requirements and current building functions that can be assigned as ESB.

ESB designation or allocation is also an iterative process along with the decision making process of spatial planning. An ESB can be built in the form of an evacuation-designated building (exclusively shelter function), or can be a multi-function building such as a mosque, school and office as listed before in *Table 8*. Considering general ESB requirements in the planning phase of such buildings would be an important step to improve the evacuation ability in urban areas. In risk assessment and management, the presence of ESB function will become a coping mechanism that reduces people's vulnerability. The dynamic and complex relationship among these components of risk, such as how far can an ESB construction reduce the vulnerability, is also an interesting topic for research.

A main objective of this thesis was to give a decision support in case of a tsunami event. Official evacuation planning is a task for local authorities and therefore the gained results and expertises have to be implemented in a local planning process. The identification of high risk areas, based on the results of the accessibility and population modelling is essential for effective evacuation planning while evacuation procedures can be focused accordingly. Critical bottlenecks can be caused by a high population density in combination with a lack of evacuation possibilities or by the concentration of high frequented evacuation routes. By the simulation of traffic flows using a tool to identify the best evacuation route in the CWD concept, problems during an evacuation can be identified early and – if possible – be mitigated accordingly. This information is also suitable to improve the signing of potential evacuation routes. If the evacuation of a hazard zone is to proceed in an orderly manner, it is essential that people know where to go, and what route to take. The identified shelter catchment areas in the accessibility modelling are bordering areas which are allocated to a certain evacuation shelter. To ensure a coordinated evacuation process, evacuation signs have to guide the correct way. A combination of the tool to identify the best evacuation route and the catchment area distribution provides a great possibility to bypass evacuees from high frequented evacuation routes to alternative routes which also lead to the same evacuation shelter.

A subsequent process of this work should intend the strengthening of the local capacities regarding technical evacuation expertises. Under the direction of GTZ- IS, a first cooperation process took place during the field work. Stakeholders which should be incorporated in the research process were identified and common process steps were concerted. Acceptance and usage of all operations in the local evacuation planning process have to be gained throughout intensive participation of all stakeholders involved. To provide and support trainings for key institutions to minimize knowledge gaps and to increase standard capacities should also be part of the cooperation process in the sense of capacity building.

7 Outlook

The research for the study area was conducted to show prospects of supporting official evacuation planning by the use of a GIS- based spatial information system. Decisive expertises are exposed in the previous Chapters whereas some limitations of the approach are already addressed. The tsunami hazard assessment providing estimates of areas that will be flooded is based on a single inundation scenario and could be improved by using a multi- scenario approach in order to look at the statistical probability that a certain tsunami event affects the study area. The calculation of the exposed population is based on statistical data and estimations of other population groups as a result of insufficient data. Due to the decisive dependence of the evacuation ability on detailed population data, further data collection is required. A detailed quantification of the tourist population and the daily commuters is necessary to gain a more reliable data base showing the actual population in the study area. An assessment of social population vulnerability identifying several characteristics that contribute to differentiate the ability to cope with a tsunami hazard, can be used to highlight population groups that need special evacuation assistance. Also the population disaggregation concept has to be improved while the weightings factors for the certain functional zones are only based on expert interviews and field observation. Further literature research regarding intra- destination movements of certain population groups would provide a better conceptual basis for this approach.

Regarding the total approach, evacuation modelling based on the CWD concept meet the demands of a spatial information system by identifying relevant spatial issues for evacuation planning. By the integration of additional parameter, different analyses steps can be improved as presented in the previous Chapters. The dynamic process of an evacuation is only considered by static parameters. To visualize the temporal behaviour of population during an evacuation, modelling software dedicated to analyzing and displaying interaction or flow data has to be integrated into the concept. The Flowmap software can be mentioned exemplarily by providing useful measures for accessibility analyses.

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DR. JOACHIM POST, German Remote Sensing Data Center (DFD) of DLR, Department on Environment and Security, Oberpfaffenhofen – 15.04.2008.

DR. KAI ZOßEDER, German Remote Sensing Data Center (DFD) of DLR, Department on Environment and Security, Oberpfaffenhofen – 15.04.2008.

DR. KAI ZOßEDER, German Remote Sensing Data Center (DFD) of DLR, Department on Environment and Security, Oberpfaffenhofen – 23.04.2008.

DR. JOACHIM POST, German Remote Sensing Data Center (DFD) of DLR, Department on Environment and Security, Oberpfaffenhofen – 19.05.2008.

Appendices

Hotel di Kelurahan Kuta

Nama hotel :
General Manager :
Contact person :
Alamat :
Telepon : Faksimile :
E-mail : HP :
(Contact person) (Contact person)

Keterangan			
1. Ada rencana evakuasi tsunami (lampirkan copy)	ADA ( )	TIDAK ADA ( )	
2. Rencana untuk menerima pengungsi dari luar hotel bila ada tsunami	ADA ( )	TIDAK ADA ( )	
3. Tempat untuk evakuasi sementara:	ADA ( )	TIDAK ADA ( )	
• Lapangan olahraga	ADA ( )	Untuk …….orang	Lantai ( )
• Lobby	ADA ( )	Untuk …….orang	Lantai ( )
• Lapangan parkir	ADA ( )	Untuk …….orang	Lantai ( )
• …………………………	ADA ( )	Untuk …….orang	Lantai ( )
4. Bangunan tertinggi berlantai berapa			
5. Luas tanah	……………m^2		
6. Luas bangunan	……………m^2		
7. Generator listrik	ADA ( )	TIDAK ADA ( )	
8. Alat peringatan bahaya (Sirene, Alarm,dsb.)	ADA ( )	TIDAK ADA ( )	
9. Jumlah staf hotel yang bekerja			
• pagi hari	………..orang		
• sore hari	………..orang		
• malam hari	.............orang		

Jumlah tamu (rata-rata)

Keterangan	Jan	Feb	Mar	Apr	Mei	Jun	Juli	Agt	Sept	Okt	Nov	Des
• Jumlah kamar yang terpakai												
• Laki-laki												
• Perempuan												
• Anak-anak di bawah lima tahun												
• Usia lanjut (>60 tahun)												
• Penyandang cacat												
• Ibu hamil-menyusui												

Appendix 1 Standardized questionnaire for the hotel sector in the study area
(Source: own composition)

Fasilitas Kesehatan di Kelurahan Kuta

Nama fasilitas....................................	Peta lokasi fasilitas kesehatan[1]	Alamat fasilitas kesehatan	Jumlah lantai/tingkat	Luas bangunan (m2)	Luas tanah (m2)	Jumlah staf siang hari	Jumlah staf malam hari	Jumlah pasien siang hari	Jumlah pasien malam hari	Rencana evakuasi[2]	Jam fasilitas kesehatan	Aman terhadap gempa pumi[3]
1.		....										
2.												
3.												
4.												
5.												
6.												
7.												
8.												
9.												
10.												

[1] ISI: ADA atau TIDAK ADA. Bila ADA, lampirkan copynya.
[2] ISI: ADA atau TIDAK ADA Bila ADA, lampirkan copynya.
[3] ISI: Aman atau TIDAK ADA

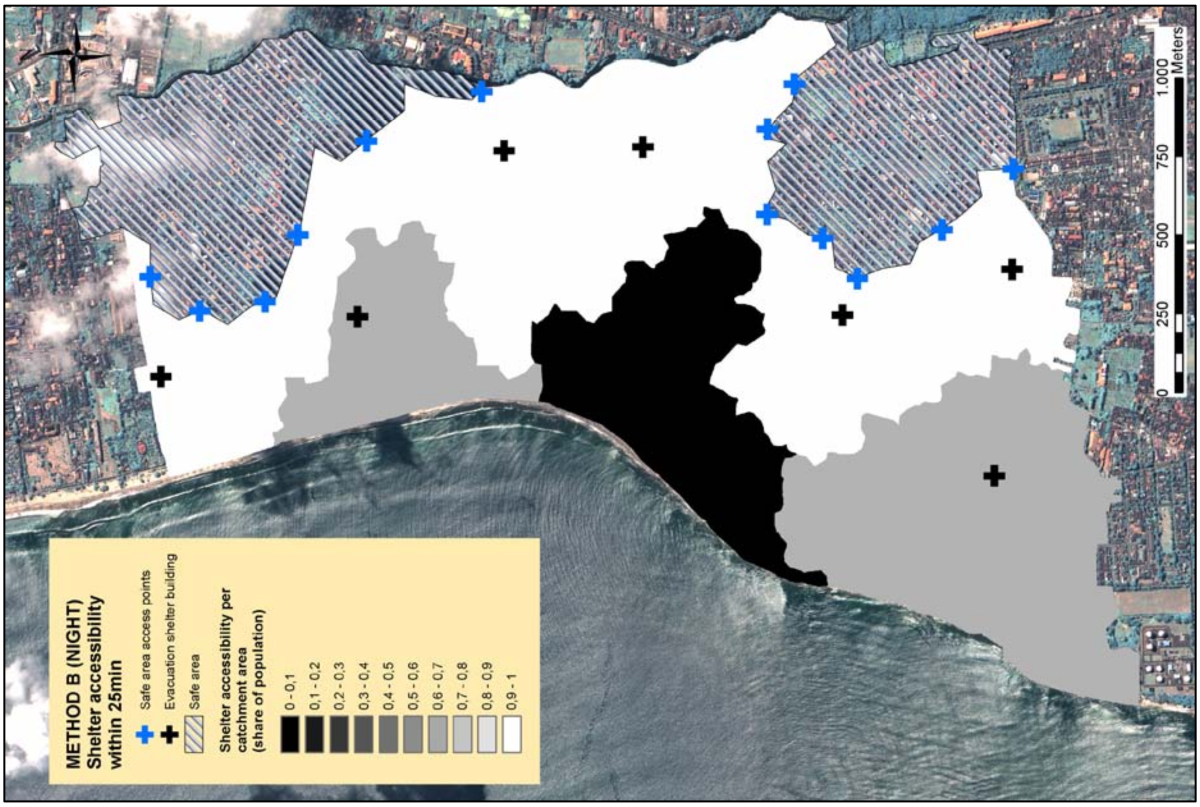
Appendix 2 Standardized questionnaire for the health sector in the study area (Source: own composition)

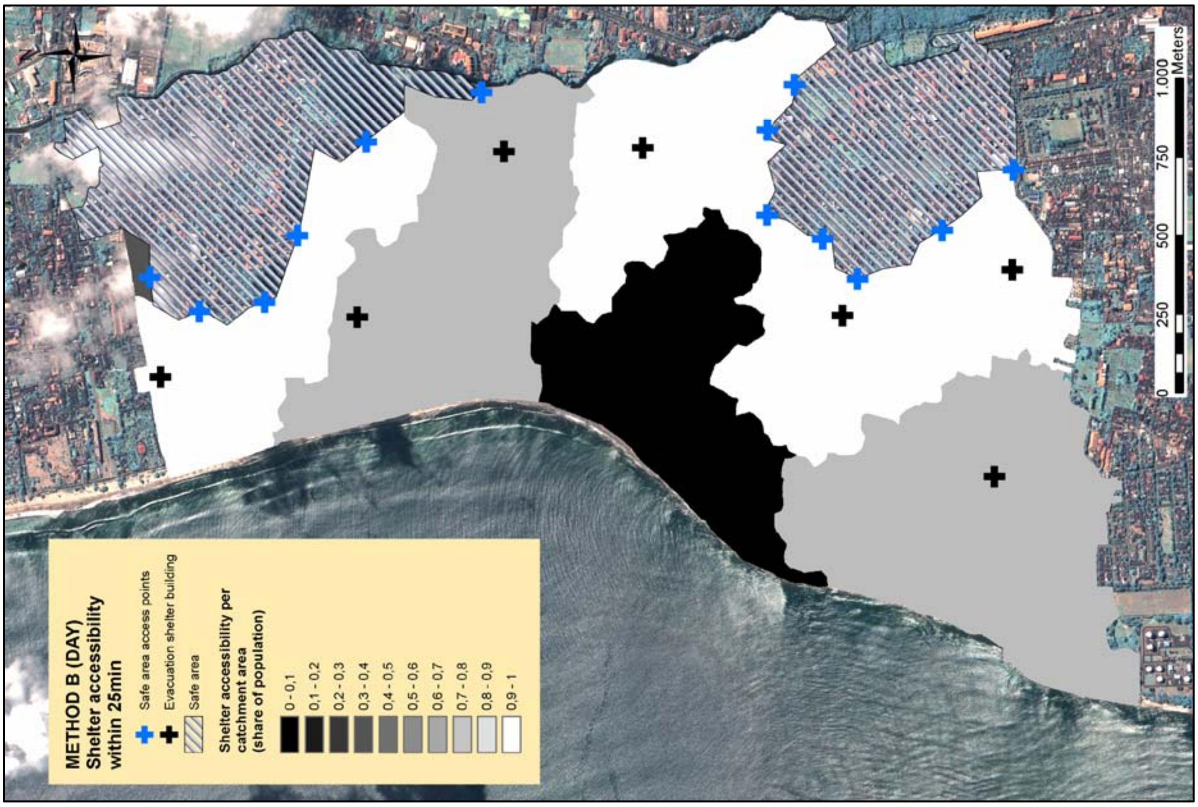
SEKOLAH DI KELURAHAN KUTA:

Nama sekolah	**Peta lokasi sekolah**[1]	**Alamat sekolah**	Jumlah lantai/tingkat	Luas bangunan (m2)	Luas tanah (m2)	Jumlah siswa	Rencana evakuasi[2]	Jam sekolah	Aman terhadap gempa pumi[3]
1. TK Indra Prasta Kuta (swasta)		………………………………………							
2. SD No3 Kuta									
3. SD Cahaya Bangsa									
4. SD Prshanti Nilayam									
5. SD No5 Kuta									
6. SD No2 Tuban									
7. SD No2 Kuta									
8. SMP Sunari Loka Kuta									
9. SMP Nasional Plus Jembatan Budaya									
10. SMK Prashanti Nilayam									

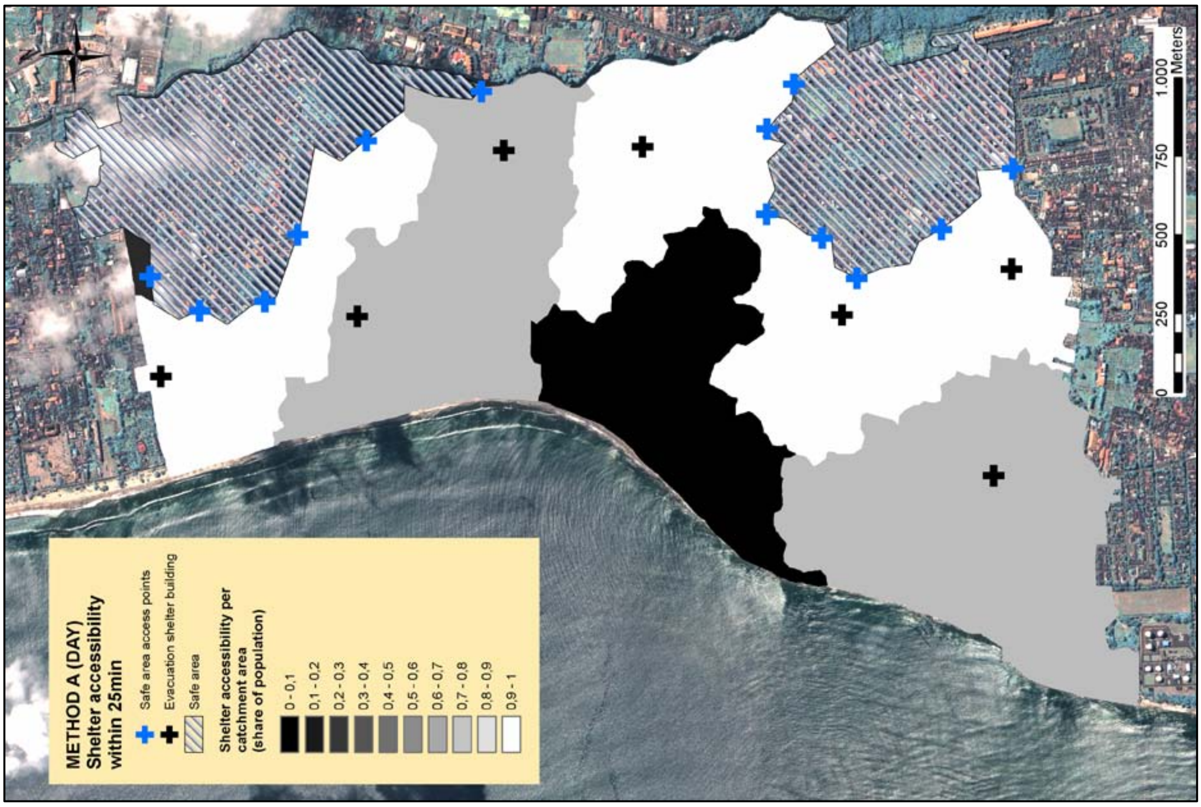
[1] ISI: ADA atau TIDAK ADA. Bila ADA, lampirkan copynya.
[2] ISI: ADA atau TIDAK ADA Bila ADA, lampirkan copynya.

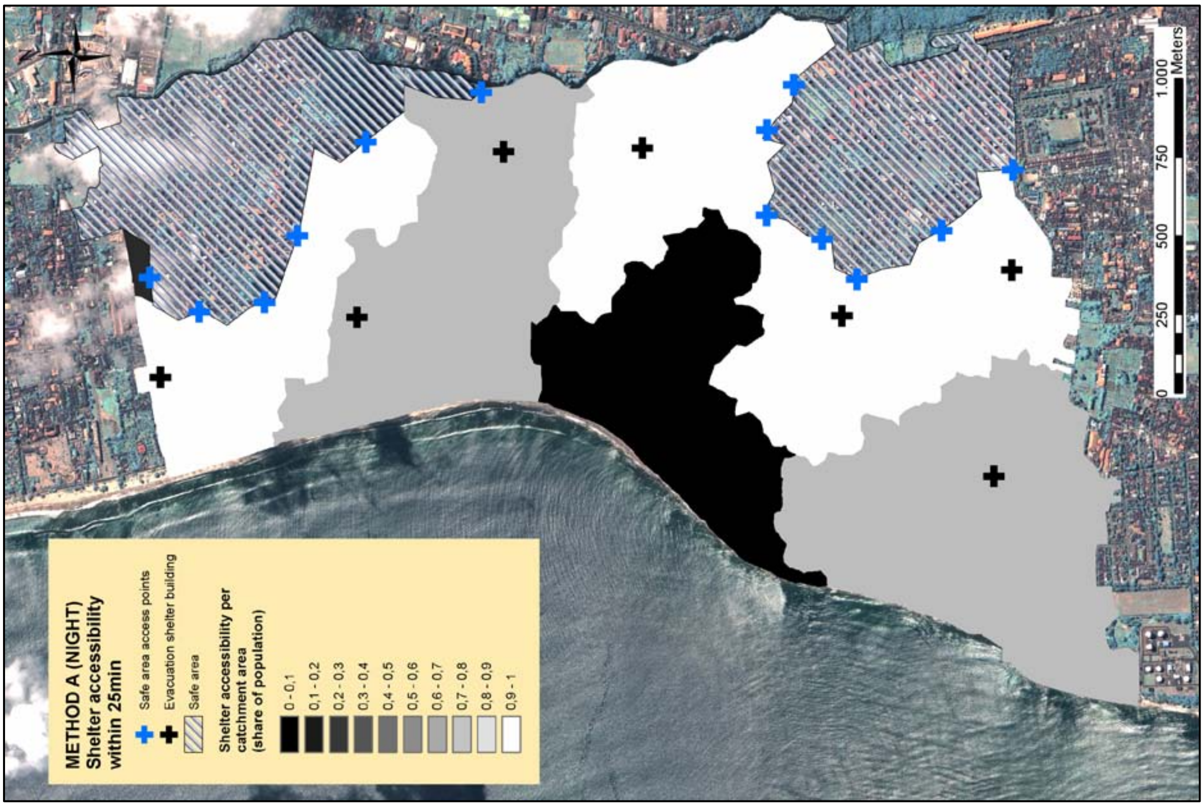
Appendix 3 Standardized questionnaire for the school sector in the study area (Source: own composition)





Appendix 4 Evacuation shelter accessibility within 25 min, calculated for day and nighttime with Method B (own illustration – Data basis: CWD surface; Map basis: catchment areas of the evacuation shelters, population data from Method B)





Appendix 5 Evacuation shelter accessibility within 25 min, calculated for day and nighttime with Method A (own illustration – Data basis: CWD surface; Map basis: catchment areas of the evacuation shelters, population data from Method A)