Technical Documentation

Tsunami Hazard Maps for Bali

Multi-scenario Tsunami Hazard Maps for Bali, 1:100,000

Multi-scenario Tsunami Hazard Maps for Southern Bali, 1:25,000

with zoning based on wave height at coast (in line with the InaTEWS warning levels) as well as probability of areas being affected by a tsunami.

Presented by

Balinese Working Group for Tsunami Hazard Mapping

compiled by

DLR / GTZ

Updated Version!

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1. Executive Summary

Bali is 'paradise' for many of the thousands of tourists who come to visit the island every year. During recent decades Bali's economy has become highly dependent on the tourism industry. Many of Bali's major developments, especially those related to tourism, are located directly on the southern shorelines facing the Indian Ocean. Below the same ocean, a couple of hundred kilometres south of Bali, lies one of the Earth's major tectonic collision zones, which is a major source of tsunamigenic earthquakes. Thus, geologists and tsunami scientists consider Bali a high risk tsunami area, because a large tsunami within range of the island would have a severe impact on its densely populated coastlines.

Bali has experienced major earthquakes and tsunamis in the past. Due to the island's proximity to the subduction zone and its seismic history, the science community presumes that tsunamis will affect Bali again in the future, although a precise prediction is not possible. As preparedness is the key to coping with tsunamis, development of local preparedness strategies is essential. Development of preparedness strategies requires a good understanding of the hazard. An **official tsunami hazard map** provides all stakeholders with a crucial reference for development of preparedness strategies.

An official tsunami hazard map is needed as the basic reference and most important planning tool for developing evacuation strategies and maps and setting up a tsunami early warning system in Bali. The map is also relevant for land use planning and development of mid-term measures to mitigate the possible impacts of tsunamis. Publication of an official tsunami hazard maps at the district and province level **is the responsibility of local governments**.

This paper is a **technical document** that describes the process and the underlying technical concepts of hazard assessment and the mapping process. The maps have been developed in the framework of the establishment of the Indonesian Tsunami Early Warning System (InaTEWS).

The purpose of this document is to provide decision-makers in Bali with background information on the tsunami hazard mapping process. This information will support further discussions and help to initiate the legalization process of the maps. The maps described here are:

- A set of **Multi-scenario Tsunami Hazard Maps for Bali, 1:100,000** covering the Indian Ocean coastlines of Bali, excluding scenarios > 9 M
- A detailed **Multi-scenario Tsunami Hazard Maps for southern Bali, 1:25,000**

The maps show <u>two zones</u> based on wave height at coast (in line with the two warning levels of InaTEWS), <u>probability</u> of areas being affected by a tsunami, and <u>estimated arrival times</u>.

The maps are the product of a multi-institutional effort including Balinese government institutions, Indonesian science institutions, and partners from the GITEWS (German-Indonesian Cooperation for a Tsunami Early Warning System) Project. The institutions involved agreed on the mapping approach and methodology. The maps were produced by DLR (German Aerospace Centre). DLR and the German Technical Cooperation (GTZ) drafted the technical document. The Balinese Working Group for Tsunami Hazard Mapping reviewed the document in March 2009. The document was updated to incorporate results from detailed inundation simulations in July 2009.

2. Background Information on the Tsunami Hazard Map for Southern Bali

Bali is located very close to the collision zone between the Indian-Australian Plate and the Eurasian Plate. The related subduction zone represents the main **source area for tsunamis** that might affect, in particular, the southern part of the island. It should be expected that tsunami waves from this area will need only 30 to 60 minutes to reach the coast. Historical tsunami records related to this source area are the Sumba (1977) and Banyuwangi (1994) tsunamis, which were caused by earthquakes with epicentres in the subduction zone.

Figure 1: Source areas of tsunamis around Bali

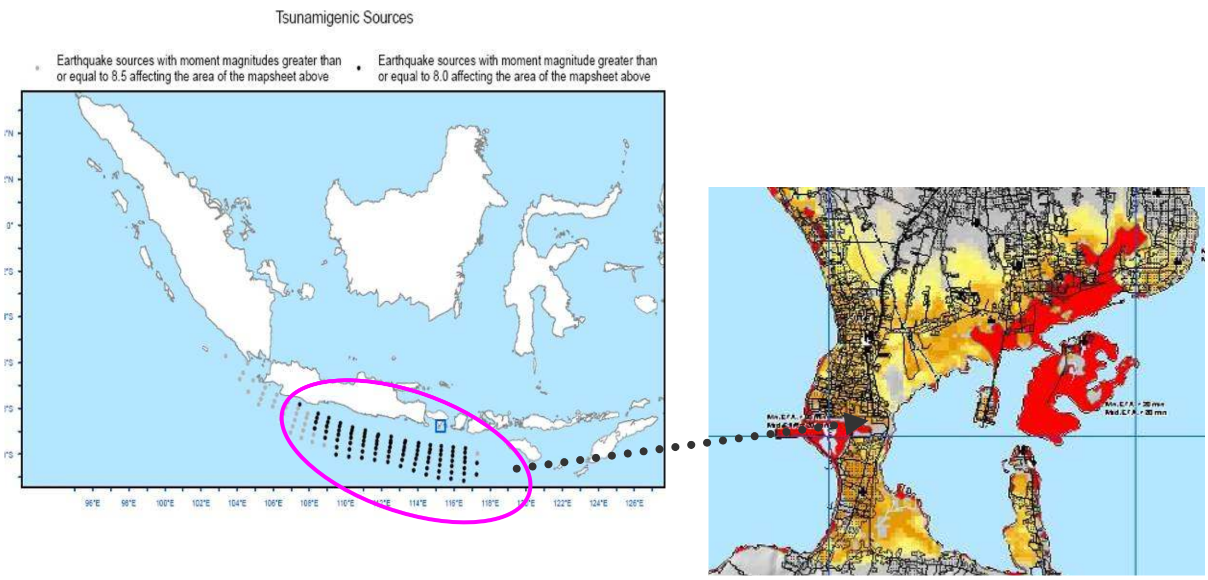
Just off the northern coast of Bali, a back-arc fault is another source area for **local tsunamis**. The Flores Tsunami (1992) was caused by an earthquake in the back-arc zone.

Beside the subduction zone in the Sunda Trench and the back-arc fault, two more sources of tsunami hazard have been identified: submarine landslides and volcanic activity. Submarine landslides are often associated with earthquakes. If they happen during an earthquake, they can increase the energy of a tsunami and therefore add up to the uplift caused by tectonic movements in the subduction zone (which are also caused by the earthquake).

Every tsunami is different! Bali might suffer the impact of a smaller tsunami; but the worst case scenario is also possible. Research on historical tsunami events provides important information about possible events in the future. To understand what might be the possible impact of a tsunami in the future one can look back into the past and learn from **historical experiences** and/or use mathematics to calculate potentially inundated areas using computerized **inundation modelling** tools.

A tsunami hazard map generally visualizes the **tsunami-affected areas** in a given region. In some cases, the maps show only the inundated areas of a tsunami that is considered the **most probable scenario**. Other maps show the affected areas resulting from a number of (hypothetic) tsunami events. This is called a **multi-scenario approach**, because it combines the inundated areas of a variety of tsunamis (or scenarios) in one map.

The tsunami hazard map presented here is a <u>multi-scenario map</u>. It visualizes the impacts on the southern coast of Bali of a large number of potential tsunamis caused by earthquakes of various magnitudes and originating from various locations within the subduction zone. It is important to note that map does not take into account tsunami hazards related to the back arc fault, to submarine landslides and to volcanic activity, because of the very limited information available regarding probabilities, occurrences and possible impacts of these kinds of tsunamis.



A number of hypothetical tsunami sources with different locations and earthquake magnitude were used in the mapping process

The red and yellow colors show the areas affected by the calculated scenarios. Yellow areas are affected only by bigger tsunamis, while the red zone is affected already by smaller tsunamis.

Figure 2: Multi-scenario approach

This **<u>tsunami hazard map is also zoned;</u>** it groups all calculated scenarios into two zones. The red zone represents the area impacted by a tsunami with a wave height at the coast between 0.5 m and 3 m. The orange zone represents areas impacted only by major tsunamis with a calculated wave height at the coast of > 3 m. Both zones are directly linked to the InaTEWS warning levels, as shown below:

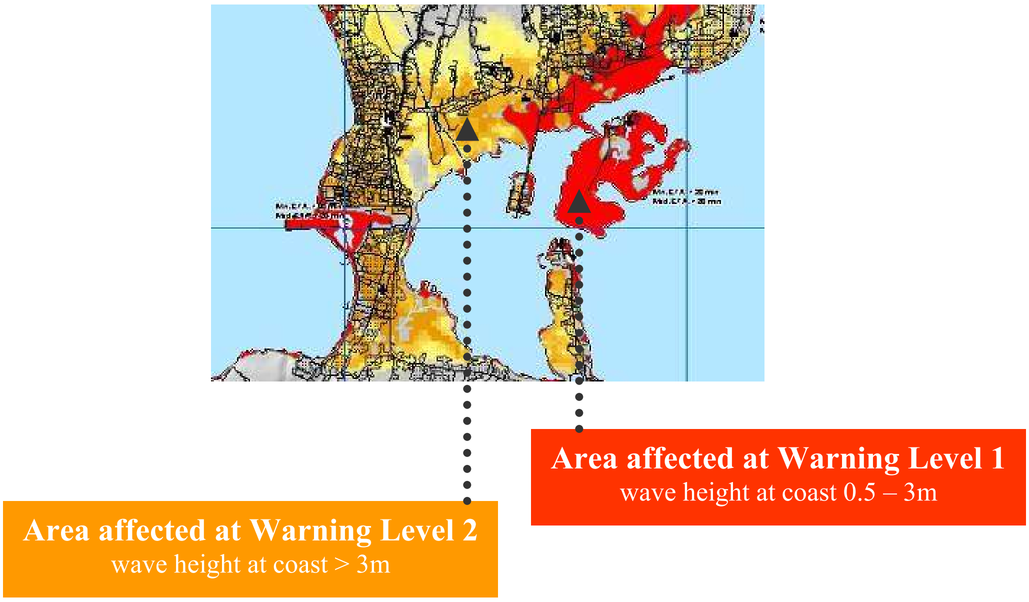


Figure 3: Zoning by wave height and warning level

When assessing the tsunami hazard it is essential to talk about **probabilities**. Tsunamis are a typical example of "**low frequency, high impact**" disasters. In other words, tsunamis do not occur very often, but if they occur, they are very dangerous and can cause great damage. On average every two years a destructive tsunami occurs in Indonesia. At a particular coastal location, however, the recurrence interval between destructive tsunamis can vary from 30-50 years or even 200-300 years. In Indonesia, most tsunamis are generated by submarine earthquakes. Tsunamis triggered by volcanic activity are much rarer events. Smaller tsunamis happen much more frequently than major tsunamis (and worst case tsunamis).

The **multi-scenario hazard map provides information about tsunami probabilities**. Red indicates the area that will be affected by tsunamis with a wave height between 0.5 m and 3 m. The range of colours from dark yellow to grey indicates the probability of an area being affected by a major tsunami.

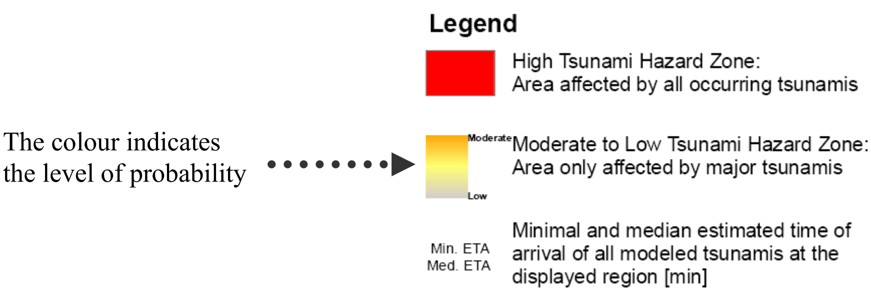


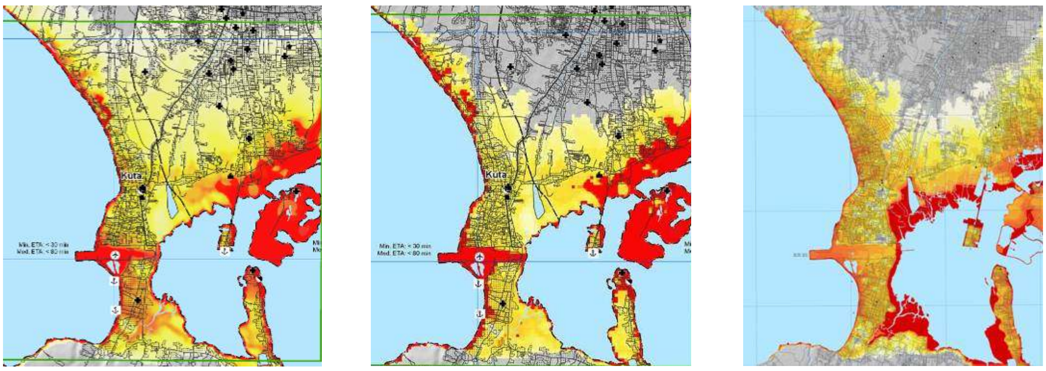
Figure 4: Visualisation of probabilities on the map

The question of probabilities leads directly to discussion about **acceptable risk**. Due to the infrequent occurrence of tsunamis, information about their possible impact, occurrence and run up heights is uncertain. It must be assumed that no action can take into account all possible risks, and that some degree of risk must be accepted due to economic reasons. Discussion about acceptable risks requires decisions that are often very difficult to make, because they involve choices, trade-offs and risks.

In the case of Bali, one question related to probability and acceptable risk is directly related to the decision whether magnitude 9 earthquakes should be considered on the multi-scenario map or not. Scientists agree that a magnitude 9 earthquake south of Bali is very unlikely; but on the other hand they also say that the available scientific data is not sufficient to completely exclude that possibility.

The broad-scale maps (1:100,000) that include magnitude 9 scenarios (see figure 5, map on the left) show extreme inundation areas that seem rather unlikely and hardly manageable in terms of evacuation planning. When using more detailed topography and bathymetry data (only available for a small area of southern Bali!) for modelling on a 1:25,000 scale (see figure 5, map on the right) these large inundation areas are reduced significantly resulting in more credible and manageable areas. Therefore for planning purposes in southern Bali the 1:25,000 map should be used.

For all other areas not covered by detailed modelling it is suggested to use the set of broad scale hazard map (1:100,000) that excludes magnitude 9 scenarios, as the inundation areas of these maps (see figure 5, map in the center) match much better with the more credible results from detailed modelling (1:25,000).



1:100,000 including M9 | 1:100,000 excluding M9 | 1:25,000 including M9

Figure 5: Comparison of results of broad-scale and detailed mapping

3. Background Information on the Mapping Process

3.1. German Indonesian Cooperation in the Framework of InaTEWS

The German government supports the implementation of a tsunami early warning system in the Indian Ocean – especially in Indonesia – through the GITEWS project (German-Indonesian Cooperation for a Tsunami Early Warning System). Funded by the German Ministry of Education and Research (BMBF), GITEWS is part of a bilateral cooperation between the governments of Indonesia and Germany, based on a joint agreement between BMBF and the Indonesian State Ministry of Research and Technology (RISTEK). The warning concept, which was developed under the guidance of the Potsdam Geo Research Centre (GFZ) and in cooperation with national and international partners, will significantly reduce warning times by making use of real-time data transfer, predetermined flooding scenarios in coastal regions, and direct warning reports. The two-year operational phase of German support for InaTEWS began in November 2008.

The scope of this cooperation covers not only the technical aspects of the early warning system, but also hazard, vulnerability and risk assessment, production of maps for the project area, and capacity building. The German cooperation partner for hazard, vulnerability and risk assessments is the German Aerospace Centre (DLR). The cooperation is coordinated and developed within the framework of the Indonesian-German Working Group on Vulnerability Modelling and Risk Assessment (see 3.2.).

Within the framework of local capacity building for tsunami early warning, the German Technical Cooperation-International Services (GTZ IS) has been supporting the Bali provincial government since the end of 2006 in the development of tsunami early warning procedures and mechanisms, clarification of roles in receiving and issuing warnings, and in overall preparedness planning. This cooperation is based on agreements with the provincial government and Badung district government.

3.2. Indonesian-German Working Group on Vulnerability Modelling and Risk Assessment

Risk and vulnerability assessment is an important component of an effective tsunami early warning system, and contributes significantly to disaster risk reduction. Knowledge of exposed communities, their vulnerabilities, and coping and adaptation mechanisms, is a precondition for the development of people-centred warning structures, local evacuation planning and recovery planning. In the past, the vulnerability was quantified based on economic damage assessments. However, based on the three pillars of sustainable development, this working group applied indicators for physical and social, as well as economic, dimensions of vulnerability.

The approach has been developed within the framework of the joint **Indonesian-German Working Group on Vulnerability Modelling and Risk Assessment**, which is coordinated by the Indonesian Institute of Science (LIPI) and the German Aerospace Centre (DLR), with contributions from Indonesian, German and international organizations, such as LAPAN, BAKOPSURTANAL, BPPT, DKP, AWI, GKKS and UNU-EHS. Its goal is to develop indicators to assess the vulnerability of coastal areas of Sumatra, Java and Bali exposed to tsunami hazard on a broad scale; and on a more detailed scale of the three pilot areas of Padang, Cilacap and Kuta. The major task is to conduct hazard assessments, and physical and socio-economic vulnerability assessments, and to produce risk and vulnerability maps and guidelines for decision makers on how to monitor risks and carry out continuous risk assessment, for effective early warning and disaster mitigation strategies.

3.3. Tsunami Hazard Mapping within the Framework of GITEWS

Within the framework of the GITEWS project, large-scale hazard maps (1:100,000) are produced, covering the whole west and south coast of Sumatra as well as the south coasts of Java and Bali. Additionally, detailed hazard maps (1:25,000) are produced for the three pilot areas of Padang, Cilacap and Kuta. During three workshops conducted in Indonesia, with participants from national and local government and research groups from various institutes, the layout and the content of the hazard and risk maps were discussed and agreed.

3.4. The Tsunami Hazard Mapping Process in Bali

Bali needs to develop a clear framework for tsunami preparedness to ensure that activities implemented by the various actors share a common goal and do not conflict with each other. Preparing an official tsunami hazard map is a priority task in achieving this goal.

Several maps related to tsunami hazards, risks and evacuation planning were available for Bali in 2008. None of them, however, could be considered the official map (see Figure 6).

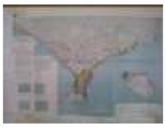
Map	Institution	Type	Zoning
	BAPPEDA	Tsunami zoning map with reference to Aceh tsunami (max. 33 m run-up)	**Zoning according topography:** Tsunami Potential medium (elevation 30-40m) Tsunami Potential high (elevation 0-30m)
	BPPT (2006)	Tsunami “Run Up Map” for scenario M 8.9 (developed for Tsunami Drill 2006)	**Zoning according flow depth:** Flow depth 0-0.1 m Flow depth 0.1-1 m Flow depth 1-2 m Flow depth 2-3 m Flow depth 3-5 m Flow depth 5-8 m Flow depth 8-15 m
	Badan Geologi CVGHM (2007)	Tsunami Hazard Prone Map based on worst case scenario M 9, 300x50km rupture south of Bali, depth 10 km, reverse fault	**Zoning based on elevation and inundation** Tsunami Prone Area: high *Elev. <10m / inund. max. 4.5 km* Tsunami Prone Area: moderate *Elev. 10-17m / inund.. ~7.8 km* Tsunami Prone Area: low *Elev. 17-25m / inund. ~ 8.3 km*
	DLR: multiscenario (Draft 2008)	Hazard Map showing affected areas by several hundreds of different scenarios with EQ-magnitudes between 7.5 and 9	**2 Zones related to BMG warning levels:** Impacted area if wave height at coast 0.5-3 m (Warning Level 1) Impacted area if wave height at coast >3 m (Warning Level 2)
	DKP (2005)	Evacuation Map based on inundation prediction: the map was built by using 'same level approximation', topographic data based on Global SRTM and the inundation height was modeled by the 1977 Sumba Tsunami (tsunami wave height in the coastline as the result of the model was 5.2 meter)	**Zoning according inundation prediction:** Inundation height 1m Inundation height 2m Inundation height 3m Inundation height 4m Inundation height 5m

Figure 6: The various approaches to tsunami hazard mapping in Bali (August 2008)

To revise all existing mapping approaches and explore knowledge of tsunami sources and impacts for Bali, a **Consultation Workshop on Tsunami Hazard Mapping in Bali** was organized by Bali provincial government with support from GTZ-IS. During the workshop, held on 7 - 8 July 2008, in Denpasar, Bali, participants from national institutions (BAKOSURTANAL, BPPT, BMKG, CGS, CVGHM, DKP, National LAPAN, and LIPI), international research institutes (AWI, DHI, DLR, GKSS), local institutions (Regional Development Planning Agency, Civil Defence, Public Works, Indonesian Military), and other stakeholders (IDEP, PMI, SAR, SEACORM), gathered to achieve a better understanding of tsunami hazards and the possible impacts for Bali to help local decision-makers and other stakeholders get better prepared for future tsunami events.

During the workshop, the researchers recommended developing a **multi-scenario map** that incorporated all scenarios taken into consideration by the various institutions. This recommendation was based on the fact that current scientific knowledge is unable to identify the most probable scenario. A multi-scenario approach combines the impacts of a large number of calculated tsunami scenarios (generated by numeric modelling) on one map.

It was agreed that the German Aerospace Centre (DLR) would integrate the scenarios developed by GITEWS and the scenarios from Indonesian partner institutions into a **Multi-Scenario Tsunami Hazard Map for Southern Bali** (scale 1:100.000). An updated version was presented at the International Conference for Tsunami Warning, in Bali, in November 2008. A second map, excluding the less probable > magnitude 9 scenario, was handed over in February 2009.

In July 2009, from detailed inundation modelling using revised data for the target area, a detailed 1:25.000 scale map for southern Bali was produced. Additional maps covering the entire Indian Ocean coast of Bali were also produced.

A **Balinese working group** with representatives from the National Unity and Community Protection Agency, the Regional Development Planning Agency and Public Works was formed to steer and participate in the mapping process. This paper presents a consolidated map and a technical report for the Balinese authorities for further consideration and official recognition.

4. Methodology

The approach used for developing the tsunami hazard map is a combination of the results of probability analyses and multi-scenario tsunami modelling. A large number of realistic tsunami scenarios, using various tsunami source locations and earthquake magnitudes along the Sunda Trench, have been calculated. Together, these scenarios cover the entire Indian Ocean coast of Sumatra, Java and Bali. These scenarios were used as input data for the hazard maps. The approach is based on an "event tree technique", which takes into account the various warning levels that are issued from the Tsunami Warning Centre. The warning levels defined in the InaTEWS (BMKG 2008) are as follows:

Tsunami Category	Warning Level	Wave Height (WH) Range [m]
<none>	<none>	0.0 = WH < 0.1
Minor Tsunami	Advisory	0.1 = WH < 0.5
Tsunami	Warning	0.5 = WH < 3.0
Major Tsunami	Major Warning	WH ≥ 3.0

Figure 7: InaTEWS warning levels (BMKG 2008).

A minor tsunami of the Advisory warning level causes little or no inundation at the coast. Hence, in this hazard mapping approach, the "advisory" and "warning" warning levels are combined. The approach used to produce a comprehensive tsunami hazard probability map involves six steps:

1. **Determine the tsunami scenarios that are relevant to the target area:** As a first step, all the scenarios that are relevant to the target area are selected from the tsunami scenario database. This involves running a spatial data query and selecting all scenarios that result in inundation of at least one point on land in the target area (e.g. using a map). The selected scenarios provide the basis for further assessment.

2. **Group the scenarios by warning level:** The second step is to group all selected scenarios into two categories of warning level. A database query asking "Which scenarios generate a wave height at coast over 3 m?" is performed. Defining the outline of the consolidated inundation of the classes produces a first map showing maximum inundation areas for each of the warning levels (Figure 8). On the final hazard map, only the zone generated by the class "wave heights at coast ≤ 3 m" is displayed (red zone in Figure 8). The other zone is substituted by a calculation of continuous tsunami impact probabilities, which is described in the steps below.

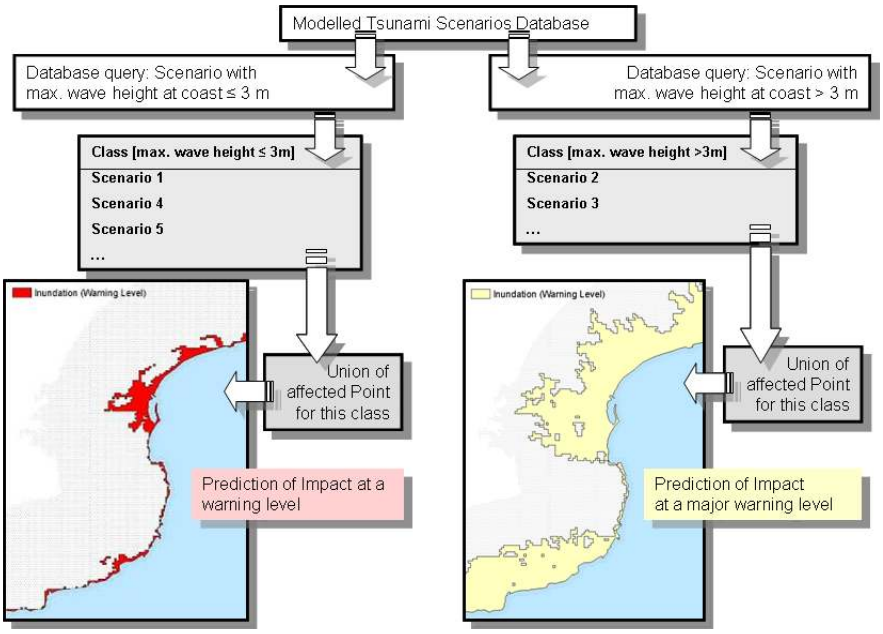


Figure 8: Grouping of tsunami modelling results by warning level

3. **Estimate the spatial distributed probability of earthquakes of specific magnitudes along the Sunda Trench:** Due to the fact that submarine earthquakes of high magnitudes occur far less frequently than earthquakes of lower magnitudes, scenarios with higher earthquake magnitudes (moment magnitude M_w) must given a lower weighting in the analysis, since the probability of a higher magnitude earthquake occurring is lower. Similarly some regions along the Sunda Trench show higher seismic activity than other regions, and some spots are characterized by special geologic conditions, such as a strong coupling of the plates in the subduction zone, which means there is a higher probability of the occurrence of high magnitude earthquakes. This means that inundation by a tsunami event caused by an earthquake with a high magnitude at a region with low seismic activity is less likely than a tsunami event caused by a lower magnitude earthquake in an earthquake hot spot. Therefore, a probability analysis of earthquake occurrence must be performed.

   This analysis involves two steps. First, the Sunda Trench region is divided into three smaller zones, by seismic activity (these have been widely published, e.g. Latief, Puspito & Imamura 2000, and can be also determined by a statistical analysis of historical earthquake data). The probability of an annual recurrence of an earthquake of each Mw is estimated using historical earthquake data (NEIC). To improve the analysis, topical investigations, such as deterministic models, are considered by weighting the occurrence probabilities between 1 (for a known hot spot where the probability of the occurrence of an earthquake of high magnitude is high) and 0.1 (for unidentified or "inactive" spots). Figure 9 presents an example of the results of weighted earthquake occurrence probability for a specific Mw. Thus, each tsunamigenic source has an individual occurrence probability (Note that the probability of an earthquake also generating a significant tsunami is included in the numerical tsunami model approach).

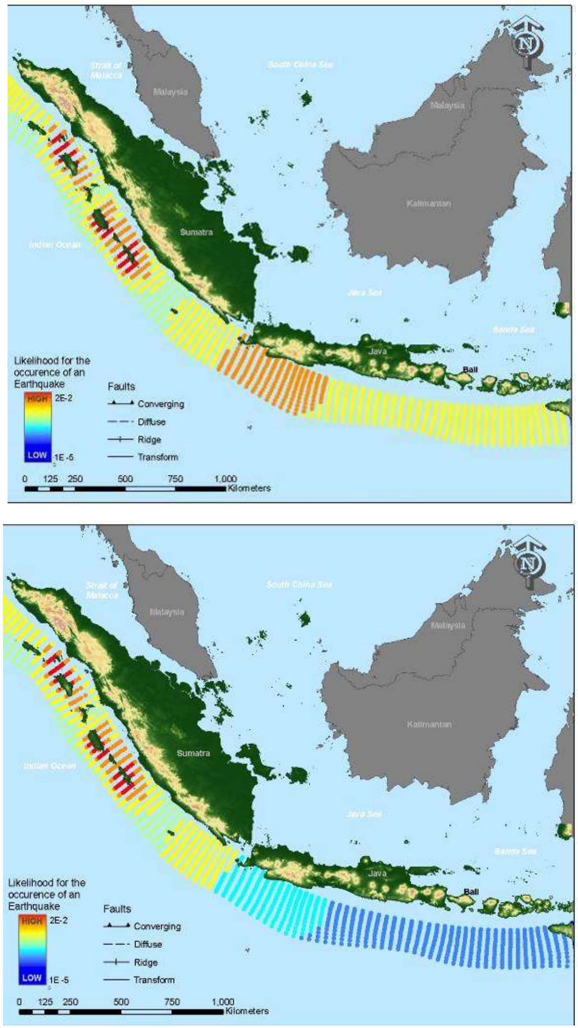


Figure 9: Analysis of the spatially differentiated probabilities of the occurrence of an earthquake of a specific magnitude along the Sunda Trench (upper figure: Mw 8.0, lower figure: Mw 9.0).

4. **Determine the spatially differentiated inundation probability:** This step involves determining a spatial differentiation for the probability of a coastal area being inundated (spatial inundation probability). The results of the modelled tsunami scenarios include their impacts on land, i.e. the area on land that will be inundated as a result of a tsunami originating from specific location and of a specific magnitude. The impacted areas of the various scenarios may, of course, overlap each other (either because the tsunami source locations are close in proximity or because they originate from same location and the scenarios differ only in terms of the magnitude of the submarine earthquake). Hence every point on land may be inundated several times in different scenarios. As a general example, a point near the coast is more likely to be frequently inundated than a point far away from the coast. Calculation of the inundation probability in a coastal area is represented by points on a grid, about 100 m apart. So, for each point on the grid (every 100 m point inland along the whole coast), the number of

scenarios that hit that point is calculated. For these selected scenarios the occurrence probabilities of their tsunami source (estimated in step 3) are summed up and divided by the number scenarios. Hence, the occurrence probability represents the probability that this point will be hit by a tsunami within a year. Figure 10 shows the query for the relevant scenarios and the total of the probabilities at one point on land. For display on a hazard map, the discrete points on land are interpolated.

Figure 11 summarises the workflow for producing tsunami impact probability maps using the event tree technique.

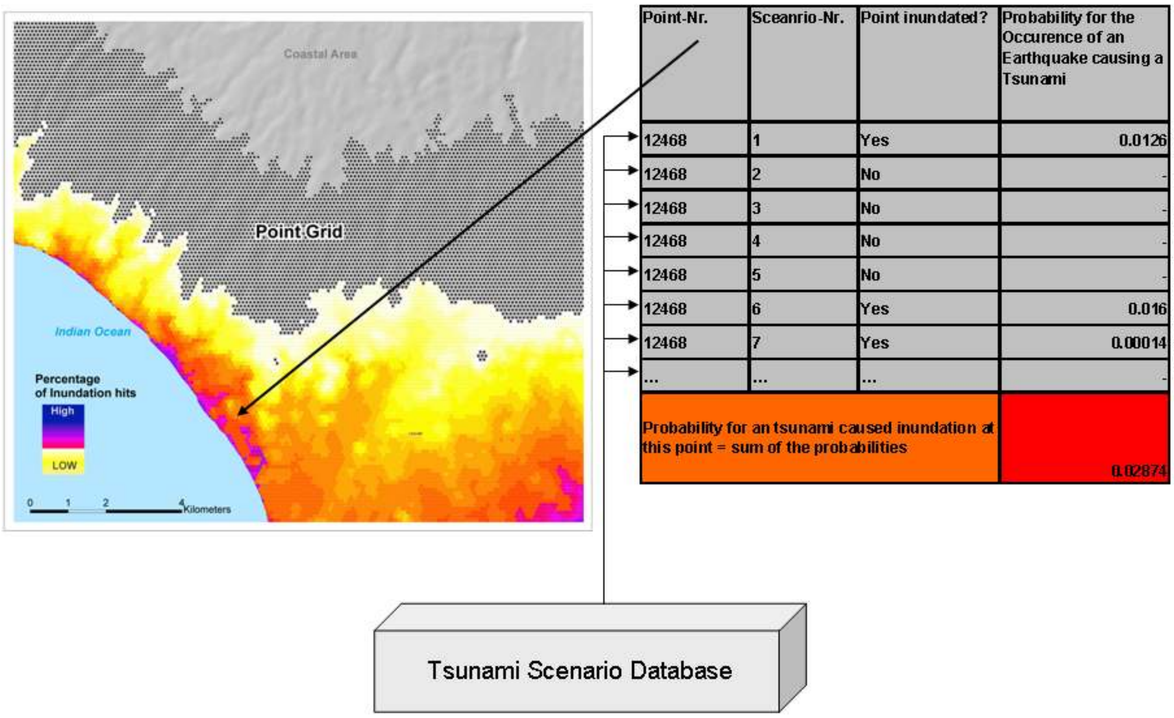


Figure 10: Example of the calculation of the inundation probability for one point on land.

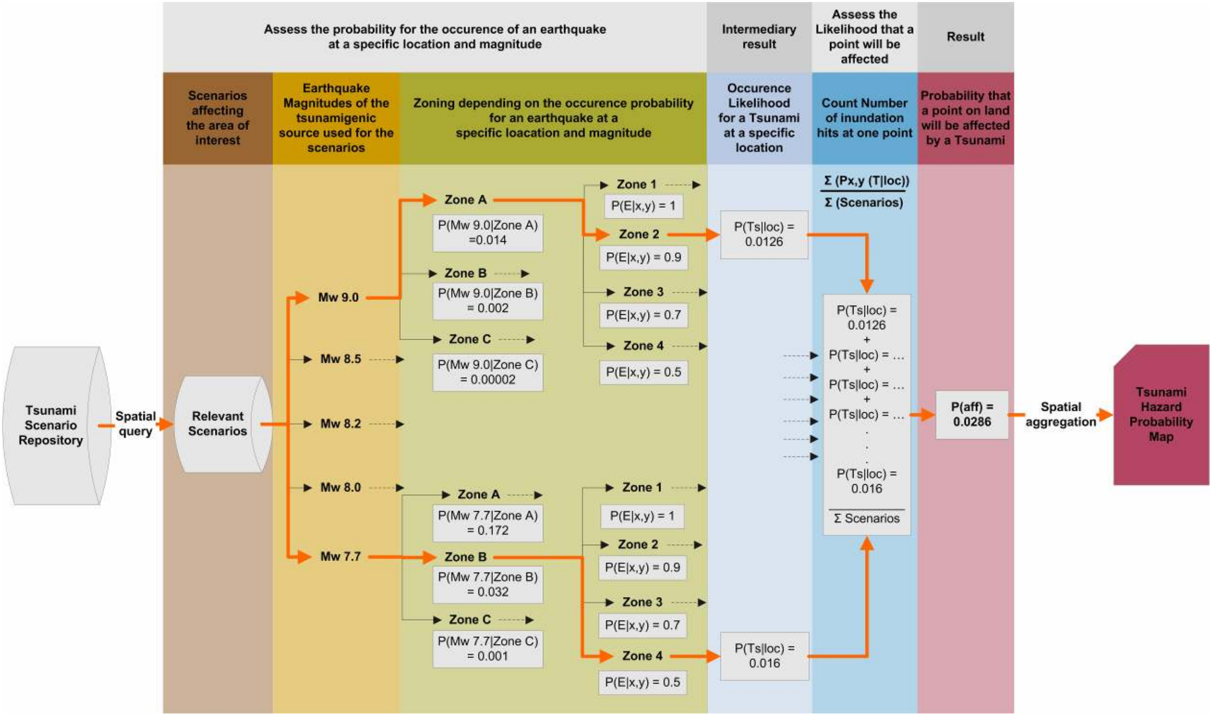


Figure 11: Overview of the workflow for processing the hazard probability maps.

Using this approach, continuous hazard probability calculations are obtained. The hazard maps show only the probabilities for the major warning zones (moderate to low probability). The areas that will be affected in a 'warning level' situation are displayed on the hazard maps as red zones. The zone is derived as described in Step 1.

5. **Combine the continuous probability with the "warning level" zone:** In this step, the continuous tsunami impact probability is overlaid on the "warning level" zone derived from step 2 on the hazard map

6. **Add additional parameters to the map**: To supplement the information on the inundation areas, additional parameters are incorporated into the hazard map that characterize the potential tsunami danger of a coastal area. Each modelled scenario includes the estimated time of arrival (ETA) of the first tsunami wave hitting the coast. The ETA can vary to a great extent, depending, in general, on the distance from the coast to the tsunamogenic source and the magnitude of the earthquake. To provide a valid value for the ETA from all possible scenarios, two values are shown on the hazard map. The min. ETA represents the minimum ETA, derived from all possible scenarios. This is the worst case for that specific point in on the map. But as this can be a very rare event, the med. ETA is also stated on the map. This value is the median of the minimum ETAs of all scenarios for that area. These values can be taken as an estimate of the time to respond after the earthquake event happened (see Figure 12).

Figure 12: Example of the ETA values displayed on the hazard maps.

The tsunamigenic sources relevant to the area are also displayed on the hazard map. They are divided into sources of high magnitude earthquakes (which are widely dispersed along the Sunda trench) and sources of lower magnitude earthquakes (which are generally closer to the coast). This information can be used to assess whether an earthquake is likely result in a tsunami affecting the area on the map (see Figure 13).

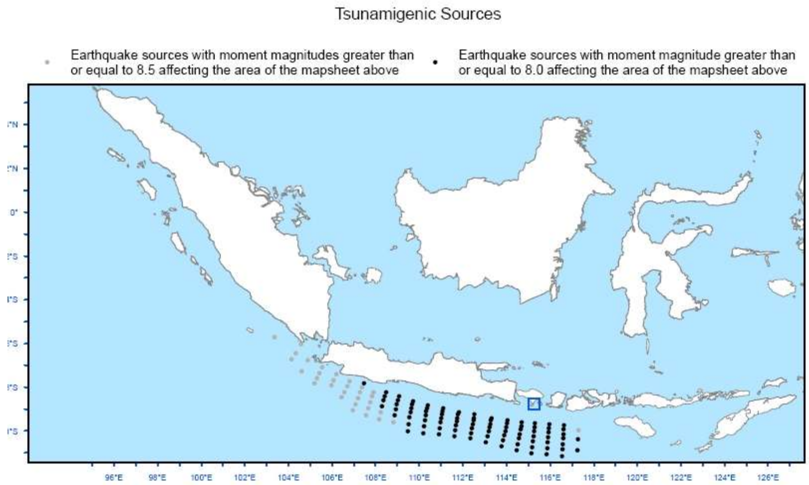


Figure 13: Example of tsunamigenic sources displayed on the map.

5. The Maps

Large Scale Tsunami Hazard Maps (1:100,000) are available for the entire Indian Ocean coastline of Bali.

The database for this approach consists of the results of the tsunami modelling performed by GITEWS partner AWI (Alfred Wegener Institute) at epicentre locations (source grid) for tsunami scenarios provided by GFZ (German Research Centre for Geosciences, 2008). The area modelled covers the south coasts of Sumatra, Java and Bali. The datasets used are global coverage GEBCO data (bathymetry data) and global coverage SRTM data (topography data). The results of the tsunami modelling based on these global datasets provide a level of detail usable only for maps of a scale of 1:100,000 or below.

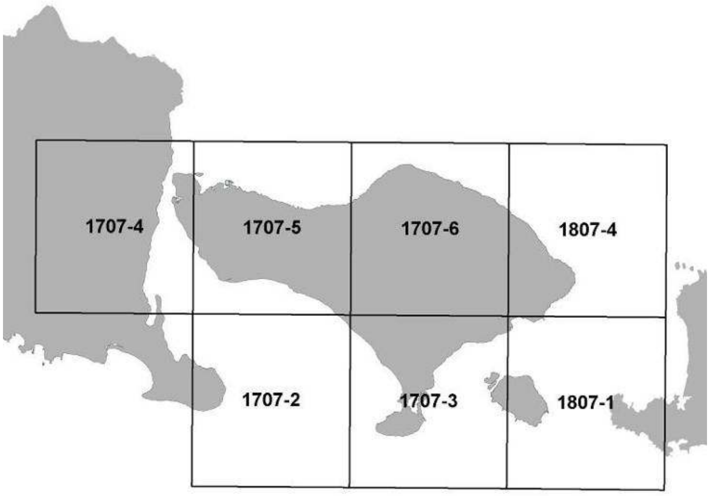


Figure 14: Available tsunami hazard maps of a scale of 1 : 100 000 for Bali. Numbers and locations of map sheets and map numbers are based on National Coordinating Body for Survey and Mapping reference system

For the area around Badung District in southern Bali a **detailed Tsunami Hazard Map** of a scale of 1:25 000 was developed.

The method used to produce this hazard map is the same as for the 1:100 000 hazard map series. For detailed inundation modelling the MIKE21 FM model from DHI-Wasy GmbH was used, and run-up modelling was performed by GKSS and DHI-Wasy. Initial bottom deformation and sea surface height as well as time series of water level elevation at the open boundaries were provided by AWI and GFZ in the frame of the GITEWS project. Spatial resolution used in modelling is between several hundreds of meters to ten meters, allowing for representation at a map scale of 1 : 25,000. The number of tsunami inundation scenarios used was 137, with moment magnitudes of 8.0, 8.5 and 9.0. The bathymetry is based on GEBCO data, C-Map data and echosounder measurements performed by BPPT and DHI-Wasy. The topography is based on digital surface model, street and building data, provided by DLR, and differential GPS measurements performed by DHI-Wasy.

The Detailed Tsunami Hazard Map (1:25,000) for Southern Bali

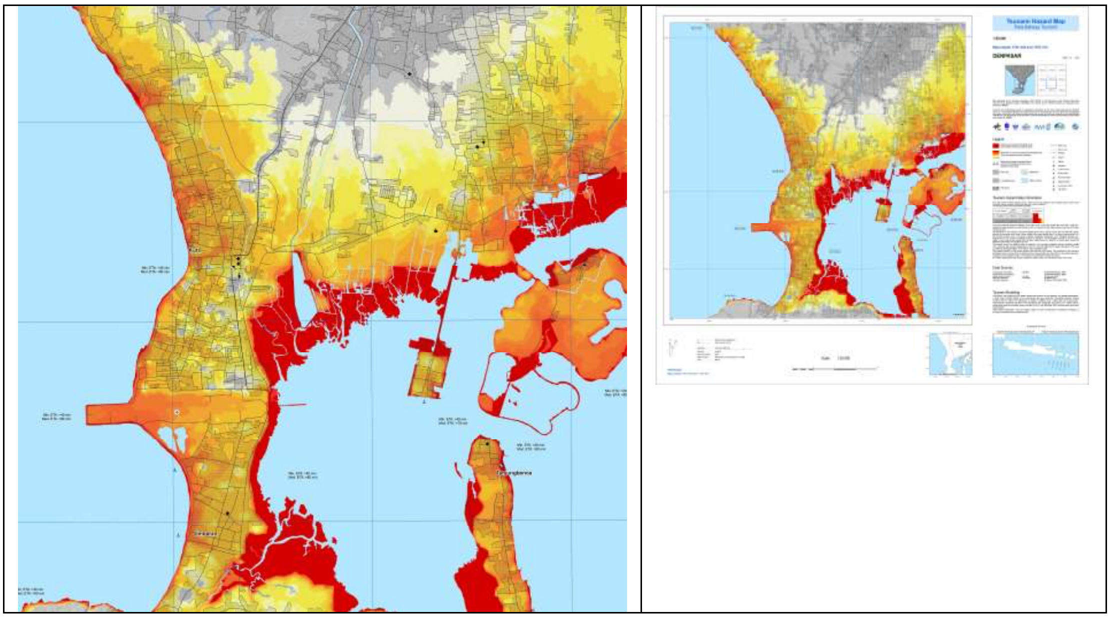


Figure 15: Hazard map of a 1:25,000 scale, based on detailed topographic and bathymetric data
(Only tsunamis from Subduction Zone source area!)

The Large Scale Tsunami Hazard Maps (1:100,000)

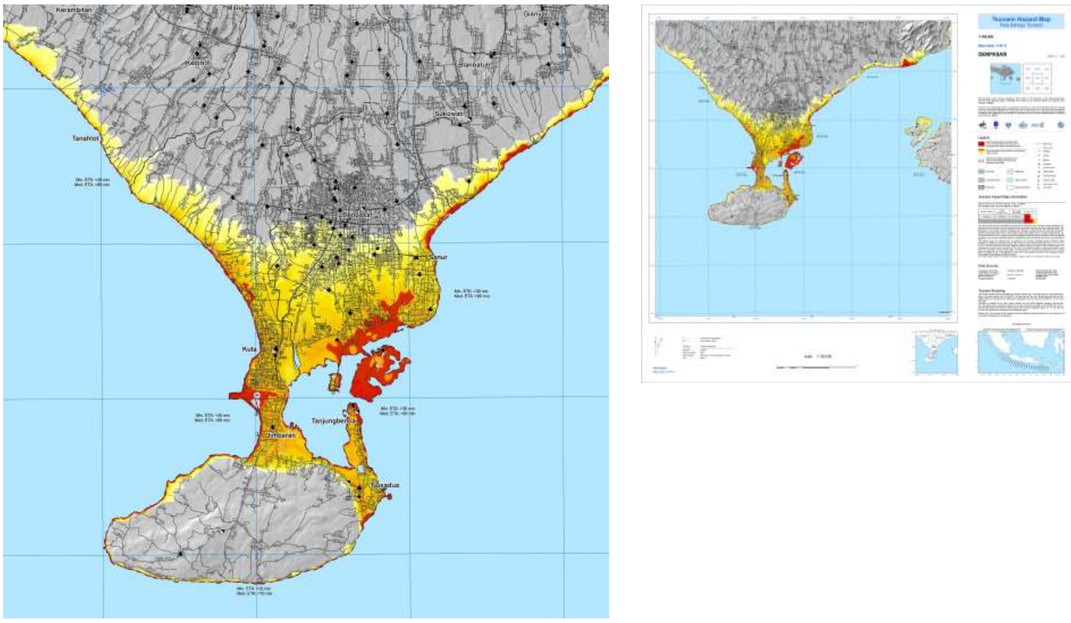


Figure 16: Tsunami Hazard Map 1707-3
Green box indicates the location of detailed 1:25,000 hazard map (see Figure 15)
(Only tsunamis from Subduction Zone source area!)

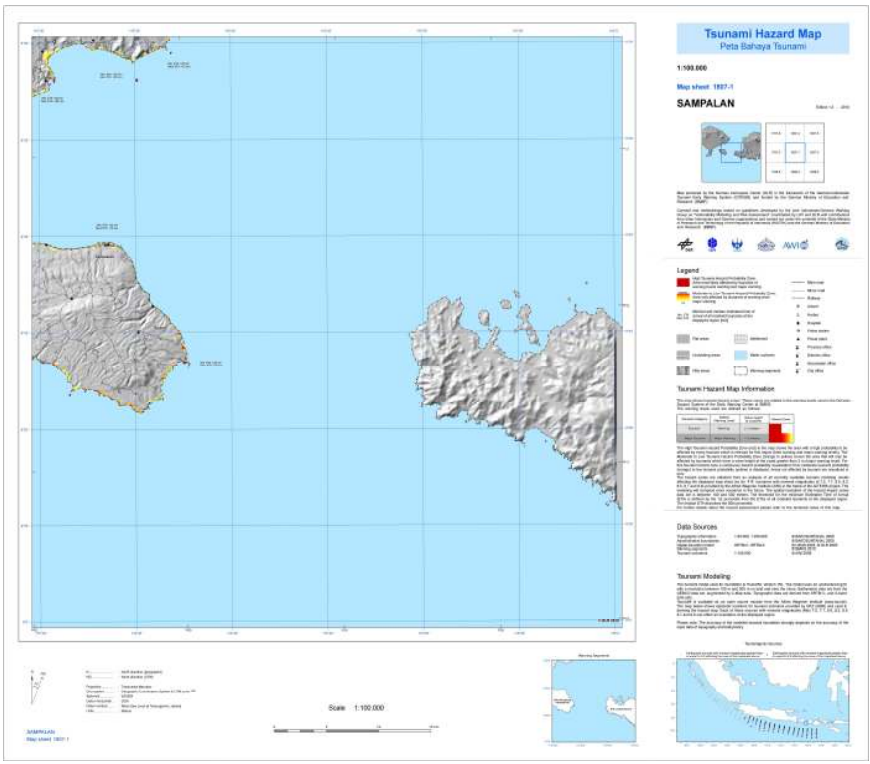


Figure 17: Tsunami Hazard Map 1807-1
(Only tsunamis from Subduction Zone source area!)

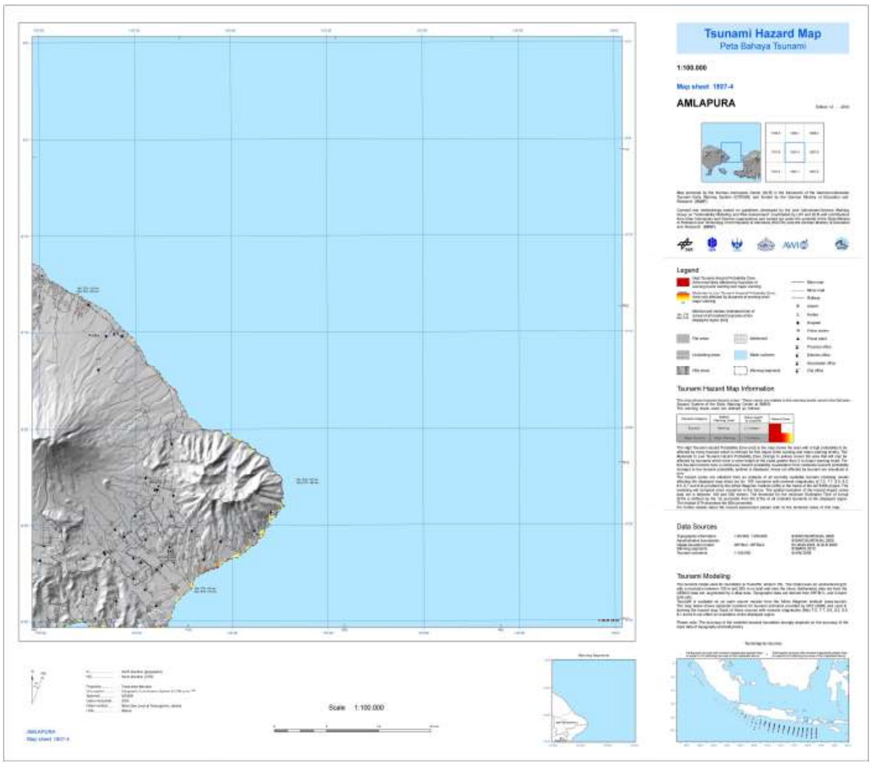


Figure 18: Tsunami Hazard Map 1807-4
(Only tsunamis from Subduction Zone source area!)

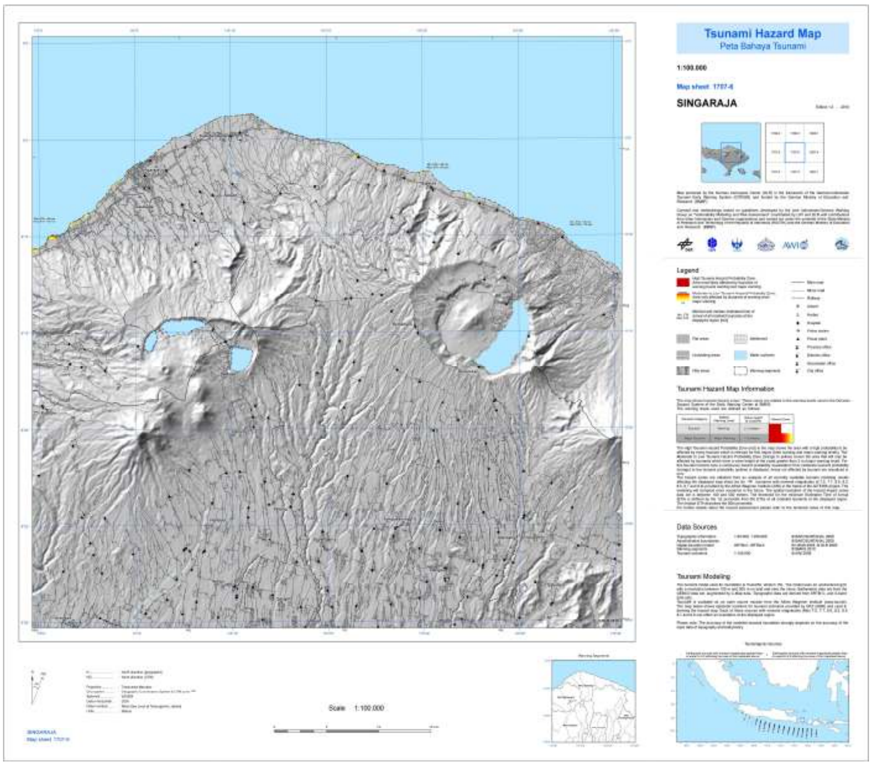


Figure 19: Tsunami Hazard Map 1707-6
(Only tsunamis from Subduction Zone source area!)

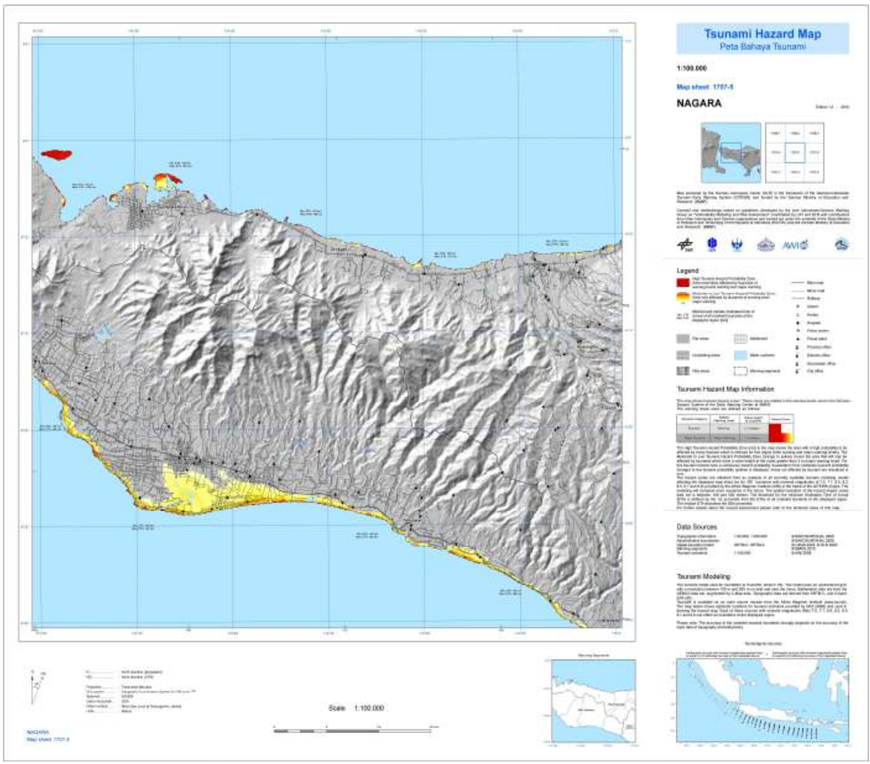


Figure 20: Tsunami Hazard Map 1707-5
(Only tsunamis from Subduction Zone source area!)

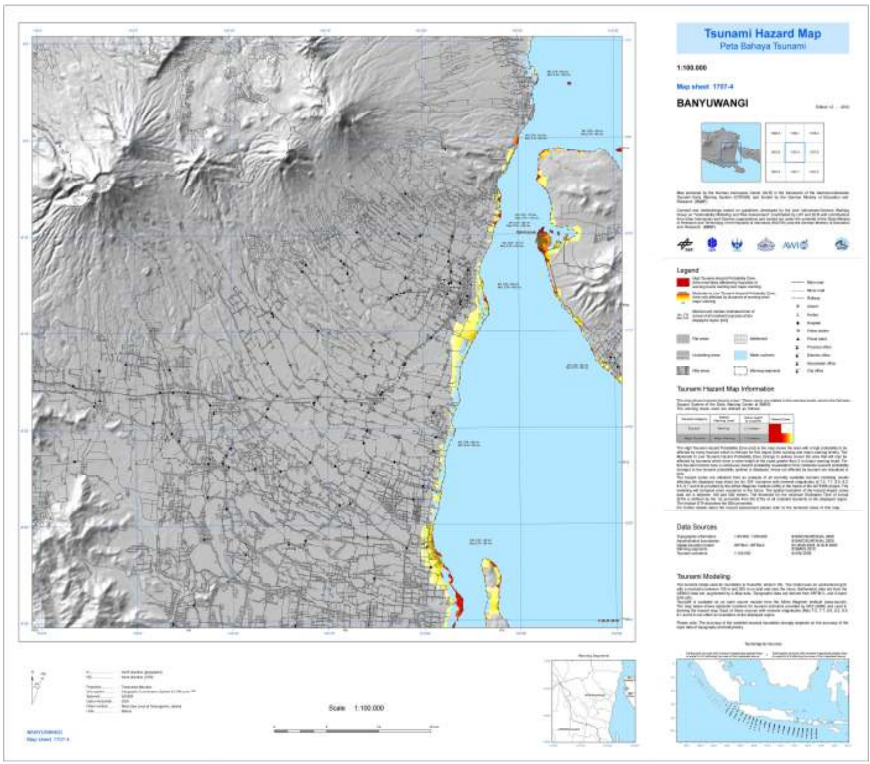


Figure 21: Tsunami Hazard Map 1707-4
(Only tsunamis from Subduction Zone source area!)

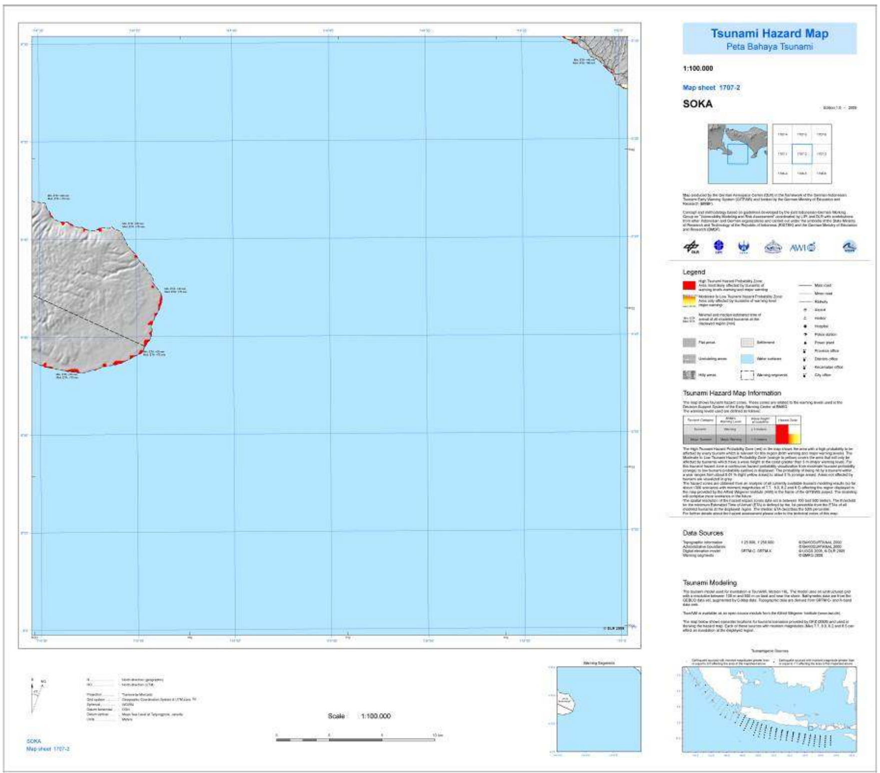


Figure 22: Tsunami Hazard Map 1707-2
(Only tsunamis from Subduction Zone source area!)

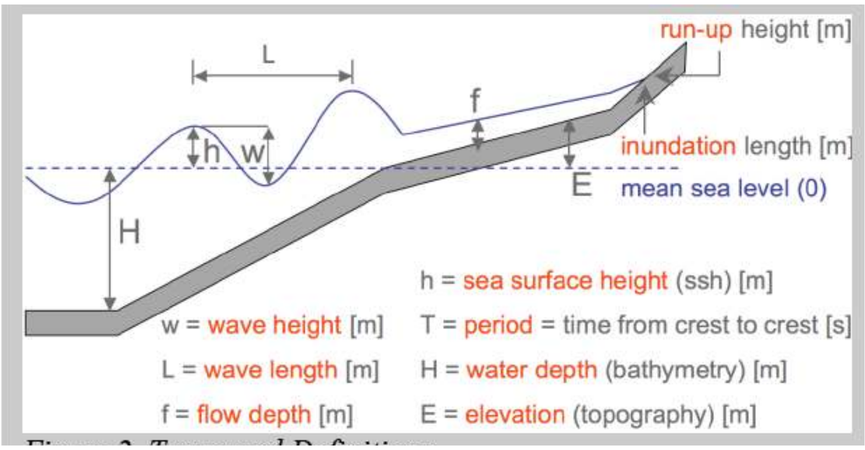
6. Definitions

This section presents commonly used terms and definitions that are used throughout this document. The terms correspond with those in the UNESCO-IOC Tsunami Glossary.

Tsunamigenic source: Source causing a tsunami. In this context, a location of a submarine earthquake of a specific magnitude.

Tsunami inundation area: Area flooded with water by a tsunami

Estimated Time of Arrival / Tsunami Arrival Time (ETA): Time taken for a tsunami to arrive at a specific fixed location, estimated by modelling the speed and refraction of the tsunami waves as they travel from the source. ETA can be estimated with very good precision (± 2 minutes) if the bathymetry and source are well known. The first wave is not necessarily the largest, but one of the first five waves usually is.



Water depth (bathymetry): The depth of water measured from mean sea level downwards [m].

Elevation (topography): The land elevation above mean sea [m].

Flow depth: The water depth above land surface in case of inundation, and is a time dependent value, given in meters [m].

Wave height: The height of a wave from crest to trough in meters [m].

Inundation length (inundation distance): The distance from shore inundated by water, given in meters [m]. Inundation is usually defined as at least 10 cm flow depth.

Run-up height: The height above mean sea level at the line of inundation, given in meters [m].

7. Abbreviations

AWI	= Alfred Wegener Institute
BAKORSURTANAL	= Badan Koordinasi Survei dan Pemetaan Nasional (National Coordinating Body for Survey and Mapping)
BAPPEDA	= Badan Perencanaan Pembangunan Daerah (Local Planning Board)
BMBF	= German Ministry of Education and Research
BMKG	= Badan Metereologi dan Geofisika (National Agency for Meteorlogy, Klimatology, and Geophysics)
CGS	= Centre for Geological Survey
CVGHM	= Centre Volcanology and Geological Hazard Mitigation
DHI	= DHI-WASY GmbH
DKP	= Departemen Kelautan dan Perikanan (Department for Marine and Fisheries)
DLR	= German Aerospace Center
ETA	= Estimated Time of Arrival
GFZ	= German Research Centre for Geosciences
GKSS	= Research Center Geesthacht
GITEWS	= German-Indonesian Tsunami Early Warning System
GTZ	= German Technical Cooperation
GEBCO	= General Bathymetric Chart of the Oceans
KESBANGPOLLINMAS	= Kesatuan Bangsa, Politik, dan Perlindungan Masyarakat (Civil Defence)
InaTEWS	= Indonesian Tsunami Early Warning System
LAPAN	= Lembaga Penerbangan dan Antariksa Nasional (National Aeronautics and Space Institute)

LIPI	= Lembaga Ilmu Pengetahuan Indonesia (Indonesian Institute of Sciences)
PMI	= Palang Merah Indonesia (Indonesian Red Cross)
PU	= Pekerjaan Umum (Public Works)
RISTEK	= Kementrian Negara Riset dan Teknologi (State Minister of Research and Technology)
SAR	= Search and Rescue
SEACORM	= Southeast Asia Center for Ocean Research and Monitoring
SRTM	= Shuttle Radar Topographic Mission
SR	= Skala Richter (Richter Scale)
TNI	= Tentara Nasional Indonesia
UNU-EHS	= United Nations University –Environment and Human Security