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Jörn Lauterjung, Horst Letz (Editors)

10 Years Indonesian Tsunami Early Warning System: Experiences, Lessons Learned and Outlook

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Preface

We will never forget the terrifying images of devastation and wide-spread destruction after a gigantic tsunami had hit the shores of countries lining the rim of the Indian Ocean. On December 26th, 2004, at 7:58 local time, the second-strongest earthquake measured to date occurred at the north-western tip of Sumatra with a magnitude Mw = 9.3 and a fracture length of around 1200km. More than 250.000 people perished, about 5 million people required immediate assistance and 1.8 million were made homeless. Indonesia alone suffered the loss of 170.000 lives, but also the coasts of Thailand, India and Sri Lanka were severely affected. Tourists from all over the world enjoying their Christmas holidays suddenly found themselves in the midst of a massive natural disaster. 537 German citizens lost their lives, the highest loss from a single event since the World War II. The sheer enormity of the disaster, the unprecedented impact on human habitat, the intense devastation in northern Sumatra and many other countries and the suffering, particularly in Indonesia, Thailand and Sri Lanka, exceeded all previously experienced scales. The tragedy unfolded furious and unstoppable - there were no organizational or structural facilities, no communication channels or trained personnel that would provide an “early warning for the Indian Ocean region”. Besides northern Sumatra, 28 countries were affected resulting in the incredible high number of fatalities.

The world community reacted swiftly by initiating a large humanitarian relief operation along with numerous fundraising campaigns. At the GFZ Potsdam immediately discussion started on how scientific institutions could support relief actions or become otherwise actively involved. As an institution conducting research on early warning systems to help protect against natural hazards since many years, the idea was born to offer cooperation in setting up of a Tsunami Early Warning System. Potential cooperation partners within the Helmholtz Association of German Research Institutions GFZ Potsdam, DLR, AWI, Geomar, HZG and further partners BGR, UNU-EHS, GIZ were quickly found. A first concept was drafted end of December 2004 and then presented by the German Minister of Foreign Affairs, Mr. Joschka Fischer, during the first donor conference in Bangkok on January 5th, 2005.

As concept development went on more representatives of the scientific institutions involved were invited to make a presentation to the German Federal Government on January 13th, 2005. Upon that the Federal Chancellor, Mr. Gerhard Schröder, decided to fund the project with 45 Million Euro. The next milestone was the Second UN Conference on Disaster Management, held in Kobe, Japan, on January 18th, 2005. Mrs. Edelgard Bulmahn, the German Minister for Education and Research, officially announced the German offer to cooperate with Indian Ocean rim countries for the development of a Tsunami Early Warning System. Germany, at that time, was the only country to officially offer a so-called end-to-end system, covering the whole spectrum from hazard detection (upstream part) to capacity development (downstream part) in local communities. On January 25th, 2005, during a further donor conference in Phuket, Thailand, Indonesia accepted the German offer to cooperate, and on March 14th, 2005, and a Joint Declaration was signed in Jakarta between the Indonesian Minister for Research and Development and the German Minister for Education and Research. The implementation of the system in Indonesia began immediately. It should be noted that it took only 2.5 months to draw up this international 45 Million Euro Project, from the very first draft concept to an implementation agreement.

The cooperation in the Indian Ocean region was then coordinated by UNESCO by an Intergovernmental Coordination Group (ICG), i.e. the ICG Indian Ocean Tsunami Warning System (ICG-IOTWS). Cooperations between Germany, Sri Lanka and the Maldives (installation of seismic equipment), Yemen (installation of seismic equipment and a tide gauge), Islamic Republic of Iran (installation of tide gauges), Pakistan (installation of tide gauges), Madagascar (installation of seismic equipment), Kenya (installation of seismic equipment) and almost all countries, including India and Australia, concerning the seismic analysis software SeisComp3.0, were established. In Indonesia, the cooperation was led by the Ministry of Science and Technology (RISTEK) and the agency coordinating the development of the Indonesian Tsunami Early Warning System (InaTEWS) was headed by Dr. Sri Woro B. Harjono, Director-General, of the Agency for Meteorology, Climatology and Geophysics of Indonesia (BMKG). The Republic of Indonesia funded the project with several hundred million US Dollars, setting up a nation-wide network of seismic sensor, GPS and tide gauge stations, a satellite communication network to connect to all remote field stations, by setting up a National Tsunami Warning Centre at BMKG offices in Jakarta and in Denpasar (Bali), and by extending institutional facilities dealing with tsunami early warning all over Indonesia.

Under the auspices of the Intergovernmental Oceanographic Commission of UNESCO and with the cooperation of international partner institutions from Germany, the United States, China and Japan, a concept was developed for a tsunami early warning system for Indonesia. Under the GITEWS project (German-Indonesian Tsunami Early Warning System, 2005-2011), Germany provided a significant contribution by setting up the core components of an integrated, state-of-the-art, in near real-time operated Tsunami Early Warning System.

The installation phase of InaTEWS is characterized by the development of required hardware and control programs, as well as appropriate strategies and procedures, the development of standards and processes.

During the GITEWS project two main system components were facilitated - the technical setup of the system ("upstream") and, by involving local administrations and residents of 4 selected pilot areas, the “downstream“ component of the project. The warning message must reach the population fast, with clear instructions that are understood and followed up by appropriate action: The end-to-end system. On November 11th, 2008, InaTEWS was ceremoniously inaugurated by the President of the Republic of Indonesia, Dr. Susilo Bambang Yudhoyono.

Dr. Susilo Bambang Yudhoyono, President of the Republic of Indonesia (seated in centre), Dr. Kusmayanto, Minister of RISTEK (seated to the right), Sálvano Briceño, UN-ISDR Director (standing), Thomas Rachel, BMBF State Secretary, (standing), Dr. Ir. Sri Woro B. Harijono, Director-General, BMKG, Dr. P. J. Prih Harjadi, Deputy for Geophysics, BMKG (standing, second last to the right) and Dr. Fauzi, Head of Centre for Earthquake and Tsunami, BMKG (last person to the right). Credits: Rahmann, BMKG).

On this occasion, BMG was officially renamed into BMKG – Badan Meteorologi, Klimatologi dan Geofisika, underlining climatology as the additional field of responsibility.

The GITEWS project components were completed and handed over to Indonesia on March 29th, 2011. The picture below was taken on July 7th, 2011, at the Tsunami Early Warning Centre, BMKG Headoffice, Jakarta.

On her visit to Indonesia, Dr. Angela Merkel, Chancellor of the Federal Republic of Germany, handed over the German contribution to Indonesian Tsunami Early Warning System. Prof. Dr. Hüttl, Director-General, GFZ German Research Centre for Geosciences (to her left), Dr. Jörn Lauterjung, Head, Scientific Infrastructure, Section 7.1, GFZ German Research Centre for Geosciences (to her right), Dr. P. J. Prih Harjadi, Deputy Director for Geophysics, BMKG, and Dr. Ir. Sri Woro B. Harijono, Director-General, BMKG. Credits: A. Helm.

The subsequent PROTECTS (Project for Training, Education and Consulting for Tsunami Early Warning Systems, 2011-2014), was the follow-up project established to enable the staff of Indonesian institutions in charge of InaTEWS to take-over full responsibility for continued system operation, maintaining system components and associated technology at the highest operational level, and keep standard operational procedures and organizational structures / requirements updated.

Scientific and technical staff of BMKG and BIG (Badan Informasi Geospasial) received advanced training focused on sustainable operation of InaTEWS. Workshops and lectures, tailor-made training courses, internships and drills provided the core of PROTECTS. More than 192 training courses, which covered all aspects of the operation and maintenance of the tsunami early warning system, were successfully implemented. The training courses were aimed at capacity development to sustain InaTEWS operations into the future. In a nutshell - the consistent need for skilled technical experts to maintain system functionality as well as “soft skills” to assess a developing tsunami scenario and then make decisions to save human lives, were of highest priority. Also involved in the process were political decision-makers and community administrators, responsible for the timely warning dissemination and appropriate action taken by at local level.

On October 12th, 2011, the IOWAVE11 drill was conducted in the Indian Ocean, testing the functionality and capability of InaTEWS and its role as Regional Tsunami Service Provider (RTSP). Today, InaTEWS performs this service in cooperation with Australia and India for the Indian Ocean region and its 28 neighbouring countries. Finally, GITEWS/PROTECTS contributed to this success and the international attention Tsunami Early Warning Systems receive today.

Jörn Lauterjung and Horst Letz

GFZ Potsdam

May 30th, 2017

Abstract

The German-Indonesian Tsunami Early Warning System (GITEWS) has been established after the devastating Tsunami in the Indian Ocean on December 26, 2004. It became an integral part of the Indonesian Tsunami Early Warning System (InaTEWS) providing sensor networks and core computational components. GITEWS follows an “end-to-end” approach to cover the complete warning chain from rapid hazard detection over decision support to capacity development of communities at risk and the implementation of disaster reduction measures. PROTECTS (Project for Training, Education and Consulting for Tsunami Early Warning Systems) followed GITEWS with its main focus on system refinements, capacity building, and elaborated training measures that covered all aspects of the GITEWS Project. This paper discusses the specific challenges of Tsunami Early Warning in Indonesia, describes recent developments in instrumentation and data analysis and summarizes the system performance over the past 5 years.

1. Introduction

Indonesia is located along the most prominent active continental margin in the Indian Ocean, the so-called Sunda Arc, making it one of the world’s most threatened areas in terms of events such as earthquakes, volcanoes, and tsunamis associated with tectonic activity. On December 26, 2004, an earthquake of magnitude 9.3 (Stein et al. 2005) occurred off the northern coast of Sumatra, causing a tsunami large enough to affect the whole of the Indian Ocean. The affected areas were neither prepared in terms of early-warning nor in disaster response.

In a quick response Germany offered support during the UN World Conference on Disaster Reduction in Kobe, Hyogo/Japan, January 2005, to help with the development of a fast and reliable warning procedure for the Indonesian population so that in future a catastrophe of such a magnitude could be avoided. Aid would be provided in the form of technical support for the development and installation of a Tsunami Early Warning system for the Indian Ocean and further to assist capacity building amongst the local communities. The Indonesian Government accepted this offer as well as affected countries like Sri Lanka, the Maldives and East-African countries. The major part of our work targeted Indonesia, the area being the main source of tsunami risk for the neighbouring Indian Ocean countries. The technical concept of such a warning system would have to deal with extremely brief alarm periods for Indonesia, due to its close proximity to the Sunda Arc. For this reason the German-Indonesian Tsunami Early Warning System (GITEWS) integrates various state-of-the-art monitoring technologies and analysis methods (Münch et al. 2011).

Indonesia is in a unique geotectonic position with its associated consequences in terms of natural hazards. The Sunda Arc lies on an active convergent plate boundary, where the Indo-Australian Plate is subducted at a speed of 67 mm/y underneath the Eurasian Plate (Tregoning et al. 1994). The subduction zone comprises of some 6,000 km from the north of Sumatra to the Aru island group running between 100 and 200 km off the coast almost in parallel to the Indonesian coastline (Fig. 1.1).

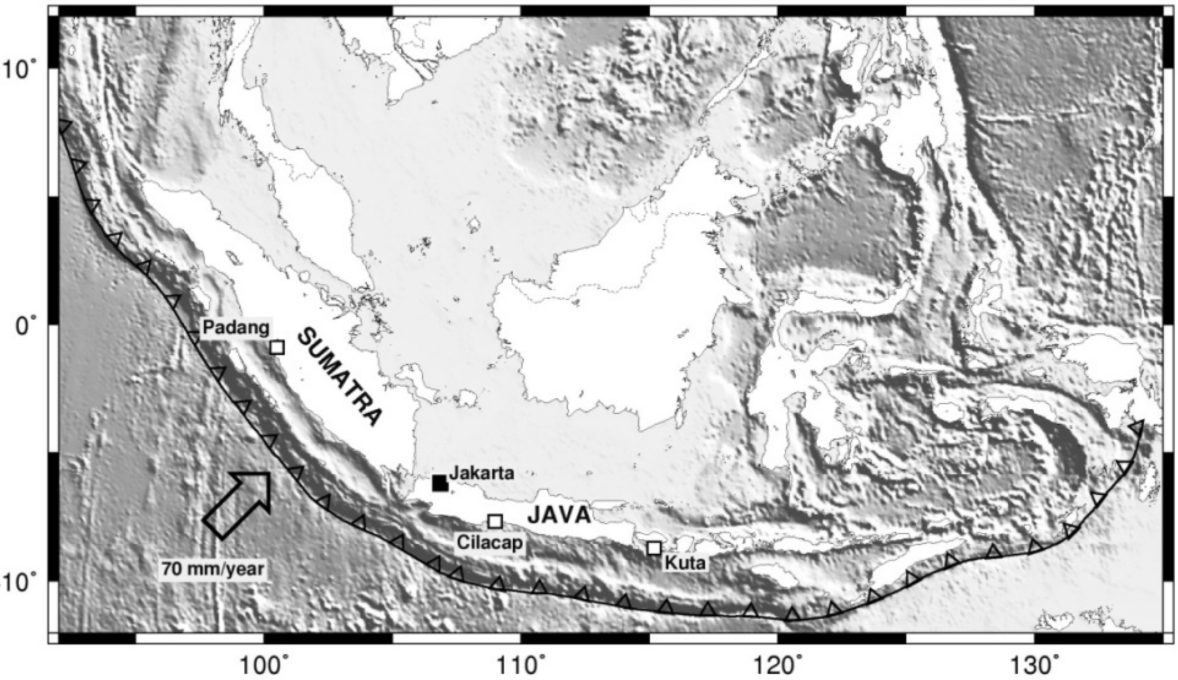


Figure 1.1: The Sunda Arc subduction zone extends from the north of Sumatra to the Aru island group in the eastern part of Indonesia. The Sunda Arc is a major active plate boundary, where the Indo-Australian Plate is subducted at a rate of 70 mm/y (arrow) under the Eurasian Plate. A more reliable rate is 45-50mm/y. The rate becomes less towards the north-western part of the collision zone (Subarya et al. 2006).

As a result of the subduction process, this region is regularly devastated by shallow mega-thrust earthquakes (McCloskey et al. 2008, Nalbant et al. 2005, Natawidjaja et al. 2006, Sibuet et al. 2007). Although the destruction resulting from energy released in a sudden slip or rupture is often devastating, far worse are the consequences that arise through a triggered tsunami. The earthquake of December 26, 2004, ruptured the ocean floor over a distance of some 1,200 km (Krüger et al. 2005) generating an ocean floor uplift of up to 10 metres. This jolt from beneath generated waves on the Indian Ocean causing a tsunami of up to 30 meters in Northern Sumatra (Borrero et al. 2006), leading to over 250,000 casualties, many as far away as the east African coastline, some 7,000 km from its origin. The specific geodynamic situation of Indonesia requires a Tsunami Early Warning System which can provide extremely short early warning times but also produce reliable tsunami warnings shortly after an earthquake based on highly uncertain data (Lauterjung et al. 2010). The scientific development and technical support for the realisation of such a system has been provided by a consortium of nine German research institutions led by the GFZ German Research Centre for Geosciences in close cooperation with partners from Indonesia, China, Japan and the United States (Rudloff et al. 2009).

Indonesia also faces tsunami risk in its North-Eastern territory (Sulawesi, Banda Sea, Molucca Sea). Various sensor systems such as seismic, GPS and tide gauge stations were installed here by Indonesian institutes and other international partners. The data is merged and integrated at the Tsunami Early Warning Centre at Badan Meteorologi, Klimatologi dan Geofisika, BMKG (Agency for Meteorology, Climatology and Geophysics), BMKG, in Jakarta, Indonesia (Fleischer et al. 2010). The system was planned and implemented as an “End-to-End” system (see Fig. 1.2). This includes:

- The necessary sensor instrumentation in Indonesia and elsewhere in and around the Indian Ocean to assess and identify the hazard as quick as possible,
- A tsunami modelling and simulation system including tsunami excitation, propagation and inundation on the coast,
- A scenario and risk information-based decision support system (DSS),
- A communication system to disseminate warnings and other information.

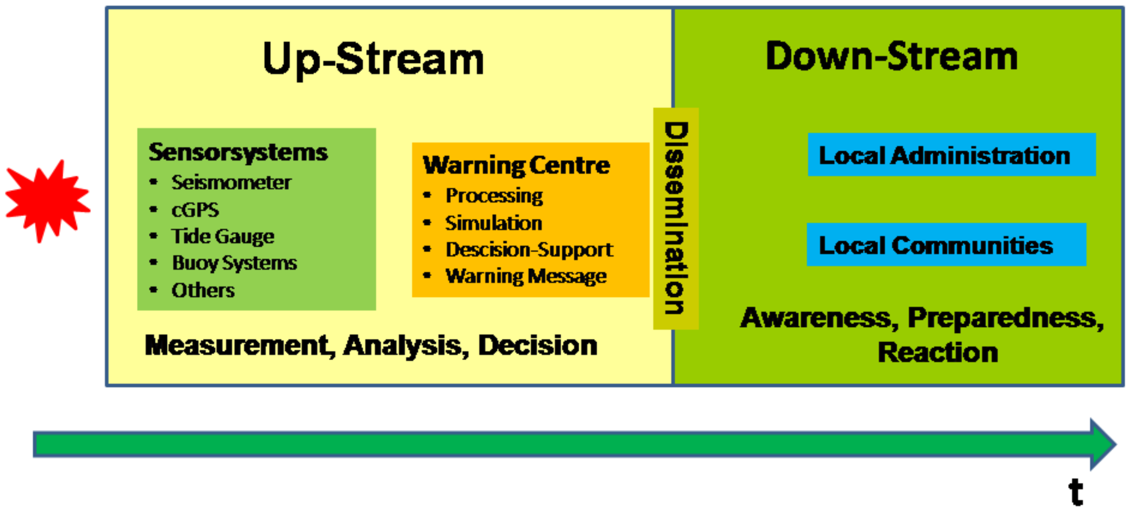


Figure 1.2: Schematic End-to-End approach of GITEWS. The up-stream part is characterized by scaling the hazard and providing decision making while the down-stream part deals with preparedness and reaction of the communities at risk.

Lastly but most importantly, a dedicated program for capacity development for system operation and maintenance as well as for preparedness and response in local communities at risk - the so called “Last Mile” - has been carried out within the GITEWS project.

2. Instrumentation

With regard to the tsunamis recorded to date, most were caused by substantial earthquakes on the ocean floor. Earthquake parameters, i.e. location and magnitude, are, therefore, commonly used as input parameters for tsunami simulation or the selection of pre-calculated scenarios from scenario databases. Strong earthquakes however are not usually confined to a single location but occur as ruptures spanning for several hundred kilometres in lengths and having heterogeneous slip distribution. Strategies for tsunami early warning, therefore, have to distinguish between the two cases:

- Far-field tsunami: Long travel distance for the tsunami compared to the earthquake rupture length. In this case, rupture orientation is essential but details such as the exact position of the rupture or slip distribution are not critical for tsunami forecast at a given coastal point.
- Near-field tsunami: Travel distances to the nearest coast are of the same order as the rupture size. The exact position and parameters of the rupture plane as well as the slip distribution are essential for tsunami forecast at a given coastal point.

Indonesia is invariably faced with near-field tsunamis (travel times from the source to the coastline between 20 – 40 minutes) so that the GITEWS system was from the very beginning conceptually and technically designed with special focus on very fast respond time, incorporating early input parameters with a high degree of uncertainties. As already mentioned, near-field tsunami forecasting is challenging due to the necessity for precise characterisation of the earthquake rupture including details of the slip distribution. In order to provide an early warning, this has to be achieved as quickly as possible (5-10 minutes after the earthquake). Within 2-5 minutes after an earthquake, classical seismological methods can only provide the primary earthquake parameters such as location, depth and magnitude (Hanka et al. 2010).

An assessment of tsunami potential and – if positive – propagation models have to be made on the basis of highly uncertain parameters and a reliable local early warning still depends largely on additional information of the rupture characteristics. A completely new approach in tackling the problem of rupture characterisation, especially and in addition to the slip distribution of an earthquake is the monitoring of co-seismic crustal deformation by real-time or near real-time GPS deformation monitoring (Hoechner et al. 2008, Sobolev et al. 2007). Other investigations (Konca et al. 2008, Vigny et al. 2005) show that GPS is suitable for detecting deformations of several centimetres to metres over a distance of several hundred kilometres from the earthquake hypocentre. This information is available a few minutes (depending on the distance to the earthquake) after the event and can be used immediately to determine the rupture's details. Therefore GPS is a striking and cost effective tool for the characterisation of an earthquake's source geometry. Within the project a GPS network consisting of a nation-wide reference network and GPS stations along the Indian Ocean coastline (combined with tide gauges following GLOSS standards) was established in Indonesia. Near real-time processing solutions for the network every 2 minutes (Falck et al. 2010) is performed at the Tsunami Early Warning Centre in Jakarta.

2.1 Seismic System

The major challenge for earthquake monitoring within a tsunami warning system is to deliver rapid information about location, depth, size and possibly other source parameters. Due to the proximity of the tsunamigenic area to the exposed coast lines along the Sunda Trench this becomes a great challenge. In fact, tsunami warnings must be issued within 5 minutes (starting from the event origin time), as BMKG was committed after the great Sumatra earthquake by the Indonesian Government. With this in mind, a seismic monitoring system was designed in the aftermath of the great Sumatra event and became operational within the GITEWS project. The dense seismic network with real-time satellite based communication and an innovative processing system today is fully integrated in InaTEWS has been further consolidated and developed during the PROTECTS project to meet the envisaged high quality and availability standards.

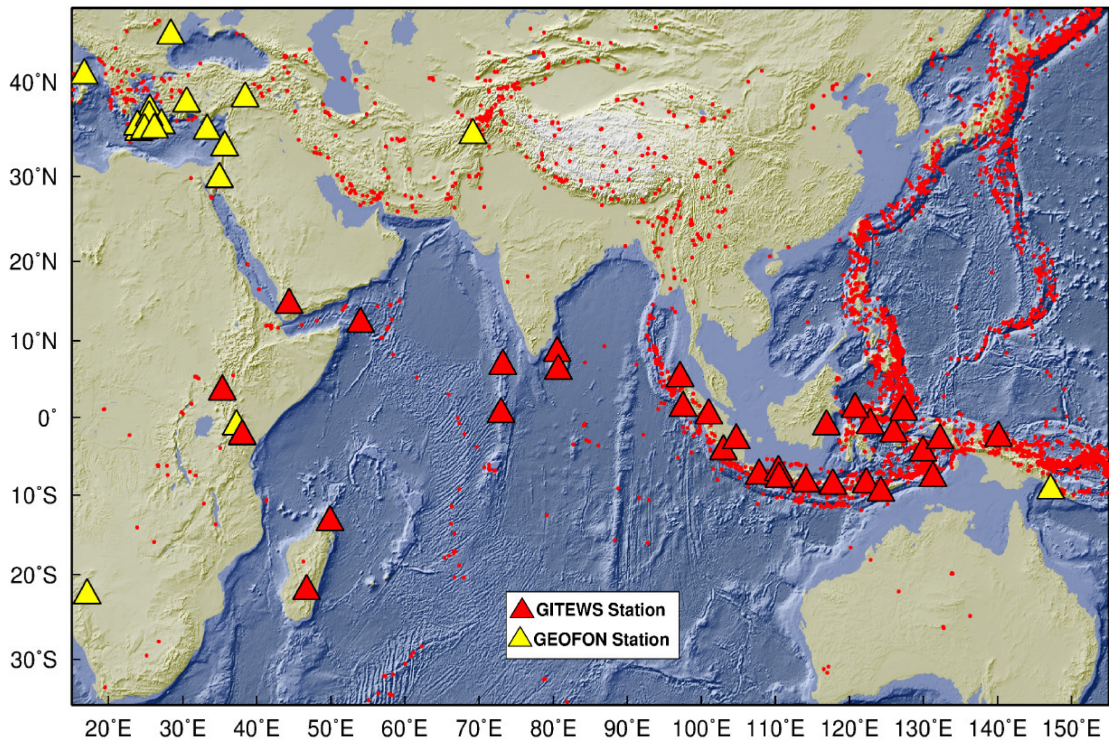


Figure 2.1.1: GEOFON network and additional 31 real-time seismograph stations installed during the GITEWS project 2005-2011, out of these 21 are in Indonesia.

The original design plan for the seismic network requested 160 stations, installed more or less equally spaced across Indonesia. However, the actual implementation became very problematic since logistics are not easy and very often compromises regarding geographical distribution and remoteness had to be made. The current InaTEWS seismic network has numerically reached the original goal with 159 high-quality seismic stations equipped with broadband and strong motion sensors throughout the country with densifications in Sumatra and Java, although not all of them are in ideal locations. Among them, 21 stations were installed as the German contribution to InaTEWS within the GITEWS project, the Japanese National Research Institute for Earth Science and Disaster Prevention (NIED) contributed another 15 stations, the Chinese Earthquake Agency (CEA) provided 10 stations while 6 stations were installed by the Comprehensive Test Ban Treaty Organization (CTBTO). Indonesia provided the remaining 109 and during the recent years some stations have been newly installed and some of them re-located.

All data is transmitted in real-time to the Indonesian InaTEWS Tsunami Warning Centre in Jakarta as well as to the backup centre in Bali. VSAT links on an Indonesian satellite (Telkom-2) with a private hub at BMKG are used for data transmission. The GITEWS network was designed as backbone/backup network, still capable to locate tsunamigenic events within the 5 minutes time limit, in case of failure of the other sub-networks. Therefore, stations were distributed across the entire Indonesian archipelago and the acquisition layout was designed to be independent from the other sub-networks to continue operation in case of failure of the remaining networks. Aiming at improving the network resolution for large events, as part of the German contribution additional 10 GITEWS stations were installed in other Indian Ocean countries, namely in Sri Lanka, Maldives, Yemen, Kenya and Madagascar. Although travel times from the Sunda Trench to these stations exceed 5 minutes (except for Sri Lanka and Maldives), these stations provide important data to improve the preliminary estimation of source depth, moment tensor and rupture propagation from teleseismic distances and monitor the Western part of the Indian Ocean including the Makran Trench area.

Moreover, within GITEWS, the existing GEOFON stations in the Mediterranean and NE Atlantic were upgraded to GITEWS standard for the surveillance of the NEAMTWS (North East Atlantic Mediterranean Tsunami Early Warning System) area as well as the teleseismic monitoring of the Indian Ocean. As the footprint of the Telkom-2 satellite covers a large part of South Asia, the Indonesian VSAT system is used also for the data transfer from Sri Lanka and the Maldives directly to the warning centre in Jakakrta. The data from the stations in the Western Indian Ocean as well as those in the Mediterranean are collected by 2 different satellites linked to GFZ via a second GITEWS VSAT hub in Europe and routed to Indonesia and other tsunami centres by Internet. In addition, data from other Indian Ocean networks (Australia, Malaysia, Thailand, South Africa, the IRIS GSN and the French GEOSCOPE network, lately also 3 stations from India) are imported via Internet, mostly via GFZ. In total, the current virtual seismic network for the Indian Ocean available at BMKG for tsunami warning consists of almost 300 stations.

Even more challenging than the setup of an appropriate seismic network was the design and implementation of efficient acquisition and processing software. As data integration is essential for accurate earthquake monitoring, data from heterogeneous instrumentations used in the various networks and sub-networks needs to be unified and integrated into one single processing scheme. Moreover, reliable rapid near real-time automatic data processing, visualization of its results and quick graphical review tools required the development of a special new software package.

Therefore, a new challenging development was initiated within GITEWS leading to the SeisComP3 software package (www.seiscomp3.org, Hanka et al. 2010) currently in use at about 300 earthquake and tsunami centres worldwide becoming one of the most popular seismological software packages. Although based on a new innovative software architecture and consisting of mostly newly written codes, the SeisComP3 (SC3) software package can be regarded as an extension of the well established SeisComP1 (SC1) and 2 (SC2) versions introducing among others new networking protocols for real-time (SeedLink) and archived (ArcLink) data which became meanwhile de facto standards. SC3 combines generalized data acquisition, data quality control, data archival, real-time data transfer protocol, automatic procedures to determine location, depth, magnitudes and rupture parameters, and sophisticated alerting and visualization tools. Although 24/7 operation is mandatory at tsunami warning centres, the basic parameter calculation is at first carried out fully automatically, but visual supervision, and, where necessary, manual interaction is possible at each stage. Audible and visual alerting tools are implemented to guarantee the attention of the seismic experts in the warning centre. They can interact at any time and improve the automatic results.

SC3 has a highly modular design and provides several new developed modules for automatic and interactive data processing. A basic automatic system of SC3 consists of modules for quality control, picking, location, amplitude and magnitude calculation, waveform quality assessment and event and station parameter management. All modules are implemented as stand-alone programs connected through messaging and a central database. This architecture allows easy replacements of any module of the processing chain. A messaging system based on the TCP/IP network protocol is used to distribute the processing results among the modules. It also allows the operation of the individual modules at different computers connected via LAN or even WAN. The interactive part of the system provides graphical user interfaces for visualizing the overall situation in respect to earthquakes locations and station status on a map, and a real time trace and event summary display. As SC3 is also designed for fast interactive analysis, it provides a toolkit for analysing the earthquake epicentre, depth and magnitudes. The included manual picker is optimized for rapid verification of pre-calculated picks from strong earthquake signals providing e.g. automatic loading of newly acquired real-time data with picks associated to the ongoing event, automatic amplitude scaling and trace alignment. However, it also allows conventional offline analysis of small and moderate regional earthquakes.

Besides the professional and highly efficient software design, magnitudes that allow a rapid quantification of very large earthquakes are an essential ingredient to effective tsunami warning. In SC3, the original Gutenberg & Richter body-wave magnitude mB, which uses the full broadband P-wave signal was adopted. It therefore does not suffer from the spectral saturation of the, more well-known, narrow-band mb. Since at the time the development started the mB calibration function was available only starting from 20° distances, in order to speed-up the mB computation, a new mB calibration function starting already from 5° was developed by Bormann and Saul (2008).

Moreover, by means of an orthogonal scaling relation between mB and Mw (CGMT) fast Mw estimations are possible using mB as proxy. The Mw(mB) magnitude obtained using this relationship performs comparably well to other P-wave based Mw estimators like Mwp (Tsuboi et al. 1999) - which is also determined by SC3 - but is much simpler to compute and less sensitive to data errors such as small gaps, which are common in real-time processing. The use of mB as a proxy for Mw thus allows quick and robust magnitude estimates after as little as 2 minutes and provides the basic tool for earthquake size quantification in SC3. Similar to estimating Mw from mB, the Mwp calculated by SeisComP3 is mapped to Mw using the “correction function” of Whitmore et al. (2002). An extension of mB to mBc (cumulative mB for giant quakes with M > 8.5 has also been implemented in the meantime by Bormann and Saul (2009).

Other standard magnitudes (ML, mb, Ms, Ms (BB)) are also computed in parallel. SeisComP3 allows manual selection of any of these multiple magnitudes as the preferred event magnitude. By default a time dependent composite magnitude “M” derived as weighted average from all well-determined individual magnitudes is set as preferred (Hanka et al. 2010).

Since the GITEWS early warning concept does not only aim at issuing unspecific warnings affecting large areas - as it would be the case with the simple decision matrix approach - but to forecast precisely inundation heights for individual coastal ranges, the GITEWS seismology group investigated more sophisticated analysis methods which could help to characterize the tsunami generating earthquake model in more detail. Meanwhile, a moment tensor (MT) tool based on matching of windowed (P, S, surface wave) pre-calculated Green's functions was developed for SeisComP3 and is implemented in the InaTEWS system at

BMKG as a major improvement within the recent PROTECTS activities. It provides automatic MT solutions for sources offshore and onshore Indonesia within about 10 minutes. Presently, only the automatically calculated Mw value is taken into account by the Decision Support System (DSS) and operators on duty may fix it as the preferred magnitude overruling the previously communicated rapid magnitude estimations.

In summary, despite the large degree of heterogeneity, the InaTEWS seismic monitoring system reached a good level of integration. Continuous efforts along the years, starting with GITEWS and continuing within PROTECTS with an intensive capacity building program, allowed BMKG to continuously improve the system and meet the challenging expectations.

2.2 The GPS-System

GITEWS became the first Tsunami Early Warning System in the world operationally using real-time GPS (Global Positioning System). The primary goal of the continuous real-time GPS network is to increase reliability and confidence of the earthquake source inversion. This task becomes extremely challenging since, according to the administrative requirements, the first warning message has to be issued no later than 5 minutes after the earthquake's origin time. This time limit is too short for the traditional seismic methods to provide a set of source parameters and accuracy necessary for a reliable near-field early warning. Shortly after the beginning of the GITEWS project, Sobolev et al. (2006; 2007) used numerical simulations to demonstrate the non-sufficiency of classical seismic parameters, such as magnitude and location, for the early warning along the Sunda Arc. They have argued, that reliable early warning offshore Sumatra needs an extended set of source parameters including rupture dimensions and at least first-order data on slip distribution relative to the epicentre. Inspired by the studies of Vigny et al. (2005) and Gahalaut et al. (2006) who detected co-seismic GPS displacements due to the Great Sumatran 2004 earthquake, Sobolev et al. (2006; 2007) suggested the concept of the "GPS-Shield" for Indonesia. Numerical simulations including kinematic rupture and seismic waveform modelling (ibid) showed that reliable source inversion with true geodetic magnitude (Mw) is possible as early as 3-5 minutes after the earthquake origin time. In the GITEWS DSS the source inversion is integrated into the multi-sensor scenario matching (see below). The concept of the GPS-Shield was later successfully tested at another similar tectonic setting: by the replay of the Great Tohoku 2011 earthquake (Hoechner et al. 2013).

An automatic system for the near real-time determination of ground motions (displacements), respectively co-seismic deformations of the Earth's surface, was developed by GFZ within the GITEWS project (Falck et al. 2010). This so called GTS (Ground Tracking System) is in operation since November 2008 and has proven a stable system performance since then. It continuously provides displacement vector data for locations that send Global Navigation Satellite System (GNSS) raw data, e.g., geodetic GNSS-stations, GNSS controlled tide gauges and seismological stations with appropriate GNSS-installations. The displacements are calculated as differences between the GNSS-stations coordinates before the earthquake and most recent available observations after the earthquake. They are used by other early warning system components, e.g., to support instant estimations on potentially tsunami-causing crustal deformations and for co-seismic tide gauge station position monitoring. The time from GNSS measurements to product deliveries is only 1-2 minutes (equal to internal processing repetition rate), provided that GNSS raw data is received in real-time.

The data processing core for the calculation of GNSS-station's coordinate time series is built upon a "Bernese GNSS Software" (Dach et al. 2012) installation, wrapped into the GTS by adaptations for data acquisitions and near real-time data processing operation. All functions of the GTS are fully automatic. Thus system operators in the warning centre may keep the system up to date and monitor the proper function, but have not to put hands on any processes neither during daily routine operations, nor during "heads up situations" (strong earthquakes).

The GTS applies a relative GNSS positioning approach by calculating multiple baselines between each "GNSS displacement sensor-station" and several reference stations. This requires a network of GNSS real-time reference stations which must have a reliable performance even under adverse conditions (e.g., during earthquakes). A network of 9 GNSS real-time reference stations was installed by GFZ during GITEWS and serves as the backbone for baseline and displacement determinations. These stations have a special design for reliable operation and simple maintenance and a direct satellite link to the warning center's VSAT-hub (Figure 2.2.1).

Eight other GNSS-stations in the region of Sumatra operated by Badan Informasi Geospasiale (BIG) – Geospatial Information Agency of Indonesia, were recently upgraded with real-time data transfer capabilities and do now also support the GTS at InaTEWS. More GNSS-stations, inside and outside Indonesia, are used either as additional GNSS reference stations or as GNSS sensor stations. The GNSS-stations to be used and their functions (sensor or reference) are selected automatically according to their distances to an actual earthquake's epicentre and actual data availabilities.

The GTS may be operated as a black box, but its GUI (graphical user interface) also provides several views and tools supporting a comprehensive monitoring and analysis of the network and system performance. The states of all accessible GNSS-stations (inclusive data quality), the GTS subsystems, running processes and the product (displacement vectors) are displayed continuously. The displacement vectors are illustrated on a map (Figure 2.2.1) by arrows and bars using a logarithmic scale, according to the wide range from the noise level (some cm) to the expectable magnitude of real displacements (some meters). Checks of intermediate processing steps or historic data are available applying a few simple manual operations. The GUI system is a web-based application, allowing all views to be displayed on many screens at the same time, even at remote locations.

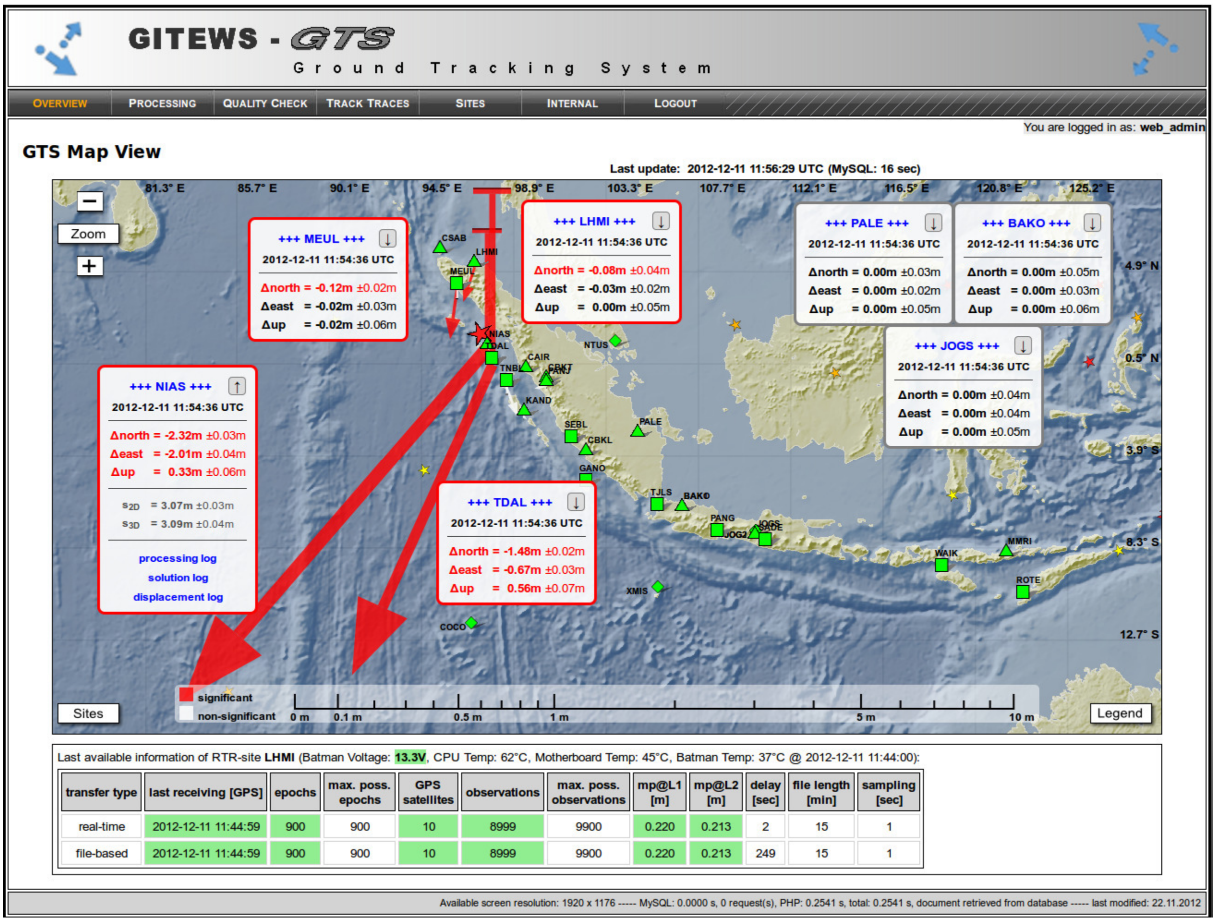


Figure 2.2.1: Example for the display of displacement vectors on the GTS Map View, based on data simulated for an earthquake that occurred on 2005-03-28, M8.6, at a depth of 30km, and GNSS-station locations providing input to the GTS (status of 2010).

2.3 Oceanographic Instruments

Successful tsunami warnings benefit from the verification of a tsunami threat or the cancellation of the warning when no tsunami wave has been generated. For Indonesia a concept was developed to detect tsunami signals offshore using GNSS-controlled buoys connected with ocean bottom pressure units and also with GNSS-controlled tide gauges at the coastline (Figure 2.3.1). In this concept the buoys had two functions: One function is to transfer the data from the underwater pressure sensors, using acoustic data transmission from the sea floor to a modem close to the water surface. The buoy forwards all data via a satellite connection directly to the Tsunami Early Warning Centre. The second application and functionality is the GNSS capability of the buoy. Although GNSS technology is not as accurate as the pressure data, it delivers valuable information on tsunami related sea level changes with a precision of 5-10 cm within minutes. Applying GNSS technology on tsunami buoys is a significant technical improvement compared to other buoy systems (Schöne et al. 2011a) and is now becoming state-of-the-art (Kawai et al. 2012).

The tectonic situation in Indonesia requires very short latencies in tsunami detection, data transmission and data processing. This implies that the position of the buoy systems is as close to the trench as possible to measure tsunami shortly after their generation. Therefore, the buoy systems suffered from two drawbacks:

(1) Near-source location of ocean bottom pressure sensors result in strong aliasing effects of the tsunami signal with the seismic noise due to Rayleigh waves displacing the pressure probe vertically. In some cases, the latter has much larger amplitudes than the tsunami signature. Due to the measuring characteristic of the pressure sensors currently available, filtering the tsunami signal from the seismic background noise is almost impossible (Meinig et al. 2005). This can be overcome, however, by the use of GNSS onboard of the buoy (Schöne et al. 2011a), which is not affected by the seismic noise.

(2) In the case of Indonesia the buoy systems had to be placed near to the coastline. They are, therefore, in the reach of local fishing boats which use the buoys as mooring place for their fishing activities. As a result the buoys regularly become damaged, which, in extreme cases, lead to a total loss. Such vandalism is a general problem for buoy systems worldwide (Data Buoy Cooperation Panel, International Tsunameter Partnership 2011) and resulted in a dramatic decrease of the availability of near coast deployments.

For these reasons it was finally decided not to rely any longer on such buoy systems due to the lack of reliability and for cost reasons. Cost/benefit calculations showed that the maintenance of the buoy systems – taking into account the aforementioned boundary conditions – would consume almost 50% of the overall budget for the maintenance and operation of the warning system as a whole.

GNSS-controlled tide gauges installed along the Indonesian coastline as well as on islands off the Indonesian mainland are capable of monitoring the instantaneous sea level changes in near real-time. An integrated concept was developed for GITEWS (Schöne et al. 2011), comprising three different tide gauge sensors, meteorological sensors and a GNSS receiver for control of the vertical stability. The GNSS-controlled tide gauges are integrated into the GNSS network for co-seismic deformation monitoring. For the warning system, all tide gauge stations available in Indonesia and from neighbouring countries are integrated into a tide gauge processing and display system and deliver de-trended tide gauge time series as well as tsunami arrival times.

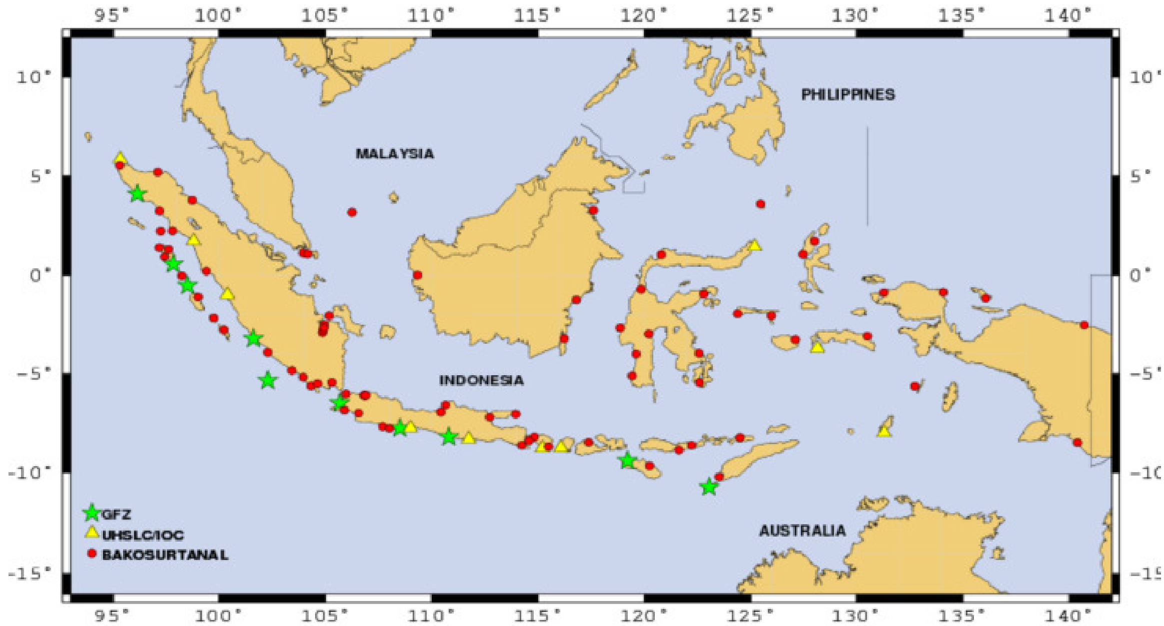


Figure 2.3.1: Tide gauges in Indonesia installed by GFZ (Germany), UHSLC (USA) and BIG (Indonesia). Tide gauges are facing tsunami-prone ocean areas are available in the warning centre. GFZ and UHSLC tide gauges are also available through http://www.ioc-sealevelmonitoring.org/.

3. The Modelling-System

Tsunami simulations are particularly important, because based on a handful of measured information an overall picture of the situation has to be calculated. Ocean-wide tsunami-simulations are pre-calculated for a dense net of earthquake locations along the Sunda Trench and for a wide variety of magnitudes (7.0 – 9.0) (Behrens et al. 2010). These pre-calculated simulations are stored in a data base and can be selected accordingly based on the available sensor data. As time plays a crucial role in the warning procedure the selection process is fully automated. To include all available sensor information in this automated process a special approach has been developed.

In a first step earthquake parameters (location and magnitude) are used to pre-select a number of scenarios with almost the same probability. All other sensors are treated as individual and non-related sources of information (GPS-stations, tide gauges). For each of these sensors theoretical response functions are calculated for every simulation (theoretical displacement vectors in case of GPS, theoretical tsunami arrival times and wave heights for buoy-systems and tide gauges). This data can be directly compared to the respective measured values and are used to reduce the list of best-fitting scenarios (for details see Behrens et al. 2010). The inclusion of GPS displacement vectors reflects, in particular, the slip distribution of a larger earthquake and supports the decision of earthquake rupture direction, which is of special importance for near-field tsunami forecasting (Fig. 2.2). Some seconds after the first earthquake evaluation the best fitting scenario resulting from the selection process gives a first impression, including wave heights, arrival times and inundation areas along the coast.

3.1 Source Modelling

The GITEWS approach to source modelling (Babeyko et al. 2010) targets two main goals. First, it should be able to provide a reasonable source model for tsunami simulations based on very limited seismic information available just few minutes after the earthquake. Second, in the case when near real-time GPS data is available (see concept of the “GPS-Shield” above), the model should be able to incorporate GPS observations for more reliable source inversion (or scenario matching) in real time.

As InaTEWS must provide a first tsunami early warning 5 minutes after an earthquake, only basic seismological parameters are available including hypocentre and magnitude (Hanka et al. 2010). At the same time, even the simplest rupture models require knowledge of a number of parameters including rupture length and width, depth, strike-, dip- and rake-angles as well as amount of co-seismic slip. To address this information deficit, GITEWS source model tries to utilize as much *a-priori* geological information as possible. In particular, it was assumed that tsunamigenic subduction zone earthquakes rupture along the plate interface of known geometry.

The plate interface between the subducting Indian-Australian and the upper Sunda plate (RUM model by Gudmundsson and Sambridge, 1998) was discretized into a 3D regular grid of rectangular patches ranging from 0 to 100 km depth. The grid consists of 25x150 patches with dimensions of approximately 40x15 km. For each patch we have pre-computed three components of the surface deformation due to the unit dip- and strike-slip using EDGRN/EDCMP software (Wang et al. 2003) and 1D layered earth model. Pre-computed surface displacements are stored in a databank of patches Green's functions. Using this databank of Green's functions, co-seismic sea-floor deformation can be instantly computed for any earthquake scenario with given slip distribution. The same can be done with co-seismic displacements vectors at GPS-sites (for source inversion or scenario matching).

Computation of co-seismic surface deformation is managed by the software code *RuptGen* (Babeyko et al. 2010). Following worst case approach, *RuptGen* assumes pure dip-slip focal mechanism for interplate earthquakes (rake angle equal to 90°). JMA's scaling law is employed to evaluate rupture dimensions from the magnitude value (Kamigaichi 2009). After projecting rupture area over the patches, *RuptGen* distributes seismic moment in accord with imposed shape function. The latter combines crack model with a smooth closure condition along width (Geist and Dmowska 1999) with linear tapering along length. After that, distributed seismic moment is converted into slip using rigidity depth profile from the assumed 1D layered earth model.

Initially, the IASP91 Earth Model (Kennett and Engdahl 1991) was implemented in *RuptGen*. However, the Mentawai 2010 tsunami earthquake forced some re-engineering of the initial source model. This earthquake was a classical 'tsunami earthquake' in terminology of Kanamori (1972) with unexpectedly high run-up at the nearby islands. Post-event numerical simulations demonstrated the need to decrease rigidity near the trench from the IASP91 35-40 GPa to 10-20 GPa, i.e., to account effectively for the soft sediment cover at the trench. The new shallow rigidity profile follows data compilation provided by Bilek and Lay (1999).

In GITEWS *RuptGen* is used in several ways: to compute scenarios for tsunami repository, to compute alternative earthquake and tsunami scenarios for system testing and training, and for instant computation of synthetic GPS-displacements during scenario matching (see later).

3.2 *TsunAWI* Modelling System

In the framework of GITEWS, the tsunami modelling group at Alfred Wegener Institute (AWI) has developed the operational model code *TsunAWI*. It started as a spin-off of the Finite Element Sea-Ice Ocean Model (FESOM, Wang et al. 2012a, and references therein), from which it inherited the main structure, the finite element discretisation, and some core routines. The first step was to drastically reduce the model physics, e.g., to eliminate the vertical dimension, the temperature and the salinity. On the other hand, inundation had to be implemented.

The code *TsunAWI* simulates all stages of a tsunami from the source to propagation and run-up by solving the nonlinear shallow water equations discretised with finite elements on a two-dimensional unstructured triangular grid. This discretisation is very flexible with respect to resolution and allows for an excellent representation of complicated coastlines and bathymetry. Other tsunami models also take the advantages of unstructured grids, though usually pared with finite volume discretisation (e.g. ANUGA (Roberts et al. 2007)). As the price for the unstructured mesh is a less efficient implementation, other models rely on regular grids, which may be nested to resolve areas of interest, the finite difference model TUNAMI-N3 (Imamura et al. 2006) being a well-known example.

The tsunami simulation code *TsunAWI* is based on the rotating non-linear shallow water equations given by the vertically averaged equations of motion and continuity. We consider the boundary value problem in Cartesian coordinates $(x, y) \in \Omega$ in the plane domain Ω with boundary $\partial\Omega$ at the time $t \in [0, T]$

$$\begin{aligned} \frac{\partial \boldsymbol{v}}{\partial t} + f\boldsymbol{k} \times \boldsymbol{v} + (\boldsymbol{v} \cdot \nabla)\boldsymbol{v} + \mathrm{g}\nabla\zeta + \frac{r}{H}\boldsymbol{v}|\boldsymbol{v}| - \nabla(K_h \nabla \boldsymbol{v}) = 0, \\ \frac{\partial \zeta}{\partial t} + \nabla \cdot (H\boldsymbol{v}) = 0 \end{aligned} \tag{SWE}$$

for the horizontal velocity vector $\boldsymbol{v} = (u, v)$ and the total water depth $H = h + \zeta > 0$ as the sum of the unperturbed water depth h and the surface elevation ζ. Furthermore, $\nabla = (\frac{\partial}{\partial x}, \frac{\partial}{\partial y})$ denotes the gradient operator, f the Coriolis parameter, $\boldsymbol{k}$ the vertical unit vector, r the bottom friction coefficient, and K_h the eddy viscosity coefficient.

On the solid part of the boundary $\partial\Omega_1$, the condition $v_\mathrm{n}|_{\partial\Omega_1} = 0$ for the velocity component v_n normal to boundary is imposed. On the open part of the boundary $\partial\Omega_2$, the radiation boundary condition

$$v_\mathrm{n}|_{\partial\Omega_2} = \sqrt{\frac{g}{H}}\zeta$$

is used for the TSR scenarios. It provides free linear wave passage through the open boundary, given the Coriolis acceleration plays only a small role.

The spatial discretisation of *TsunAWI* is based on the finite element approach by Hanert et al. 2005 with modifications like added viscosity and bottom friction, corrected momentum advection terms, radiation boundary condition, and nodal lumping of the mass matrix in the continuity equation. Originally, *TsunAWI* should only simulate the tsunami propagation in deep water and extrapolate the estimated wave height at the coast, but it soon turned out that an inundation scheme was essential for a realistic simulation of the wave reflection at the shoreline. *TsunAWI* proved to be suitable to estimate the extent of the inundation in benchmarks like the Monai beach channel experiment and in comparison with field measurements e.g., in Banda Aceh 2004. Meanwhile, *TsunAWI* was improved by adding the non-linear advection term, by replacing the linear viscosity $K_h = c_\mathrm{lin}\Delta x\Delta y$ by the more realistic Smagorinski viscosity $K_h = c_\mathrm{smag}\Delta x\Delta y\Delta t\sqrt{(u_x)^2 + (v_y)^2 + \frac{1}{2}(u_y + v_x)^2}$, and by a revision of the inundation scheme. Furthermore, the code was parallelized with OpenMP, optimized with regard to cache efficiency, and ported to new generation processors. Though the model physics became more complex, the computation time for one scenario could be reduced from approximately 18 hours to 35 min. In addition, the framework of post processing routines for quality control and extraction of data products was streamlined for batch processing. On the current state of *TsunAWI* see (Rakowsky et al. 2013).

3.3 Mesh Generation

TsunAWI employs triangular meshes, which allow for realistic representation of coastlines and bathymetric peculiarities. In contrast to the approach of deriving warning products by extrapolating wave properties of near shore locations to the coast, the simulations with *TsunAWI* do actually determine wave height and arrival time in forecast points right at the coast. This is achieved by generating a mesh with sufficiently high resolution at the coast, which covers the near shore coastal area on land. This approach allows for realistic tsunami reflections in the simulations since the calculations include wetting and drying along the complete coastline.

However, the quality of model results heavily depends on the quality of the triangulation. Therefore, the mesh generation is a crucial step in the simulation process. The practical approach is divided into three steps:

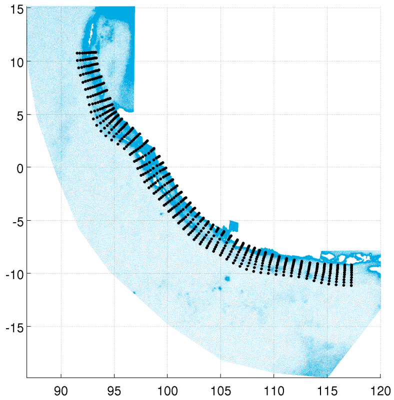
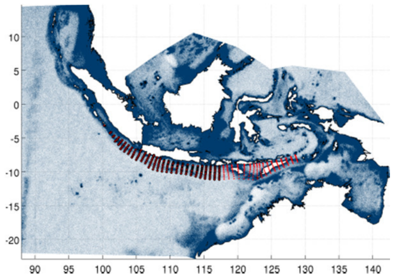
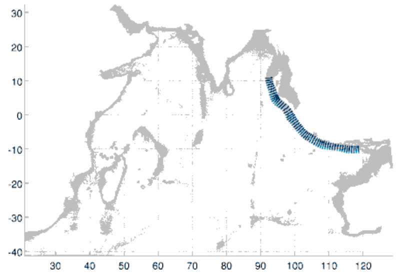
- Coarse triangulation of the model domain,
- Refinement of the initial discretisation according to the available topography and bathymetry data,
- Smoothing of the resulting triangulation.

Steps 1 and 2 are carried out using the freely available mesh generator Triangle (Shewchuk 1996). The mesh generator Triangle allows to specify a minimum angle permitted in each individual triangle up to 30 degrees, which is sufficient to avoid degenerated triangles.

As the warning products for the Indonesian Warning System are calculated directly at the coastline, accurate bathymetry and topography information in the computational mesh is crucial. The mesh generation is based on the General Bathymetric Chart of the Ocean (GEBCO 2008) with a resolution of 30 arc seconds which corresponds to approximately 1km. The forecast points along the coast are provided at higher resolution; therefore, in case of discrepancies close to the shoreline, the GEBCO values are modified to ensure an adequate triangle size along the coastline. After the mesh density is chosen appropriately by this method, the GEBCO values are replaced wherever better information is available. These data sets are SRTM topography measurements, results obtained on ship cruise Sonne SO186 (Krabbenhoeft et al. 2010) or near shore bathymetry measurements. Gridded data sets are interpolated bi-linearly, whereas unstructured data are treated in a nearest neighbor manner.

The density of forecast points along the coast was adjusted to match the mesh resolution. During mesh generation, these points are prescribed as fixed mesh vertices. However, during the relaxation step, only those forecast points not diminishing the mesh quality are kept as vertices, and in all other forecast points, warning products are interpolated from the surrounding nodal values. Since the numerical solution of the sea surface height is piecewise linear in the triangles, the interpolation is well defined. A statistical overview of the Tsunami repository is given in the table below.

Table 3.3.1: A statistical overview of the Tsunami repository.

Regional ***GITEWS 2011***	***Regional, Extension*** ***PROTECTS 2013***	***RTSP*** ***PROTECTS 2011***
Computational grids		
		
Grid size (number of nodes)		
1,442,096 Reduced from 2,317,345 after all scenarios had been calculated (delete land nodes that were never flooded)	7,494,962 Reduced from 15,341,091 after scenarios for Mw=8.8, 9.0 had been calculated (delete land nodes that were never flooded)	6,640,217 Post processing only for water depth> 50m, i.e., one grid with 1,777,362 nodes.
Grid resolution: (project region –) coastline – deep ocean		
50m - 150m - 12.2km	55m - 150m - 19.4km	200m - 24.6km
Modell time		
3h	12h	24h
Sources (*RuptGen*2.1, Mw=7.2, 7.4,…,9.0)		
528 epicentres 3470 scenarios	187 new epicentres for Eastern Sunda Arc 1100 new Eastern scenarios, 1100 Western scenarios replaced (warning levels East of	660 epicentres 1870 scenarios (for each epicentre only Mw for which MWH>0,5m outside of

Regional ***GITEWS 2011***	***Regional, Extension*** ***PROTECTS 2013***	***RTSP*** ***PROTECTS 2011***
	Bali)	Indonesia)
Data products		
• Scenarios (netcdf, with time steps 1min) • Isolines ETA, MWH • ETA, MWH at coastal forecast points • Mareograms at gauge and buoy locations	• Scenarios (netcdf, without time steps) • Isolines ETA, MWH • ETA, MWH at coastal forecast points • Mareograms at gauge and buoy locations	• No Scenarios (netcdf) • Isolines ETA, MWH for water depth deeper than 50m • ETA(T1, T2, T3, T4), MWH at forecast points in deep water

3.4 Simulation System (SIM)

The warning centre at BMKG has a repository of currently 4470 synthetic tsunami scenarios to its disposal. The Simulation System (SIM) forms the interface between the tsunami scenario repository and the decision support system (DSS). This section introduces the components of the SIM, in particular the matching algorithm for obtaining a set of best fitting tsunami scenarios to an earthquake. The SIM is a Java web application which displays communication interfaces as web processing WPS and web notification services WNS implementing the open GIS consortium OGC standard. The software is thus accessed through HTTP-requests and request and response values are transmitted in XML format to and from the SIM.

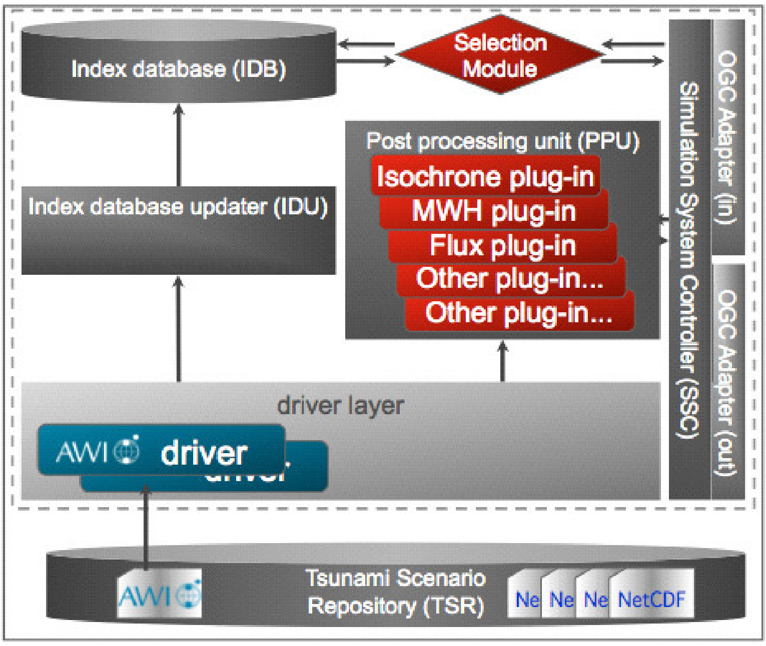


Figure 3.4.1: Components combined in SIM – The Index database contains data products crucial for selecting the best fitting scenarios (performed by the selection module) in an earthquake event. The data products are extracted from the tsunami scenario repository by the Index database updater. Access to the scenario files is made possible through drivers whereas the post processing unit compounds C-Routines for extracting scenario data and for creating various SHP-files representing scenario data. All tasks are communicated to the SIM via the OGC Adapters and distributed by the controller.

The main SIM components as displayed in Figure 3.4.1 are

- Index Database IDB: To ensure fast response, significant data products from each scenario in the pre-calculated scenario repository (TSR) are extracted during maintenance prior to using the SIM in operational mode. The IDB contains data necessary for selecting a set of best fitting scenarios to an earthquake event. These include the earthquake parameters i.e. epicentre and magnitude, as well as GPS displacement vectors. The latter are obtained directly from the rupture simulation module *RuptGen*. Additionally, arrival times and wave height time series at tide gauge and buoy locations may be stored.
- Index Database Updater: Functional units to store the data products mentioned above in the Index Database are implemented in the Index Database Updater.
- Post Processing Unit PPU: All data products are extracted from the tsunami scenarios via the post processing plugins compounded in the PPU. To employ fast mathematical calculation, the plugins are written in C. The plugins for one extract the data to be stored in the IDB and secondly generate SHP-files to be ingested in the Decision Support System (DSS). They are used to visualize the theoretical impact of scenarios fitting to an earthquake event in the DSS and thus form the basis for

warnings. Data products to extract include maximum sea surface height (MWH) and arrival times at coastal forecast zones, isolines of MWH, isochrones as well as GPS displacement values. Furthermore, SHP-files comprising simulated inundation can be generated. These may be used as a basis for a priori risk assessment and hazard maps.

- Driver Layer: To enable the integration of scenarios from different simulation providers and in different formats, the driver layer was introduced. A distinct driver for each scenario (type) may be defined and added to the driver layer. This architecture allows for the separation of the scenario data format from the internal data representation and data management in the SIM. Currently, the SIM only contains scenarios calculated with *TsunAWI*.
- Scenario Selection Module: This component, described in more detail below, selects a set of best fitting scenarios to an earthquake event. After being triggered with corresponding earthquake parameters, the process is performed completely automatically.
- Tsunami Scenario Repository TSR: It contains the pre-calculated scenarios from which data in the IDB and for generating SHP-Files is obtained.

Selection Algorithm

To acquire a set of best matching scenarios to an earthquake event, the selection algorithm implements a multi sensor approach combining the different available sensor types. Uncertainties occurring from inaccurate measurements and modelling errors in the tsunami model itself are reduced by basing the selection on more than one sensor data type.

In the initial selection algorithm as described in (Behrens et al. 2010), the different sensor types and also the individual sensor stations were weighted to regulate their individual estimated uncertainty. The selection module generated so called matching values for each sensor type for a scenario and accumulated them to an overall weighted sum of matching values hereby defining a measure of suitability of the scenario to the current event.

In the course of the GITEWS project, experiences with real sensor data showed that each sensor group needs to be regarded separately bearing its characteristics in mind. Therefore a stepped approach was introduced replacing the weighted sum over all matching values as a measure of suitability. Seismic data delivering the most robust values is now the basic criteria for selecting a set of best fitting scenarios (pre-selection), which is then narrowed down or adjusted according to GPS displacements in a second step.

The algorithm was adapted for the Sunda Arc taking into account a rupture oriented along the trench. By determining an elliptic area around the observed epicentre, corresponding scenarios to an earthquake event are pre-selected, see Figure 3.4.2. Scenarios lying within the ellipse are chosen in a first step. The dimension of the ellipse depends on the magnitude M_w with the long axis given by and the short axis. The minimum length of 180 km ensures that for small magnitudes at least one scenario is covered. The orientation of the ellipse is aligned in parallel to the trench. From the pre-selection, only scenarios within the uncertainty range [Mw-0.5, Mw +0.3] are taken into account. With the transmission of the more accurate moment tensor magnitude the uncertainty range is reduced to [Mw-0.5, Mw +0.2].

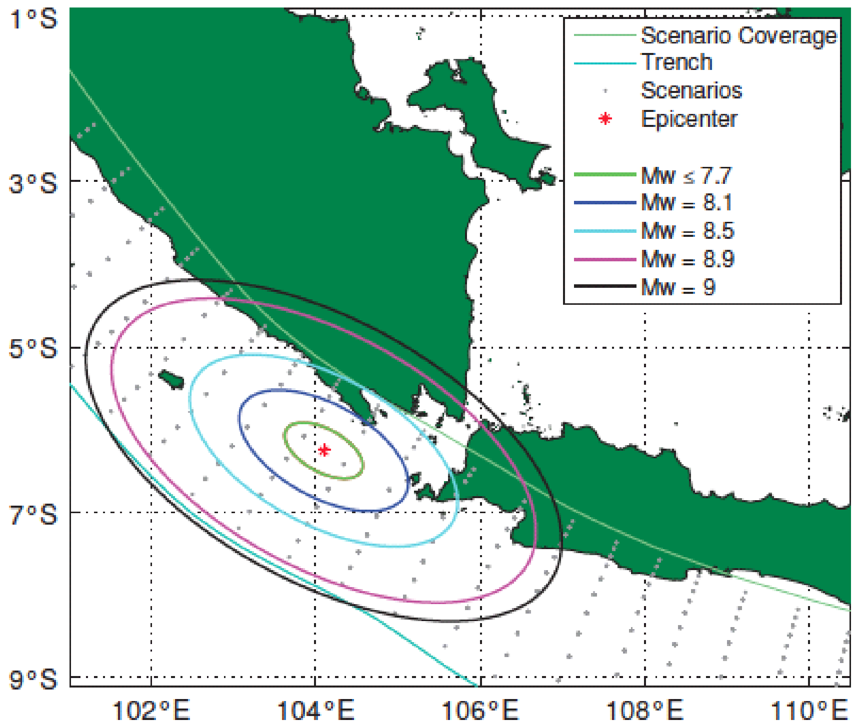


Figure 3.4.2: Ellipses derived from seismic data for different magnitudes from 7.7 to 9.0.

In the subsequent step, GPS displacement vectors are regarded. As GPS sensor data is reliable and the observation data arrives at the DSS fast, it allows for a better estimate of the tsunami threat in the first few minutes after the earthquake. Technically, for each sensor and each scenario obtained after pre-selection, the length of the observed and of the corresponding scenario GPS displacement vector are compared. The algorithm also regards the confidence interval *k* transferred for each observed displacement value. Additionally, an addition uncertainty factor (currently 3.5) is assumed to factor the uncertainty of the rupture model, the discrete set of available scenarios, and the little experience with GPS displacement data in Indonesia up to date. Sensors with simulated displacements which apply to

$$\frac{\max(0, L_{\text{obs}} - k)}{\alpha} \leq L_{\text{scen}} \leq \alpha \cdot (L_{\text{obs}} + k)$$

are considered as matching. Thus, currently the horizontal length is considered so to account for overshoots and that pre-calculated scenarios never fit perfectly to the observed epicentre.

A defined minimum number of GPS sensors have to match accordingly to mark the scenario as suitable for the final selection. By applying the GPS matching algorithm, the magnitudes in the seismic pre-selection may be reduced or epicentres with scenarios removed completely.

3.5 "On-the-fly"-System *easyWave*

The GITEWS scenario repository covers only earthquakes along the Sunda Arc. This selection has historical reasons: initially, GITEWS was designed for the early warning in the Indian Ocean only. Further Project development expanded assessment area over the whole Indonesia. To accommodate for this geographical expansion, on-the-fly tsunami simulation tool was embedded into the Decision Support System. After DSS receives alarm information from SeisComP3 about a new incident, it checks if the epicentre lies within the area covered by tsunami scenario repository. If not, DSS starts on-the-fly simulation tool. This tool is based essentially on the *easyWave* tsunami simulation code (Hoechner et al. 2013; Greenslade et al. 2014). *easyWave* integrates shallow-water equations in linear approximation in spherical coordinates. The numerical leapfrog explicit time-stepping on a staggered finite-difference grid follows the well-established and widely used TUNAMI-F1 algorithm (IUGG/IOC Time Project, 1997). Boundary conditions impose full reflection on land and free transmission at the open sea boundary. As usual in linear simulations, inundation modelling is not performed, instead, coastal flow depths (used for evaluation of EWH – estimated wave height) are extrapolated from the offshore positions (typically, in 50–100 m water depth) using Green's law accounting for wave shoaling, - an approach which was validated and employed by the Japanese tsunami early warning system (see discussion in Kamigaichi 2009).

easyWave tool is loosely coupled to the GITEWS DSS and can be modified and improved any time. As input parameters, it takes from DSS hypocenter and scalar magnitude; output includes estimated wave heights (EWH) and estimated times of tsunami arrival (ETA) at predefined coastal positions. Thus, depending on the epicentre position, DSS effectively branches between either requesting SIM for scenario matching or calling *easyWave* simulation 'on-the-fly'.

On-the-fly wave propagation is integrated for 240 minutes model time at the 4 arc minute grid re-sampled from the ETOPO-1 global bathymetry (Amante and Eakins 2009). Organizing the computation on an expanding grid makes it very efficient, especially at the early stages of tsunami propagation. Typical DSS waiting time after calling *easyWave* is about 20 seconds. Recently, *easyWave* was successfully parallelized for the GPU (Graphical Processing Units) with an overall speedup factor around 20. Due to its linear approximation and coarser bathymetric resolution, on-the-fly simulation tool cannot compete in simulation accuracy with the *TsunAWI* computations stored in the scenario repository. Instead, it is used to provide first-order situation assessment in the regions not covered by the pre-computed scenarios.

The weakest part of the current 'on-the-fly' implementation is its source model. As mentioned above, NE-Indonesia is characterized by a very complex and heterogeneous tectonic situation, so that *a priory* definition of numerous rupture zones geometries, like in the case of

Sunda Arc (see section on Source Modelling above), is hardly possible. Thus, on-the-fly simulation tool does not use pre-defined rupture geometry like in the Sunda Arc, but instead, employs a simplified source model. In practice, since there is little knowledge about the strike and dip angles the initial tsunami wave field is approximated by a symmetric hemispherical uplift. Diameter of the uplifted area is proportional to usual scaling law, and vertical amplitude is estimated such that resulting tsunami energy equals that of a 45° trust fault at hypocenter.

It is clear, that this simplified source model does not imply any source directivity and, hence, should result in under- and over-estimation of radiated wave heights depending on the direction of true rupture. Significant future improvement should be linking on-the-fly simulations to the moment tensor solution (which would be, anyway, not possible within 5 minutes after the origin time). Another improvement might include incorporation of preferred focal mechanisms depending on local tectonic structures and/or local CMT statistics. Both options were, however, out of the scope and possibilities of the current project.

4. Tsunami Early Warning Decision Support

The challenge remains to provide the best early warning decision possible within the very short warning times in Indonesia's geological setting of near field tsunamis. As tsunami waves might reach the Indonesian coastline in as short as 20-40 minutes after an earthquake, the Indonesian Agency for Meteorology, Climatology and Geophysics (BMKG) is officially obliged to issue a first warning within five minutes after an earthquake.

To further support the Chief Officer on Duty (COOD) in the InaTEWS Warning Centre during the assessment of a given (potential) tsunami situation and the management of the early warning process, a first-of-its-kind Decision Support System (DSS) was developed and put into operation in 2010.

4.1 The InaTEWS DSS

The DSS is embedded in the InaTEWS Early Warning System which consists of individual sensor systems (seismic monitoring system, tide gauge system and continuous GPS network system) and a simulation system.

The simulation system (SIM) provides access to a large set of pre-calculated tsunami scenarios using the *TsunAWI* model from Alfred-Wegener-Institute (AWI). The SIM performs a matching of a set of sensor observations against the scenario database in about one second (Behrens et al. 2010), delivering a list of best-matching scenario identifiers together with additional quality and mismatch parameters. In order to achieve these response times, the tsunami scenarios must be pre-processed by the SIM and the DSS in an offline procedure which involves statistical data mining ("ingestion process").

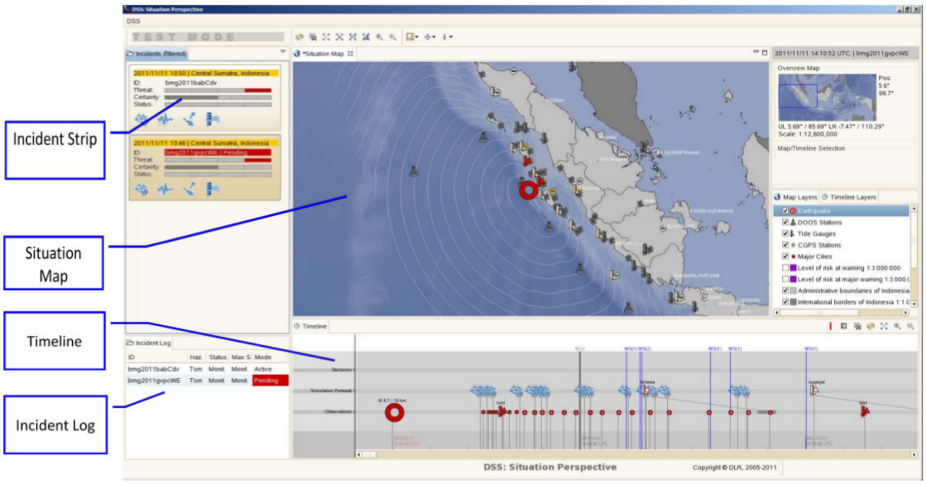
Tsunami early warning decision making can be characterized by very short deadlines, high degree of uncertainty, initially missing or incomplete/imperfect information received in a non-deterministic sequence and high stress factor. The DSS has been designed for and aims at being easy and fast to use even under high time and mental pressure in order to make decisions regarding spatially discontinuous warnings easier and faster whilst meeting highest reliability demands.

Based on the situation awareness concept by Endsley (Endsley et al. 2003) the DSS acts as a monitoring system which updates the situation information as soon as new sensor input becomes available or deadlines are reached. Focus has been put on the development of an optimized graphical user interface (GUI) which on the one hand supports the decision maker to concentrate on the most important information required for decision making, and on the other hand allowing access to all available information for cross-checking if required (Friedemann et al. 2010). A photograph shows the DSS installation in the Tsunami Early Warning Centre at BMKG (Figure 4.1.1).

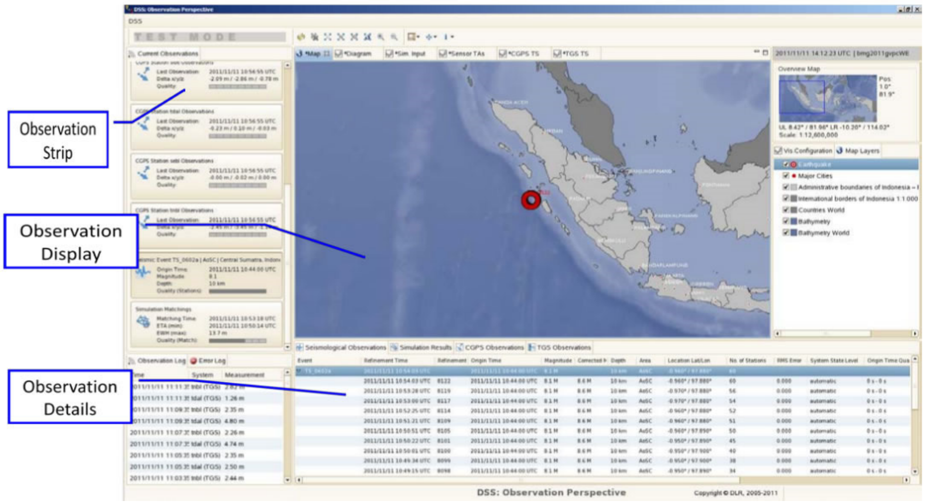
Figure 4.1.1: DSS installation in the InaTEWS Tsunami Early Warning Centre at BMKG Headquarters, Jakarta, Indonesia.

Using fast information fusion and aggregation, the DSS GUI can thus be operated by a single skilled user to take the decision whether or not to send a warning in a timely manner. The sequence of perspectives is shown in Figure 4.1.2. The DSS assesses every change of the situation detected by any of the individual sensor systems and reacts dynamically to those changes by compiling and visualizing a new warning configuration. It then configures and creates warning messages in pre-defined formats when the user decides to be “ready for sending”. It is up to dissemination systems operated by BMKG to disseminate the warnings to pre-configured receivers.

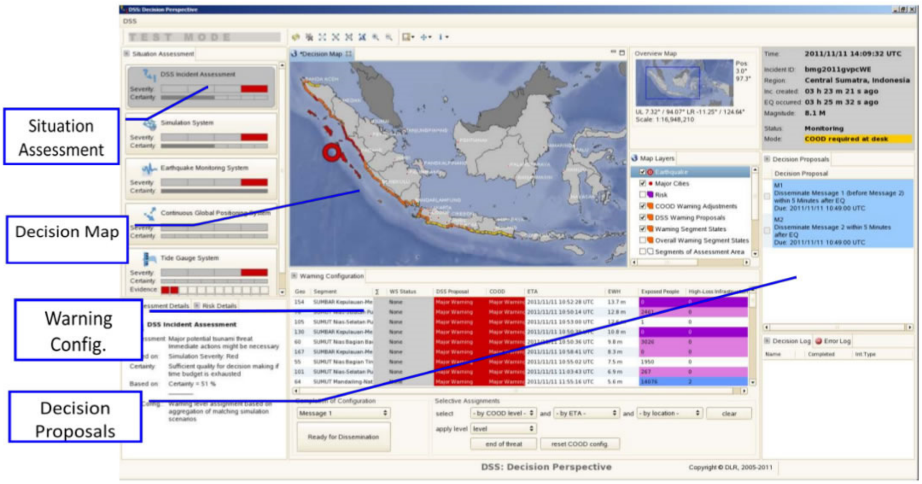
a) Situation Perspective:



b) Observation Perspective:



c) Decision Perspective:



d) Product Perspective:

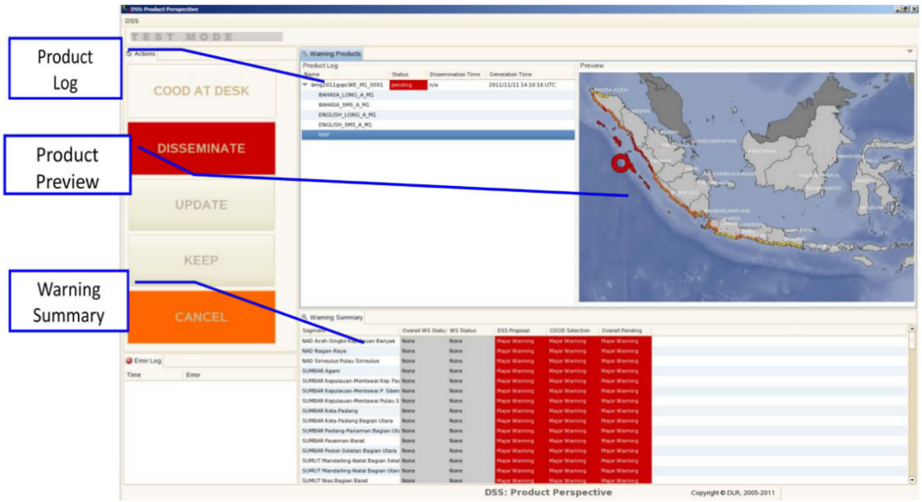


Figure 4.1.2: The Graphical User Interface (GUI) of the InaTEWS Decision Support System – a summary of perspectives.

Furthermore, results of the tsunami risk assessment have been integrated into the DSS to support the decision maker with dedicated risk information (e.g. affected people, high loss objects) (Post et al. 2010, Steinmetz et al. 2010).

While the InaTEWS DSS focuses on the national tsunami early warning process for Indonesia, UNESCO/IOC coordinated efforts to provide tsunami early warning information for the whole Indian Ocean. According to the specifications of UNESCO/IOC, we developed a lightweight extension to the InaTEWS DSS focusing on tsunami information for the Indian Ocean based on pre-modelled ocean wide tsunami scenarios. Installed in 2010, the DSS RTSP Extension enables BMKG to officially act as a Regional Tsunami Service Provider (RTSP) approved by UNESCO/IOC.

4.2 Experiences and Enhancements

The development, maintenance and optimization of a tsunami early warning system is an infinite cyclic process of operational experience, event analysis, lessons learned and subsequent modifications and extensions of hardware, software, rules/workflows and standard operating procedures (SOPs). Comprehensive training of staff members (COODs, technicians, administrators) involved in operations / maintenance / upgrade / migration tasks is another key factor for sustainable DSS operation. During PROTECTS, a large number of trainings has been conducted by the PROTECTS project partners in order to enable BMKG to achieve this goal.

Since the InaTEWS DSS and the RTSP Extension became operational, a number of improvements have been developed and deployed, ranging from minor updates of a single InaTEWS component up to major updates of several InaTEWS systems along the information processing chain.

Among the major improvements are:

- The extension of the area covered by pre-calculated tsunami scenarios, together with scenario updates in areas already covered, thus increasing the area for which detailed tsunami wave estimations are available;
- An interface to the online simulation system *easyWave* which is able to provide less detailed tsunami estimations in real time in areas not yet covered by pre-calculated scenarios, thus extending the area in which simulation-based situation assessments are available;
- The update of risk and vulnerability information in the DSS based on the updated set of pre-calculated tsunami scenarios, providing additional information to the decision maker;
- The extension of the database of ocean wide scenarios, thus allowing the DSS RTSP Extension to select from a wider range of possible tsunami scenarios;
- The improvement of the SIM matching algorithm by AWI, including a more sophisticated way of result set reduction based on GPS measurements indicating the rupture process of the earthquake resulting in a more precise situation assessment by the DSS;
- The extension of GPS measurement analysis and visualization in the DSS GUI, providing more GPS-based support to the decision maker;
- The availability of a moment tensor magnitude, provided by the seismic monitoring system SeisComP3, including modifications along the processing chain SeisComP3 – DSS – SIM to correctly process this new magnitude type (i.e., switch off magnitude correction algorithms once the moment tensor magnitude is available). This allows a

faster and more precise assessment of the earthquake and thus the subsequent tsunami threat assessment.

As a result, the InaTEWS DSS and the other InaTEWS system components have been extended and improved over the recent years to provide three levels of situation assessment:

- The most detailed situation analysis is based on pre-modelled AWI scenarios if the earthquake is within the *area of simulation coverage* (AoSC);
- Simulation based situation assessment based on the *easyWave* online simulation is possible for a large area outside the AoSC;
- For all other areas within the *area of interest*, a set of rule-based workflows can be applied to derive warning levels mainly based on earthquake information.

4.3 Testing and Training Environment

Main data processing unit of the German-Indonesian Tsunami Early Warning System consists of the Decision Support System (DSS) with the Simulation Module (SIM) and the Tsunami Service Bus (TSB), each of them being a unique complex of hard- and software solutions. Successful development and launch of such a complicated operative system requires extensive testing for system verification and validation. GITEWS testing strategy is based on the concept of virtual sensors. Whereas during normal operational activity, TSB/DSS receive data directly from the sensor systems, in testing environment, Scenario Player simulates all sensor data streams on input to the TSB/DSS. By doing that, Scenario Player replays a system test scenario retrieved from the Test Scenario Library. Test scenarios consist of ordered series of sensor messages resembling historical or purely virtual events. In other words, test scenarios are images of events (earthquakes, tsunamis) as recorded by sensors (seismic, GPS, buoys, tide gauges).

Since instrumental records of tsunamis in Indonesia are extremely scarce, most testing scenarios are based on purely virtual events or combine real sensor records with simulated (e.g., real historical SeisComP3 data stream combined with simulated tide gauge series for the same event). In any case, test scenario is based on a consistent physical model of earthquake and corresponding tsunami. This fact guarantees that sensor messages of different sensor types are fully internally consistent and physically reliable. Test scenarios are produced with the same set of simulation tools as used for Tsunami Repository and on-the-fly simulations: *RuptGen, TsunAWI, easyWave*. Instrumental time series, simulated at individual sensor positions, are then converted into the native sensor formats and stored along relative time line.

Since scenarios are fully controlled by their developers, starting from the rupture model down to the final coastal run-up, it is a-priori known, which TSB/DSS/SIM data processing and situation assessment is expected to be a right one. This explains extensive use of virtual scenarios for system verification and validation. GITEWS Scenario Library covers all possible important earthquake and tsunami use-cases which may occur during everyday TEWS operation. Designed primary for testing, most of these scenarios also carry large potential for teaching and training of the DSS operation personnel. In particular, automatic scenario generation tool was designed in order to facilitate officers-on-duty in creating and running their own scenarios to teach and train themselves, as well as to prepare themselves for future challenges.

5. System Performance

The Tsunami Early Warning System (TEWS) has produced its first tsunami warning on September, 12, 2007, following the Bengkulu earthquake off the coast of south Sumatra. As the warning system is simulation based, it is able to give warning information for single segments along the coastline. For the implementation, the administrative districts of Indonesia along the coastline have been chosen as warning segments. In principle a warning can be produced for even smaller segments but as the final responsibility for the reaction lies on district level those entities have been chosen. The warning computed from the scenarios is divided into four warning levels depending on the estimated wave height (EWH) at the coastline (Tab. 5.1).

Figure 5.1: A summary of different warning levels.

	Earthquake information only	No tsunami
Advisory	a minor tsunami might has been generated	EWH < 0.5 m
Warning	a tsunami has been generated	0.5 m < EWH < 3.0 m
Major Warning	a major tsunami has been generated	EWH > 3.0 m

Communities at risk need to react very fast in case of a major hazard, therefore the warning messages need to be clear and comprehensible, because the trained reaction schemes of the population (evacuation etc.) can only cover a few cases within the short time available for reaction.

Table 5.1.2. shows the warning information which was published by the warning system for large earthquakes around Indonesia during the past 5 years of operation from 2007 to 2012. The table compares predicted warning levels against observed tsunamis. In 15 of 19 events a correct estimation in terms of warning levels has been documented (green colour). Only in 3 cases an incorrect estimation of the warning level has been recorded where the warning level was one level too high (two cases) or one level too low (one case). For only one case a major overestimation (false alarm – red colour) has been published. No tsunami remained undetected by the system. However, it must be mentioned that the direct comparison of predicted wave heights and measured wave heights (i.e. at tide gauges) may deviate up to 50 %, in most cases predictions overestimate observations. This is due to the worst case scenario approach which is implemented in the system according to the large uncertainties in the input data a few minutes after the earthquake. On the other hand, estimated arrival times for the warning segments generally show much better agreement with actually measured arrival times as the wave heights.

Table 5.1.2: List of tsunami alerts triggered by the warning system from 2007 – 2012 (source BMKG).

Region	**Date**	**M**	**Depth**	**Dec**	**MTH**	**Comment**
Southern Sumatra	12.09.2007	7.9	10 km	major	4 m	
Southern Sumatra	12.09.2007	7.7	24 km	warn	1 m	
Talaud Islands	13.09.2007	6.4	30 km	EQ	n.a.	
Southwest of Sumatra	24.10.2007	7.0	10 km	adv.	n.a.	
Sumbawa Region	25.11.2007	6.8	45 km	EQ	n.a.	
Southern Sumatra	25.02.2008	7.2	10 km	major	12 cm	Initially overestimated M (final is 7.2)
Southern Sumatra	25.02.2008	7.0	26 km	adv	n.a.	
Sunda Strait	26.08.2008	6.6	20 km	EQ	n.a.	
Halmahera	11.09.2008	7.6	109 km	EQ	n.a.	Deep earthquake
Irian Jaya Region	03.01.2009	7.2	10 km	major	78 cm	

Java	02.09.2009	7.3	30 km	warn	80 cm	
Banda Sea	24.10.2009	7.3	165 km	EQ	n.a.	Deep earthquake
Northern Sumatra	06.04.2010	7.2	32 km	adv	40 cm	
Northern Sumatra	09.05.2010	7.2	30 km	adv	n.a.	
Nicobar Islands	12.06.2010	7.5	21 km	adv	n.a.	
New Britain Region	18.07.2010	7.1	26 km	EQ	n.a.	
Southern Sumatra	25.10.2010	7.8	10 km	warn	>10 m	Mentawai slow tsunami quake
South of Java	04.03.2011	7.2	24 km	EQ	n.a.	normal event off trench
Northern Sumatra	11.04.2012	8.9	10 km	major	80 cm	strike-slip quake, no major tsunami

Keys: M = Magnitude

Dec = Decision proposal by DSS;

EQ = only earthquake information;

adv = Advisory (EWH < 0.5 m);

warn = Warning (0.5 m < EWH < 3 m);

major = Major Warning (EWH > 3 m)

MTH = measured tsunami height (at nearest tide gauge)

Colour coding: green = predicted warning level ok;

yellow = predicted warning level is one level too high or too low;

red = false warning

The Indian Ocean Earthquake of April 11, 2012, Mw 8.6, about 450 km west of Northern Sumatra, produced only a minor tsunami of about 1 m at the Indonesian coastlines. This is due to the strike-slip character of this intra-plate quake and the consequently low co-seismic vertical displacement of the ocean floor. The earthquake was registered by the warning system after 3.5 minutes with an overestimated magnitude of 8.9. Due to the Standard

Operations Procedures in the Tsunami Early Warning Centre a major tsunami warning was issued after 4 minutes and 30 sec based on this value. Simultaneously, on-the-fly tsunami simulation was started (see section 3.5 above) based on the same magnitude. Since focal mechanism is not available to the on-the-fly simulation tool, default worst-case source model have strongly overestimated the tsunami generation potential for this earthquake. Resulting estimated wave heights (EWH) were as high as 5 metres and even more. This case demonstrated a role which fast CMT coupled with on-the-fly tsunami simulations could play for the early warning (Wang et al. 2012b.

6. Tsunami Risk Assessment – Linking National Level Early Warning with Local Level Disaster Risk Reduction

For disaster risk reduction, early warning systems play a key role: "If an effective tsunami early warning system had been in place in the Indian Ocean region, thousands of lives could have been saved" (UN/ISDR-PPEW, 2006). In most countries around the globe risk management structures and capacities are not sufficiently developed to tackle the level of risk they face. This is largely due to the fact that they do not know their risks and vulnerabilities, thus leaving risk management structures ineffective. Hence, tsunami risk assessment and monitoring is an indispensable requirement for effective early warning and community level disaster management.

When risk and vulnerability assessments are successfully conducted, their results can significantly contribute to the design and implementation of knowledge-based effective risk management. To support the disaster preparedness and mitigation, the knowledge about the tsunami risk in coastal areas is one of the essential components of an end-to-end early warning system. In the framework of the joint Indonesian-German Working Group on Vulnerability Modelling and Risk Assessment led by the Indonesian Institute of Sciences (LIPI) and the German Aerospace Centre (DLR) together with national and international researchers, a concept was developed and risk maps as well as information to various disaster management institutions in Indonesia provided. This included the local level as well as the National Agency for Disaster Management (BNPB) at national level. Moreover, key risk parameters were derived from these maps and were integrated into the Decision Support System (DSS) of the Tsunami Early Warning System (InaTEWS) at the National Agency for Meteorology, Climatology, and Geophysics (BMKG). In addition to this, detailed technical descriptions and guidelines were elaborated to explain the developed approach, to allow future updates of the results, and to enable the local authorities to conduct tsunami risk assessment by using their own resources. Amongst others, contributions were made to the Guidelines for Tsunami Risk Assessment of the UNESCO IOC (UNESCO-IOC, 2009 a, b).

6.1 The Approach: From Science to Practical Implementation

The overall goal of the provided risk assessment is to develop knowledge in such a way being relevant for end-users who are involved in InaTEWS on the national, regional and local level, hence for effective disaster management.

Risk assessment is based on the outcome of the preceding tsunami hazard and vulnerability assessment. The hazard assessments have to define the tsunami extent and intensity, the exposure parameters and the occurrence probability. The vulnerability assessment encompasses the identification and assessment of the vulnerability of the population exposed. Risk assessment aims at identifying the capacities and resources available to address or manage tsunami threats.

As a conceptual base for the risk assessment, a Tsunami Early Warning reaction scheme has been developed based on the four elements of Early Warning Systems (EWS) (UN/ISDR 2006a). It provides an overview of a sequence of hierarchical processes that need to be accomplished for saving lives within the time span from the detection of a tsunami event until the materialization of a tsunami at the coast. Especially, for the case of Indonesia, there is a need to develop quick institutionalized response mechanisms of organizations involved in the issuing of a tsunami warning, and of exposed populations to react to warnings and find a safe place before the first tsunami wave hits. This is due to the fact that the Estimated Time of Arrival (ETA) of a detected tsunami at the coastline in Indonesia facing the Sunda Trench is very short (below one hour), which poses an extraordinary challenge for the development of efficient warning as well as response structures.

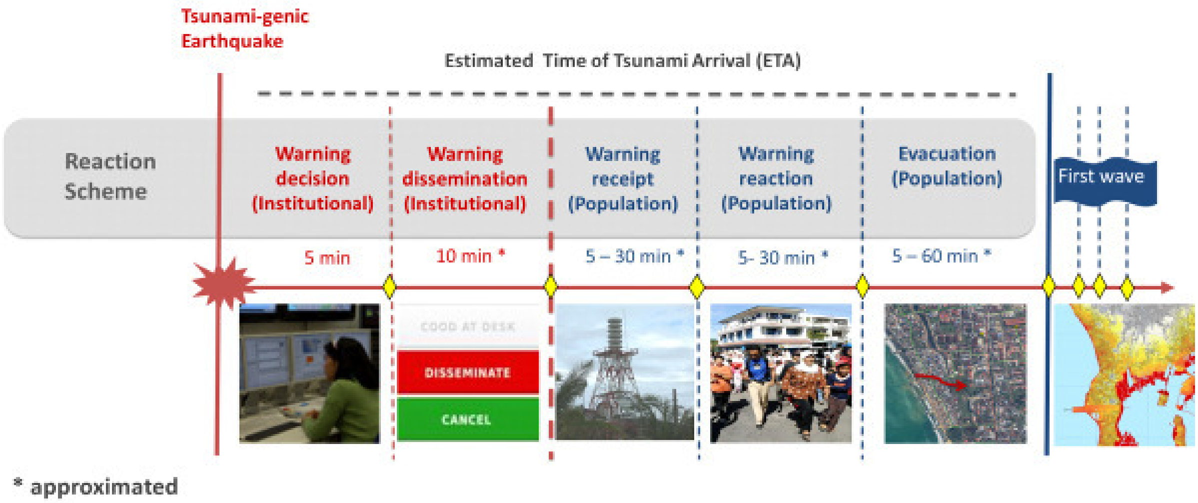


Figure 6.1.1: Reaction scheme of people centred early warning systems.

Figure 6.1.1 schematically illustrates the reaction and time sequences of an early warning system (downstream component) from the moment of tsunami warning detection until the evacuation of the population at risk. It serves as the basis for the risk assessment approach. The assessment of the efficiency performance of the above mentioned components of the reaction scheme are methodologically combined to provide an integrated picture of tsunami risk. The result is a quantification of the spatial risk of loss-of-live and can be presented in form of maps or time-dependent casualty numbers per administrative unit.

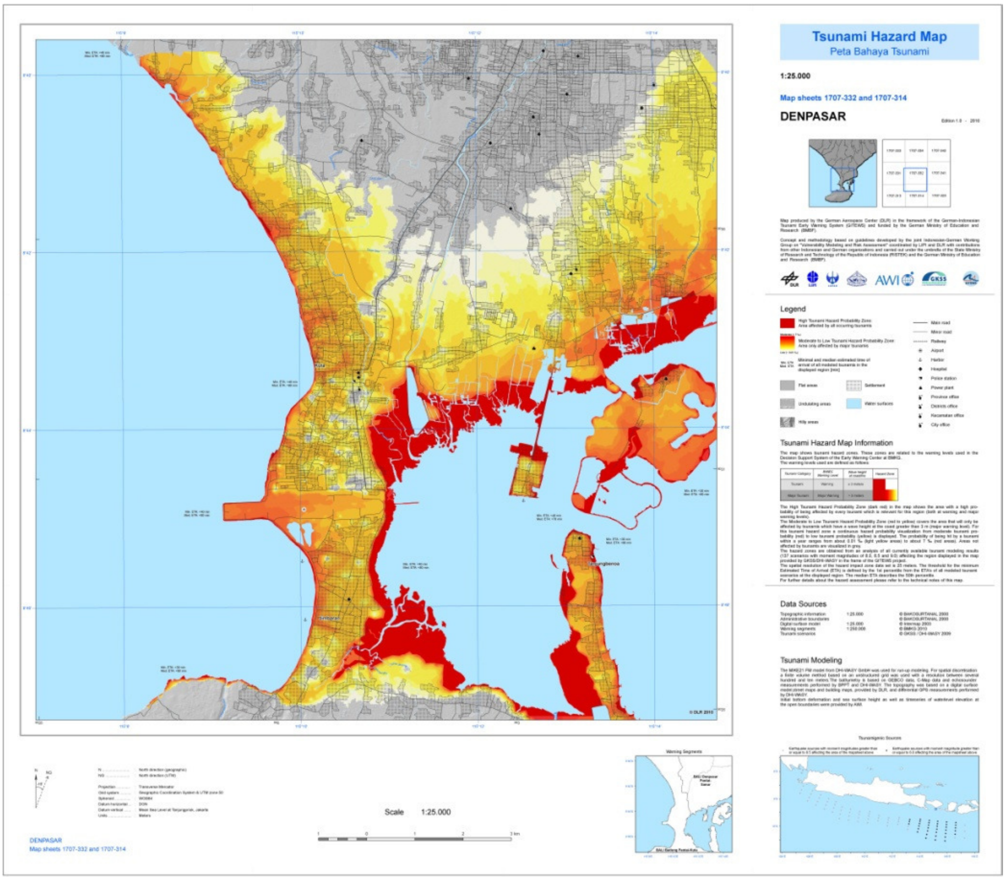
Using this information the decision maker can intuitively see and evaluate areas possessing high risk. This consequently indicates a high probability of early warning and evacuation failure and hence a high probability of loss of lives. This integrated picture can strongly support decision for all disaster risk management aspects within the disaster cycle.

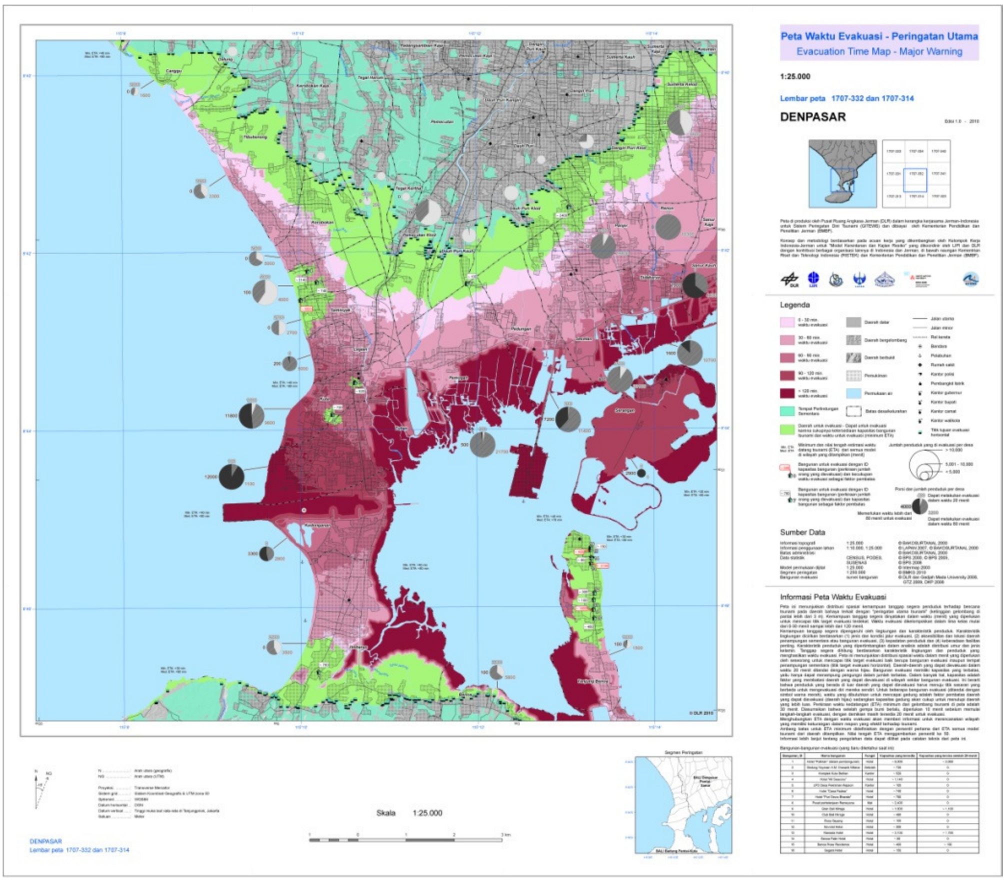
The assessment was carried out focusing on two main objectives. First, to provide risk information on a coarse overview map scale (1:100,000) for large coastal areas relevant for the early warning system and the warning process. Secondly, to provide risk information based on a “detailed-scale” assessment (1:25,000) for selected pilot regions, which serves as basis for the disaster preparedness and for the development of disaster risk reduction and mitigation strategies conducted by the local authorities. Through this the full chain of national early warning and local level disaster risk reduction is ensured.

The methods developed and implemented for risk assessment follow the assessment of hazard, vulnerability and risk. The generated results and products link directly to the reaction scheme components and the risk management tasks. In the following all components of risk assessment as conducted within GITEWS and PROTECTS will be highlighted shortly. More details can be found in Post et al. 2008, 2009, 2011; Mück et al. 2013, Imamura et al. 2011, Wegscheider et al. 2011, Muhari et al. 2010, 2011, Khomarudin et al. 2009, Taubenböck et al. 2008, Anwar et al. 2008, Strunz et al. 2011.

6.2 Multi-Scenario Tsunami Hazard Assessment

The multi-scenario approach consists of the following steps: (1) the identification of the possible tsunami sources extracted from the tsunami database and the approximate assignment of probabilities to these events; (2) the modelling of the tsunami propagation and its inundation on land; (3) the multi-scenario aggregation and computation of statistical parameters for the potentially inundated areas, which is based on the analysis of all scenarios; (4) the derivation of the probabilities for inundation based on the uncertainty propagation using all scenarios; and (5) the generation of the hazard maps.


Tsunami Hazard Map
Peta Bahaya Tsunami
1:25.000
Map sheets 1707-332 and 1707-314
DENPASAR
Legend
Tsunami Hazard Map Information
Data Sources
Tsunami Modeling
Scale 1:25.000
DENPASAR
Map sheets 1707-332 and 1707-314


Peta Waktu Evakuasi - Peringatan Utama
Evacuation Time Map - Major Warning
1:25.000
Lembar peta 1707-332 dan 1707-314
DENPASAR
Legenda
Sumber Data
Informasi Peta Waktu Evakuasi
Skala 1:25.000
DENPASAR
Lembar peta 1707-332 dan 1707-314

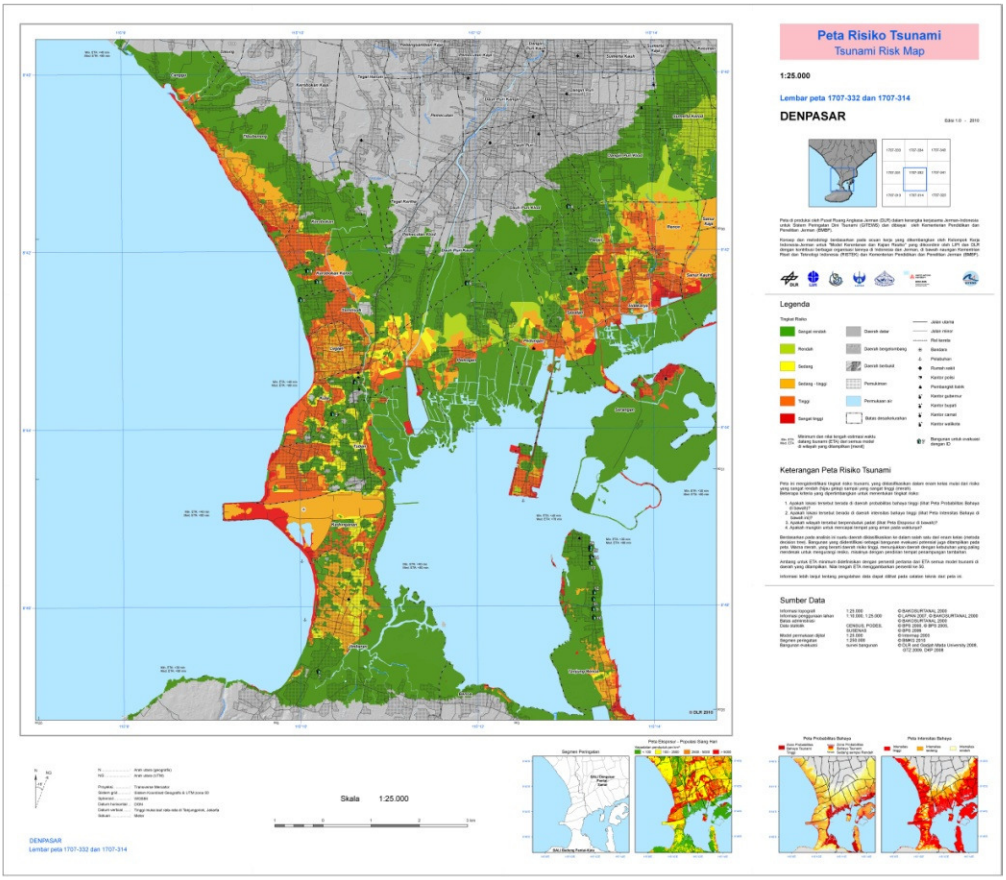


Figure 6.2.1: Tsunami hazard, evacuation time and risk map

The tsunami hazard map (Figure 6.2.1, to the left) shows the probability of tsunami occurrence (tsunami inundation with at least 0.5 meter water depth) on land and the two hazard zones related to warning levels defined by the Indonesian Tsunami Warning System. It also provides the minimum and median values of the ETA. On the lower right side of the map the locations of the tsunamigenic sources are given, at which earthquakes along the Sunda Arc can cause impacts at the respective coastal area.

6.3 High Resolution Tsunami Inundation Modelling for Hazard Assessment

For 3 selected areas, Kuta (Bali), Padang (West-Sumatra), and Cilacap (southern coast of Java) a high resolution inundation study for the generation of hazard and risk maps was performed. The modelling System MIKE 21 FM (Gayer et al 2010) integrates non-linear shallow water (NLSW) equations using a cell-centred finite volume method and includes lateral stresses which depend on viscous friction, turbulent friction and differential advection.The bottom shear stress is determined by a quadratic friction law, where the friction coefficient can be expressed with the Manning number or the Chezy number.

At the outer open boundaries the model was driven with time series of *TsunAWI* (section 3) results interpolated to grid nodes with a spatial resolution of 100 m. In coastal waters and on land the model grid resolution was in the order of 10 m enabling to adequately resolve topographical and land use features. Data used were echo sounder measurements (BPPT, Indonesia, DHI-WASY and University of Hannover), navigational charts (C-Map), GEBCO, digital surface and terrain maps, street and building maps (DLR), and GPS measurements (DHI-WASY). During inundation the flow velocities of a tsunami are strongly influenced by bottom roughness (i. e. Leschka et al. 2011). For this reason great care was taken to establish maps of equivalent roughness values of 43 land use classes (e.g. different types of buildings, rural areas, and urban subareas). The importance of using such a detailed representation of different roughness elements could be shown by comparing the model results with those of a run using a constant Manning coefficient of 1/32 (a value representing the roughness of sand and often used in hydro-dynamical modelling). For detailed discussion see (Gayer et al. 2010).

6.4 Exposure and Vulnerability Assessment

The analysis of the vulnerability requires reliable information about the population and the critical assets that are exposed to the tsunami hazard. The approach, which has been developed in GITEWS, is based on a combined approach using in-situ assessment and remote sensing data in order to generate detailed day- and night-time population information as well as building and infrastructure characteristics. Vulnerability was measured in assessing people's response capabilities and their preparedness through assessment of (1) warning dissemination, (2) anticipated response and (3) evacuation capabilities. The quantification of human response and evacuation capabilities is a complex issue that involves the consideration of all aspects that influence the people's ability to reach a safe area after receiving the tsunami warning. The evacuation time map (see Figure 6.2.1) shows the spatial distribution of evacuation time and hence people's evacuation capability when compared to the estimated times of tsunami arrival. Also the amount of people per administrative unit, which are able and not able to evacuate for minimum and mean tsunami arrival times, is assigned. This helps to detected hotspots of evacuation failure and to prioritize intervention measures accordingly.

6.5 Tsunami Risk Assessment

Risk assessment combines the outputs of the hazard and the vulnerability assessments. In our people-centred approach the risk assessment is aiming at analysing the risk that people cannot reach safe areas on time and are hit by the tsunami. Hence it delivers the risk of warning and evacuation failure and the risk of loss-of-lives.

The tsunami risk map (see Figure 6.2.1, to the right) shows levels of risk from low to high based on the combination of hazard, exposure and vulnerability components. Through this, hotspot areas featuring high risk can be assigned and risk reduction strategies can be planned specifically, e.g. adding additional vertical evacuation capabilities.

On the basis of these risk maps along the southern coasts of Sumatra, Java and Bali selected key parameters were derived and provided for the operational use in the early warning system. These values are pre-computed for the two levels of tsunami warnings and integrated into the Decision Support System (DSS) of the Early Warning System.

The knowledge about the tsunami risk and the mitigation of these risks are essential. Therefore, it is necessary to ensure that the products and maps are transferred to the relevant governmental disaster management and planning authorities.

6.6 Experiences and Enhancements

A common framework and methodology to derive risk assessment products for tsunami disaster management and early warning has been worked out. The scientifically developed and implemented risk assessment measures the risk of loss of lives according to a defined reaction scheme reflecting the end-to-end early warning chain. This ensures that the results and findings can directly be used for national level early warning decisions as well as for local level disaster risk reduction efforts. Implementing risk knowledge into end-to-end early warning systems has been achieved for the first time and has been proven as successful, highly relevant and beneficial. The risk assessment products were mainly provided in the form of thematic maps and geospatial information that have been implemented into the DSS and provided to BNBP with continuous stakeholder involvement and capacity building efforts. International, national and local level guidelines in the field of tsunami risk assessment have been elaborated and contributed to organizations like UNESCO-IOC (UNESCO-IOC, 2009 a, b), BNPB and responsible authorities at local level.

Bringing together people with scientific expertise and practical experience in the field of tsunami risk assessment in Indonesia was essential to work out the risk knowledge. The transfer of created risk knowledge driven by the scientific community towards implementation and practical use in decision making and resource allocation for disaster risk reduction was successful. But it will require a long-term strategy and perspective. There is a strong need for a sustainable institutional implementation of the knowledge and development process bridging scientific approaches and practical requirements. The potential for the development of specific risk products related to concrete planning requirements and based on a solid scientific basis is still high. Attached to this is the apparent need for a continuous process in developing human resources. Based on the jointly developed methodology the transferability to other tsunami endangered regions is possible. The approach and framework was laid out to allow its adaptation for multi-hazard risk assessment, such as in the fields of climate change and extreme hydrological events.

7. Tsunami Preparedness at Community Level - Experiences from 7 Years of Capacity Development in Indonesia

The ultimate goal of people-centred early warning systems is to “empower individuals and communities threatened by hazards to act in sufficient time and in an appropriate manner to reduce the possibility of personal injury and loss of life” (UNISDR 2006a, b).

As part of the GITEWS project, a capacity development project was implemented from 2006 to 2010 by the German International Cooperation (GIZ) and its Indonesian partners. A national and local level support to the development and implementation of mechanisms and strategies was given to enable people in tsunami-risk areas to receive prompt alerts and to be able to execute adequate life-saving responses quickly. It was designed as a pilot project with prime locations in West Sumatra; Bali and Java (Spahn et al. 2010).

Figure 7.1: Project areas during GITEWS and PROTECTS.

The activities were followed by the PROTECTS project (2011 to 2013). PROTECTS made use of the products of GITEWS and the experiences in the pilot areas as inputs for the development of national references and the integration of tsunami early warning and preparedness into the overall Indonesian disaster management. Furthermore, the results strengthened local disaster management agencies in community oriented tsunami risk management to make tsunami early warning effective. The project also contributed to promote a common understanding of InaTEWS and the warning services on the part of the related institutions and the general public. Experiences from Indonesia were shared with international and regional platforms like the ICG IOTWS and UNISDR.

7.1 The Setting

Coastal communities in Indonesia have to cope with the threat of near-field tsunamis. The very short travel time of this kind of tsunami from its source – a nearby epicentre – to the shore generally limits warning and evacuation times to 20-40 minutes. Specific local tectonic, seismic and bathymetric conditions may make warning and evacuation times even shorter in some areas.

The devastating 2004 tsunami was not only the starting point of InaTEWS, but also triggered the setting up of a new institutional framework for disaster management. Following the Disaster Management Law issued in 2007, the National Disaster Management Agency (Badan Nasional Penanggulangan Bencana – BNPB) was setup in 2008. Despite the fact that most provinces and districts have now established a Local Disaster Management Agency (Badan Penanggulangan Bencana Daerah - BPBD) in their respective areas, local authorities generally still lack an understanding of their role in local preparedness planning and tsunami early warning; particularly in terms of determining how to react and how to disseminate official calls for evacuation to their communities based on warnings from the National Tsunami Warning Centre (NTWC). Many of the newly established BPBDs still struggle with a lack of skilled personnel at management and operational levels.

7.2 Our Experiences

Based on more than seven years of practical experiences to strengthen tsunami early warning and preparedness at community level in Indonesia the following experiences and lessons learnt are to be highlighted:

A Consecutive Step & Multi-Level Approach to Build Tsunami Preparedness

The learning process during the GITEWS project led to the development of a step-by-step approach towards tsunami preparedness across multiple levels (Spahn et al., 2014).

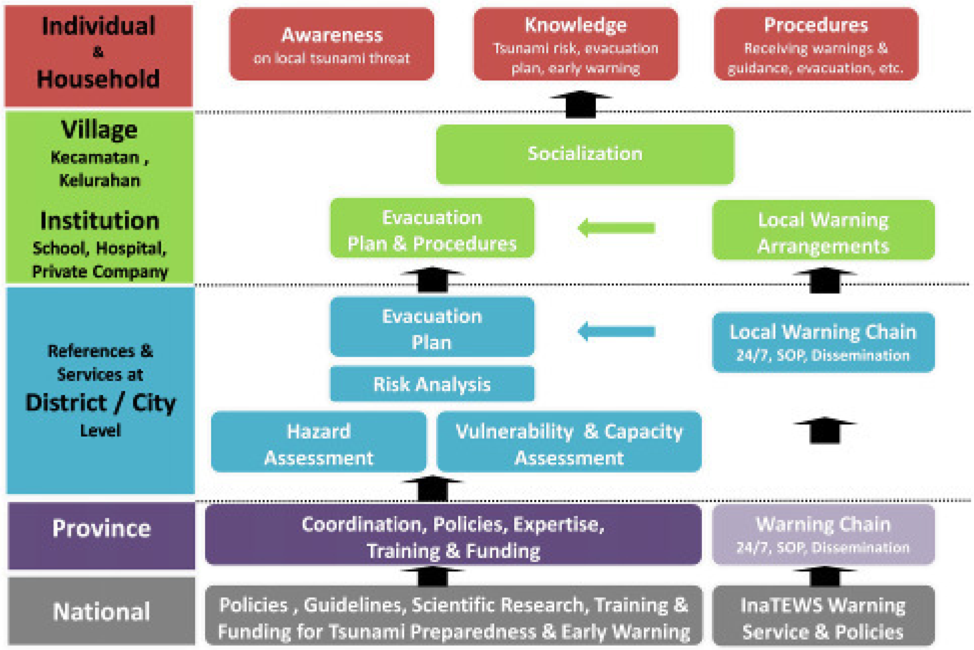


Figure 7.2.1: The consecutive step by step and multi-level approach.

The rationale for this approach is based on the assumption that the chances to survive a near-field tsunami depend very much on the capacities of the affected people to quickly assess the situation and take the right decisions and actions based on basic but solid knowledge of local tsunami risks and preparedness plans, even in the case of the failure of warning services or in the absence of guidance from local authorities during an emergency. Therefore people in areas at risk need to be aware about tsunami hazard and risks and understand local warning and evacuation procedures. Furthermore, individuals and families should be encouraged to discuss and agree on own emergency procedures (self-protection arrangements) within their environment (Red Level, Figure 7.2.1).

To provide people in communities at risk with more than thumb rules or general instructions on how to react to a tsunami threat, it is necessary to develop specific local evacuation maps and procedures as well as warning arrangements in a participatory way and communicate them to all community members (Green Level, Figure 7.2.1). Developing such plans at village or institutional level usually requires references regarding hazard and safe zones and recommended evacuation strategies, as well as the development of local warning services. The responsibility to provide such references, including risk assessments, evacuation plans and the setting up of mechanisms for decision making and disseminating warnings lies with district and city governments (light Blue Level, Figure 7.2.1).

To build local tsunami preparedness in a consistent and coherent way, national guidelines and policies are required to provide the necessary framework for local actors (Grey Level).

The National Guideline on Tsunami Warning Services, as developed by BMKG, provides official information regarding the Indonesian Tsunami Early Warning System (InaTEWS), the warning chain from national to local levels, the sequence and content of warning messages - including recommendations on reaction to local authorities – as well as clarification on the roles, responsibilities and procedures of all relevant bodies. Other guidelines by the National Disaster Management Agency (BNPB) are addressing topics like risk assessments, local emergency centres and contingency plans.

During the PROTECTS project the above scheme proved to be an excellent tool to negotiate and organize the capacity development process with partners and target groups in the project areas. The simplicity and convincing logic of the scheme helped a lot to communicate and visualize the joint working process and expected outputs at any stage on the route.

Hard to Get a Good Foundation – Solid Hazard Maps are Still Scarce

Understanding tsunami hazard and the assessment of possible impacts on their community are preconditions for local decision makers and other stakeholders to initiate activities and plans to get better prepared for future tsunami events. In Indonesia, such information is often unavailable, meaning that most of the preparedness activities at a community level are based on assumptions derived from rule of thumb and limited information. Although a minimum standard for tsunami risk assessment has been developed, implementation is still a big challenge due to the limited availability of experts and adequate data to support local processes. Therefore, community evacuation plans are often developed based on rough contour maps without reliable information on tsunami inundations, which in turn results in non-specific, generalized tsunami awareness, preparedness and education materials being used for community trainings. Indonesia has yet to agree on a standardized methodology and a lead agency at national level to develop tsunami hazard maps at appropriate scales.

A difficult Warning Chain – Decision-Making in a Situation of Uncertainty

InaTEWS policy obliges the National Tsunami Warning Centre (NTWC) to disseminate a first tsunami warning within five minutes after the occurrence of an earthquake with tsunami potential. During these first few minutes, the NTWC relies on seismic and land-based Global Positioning System (GPS) real-time data, as well as on predetermined flooding scenarios for the potentially affected coastal areas, which are processed by a decision-support system. The actual generation of a tsunami is not confirmed when sending out the first warning.

Decision making in calling for an evacuation and the dissemination of guidance at local levels are important steps during the downstream process and are mandated to local authorities. This remains one of the major challenges as it requires the implementation of local 24/7 services, quick decision-making processes as well as procedures and technologies to disseminate a call for evacuation.

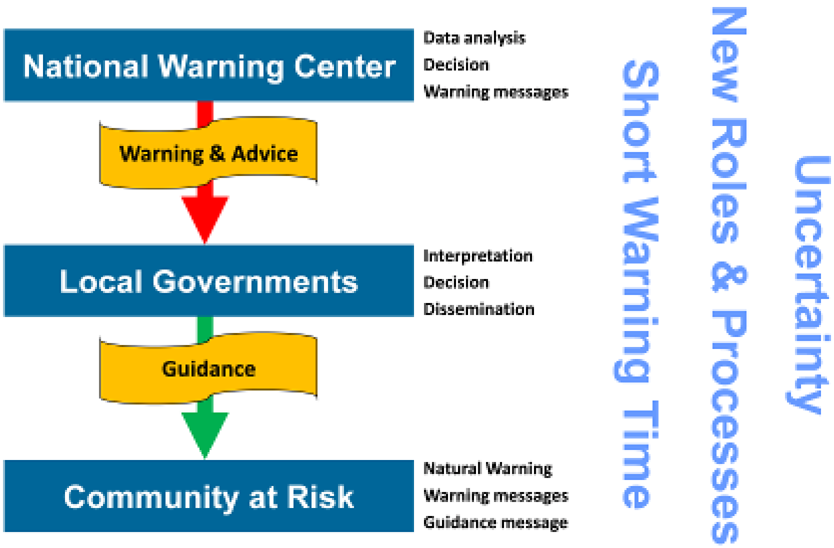


Figure 7.2.2: Roles of NTWC and local governments in the Indonesian warning chain.

Despite the fact that Indonesia has developed a solid framework for tsunami warning services (overall tsunami warning chain, warning sequence and time-line, warning level and policies for providing guidance and advice, dissemination system) it has to be recognized that at the current moment only few a cities and districts actually have implemented a reliable local warning mechanism on a 24/7 basis. Most areas in Indonesia have not managed to fulfil their role in the system. There are a number of reasons leading to this situation.

To enable local communities to play their role the following issues need to be addressed. First of all it need to be assured that local institutions in charge of tsunami warning services are provided with a clear mandate backed up by political commitment which is expressed by sufficient allocation of funds and human resources to provide the required warning services. Their capacities need to be strengthened especially in terms of human resources, standard operation procedures and equipment. Due to the huge extension of tsunami prone coastlines in Indonesia and the number of institutions involved the necessary improvements can only be achieved with a systematic approach for capacity building.

Furthermore, efforts are required to create a better understanding of the early warning system at all levels as well as a stronger sense for service orientation.

As long as these bottlenecks cannot be solved, the warning chain depends very much on the national media to disseminate warnings. Fortunately, considerable progress has been made in this field during the past years. Additionally, there should be a strong emphasis to combine approaches based on natural warning signs and the early warning system. Understanding and reacting appropriately to natural warning signs should always be the first line of defence, while official tsunami warnings and guidance are important to reinforce or cancel evacuations.

Solid Evacuation Plans at Various Levels are the Core of Tsunami Preparedness Strategies

Tsunami evacuation plans play a strategic role in tsunami preparedness in any tsunami preparedness process as they combine key information on local tsunami hazard, with warning and evacuation procedures, thus providing essential orientation for the communities to save themselves in an emergency situation.

While the provision of local tsunami evacuation plans is task of district authorities (BPBD), the planning process itself requires the participation of many stakeholders. District evacuation plans are important references for the further development of tsunami evacuation procedures at institutional, grass root and family level.

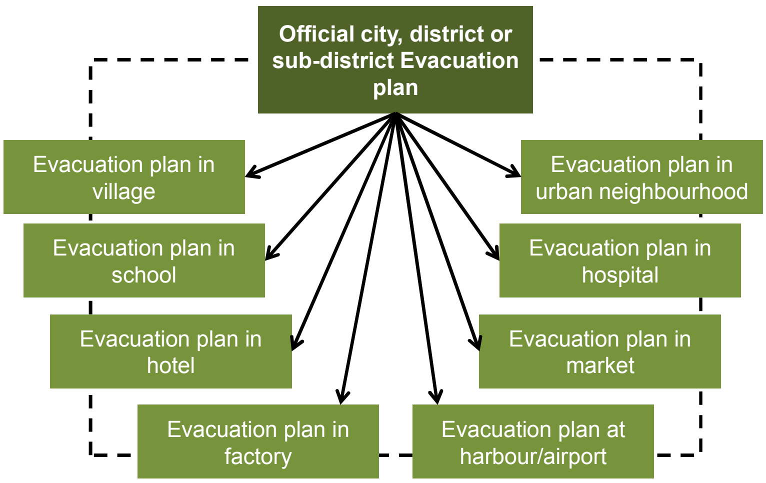


Figure 7.2.3: District evacuation plans provide the reference for evacuation plans and maps at institutional or village level.

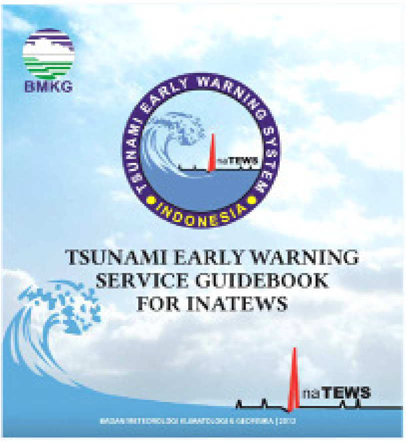
As part of the GITEWS – PROTECTS capacity development program a guidebook for tsunami evacuation planning and a training module have been developed to prepare professionals related to local disaster management to advise and to facilitate district tsunami evacuation planning processes. Besides the provision of references and trainings it turned out that technical backstopping during the development process of local evacuation plans was essential to assure appropriateness of local evacuation strategies and good quality of the developed plans.

Understanding the System

One of the big challenges during the entire project time was the issue to build a common understanding of the system. There were many opinions, statements and perspectives out there which often hardly matched the stage of implementation of the system. Early warning was often seen as a technological process, without seeing the critical role of the institutions and people involved.

To build a common understanding of the system and encourage all actors to assume and play their respective roles, the provision of adequate references and guidelines is necessary. Developing these references is a multi-stakeholder task. Only a joint learning process can produce a tailor-made warning chain that really addresses the needs of communities at risk. Another aspect is the public understanding of the warning service and the contents of warnings. In 2012, InaTEWS introduced a new warning scheme based on three different warning levels. It is still necessary to train interface institutions and inform the public as to what reaction is expected according to each level.

To address this critical issue, the project spent considerable efforts to support the national partners in developing a number of documents and materials to explain about the system and to create a better understanding.



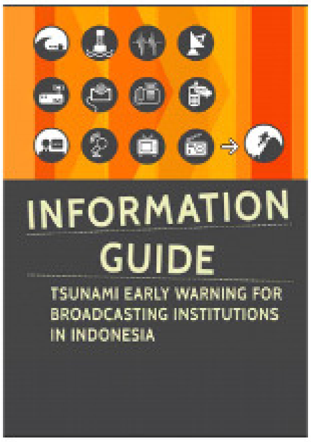


Figure 7.2.4: Specific information material for institutions involved in InaTEWS - Tsunami Early Warning Service Guidebook (BMKG, 2012), the public media (Media Handbook) and the public in general (campaigning materials).

The Importance of Local Political Commitment

An evaluation of 26 districts and provinces which have participated in the GITEWS and PROTECTS projects showed that the current level of implementation of local warning chains and 24/7 services is still low. Only 5 areas out of 26 have managed to establish solid mechanism and procedures. Another 7 have made certain progress, but are not yet considered to be able to provide a reliable warning service (Spahn, 2014a).

Main underlying reasons can be found at the political level. As a public service, the provision of tsunami early warning is primarily a government responsibility. Unfortunately, the clarification process regarding the division of roles and responsibilities in the downstream part has not been resolved yet. This is the case especially between the National Disaster Management Agency (BNPB) and the National Tsunami Warning Center at BMKG on national level as well as between province and district levels. Therefore many local heads of government are not fully aware of their role in the warning system and accordingly, local political commitment is often low. As a consequence the required institutional arrangements, local legal frameworks and sufficient resources to implement effective local warning services are not provided.

The Capacity Development Process – Exchange, Peer-Learning, Training, Facilitation

The fact, that the system greatly depends on human capacities and skills, systematic local preparedness planning, agreed procedures, decision-making capacity and a common understanding of what to do and how to react is often not taken sufficiently into consideration.

The consecutive step by step and multi-level approach (see above) does not only show the interdependence between the different levels but also illustrates the logic sequence of steps to be taken when building local tsunami preparedness. Without a local scale hazard map or risk assessment it is virtually impossible to develop solid evacuation plans. And it also does not make much sense to start public education without having previously agreed on evacuation procedures and warning arrangements.

Therefore, the capacity development process in its initial phase puts a strong focus to develop the required capacities at district or city level, especially in the local disaster-management agencies (BPBD). The purpose is to strengthen and support local stakeholder and the BPBDs in providing the necessary references and services to the communities. Once basic references and services are available and considered solid enough, the capacity development process shifts to the community level to strengthen local actors to develop more detailed maps and procedures which are tailor made to the local conditions at village or institutional level and to communicate them to the individuals and families.

Coordination and communication between provincial, district, city and national levels proved to be prerequisite for both an effective InaTEWS and locally adapted, sustainable capacity development within tsunami-risk management. Experiences from the project showed that a facilitated exchange or dialogue process between local and national levels resulted in a better understanding of the system and contributed towards the improvement of procedures, mechanisms and institutional capacities, in particular by addressing the link between the NTWC and local-level actors. The results from these exchange processes produced inputs for the development of national references and guidelines for InaTEWS, drawing on the participation of stakeholders at all levels. The horizontal and vertical exchange of experience and knowledge plays an important role in future up-scaling processes. A peer-to-peer learning approach can facilitate the transfer of knowledge between tsunami-prone regions.

Learning from practical experience and case studies was another pillar of the capacity development process as it not only provided realistic insights into what works and how to overcome obstacles but also increases the motivation for the implementation and replication of processes based on positive examples.

7.3 Project Documentation: Tsunami*Kit*

In order to make the experiences and results available to other coastal communities and their governments in tsunami-prone areas in Indonesia as well as to the international community, the project developed a comprehensive documentation – the Tsunami*Kit* (www.gitews.org/tsunami-kit), (GIZ-GITEWS, 2013). The content of the kit is organized according to the key elements of tsunami early warning (Risk Knowledge, Monitoring and Warning Services, Dissemination and Communication, Response Capacity, Knowledge and Awareness, Governance and Institutional Arrangements). For each of these six elements different types of documents were prepared, providing background information (reference and introduction documents, fact sheets) and support for local stakeholders to plan and implement tsunami warning systems and to strengthen preparedness (checklists, manuals, guidebooks and guidelines). In addition, a collection of materials for public education was included.

8. Conclusions

New concepts and procedures for the fast and reliable determination of strong earthquakes, the modelling and simulation of tsunami, and the assessment of the situation have been implemented in the warning system. In particular, the direct incorporation of a broad variety of different sensors provides fast information on independent physical parameters, thus, resulting in a stable system and minimizing breakdowns. The operational Early Warning System was handed over to Indonesian authorities on March, 29, 2011, and is since then operated in full responsibility by BMKG.

Newly developed seismic processing software package dedicated to rapid evaluation of strong earthquakes (Hanka et al. 2010) has been in operation at the warning centre since 2007. The software has proven its functionality not only in Indonesia, but also in over 40 operational centres world-wide (i.e. India, New Zealand, Maldives, France, and many more).

The various applications of GPS developed within the project show great potential in receiving additional information on earthquake mechanisms.

Information from the different sensor systems is processed in the Tsunami Early Warning Centre at BMKG in Jakarta. Using a Decision Support System sensor data is matched with the pre-calculated tsunami scenarios and additional geospatial data and maps to enable the responsible officer on duty to access the danger and to release warning bulletins or warning cancellations respectively.

The experiences from the capacity development programme for local communities have been made available in form of the Tsunami*Kit* that provides practical concepts that have been tested and validated, materials and tools for ongoing and future initiatives to strengthen local warning chains and tsunami preparedness throughout Indonesia. It is important to keep in mind that the effectiveness of InaTEWS greatly depends on the ongoing and future efforts to develop the required capacities in the downstream process.

Recent developments in GPS processing Real-time Precise Point Positioning (Ge et al. 2011) have made it possible to use co-seismic displacement vectors registered by GPS more efficiently in the early warning process especially in the case of near-field tsunami. Babeyko and co-workers presented their recent results using a limited number of Japanese GPS stations for the direct inversion of co-seismic displacements into the slip distribution of the 2011 Tohuku Earthquake (Babeyko et al. 2012). They demonstrated how the slip distribution of an earthquake can be calculated with sufficient accuracy for early warning purposes within 2-3 minutes with a sufficient number of GPS stations. These findings have also been confirmed by other groups (i.e. Wei et al. 2011). Together with near-real time Tsunami modelling tools this will open a new perspective to switch the early warning process especially for near-field cases from the static, database oriented approach using pre-calculated Tsunami scenarios to a forecast approach based on directly measured sensor information from seismic and GPS networks in real-time.

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