Chapter 9
The Earthquake and Tsunami Early Warning System for the Indian Ocean (GITEWS)

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Abstract The German-Indonesian Tsunami Early Warning System (GITEWS) has been established after the devasting Tsunami in the Indian Ocean on December 26, 2004. The system 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. The 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.

9.1 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 26 December 2004 an earthquake of magnitude 9.3 (Stein and Okal 2005) occurred off the northern shores of Sumatra, causing the tsunami great enough to affect the whole Indian Ocean, with almost a quarter of a million people losing their lives. The affected areas were neither prepared in terms of early-warning nor disaster response.

In quick response Germany offered—during the UN World Conference on Disaster Reduction in Kobe, Hyogo/Japan in January 2005—to aid the development of a fast and reliable warning procedure for the Indonesian population so that a catastrophe of such scale could be avoided in the future. This 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

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amongst the local communities. The Indonesian government accepted this offer as well as affected countries such as Sri Lanka, the Maldives and even East-African countries. The major part of our work targeted Indonesia, the area being the main source of tsunami risk for the surrounding Indian Ocean. The technical concept of such a warning system would have to deal with the 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 has 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 ~7 cm/y under the Eurasian Plate (Tregoning et al. 1994). The subduction zone comprises some 6,000 km from the north of Sumatra to the island of Sumbawa, running between 100 and 200 km parallel to the Indonesian coastline (Fig. 9.1). As a result of the subduction process, this region is regularly devastated by shallow megathrust 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 consequences arise through the tsunami triggered. The earthquake on 26 December 2004 ruptured the ocean floor over a distance of some 1,200 km (Krüger and Ohrnberger 2005) generating an ocean floor uplift of up to 10 m. This jolt from beneath generated waves on the Indian Ocean causing a tsunami of up to 30 m (northern Sumatra) (Borrero et al. 2006), leading to over 200 thousand casualties, as far away the east African coastline 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 after an earthquake based on highly uncertain data. The

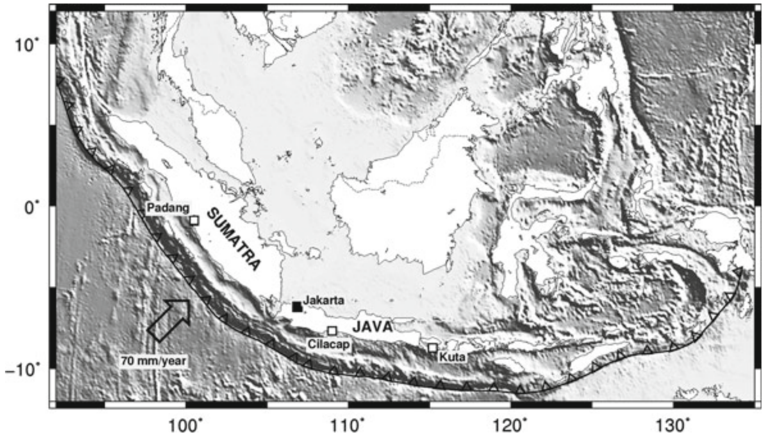

Fig. 9.1 The Sunda Arc is a major active plate boundary, where the Indo-Australian Plate is subducted at a speed of ~7 cm/y under the Eurasian Plate. The subduction zone (Sunda Arc) extends from the north of Sumatra to the island of Sumbawa

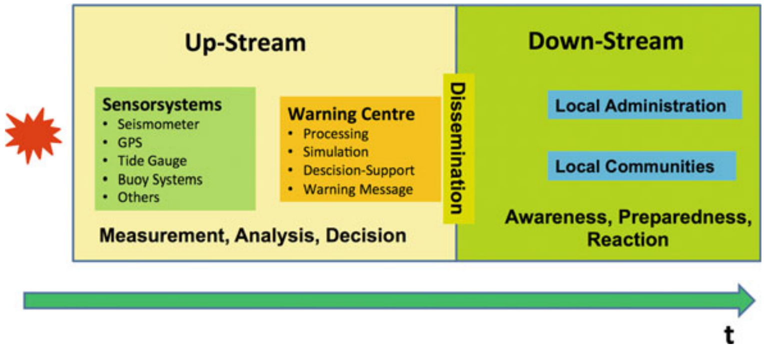

Fig. 9.2 Schematic End-to-End approach of GITEWS. The *up-stream* part is characterized by the measurement of the hazard and decision making while the *down-stream* part deals with the preparedness and reaction of the communities at risk

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 US (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 and GPS stations as well as tide gauges were installed here by Indonesian institutes. The data is merged and integrated into the central warning centre in Jakarta (Fleischer et al. 2010).

The system was planned and implemented as an "End-to-End" system (see Fig. 9.2). This includes:

- the necessary sensor instrumentation in Indonesia and elsewhere in the Indian Ocean to assess and identify the hazard as quickly 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.

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 ("Last Mile") has been carried out within the GITEWS project (Lauterjung et al. 2010).

9.2 Technical Concept

Of 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. Usually earthquake parameters are the initial information available for tsunami early warning. Strong earthquakes however are not confined to a single location but occur as ruptures of several hundred kilometres in length with a complex slip distribution along the fault plane(s). Strategies for tsunami early warning, therefore, have to distinguish between two cases:

- Far-field tsunami: A long travel distance for the tsunami compared to the earthquake rupture length. In this case the rupture orientation (given by the fault 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: Tsunami travel distances of a similar order (of magnitude) to the earthquake rupture length. 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 min) so that the system was technically designed with a focus on high speed, incorporating early input parameters with high 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 min after the earthquake). Seismological observations can only provide the primary earthquake parameters such as location, depth and magnitude within 2–4 min (Hanka et al. 2010). Thus, the epicentre and magnitude are poorly defined immediately after the earthquake, and errors in both depth and location of up to 50 km can occur. Therefore, 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 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. This information is available 5–10 min (depending on the distance to the earthquake) after the event and can be used immediately to determine the rupture's direction. 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[1] standards) was established in Indonesia. Near real-time processing (solutions for the network every 2 min, Falck et al. 2010) is performed at the early warning centre.

[1] Global Sea Level Observation System.

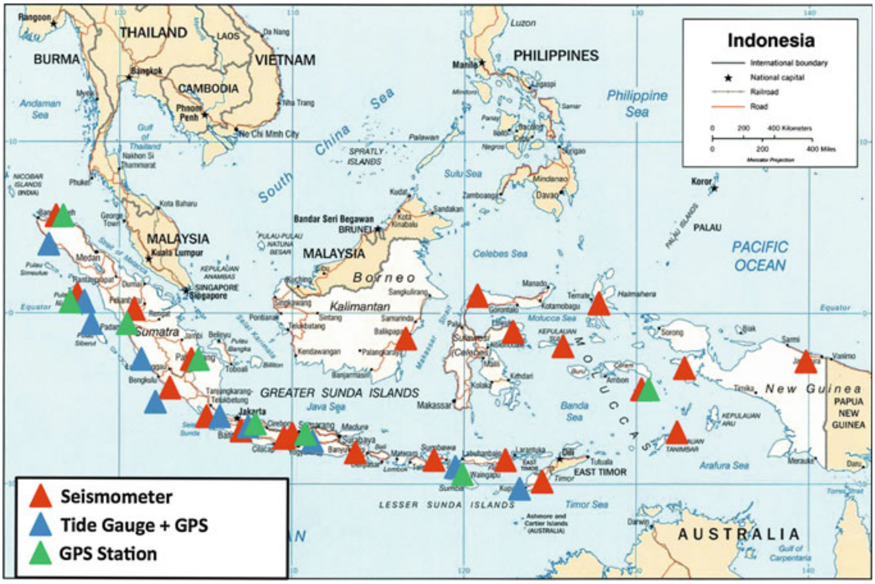

Fig. 9.3 Actual distribution of sensor instrumentation in Indonesia (German contribution to the warning system only)

The Indonesian tsunami early warning system consists of terrestrial networks such as seismological and geodetic stations as well as oceanographic instruments (see also Fig. 9.3). To minimize false alarms and to ensure redundancy, the application of different sensor technology is extremly important. All data are transmitted via satellite to the Warning Centre at BMKG (Badan Meteorologi, Klimatologi dan Geofisika) in Jakarta and are evaluated immediately.

The core of the early warning system is a network of seismic broadband stations (150 Stations, thereof 105 from Indonesia, 20 from Germany, 15 from Japan and 10 from China) as it gives the first important information on a possible tsunamogenic event. Data is transmitted in real time via VSAT[2] to the warning centre in Jakarta and analysed with the newly developed seismic processing software SeisComP3 (Hanka et al. 2010). The warning centre has access to about 230 seismic stations in the region and also includes data from seismic stations around the Indian Ocean. This system has been in operation at the BMKG since 2007 and successfully provides rapid nationwide earthquake information for Indonesia and all Indian Ocean neighbours including the ASEAN countries. Nevertheless, based on seismological measurements alone it is mostly impossible to decide in the first minutes after an earthquake whether a tsunami has been generated or not.

Therefore, a plan was drawn-up to detect tsunami signals directly on the ocean using GPS-buoys connected with ocean bottom pressure units and tide gauges at the

[2] Very Small Aperture Terminal.

coastline. The buoys have two functions: (1) they work as a relay station for 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 warning centre. (2) The other application and functionality is the GPS technology of the buoy. Although GPS is not as accurate as the pressure data, it delivers valuable information on sea level change with a precision of 5–10 cm within minutes. Applying GPS technology on tsunami buoys is a significant technical improvement compared to other buoy systems (Schöne et al. 2011a).

Again, the requirement of the warning system being as fast as possible made it necessary to position the buoy systems as near to the trench as possible to measure tsunami shortly after their generation. This also implies that the buoys are near to the coastline due to the geographic situation in Indonesia. Therefore, the buoy systems suffer from two drawbacks:

(1) The necessary position of the buoy system and the pressure sensor nearby the earthquake source (the trench) results in a strong aliasing of the tsunami signal by seismic noise (in many cases much larger than the tsunami signal). Due to the measuring characteristic of the pressure sensors currently available (15 sec integration time), 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 GPS onboard the buoy (Schöne et al. 2011a).
(2) In the case of Indonesia the buoy systems have to be placed near to the coastline. They are, therefore, in the reach of local fisher boats which use the buoys as mooring place for their fishing activities. As a result the buoys regularly become damaged leading in extreme cases to a total loss. Such vandalism is a general problem for buoy systems worldwide (Data Buoy Cooperation Panel, International Tsunameter Partnership 2011) and results in a dramatic decrease of the availability of near coast deployments.

For these reasons it was finally decided to no longer rely on such buoy systems due to the lack of reliability and for cost reasons. Cost 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.

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. 2011b), comprising three different tide gauge sensors and a GPS receiver for vertical movement control (and as part of the GPS network for co-seismic deformation monitoring) at each site.

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 (7.5–9.0) (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

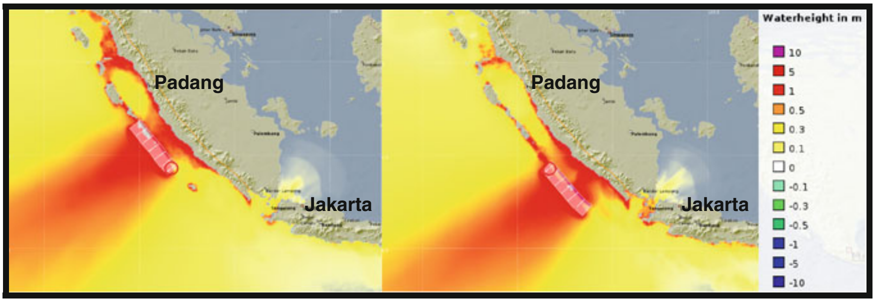

Fig. 9.4 Tsunami simulation based on location and magnitude (8.4) of a hypothetical earthquake off-shore Bengkulu, Sumatra. The figure *left* depicts the situation for the earthquake with a rupture running from the epicentre to the north. Especially the big city Padang is strongly effected, the south of Sumatra is not. The figure on the *right* hand depicts the situation for the earthquake with a rupture running from the epicentre to the south. Now the City of Padang is not affected but the south of Sumatra

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 height for 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. 9.4). 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.

In the Decision Support System (DSS) the different information will be aggregated to quickly draw a detailed picture of the actual situation (Fig. 9.5) (Steinmetz et al. 2010). In combination with additional static geo-information i.e. hazard and/or vulnerability maps (Strunz et al. 2011), settlement structure in the affected coastal areas, this is essential for the decision making process of the authorities and the population. In this way the staff responsible at the warning centre attains a clear picture of the situation and based on this, can disseminate an adequate warning.

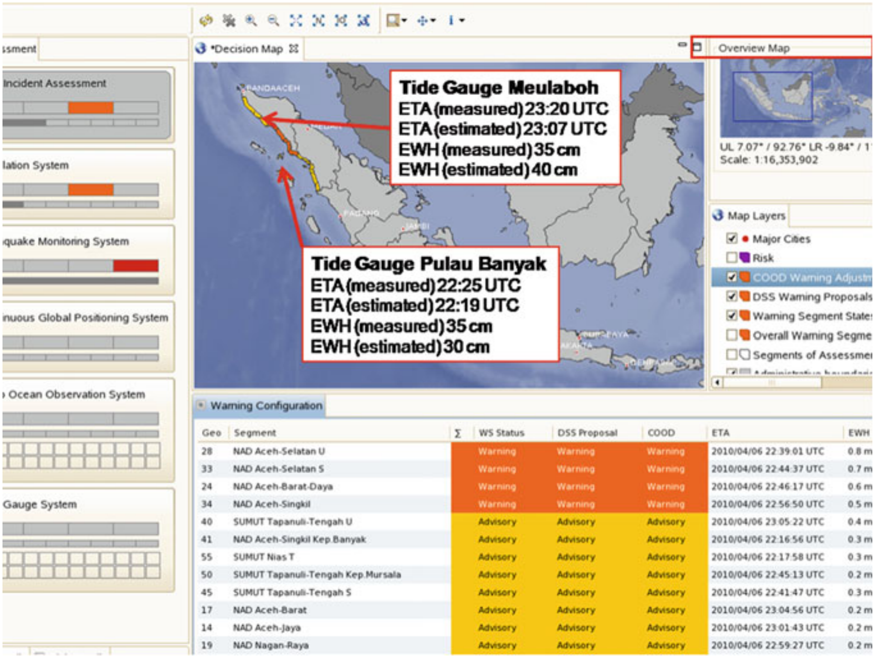

Fig. 9.5 Decision view of the Decision Support System. Shown is a map of the region of interest, the individual warning segments (administrative units) and the respective warning levels (in this case orange for warning and yellow for advisory). Also shown are the readings of two tide gauges in comparison with the predicted values for the tsunami generated by the earth-quake of 6 April 2010 off-shore North Sumatra. This aggregated view of the situation is the basis for the decision to be taken by the so-called Officer-on-Duty in the warning centre

9.3 System Performance

The Tsunami Early Warning System (TEWS) has produced its first tsunami warning on 12. September 2007 following the Bengkulu quake off shore 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 (Table 9.1):

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 9.1 Different warning levels

EQ (earthquake)	Earthquake information only	No tsunami
Advisory	A minor tsunami might have 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

Table 9.2 List of tsunami alerts triggered by the warning system from 2007 to 2012

Region	**Date**	**M**	**Depth (km)**	**Dec**	**TH**	**Comment**
Southern Sumatra	12.09.2007	7.9	10	Major	4 m	
Southern Sumatra	12.09.2007	7.7	24	Warn	1 m	
Talaud Islands	13.09.2007	6.4	30	EQ	n.a.	
Southwest of Sumatra	24.10.2007	7.0	10	Adv.	n.a.	
Sumbawa Region	25.11.2007	6.8	45	EQ	n.a.	
Southern Sumatra	25.02.2008	7.2	10	Major	12 cm	Initially over-estimated M (final is 7.2)
Southern Sumatra	25.02.2008	7.0	26	Adv	n.a.	
Sunda Strait	26.08.2008	6.6	20	EQ	n.a.	
Halmahera	11.09.2008	7.6	109	EQ	n.a.	Deep earth-quake
Irian Jaya Region	03.01.2009	7.2	10	Major	78 cm	
Java	02.09.2009	7.3	30	warn	80 cm	
Banda Sea	24.10.2009	7.3	165	EQ	n.a.	Deep earth-quake
Northern Sumatra	06.04.2010	7.2	32	Adv	40 cm	
Northern Sumatra	09.05.2010	7.2	30	Adv	n.a.	
Nicobar Islands	12.06.2010	7.5	21	adv	n.a.	
New Britain Region	18.07.2010	7.1	26	EQ	n.a.	
Southern Sumatra	25.10.2010	7.8	10	Warn	>10 m	Mentawai slow tsunami quake
South of Java	04.03.2011	7.2	24	EQ	n.a.	Normal event off trench
Northern Sumatra	11.04.2012	8.9	10	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), *TH* = measured tsunami height (at nearest tide gauge), *Color coding*: *green* = predicted warning level ok, *yellow* = predicted warning level is one level wrong, *red* = false warning (for color see online)

Table 9.2 shows the warning information which was published by the warning system for larger earthquakes around Indonesia during the past 5 years of operation from 2007 to 2012. In 15 of 19 events (see Table 9.2) a correct estimation in terms of warning levels has been documented. Only in 3 cases an incorrect estimation of the warning level (always an overestimation) has been recorded where the warning level was one level too high, and in only one case a major overestimation (false alarm) has been published. No tsunami stayed undetected by the system. However it must be mentioned that the direct comparison of estimated wave heights and the measured wave heights (i.e. at tide gauges) may give deviations of up to 50 %, in most cases overestimations by the system. This is due to the worst case scenario approach which is implemented in the system due to the large uncertainties in the input values in the early time after an earthquake. On the other hand the estimated arrival times for the warning segments show much smaller deviations from the measured arrival times as the wave heights.

The recent 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 intraplate quake and the consequently low co-seismic vertical displacement of the ocean floor. The Earthquake was registered by the warning system after 3.5 min with an overestimated magnitude of 8.9. Due to the Standard Operations Procedures in the warning centre a major tsunami warning was issued after 4 min and 30 s based on a magnitude 8.9. As the region where this quake occured is not covered by precalculated scenarios (too far off the subduction zone) an online tool for tsunami forecasting was used based on a subduction-like source model. Therefore the estimated wave heights (EWH) leading to the major warning level have been much too high (in some parts of the coastline 5 m and more).

9.4 Capacity Development

Not only does the sustainable operation of the system depend on the establishment of the necessary technological bases for hazard detection, modelling and decision support, but the development of the institutional and human capacities necessary for the nationwide implementation and application of the system as well as structures for effective decision making in Indonesia are just as important. In addition to the implementation of its technical components, GITEWS consequently included Capacity Development activities aimed at individuals, decision-makers, administrative bodies, disaster risk management organizations as well as the private sector at local and national levels (Schlurmann and Siebert 2011).

In general, the basic concept of Capacity Development (CD) aims to disseminate a realistic assessment of risks concerning extreme natural hazards with appropriate technical and socio-economic equipment. CD, therefore, incorporates training programmes, aimed at strengthening the capabilities of individuals and institutions to focus on the occurrences and effects of natural hazard-related phenomena and processes, and their associated risks to prevent or mitigate disasters. Moreover, academic scholars have been integrated into relevant research projects in order to gain useful practical insights and the basic conceptions of project management through continuing education. Governmental agencies and other national and international decision-makers also needed a range of scientific and engineering tools to effectively prevent or mitigate disasters and have been supported by experts and other competencies within the framework of the project by means of capacity development programmes as well as through co-operations and networking.

Based on these objectives, the GITEWS capacity building programme incorporated three levels being integrated in subprojects targeting the scientific audience and technological sphere as well as national institutions and local communities:

1. Academic and technical programmes: development and enhancement of research capabilities and technical skills by means of coordinated PhD and tailor-made Post-doc programmes, with workshops and seminars to expand the abilities and expertise of scientists and technicians in the relevant organizations and institutions in order to meet the scientific and technological needs of GITEWS.
2. Institutional development programmes: development and strengthening of operational institutions and governmental bodies to enable cooperation, management and organizational structure of TEWS at the national level.
3. Local disaster mitigation programmes: generate and bring-on warning and disaster preparedness mechanisms and strategies at local administrative and organisational level in three pilot areas, i.e. Padang, Western Sumatra; Cilacap, South-Java, and Kuta, Bali (Spahn et al. 2010). Strategies and measures to educate the population in coastal areas to respond correctly to warning information transpired to be of utmost importance. This is particularly true due to the extremely short time span (20–40 min) between the earthquake and the tsunami impact. Standard Operation Procedures (SOPs) and evacuation plans have been customised for this specific precondition (Tsunami Kit, Early Warning and Community Preparedness in Indonesia 2010).

9.5 Conclusions and Outlook

New concepts and procedures for the fast and reliable determination of strong earthquakes, the modelling and simulation of tsunamis 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 29 March 2011 and is since then operated in full responsibility of the BMKG.

A newly developed seismic processing software 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 data and warning 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 or detecting sea level changes at an early stage.

Information from the different sensor systems converge in a Central Early Warning and Mitigation Centre at the BMKG in Jakarta. Using a Decision Support System the 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. In this context the education and training of local authorities and the population at risk is an important ongoing task within the capacity development programme.

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 coworkers (2012) 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. They demonstrated how a respective density of GPS stations the slip distribution of an Earth quake can be calculated with sufficient accuracy for early warning within 2–3 min. 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 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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