# 3.3 Geophysical risk: tsunami

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## 3.3.1 Tsunamis in the global ocean

### 3.3.1.1 Tsunami physics, generation mechanisms and impact

The word tsunami comes from the Japanese for 'harbour wave'. Tsunamis are sea waves with periods that typically range from a few minutes to about 1 hour. The wavelength ranges from tenths to hundreds of kilometres depending on the causative source. The majority of tsunamis (≈80%) are produced by submarine earthquakes that are characterised by a shallow focus (≤100 km), a large magnitude and a faulting mechanism with a significant vertical component. Volcanic eruptions and landslides also produce tsunamis. Subduction zones (i.e. major lithospheric plate boundaries) are particularly prone to tsunami generation (e.g. Figure 3.14). Meteorological effects may also cause wave phenomena resembling tsunamis (meteotsunamis).

In the deep ocean, tsunami speed depends on the water depth, D. At first approximation, the shallow water wave speed C is:

$$C = \sqrt{gD}\ ,$$

where g is gravity acceleration.
In deep water, the wave amplitude may remain small, typically ranging up to a few metres. The waves become higher and shorter in shallow water and may have run-up heights that exceed several tens of metres (Figure 3.15); exceptional landslide tsunamis have even been recorded that reach several hundreds of metres vertically (Miller et al., 1960).

Tsunamis may have catastrophic consequences, such as loss of life, destruction of infrastructure, buildings and vessels, and economic and social impacts, the last of which may be felt both locally and remotely. In total, 16 major tsunamis killed 250 900 people in 21 countries between 1996 and 2015 (UNISDR/CRED 2016). The great Sumatra tsunami of 26 December 2004, which was caused by an M9.3 magnitude earthquake, caused the deaths of 226 000 people in 12 Indian Ocean nations.

> *Tsunamis are long-period sea waves generated by earthquakes, volcanic eruptions and landslides. They may have large wave heights in coastal zones, and can cause destruction to populations, infrastructures, properties and the natural environment.*

The Tohoku tsunami of 11 March 2011 that hit north-east Japan (Pacific Ocean) following an M9.0 earthquake was also devastating. The maximum run-up exceeded 40 metres, and the tsunami penetrated more than 5 km inland in places. The estimated total death toll was about 19 000 people, nearly 90 % of whom died as a result of the tsunami. The direct economic loss was reported to be USD 210 billion (EUR 198 billion), which was orders of magnitude higher than for the 2004 Sumatra tsunami, the cost of which was estimated to be USD 4.4 billion ((EUR 4.1 billion) (Løvholt et al., 2015). The Fukushima nuclear power plant was damaged by the tsunami and there was a meltdown of three reactors.

Intensity is an estimation of the event impact, which is measured using empirical scales such as the 12-grade Mercalli–Sieberg scale, which was introduced more than a century ago and is gradually improving. Magnitude measures earthquake size in terms of the energy released. Richter (1935) introduced an initial magnitude scale, which was later improved by the concept of moment-magnitude (Kanamori, 1977). However, no standard and satisfactory tsunami magnitude scales have been proposed so far owing to the lack of appropriate tsunami instrumental records. Therefore, tsunami intensity, expressing the event impact (e.g. using the six-grade tsunami intensity scale introduced by Sieberg (1927)), is still a rough proxy of the event size. A 12-grade scale was introduced by Papadopoulos and Imamura (2001), which is similar to the one used in seismology: for example, a tsunami of grade 6 intensity indicates a slightly damaging event, while a grade-10 tsunami is very destructive. However, for tsunami risk and vulnerability assessments, one has to turn to more stringent tsunami metrics, such as the expected tsunami run-up height and onshore flow depth, to calculate possible damage and losses.

### 3.3.1.2
### Major tsunami sources in the Earth

Large tsunamis occur frequently along the 'Ring of Fire' in the Pacific Ocean. Landmark examples include the 1960 (Chile), 1964 (Alaska) and 2011 (Japan) tsunamis, which were all of a large magnitude and occurred along subduction zones. The large number of tsunamis in the Pacific Ocean (NGDC/WDS, n.d.) are caused by widely different sources, such as non-subduction earthquakes, landslides and volcanoes.

Subduction zone earthquakes also occur in the Indian Ocean, along the Sunda Arc and in Makran (Pakistan). Thrust faulting earthquakes, such as the one that occurred in 2004 in Sumatra, and large volcanic eruptions, such as that of 27 August 1883 in Krakatoa (Sunda Strait, Indonesian Arc), produced devastating transoceanic tsunamis. Tsunamigenic zones are also present in the North-East Atlantic, the North-East Atlantic and the Mediterranean (NEAM) region, the Caribbean Sea, Indonesia and the Philippines. Tsunamis can also occur in areas with little earthquake activity.

### 3.3.1.3
### Tsunamis in the North Eastern Atlantic and the Mediterranean region

In the NEAM region, the historical tsunami record is rich thanks to many relevant documents that have been preserved throughout history. Geological evidence both onshore and offshore, such as sediment deposits, boulders having been moved inland and geomorphological changes, has contributed to the identification of paleotsunamis (e.g. Papadopoulos et al., 2014). Apart from a few mega or basin-wide tsunamis, more than 300 smaller tsunamis, either local or regional, have been documented so far (Figure 3.18).

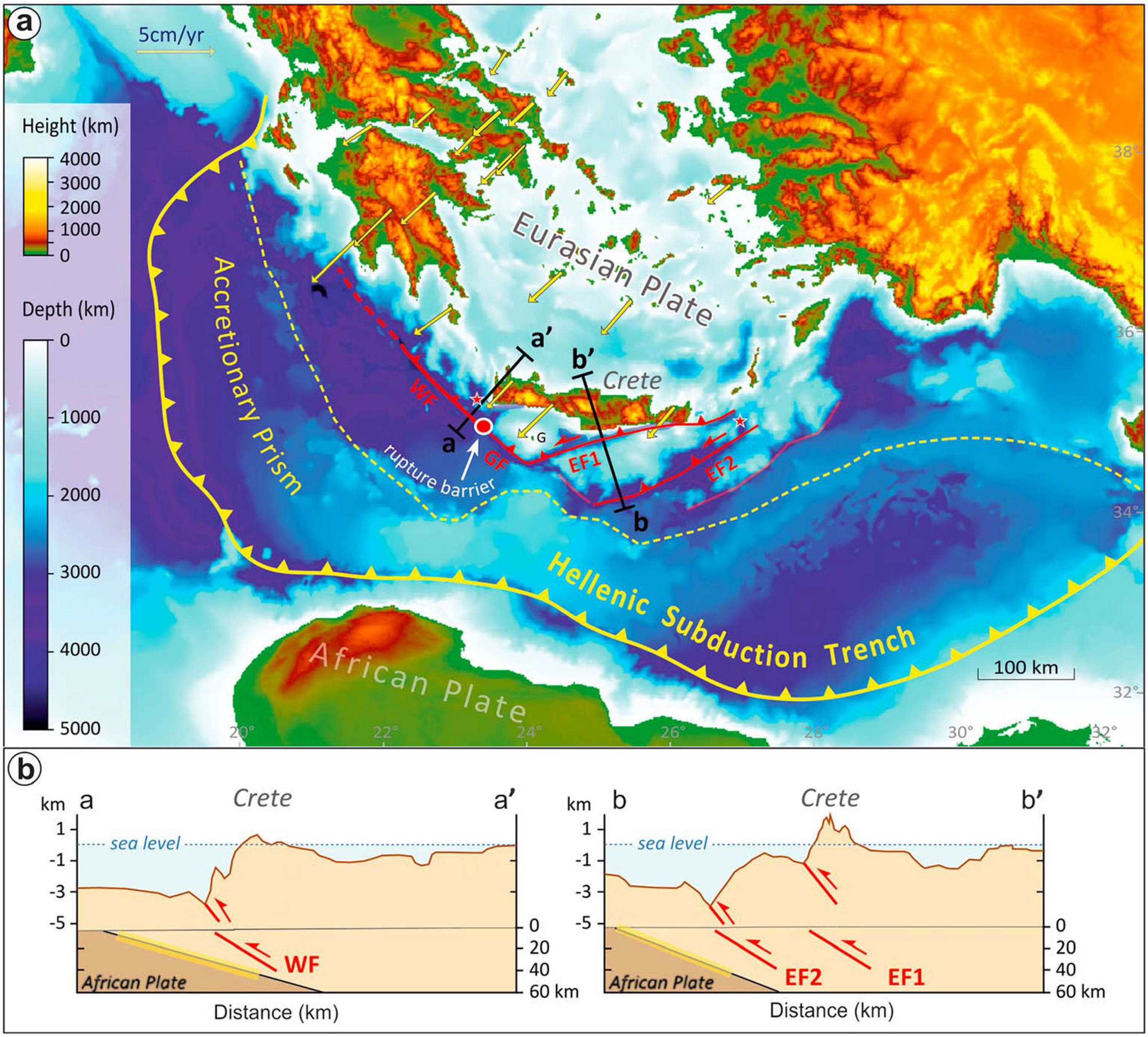
The main geotectonic structure producing tsunamis in the Mediterranean Sea is the Hellenic Arc subduction zone (see Figure 3.14). Large earthquakes (M≈8.5), presumably recurring at intervals of hundreds to thousands of years, generate basin-wide, destructive tsunamis, such as those that occurred in AD 365 and 1303 in Crete, and the large Minoan (17th century BCE) tsunami produced by the giant eruption of the Santorini volcano. Strong tsunamis also occur in less active regions, such as the Algerian thrust (North Africa, e.g. Schindelé et al., 2015), the Calabrian Arc (southern Italy) and the Cyprus Arc. Several other seismic, volcanic and landslide tsunami sources are distributed in the Mediterranean Sea, including in closed basins (e.g. the Corinth Gulf, Central Greece), the Marmara Sea and the Black Sea. In the North-East Atlantic, the area offshore south-west Iberia constitutes a major source of basin-wide destructive tsunamis (e.g. the one caused by the Lisbon earthquake (M≈8.5) on 1 November 1755). However, local tsunamis occur in the Azores Islands, in the English Channel and in Norwegian fjords, the last

**FIGURE 3.14**

**The Hellenic subduction zone of the African lithospheric plate beneath the Eurasian plate in the South Aegean Sea is a cause of tsunami generation from strong submarine earthquakes**
**Source: after Mouslopoulou et al. (2015)**

(a) Stars indicate the epicentres of the large tsunamigenic earthquakes of AD 365 (west) and 1303 (east) off the island of Crete. Yellow arrows indicate plate movement from Global Positioning System stations. G, Gavdos Island; WF, Western Fault; GF, Gavdos Fault; EF1, Eastern Fault 1; EF2, Eastern Fault 2.

(b) Subduction cross-sections in western (a-a☒) and eastern (b-b’☒) Crete. Black line indicates plate interface. The weakly locked portion of the interface is highlighted in yellow (vertical scale changes with depth). A large earthquake in one of the faults of the area causes upward displacement of the crust and pushes the water column upwards, thus producing a large tsunami.



of which are associated with coastal landslides.

Nearly all the tsunami sources in the NEAM region are located at a short distance from coastlines, and tsunami travel times are very short, in most cases less than 30 minutes. The near-field issue is of crucial importance for the effective operation of Tsunami Early Warning Systems (TWSs) both in the NEAM region and elsewhere (e.g. Schindelé, 1998).

**FIGURE 3.15**

Schematic explanation of some commonly used tsunami terms.
The term “run-in” is also in use instead of inundation.
The term “tsunami amplitude” is in use by some authors to describe either tsunami height at shore or wave amplitude in the open sea.
Source: Papadopoulos et al. (2014); modified from IOC (1998)

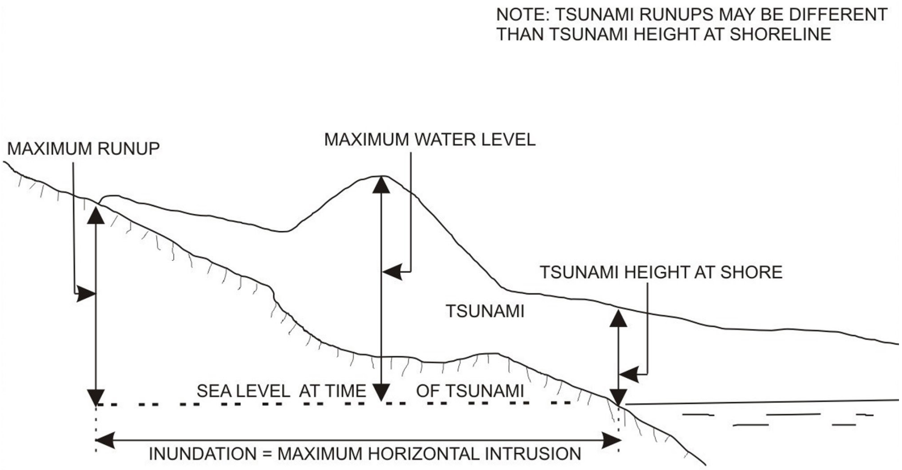


**FIGURE 3.16**

Brick building in Sri Lanka destroyed by the large Sumatra tsunami of 26 December 2004.
Source: photo courtesy by G. A. Papadopoulos

## 3.3.2
## Monitoring system

### 3.3.2.1
### Seismograph networks

National institutions maintain their own seismic networks all around the globe, including in the NEAM region, to pursue their main mission of national seismic monitoring. Data archiving and/or real-time data exchange occurs within the framework of international organisations, consortia and federated networks. The sustainability of the European component of these services is supported by national and EU funding and by the European Plate Observing System European Research Infrastructure Consortium, which is a pan-European long-term infrastructure programme. For example, the permanent stations available at the time of writing through the European Integrated Data Archive portal (http://www.orfeus-eu.org/data/eida/) are illustrated in Figure 3.19. This integration of national networks into a single system allows for a better and more rapid characterisation of strong (M6-6.9) to major and great (up to M8 or more) earthquakes. This important asset feeds a vital data bank that can be exploited for a better understanding of the seismic potential of a region, which is also a fundamental tool for seismic and tsunami monitoring and the long-term assessment of tsunami hazard and risk.

In high-magnitude earthquakes (e.g. Sumatra 2004), the very long rupture duration along the seismic fault makes it difficult to form a rapid assessment of earthquake magnitude, which, however, is a prerequisite for an effective TWS. This is a problem known as ‘earthquake magnitude saturation’. The 2004 event spurred the development of ad hoc seismological techniques (e.g. Lomax and Michelini, 2009a, 2009b), including improvements in inversion methods for finite source models (e.g. Shearer and Bürgmann, 2010). In several areas there is a significant gap in coverage due to the lack of sufficient seismic station coverage. This is the case along the coasts of North Africa. In the North-East Atlantic, the coverage is also limited owing to the absence of land areas. These limitations in turn affect the accuracy and rapidity of the assessment of tsunami potential when an earthquake is not surrounded by a sufficient number of nearby seismic stations. Improvements in station coverage would reduce both the number of false alarms and the uncertainty of real-time tsunami forecasting provided by TWSs.

**FIGURE 3.17**

Large fishing boats that were moved ashore by the Japanese tsunami of 11 March 2011.
Source: photo courtesy by G. A. Papadopoulos

### 3.3.2.2
### Global Navigation Satellite System networks

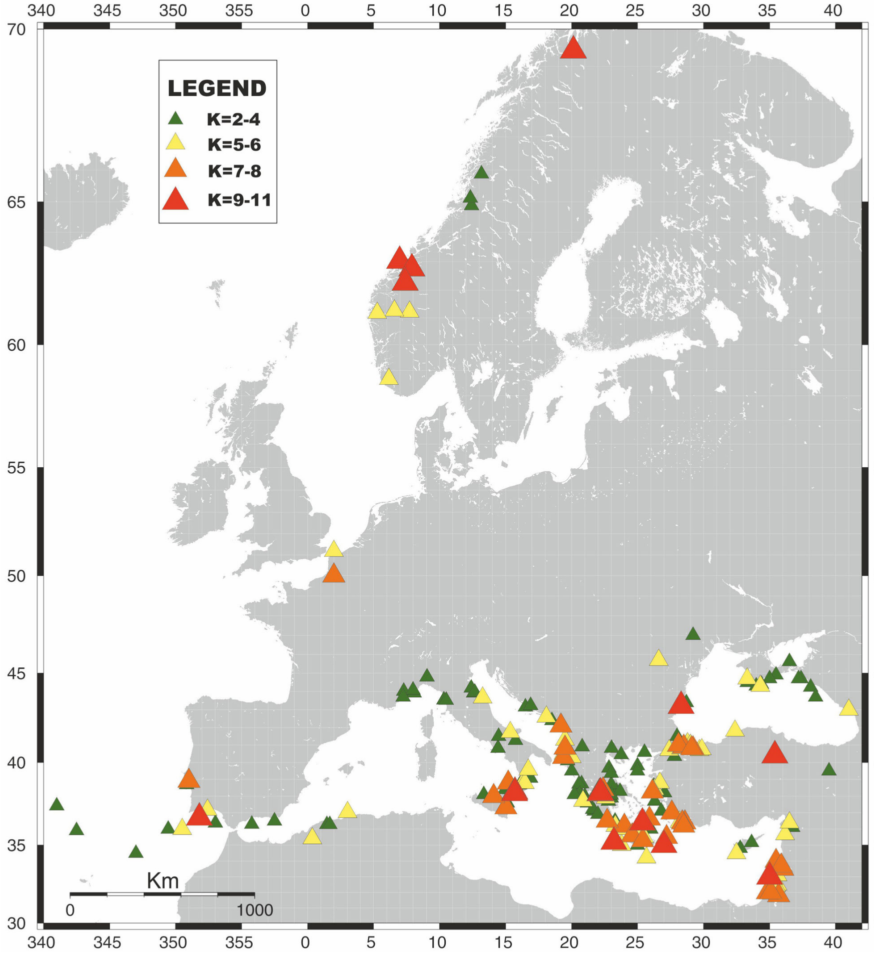
An alternative way to overcome the problem of earthquake magnitude saturation is to use the Global Navigation Satellite System (GNSS) to measure large earthquake magnitudes. The underlying idea is that GNSS stations, which do not saturate when measuring large co-seismic ground displacements, can be closer to the source than the seismic broadband stations, and thus may contribute to faster TWS response times.

> *The monitoring of earthquakes, crustal deformation and sea-level changes through geophysical networks constitutes the cornerstone for tsunami monitoring and early warning. Innovative solutions are needed for substantial monitoring improvement.*

Global Navigation Satellite System is the modern terminology used for geo-spatial positioning systems in general, including Global Positioning System (GPS) and several regional networks (e.g. GLONASS, Galileo, BeiDou). Numerous national and international organisations maintain permanent networks of receivers that contribute to this global system. At a European level, one of the most important is the EUREF Permanent Network (EUREF, 2011), to which more than 100 organisations actively contribute. In addition to their applications in geodesy and geophysics, GNSS data transmitted in real time can significantly improve the earthquake monitoring and tsunami forecasting capabilities of the TWSs. The 2004 Sumatra event triggered worldwide efforts for the augmentation of TWSs with a GNSS-based component (Blewitt et al., 2006; Sobolev et al., 2007; Song, 2007; Falck et al., 2010; Babeyko et al., 2010). Following the 2011 Tohoku tsunami disaster, thanks to the exceptional Japanese GEONET network, it was possible to show the feasibility of a GNSS-based TWS (Ohta et al., 2012; Hoechner et al., 2013). In addition, Chile and the United States, among others, are now actively progressing in the same direction (e.g. Melgar et al., 2016).

**FIGURE 3.18**

**Geographical distribution of the tsunami sources reported in the Europe-an-Mediterranean region from antiquity to the present. K is the maximum tsunami intensity in the 12-grade Papadopoulos and Imamura (2001) scale.**
**Source: Papadopoulos (2015)**



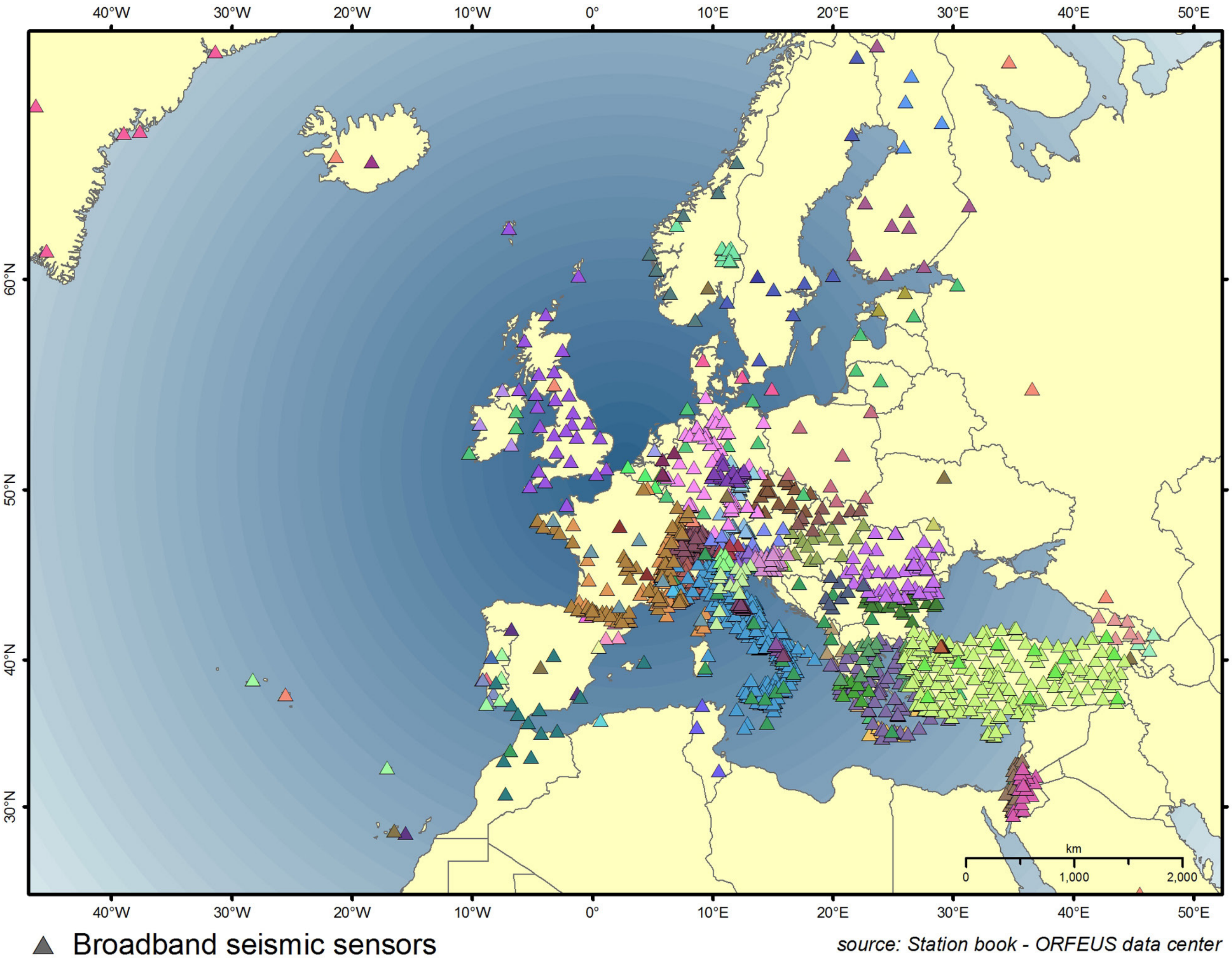
In the Mediterranean, among other In the Mediterranean, the Istituto Nazionale di Geofisica e Vulcanologia (INGV; Italy) and the National Observatory of Athens (NOA; Greece), as well as other Tsunami Service Providers (TSPs) acting in the Intergovernmental Coordination Group for the Tsunami Early Warning and Mitigation System in the North-eastern Atlantic, the Mediterranean and connected seas (NEAMTWS/IOC/UNESCO) (see Chapter 3.3.3.4), operate GPS networks transmitting data in real time. These networks provide a good coverage around the Ionian Sea (Figure 3.20), where several potentially tsunamigenic seismic sources are situated (e.g. Basili et al., 2013). In cooperation with GFZ (Germany), these centres are assessing the feasibility of the incorporation of GNSS-based solutions in their operations, within the framework of the EU-FP7 project ASTARTE (2013); the installation of new stations is ongoing in both Greece and Italy, funded by the MIUR (Italian Ministry of University and Research) Italian Flagship project RITMARE (Figure 3.20). This is an innovative prospect for the NEAM TWS, given that no operational examples are in place so far in the existing major tsunami warning systems. Of potential innovative interest is also the development of transoceanic submarine cabled observing systems composed of electro-optical seabed cables with optical repeaters for the transmission of data (Howe et al., 2016). Adding environmental sensors to the repeaters would provide an unparalleled global network of real-time data for ocean climate and sea level monitoring and disaster mitigation from earthquake and tsunami hazards.

### 3.3.2.3
### Measuring sea level changes

The measurement of sea-level changes is performed by permanent tide gauge stations installed at coastlines, as well as by ocean buoys, which are floating devices on the sea surface that report the sea level by measuring the pressure on the bottom of the sea. Tide gauges are useful for long-term multihazard purposes and geodynamic and oceanographic studies (e.g. climate change), but they are also useful in tsunami warning if the time interval between the data points and the data latency are sufficiently small. Tide gauges have registered tsunamis since the mid-19th century. For the

**FIGURE 3.19**

**Broadband seismic sensors operating in the NEAM region (data retrieved from ORFEUS Data Centre; Different colours indicate different institutions operating sensor networks. Source: figure prepared by M. Charalampakis, National Observatory of Athens, Greece**



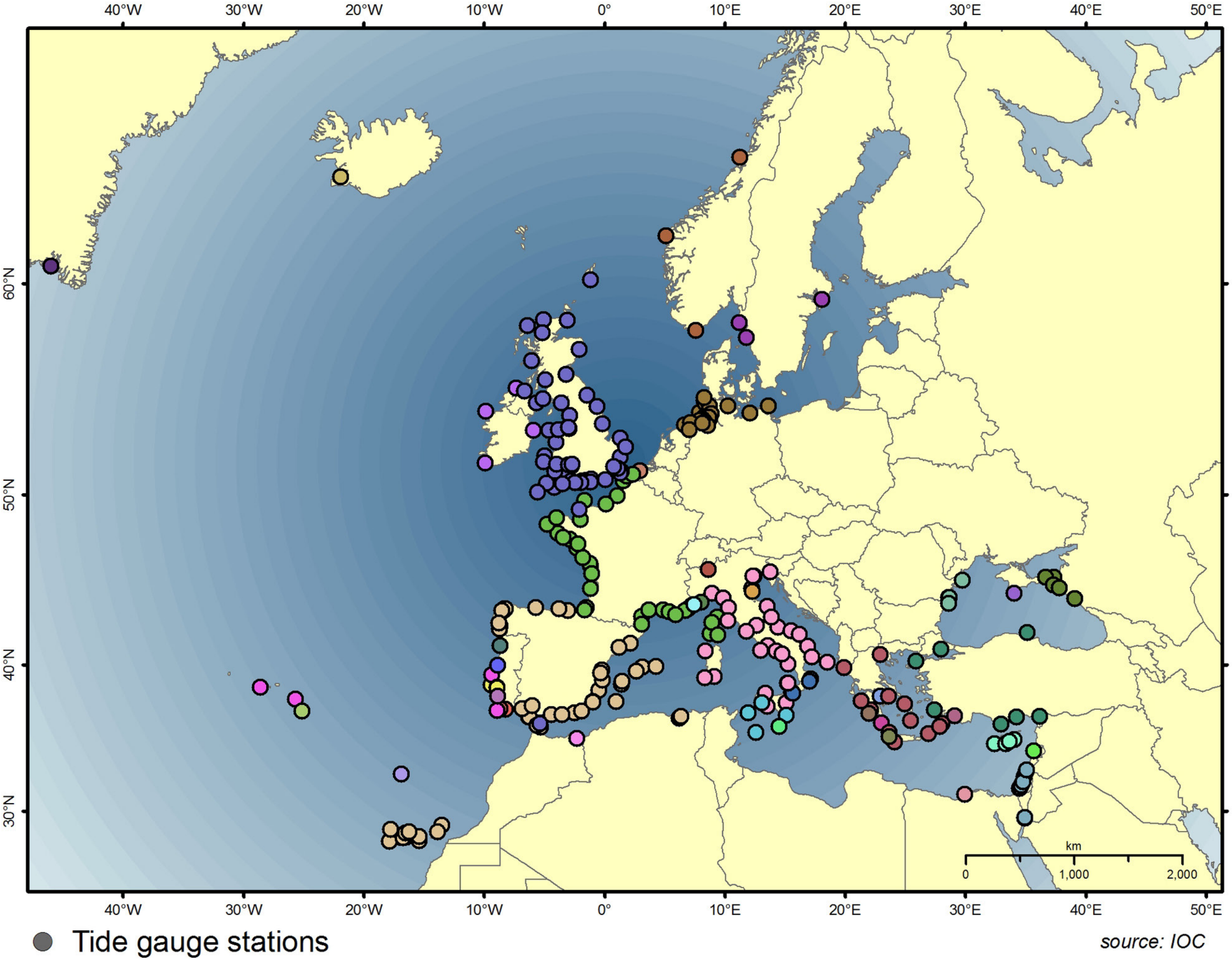
*source: Station book - ORFEUS data center*

NEAM region, about 310 stations contribute data to the inventory provided by the Flanders Marine Institute (VLIZ) in Oostende, Belgium, and UNESCO/IOC (2017) (Figure 3.22). However, only a few are available in real time, which is a necessity for early warning. The Joint Research Centre (JRC) of the European Commission offers sea-level data redundancy by means of its web service (Webcritech, n.d.). In recent years, JRC has provided more than 20 new Inexpensive Devices for Sea Level (IDSL) measurements in the NEAM region (Annunziato, 2015).

Ocean buoys are linked with pressure sensors on the ocean floor called tsunameters. The pressure change caused by the passage of a tsunami is transmitted to the linked buoy and then to the monitoring centres by satellite. Incorporation of such offshore measurements is desirable to detect a tsunami well in advance of its arrival at the coasts. Measurements of offshore sea levels are achieved by the Deep-Ocean Assessment and Reporting of Tsunami (DART) buoys, which operate in the Pacific, Indian and western

**FIGURE 3.20**

**Broadband seismic sensors operating in the NEAM region (data retrieved from ORFEUS Data Centre, Figure prepared by M. Charalampakis, NOA, Greece). Different colours indicate different institutions operating sensor networks.**
**Source: figure prepared by M. Charalampakis, National Observatory of Athens, Greece**



Atlantic Oceans. However, there is no clear consensus among the scientific community as regards the suitability of the DART system in more narrow and confined regions such as NEAM, owing not only to their high cost but also to the near-field issue characterising tsunami early warning operations in the NEAM region.

Other types of sea-level measurement include floating GPS systems and the undersea pressure cables, both of which are used operationally by Japan. The first of these measures the sea-level change by the differential measurement with respect to a fixed point on Earth; the second uses a series of pressure measurements that are connected to land stations via submarine cables.

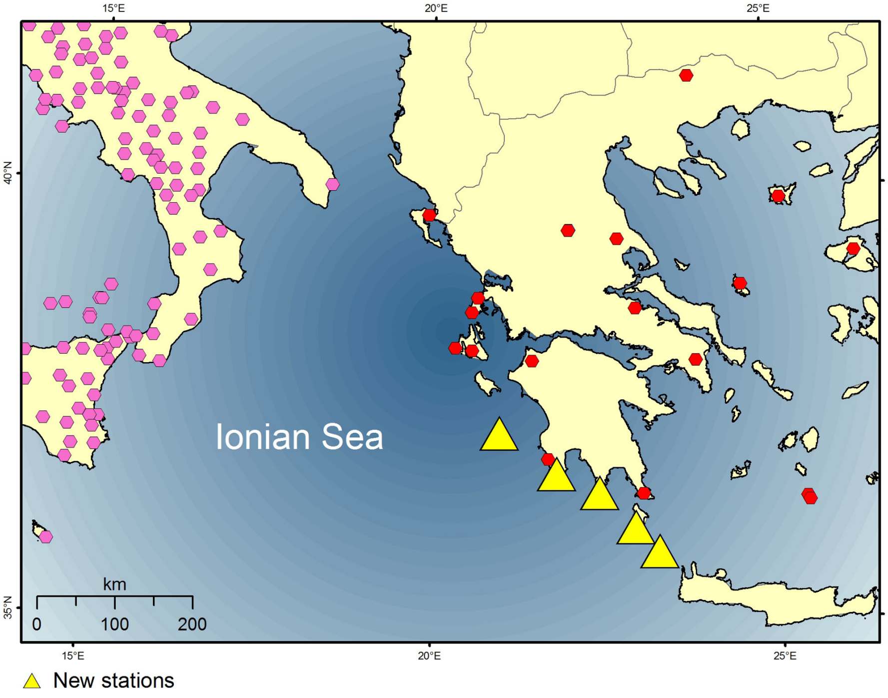
## 3.3.3
## Tsunami risk assessment and reduction

### 3.3.3.1
### Lessons learned from key tsunami events

The mega tsunamis of 2004 (Sumatra) and 2011 (Japan) not only had tragic consequences, but also changed our thinking on how to deal with such low-frequency but high-impact events (e.g. Lorito et al., 2016). Both tsunamis led to a reanalysis of previous models for predicting where large earthquakes might recur and how large they might be. At present, we cannot rule out the occurrence of similar megathrust earthquakes along any subduction zone across the Earth, including in the Mediterranean Sea (e.g. Kagan and Jackson, 2013). Harsh lessons have also been learned from more localised tsunamis occurring after smaller earthquakes.

**FIGURE 3.21**

**Map showing stations of the INGV RING (purple dots) and NOANET (red dots) networks. Yellow triangles are the new planned stations, the installation of which has been ongoing since October 2016.**
**Source: Michelini and Charalampakis 2016**



The 1998 Papua New Guinea event was an eye-opener for the tsunami community, as it proved that submarine landslides after an earthquake may cause massive tsunamis. The 25 October 2010 Mentawai (off Sumatra) tsunami was caused by an M7.7 'slow' earthquake, which is characterised by a relatively small magnitude compared with the size of the associated tsunami. The shaking from this event was not very strong, but it lasted for a long time. This may be one reason why many people did not self-evacuate, which unfortunately led to more than 400 casualties (Synolakis, 2011). These types of event are termed 'tsunami earthquakes' (Polet and Kanamori, 2009); however, their mechanism is still not completely understood, and the estimation of their frequency and possible locations remains elusive.

### 3.3.3.2
### Tsunami hazard, vulnerability and risk assessment

Tsunami hazard measures the likelihood that a tsunami of a certain size will hit a coastal location in the future, that is, the probability of a tsunami exceeding a run-up height of 10 metres within a period of 50 years. Likewise, building vulnerability describes the probability of tsunami damage and exposure relates to the people, buildings or assets that are subject to potential losses. The tsunami risk measures the probability of future tsunami consequences and any potential losses. In simple terms, the tsunami risk is the convolution between tsunami hazard, vulnerability and exposed elements at risk.

Rare but often destructive events dominate tsunami risk worldwide. Historical tsunami records are too short to reveal run-up heights at the level of hazard for which we need to prepare. This is a fundamental difference between tsunamis and earthquakes, floods or cyclones, for example, for which destructive events can be found in regional historical records and for which the hazard posed by future events can be more robustly extracted from the available data. The considerable uncertainty characterising the assessment of tsunami hazard in most locations needs to be reduced by corroborating, or even replacing, the statistical analysis of past events with the statistical and physics-based modelling of potential future sources, in combination with numerical modelling of tsunami generation, propagation and inundation (e.g. Geist and Parsons, 2006; Burbidge et al., 2008; Power et al., 2013).

Traditionally, the tsunami threat was analysed by modelling the inundation for just a few scenarios, sometimes termed worst-case scenarios. In this way, neither the relative likelihood of events of different sizes (the natural or aleatory uncertainty) nor the degree of belief that one has regarding different plausible but alternative models of the same phenomenon (the epistemic uncertainty) is generally addressed. Moreover, the worst-case approaches are prone to overlook the hazard and risk posed by more frequent, smaller events, which may dominate the risk at certain locations exactly because they are more frequent.

*Tsunami risk management requires synergy between the scientific community, decision-makers, civil protection authorities and other stakeholders for hazard, vulnerability and risk assessment, warning systems operation, preparedness, training and emergency planning.*

Presently, however, probabilistic tsunami hazard (PTHA) and probabilistic tsunami risk assessments (PTRAs) are progressively replacing the traditional worst-case scenarios methods, which nevertheless remain an important initial screening tool. Probabilistic methods allow systematic analyses to be made of how the sources of uncertainty affect the hazard and risk assessment, which are inherently large for tsunamis. All of this information is vital for any risk-reduction planning measure, including the cost–benefit analysis in comparison with other risks at a given site. PTRA (Løvholt et al., 2015) is already conducted at a global scale for the 2015 UNISDR Global Assessment Report (UNISDR, 2015a). A global analysis of epistemic uncertainty was incorporated in a follow-up global PTHA study (Davies et al., 2016). Previous hazard and risk analyses in the NEAM region have been based mostly on scenario analysis (e.g. Tinti and Armigliato, 2003; Tinti et al..,2005; Lorito et al., 2008; Tonini et al., 2011). More recently, studies dealing with new PTHA methods have been applied in the NEAM region, mostly for earthquake sources (Grezio et al., 2010; Sørensen et al., 2012; Lorito et al., 2015; Omira et al., 2016; Selva et al., 2016). Some risk scenarios have been developed within the EU FP7 ASTARTE project, and approaches to PTRA have also been explored within the EU FP7 STREST project, which deals with natural hazard multirisk assessment for non-nuclear critical infrastructures.

One important ongoing initiative is the TSUMAPS-NEAM project (n.d.), funded by EU budget, which in 2017 will provide the first official community-based and homogeneous regional PTHA for the NEAM region. Recently, probabilistic tsunami hazard maps have been developed on a national scale (e.g. in Italy, Greece, Portugal), which will probably benefit from the existence of the regional assessment. To date, approaches for tsunami risk analysis are not well standardised. To improve the situation, the Global Tsunami Model initiative (n.d.) aims to provide a coordinated response to tsunami hazard and risk assessment worldwide.

This effort has already been endorsed

by the Global Facility for Disaster Reduction and Recovery and UNISDR, with the goal of contributing to the implementation of the 2015–30 Sendai framework for disaster risk reduction (UNISDR, 2015b). Although the GTM is not yet fully operational, several GTM partners have been involved in the TSUMAPS-NEAM multiple-expert integration process and review, in an important first step towards standardisation.

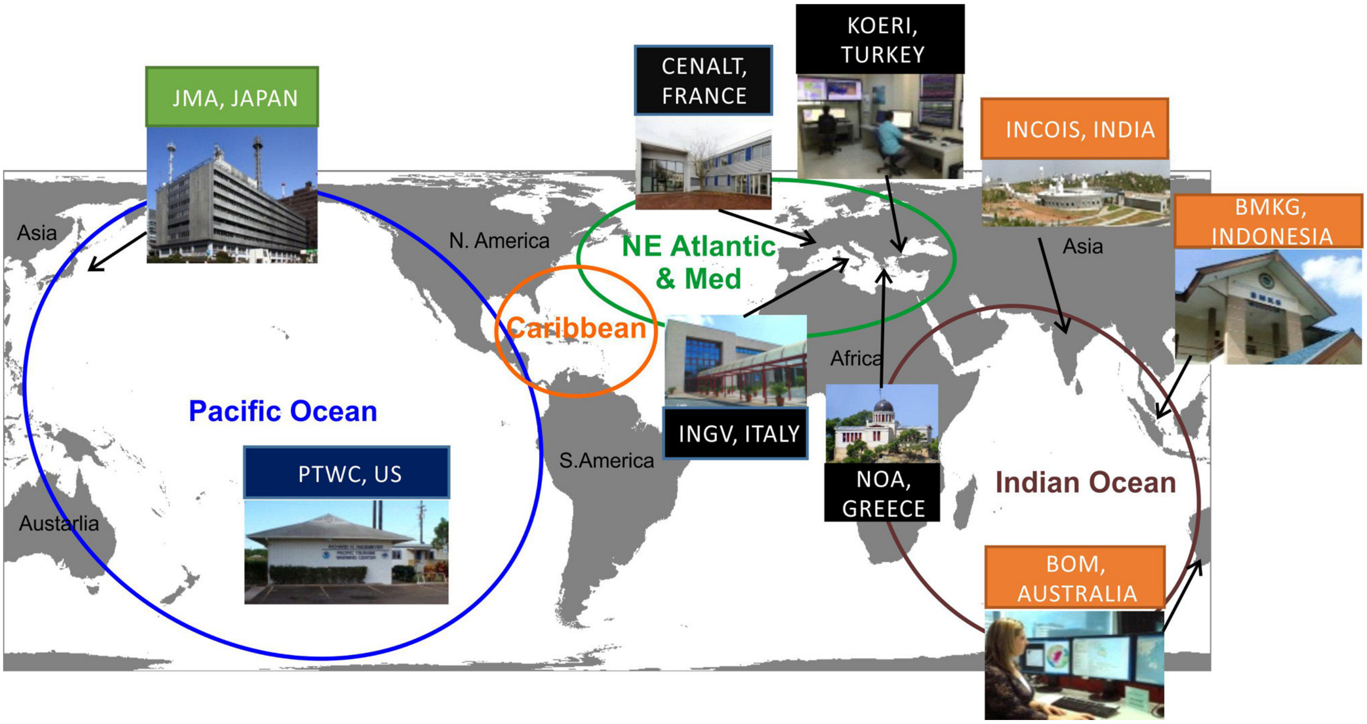
Another difficulty in reliably assessing tsunami risk is that vulnerability is a highly time-dependent parameter, owing not only to changes in the built environment and socioeconomic situations in the long term, but also to temporal variations in exposure (e.g. seasonal and daily variations of population).

### 3.3.3.3
### Early warning systems: a worldwide overview

The objective of a TWS is to identify earthquake tsunami sources, detect tsunamis in advance and issue warnings to communities at risk, to prevent loss of life and to reduce damage. A typical TWS has four main components: risk knowledge, monitoring and warning, dissemination and communication, response capability. A national TWS has operated in Japan since the 1950s. In the Pacific Ocean, a coordinated TWS involving many nations was established in 1965 and has been operating under the IOC/UNESCO umbrella. In the aftermath of the devastating 2004 Sumatra tsunami, the national delegates at the IOC/UNESCO meeting decided to establish three international systems, one in each of the Indian Ocean, Caribbean Sea and the NEAM region. At present, four international systems operate under the IOC umbrella (Figure 3.22). All four systems operate based on National Tsunami Warning

**FIGURE 3.22**

**The four major TWSs operating around the globe under the coordination of IOC/UNESCO and the TSPs already established.**
**Source: IOC, modified by A. Rudloff, GFZ, Germany**



Centres (NTWCs) coordinated by the relevant Intergovernmental Coordination Groups (ICGs). Germany strongly supported efforts to build up a national TWS in Indonesia (Rudloff et al., 2009; Münch et al., 2011).

The identification of earthquake sources is made possible by seismograph networks, while GNSS networks have the potential to achieve the rapid and accurate assessment of magnitude for large earthquakes in the future. Tsunami detection and confirmation is achievable using sea-level records from tide gauges, which are also useful for warning distant places. Many European Member States have invested a lot during the past decade to upgrade their sea-level networks for faster and better tsunami detection, but much remains to be done for an effective warning system. However, offshore instrumentations of the DART type are very expensive in comparison with tide gauge networks. Japan has implemented cable systems that include pressure sensors, seismometers and accelerometers. Such equipment is expensive but lasts more than a decade and has a very low maintenance cost.

Setting up an end-to-end TWS requires partnership and coordination among different national and international institutions and organisations, including those responsible for seismic and sea-level monitoring, civil protection authorities and communities at risk. Moreover, it requires considerable financial investment to support tsunami research, to build, maintain and upgrade comprehensive monitoring networks, and to raise community awareness and preparedness.

There is also a need to develop clear

**TABLE 3.1**

**Decision matrix for the Mediterranean basin, proposed by the ICG/NEAMTWS/IOC/UNESCO system in November 2010. Since then, NTWCs have slightly updated/modified this DM but its main structure remains operational. The DM adopted for the North-East Atlantic is similar.**
**Source: authors**

| Focal depth | Epicentre location | Mw | Tsunami potential | Tsunami message type | | |
|---|---|---|---|---|---|---|
| | | | | Local | Regional | Basin |
| <100km | Offshore or close to the coast (≤40 km inland) | >5.5 and ≤6.0 | Weak potential for local tsunami | Advisory | Information | Information |
| | | >6.0 and ≤6.5 | Potential for a destructive local tsunami (<100 km) | Watch | Advisory | Information |
| | Offshore or close to the coast (≤100km inland) | >6.5 and ≤7.0 | Potential for a destructive regional tsunami (<400 km) | Watch | Watch | Advisory |
| | | >7.0 | Potential for a destructive basin-wide tsunami | Watch | Watch | Watch |
| ≥100km | Offshore or inland ≤100km | >5.5 | Nil | Information | Information | Information |

legal frameworks for each country, whereby the roles and responsibilities of the institutions and organisations involved will be clearly defined.

### 3.3.3.4

### Tsunami warning systems in the NEAM region: the NEAMTWS/IOC/ UNESCO and JRC/EC initiatives

Since the establishment of the ICG/NEAMTWS/IOC/UNESCO system in 2005, the member countries have worked together to build up the system. Initially the system was based on four NTWCs, which, since the summer of 2012 (France, Greece, Turkey) and spring of 2014 (Italy), have acted as candidate TSPs (CTSPs) for all ICG Member States interested in subscribing to the service. The current average time to issue tsunami warnings is approximately 8-12 minutes. Tsunami messages are also sent to the IOC (Paris), the ERCC (EU, Brussels) and the JRC (Ispra). Following a table-top accreditation procedure by international experts, the CTSPs were successfully evaluated and nominated as TSPs at the 13th ICG Session, Bucharest, September 2016. Since the operational NEAM TWS started (summer 2012), the system was activated in about 25 earthquake events of M ≥ 5.5. The NTWCs of Portugal and Romania are preparing to start acting as CTSPs soon.

The TSPs are supported in their operations by a decision matrix (DM), namely a simplified and conservative set of empirical rules for the possibility for tsunami generation depending on the earthquake magnitude, epicentre and focal depth (Table 1). The tsunami severity scales with the earthquake magnitude range to produce three tsunami message types: Tsunami Information, Tsunami Advisory, Tsunami Watch. The magnitude range also determines the maximum distance at which a tsunami impact is likely to be caused at coastlines. Therefore, local (≤ 100 km), regional (≤400 km) and basin-wide tsunami message types are considered. Tsunami arrival times in pre-defined coastal forecast points are calculated and inserted in the alert message. Next, sea-level data analysis is undertaken to monitor and confirm the tsunami by issuing ongoing alert messages or to cancel the message if no tsunami is detected. The above procedure underlines the importance of seismograph and tide gauge networks in tsunami warning operations.

**FIGURE 3.23**

Tsunami evacuation building in Japan
Source: photo courtesy by G.A. Papadopoulos

Regular communication tests among TSPs and continuous staff training are of utmost importance given that tsunamis are infrequent events. A good example was the Global Tsunami Informal Monitoring Service (2013-16), coordinated by the JRC. Several national TWSs of the NEAM region participated. After a strong (M≥7), potentially tsunamigenic, earthquake, the TWSs staff initiated a monitoring procedure for the collection of tsunami-related information and records (e.g. in tide gauges) and reported this to the JRC.

Tsunami Service Provider operations might be of great importance not only for early warning, but also for prompt scientific advice on post-disaster management in a multihazard context. The ongoing pilot project

ARISTOTLE, funded from budget of European Union, is providing scientific support not only on tsunamis but also on other types of natural hazards, including earthquakes, volcanic activity and meteorological hazards, to ERCC in the period 2016-17.

### 3.3.3.5

### Preparedness-Education-Training and the role of Civil Protection

The mitigation of tsunami risk should rely not only on early warning but also on the synergy of several actions, including preparedness and emergency planning, exercises, training, education and public awareness. For such activities, the civil protection and other national authorities have a key role to play in order to make the downstream component of the TWS effective down to its 'last mile'.

A key preparedness element is the designation of 'hazard zones' along tsunami-prone coastal segments, which entails an inherently political cost–benefit assessment, relying on the input scientific information provided through hazard and risk assessment. Hazard zones are necessary for long-term risk management actions, including urban and emergency planning. Evacuation during the early warning stage is facilitated by the existence of hazard zones, since everybody needs to know beforehand the area that should be evacuated. Designation of appropriate evacuation buildings is also important for vertical evacuation (Figure 3.23).

Inaccurate hazard assessment may result in an underestimation of the hazard zone, which can have tragic consequences. Japanese tsunami hazard maps prior to 2011 were based on historical earthquake records with upper bound earthquake moment magnitudes that were too small (Geller, 2011). This is probably reflected in the (ex post) insufficiently cautionary risk management of the Fukushima nuclear power plant (Synolakis and Kanoglu, 2015). In some coastal areas, evacuees felt sufficiently safe to move just outside the hazard zone limits. However, the 2011 tsunami proved larger than the 'design tsunami' and killed many people outside the hazard zones.

Awareness and preparedness may be enhanced by table-top drills based on tsunami scenarios, such as the NEAMWAVE12 (2012) and NEAMWAVE14 (2014), which involved TSPs, civil protection authorities and the ERCC. Operational exercises also offer a good basis on which to test and improve emergency plans and rescue capabilities (e.g. POSEIDON-2012, supported by EU budget, was an exercise performed on Crete, Greece). Education and public awareness are very important, since their aim is to teach people about tsunami risk and ways to reduce it.

## 3.3.4

## Conclusions and key messages

Tsunamis are caused mainly by submarine earthquakes but also by landslides, volcanic eruptions or other causes. Complex cascading effects involving more than one tsunami generation mechanism should not ignored (e.g. tsunamis caused by landslides that are triggered by earthquakes).

Tsunamis are characterised as low-probability but high-impact events. While they are most frequent in the Pacific, the tsunami hazard is also present in the Indian Ocean, the NEAM region, the Caribbean Sea and elsewhere. The assessment of tsunami hazard and risk is susceptible to a variety of uncertainties, including our limited knowledge of the likelihood of infrequent tsunami sources, or the complexity of the tsunami inundation.

### Partnership

The assessment of the impact incorporates many fields of physical sciences, hazard modelling, engineering and social sciences. Neglecting any of these fields will inevitably reduce the accuracy, reliability and usefulness of the resulting risk metrics. The process of risk identification should involve stakeholders from the public and private sectors and should leverage ongoing national and international initiatives with the mandate to calculate, communicate and reduce geophysical risks.

Even the most advanced TWS is not effective without a well-trained downstream component. Tsunami risk mitigation thus requires synergies between the scientific and technological communities, decision-makers, civil protection authorities and other stakeholders. The common aim should be continual exercise and training, education and public awareness; this is vital, since the public perception of the risk from infrequent events naturally tends to fade over time, until the next catastrophe happens.

## Knowledge

A thorough understanding of tsunami hazard and risk should not be based solely on the analysis of past events, but must exploit broader scientific analysis and modelling in order to assess the potential for future hazards. Exposure and vulnerability (e.g. of populations) are time-dependent parameters, which makes risk assessment a complex procedure. Standards and best practices for tsunami hazard and risk assessment need to be further established by the international community, in order to better support preparedness and emergency planning.

## Innovation

The experiences of the past 20 years or so leave no doubt that TWSs that are well suited to the rapid detection of large magnitude earthquakes are necessary. Well-developed instrumental networks of seismographs, tide gauges and tsunameters substantially support TWSs. However, major gaps still exist in the coverage of large areas (e.g. North Africa). The present TWS performance could be improved by filling in network gaps. An important issue, however, is the constant TWS maintenance, which requires regular funding and technical support.

Technological innovations that may drastically improve TWS performance include the utilisation of GNSS networks for rapid and accurate large earthquake magnitude calculation. Of innovative value is the utilisation of submarine cable systems for the transmission of seismic, tsunami and other signals recorded on the sea floor for multihazard purposes, including seismic, volcanic and tsunami early warning, climate monitoring and other future societal needs. Satellite data (e.g. buildings, road networks) will become more and more valuable for risk assessment.

Civil protection authorities should elaborate plans to determine coastal hazard zones as well as to ensure that tsunami warnings arrive on time to local authorities and the general public. In parallel, best practices for evacuation procedures should be elaborated and communicated to the public. These are issues of critical importance given that many tsunami sources in the NEAM and beyond are located in the near-field domain; thus, coastal populations are threatened by the fact that any tsunami could reach the coastline in less than 30 minutes.

# Recommendations

Earthquakes, volcanic eruptions and tsunamis are characterised as low-probability but high-consequence events. The assessment of the impact of such catastrophic events incorporates many fields of physical sciences, hazard modelling, engineering and social sciences. Neglecting any of these fields will inevitably reduce the accuracy, reliability and usefulness of the resulting risk metrics. The process of risk identification should involve stakeholders from the public and private sectors and should leverage ongoing national and international initiatives with the mandate to calculate, communicate and reduce geophysical risks.

In the past two decades or so, the European Commission has supported a large number of projects that have significantly advanced the science of earthquake, volcanic and tsunami hazard modelling and risk assessment. Other national and international programmes have also produced datasets, models and tools that are fundamental for the assessment of geophysical risks. Leveraging on this wealth of resources will reduce the replication of efforts. It is also important that the international community investigates efficient approaches to, and develops standards and best practices for, hazard and risk assessment based on existing risk knowledge to enable effective DRM, including preparedness and emergency planning.

Existing instrumental networks support EWSs mainly for earthquakes and tsunamis and, to a lesser degree, volcanic eruptions. However, major gaps still exist in the instrumental coverage of large areas. The present performance of TWSs for the protection of populations should be improved by filling the gaps in these networks. However, even the most advanced EWSs are not effective without a well-trained downstream component. Geophysical risk mitigation thus requires synergies between the scientific and technological community, civil protection authorities and other stakeholders. The common aim should be continual exercises and training, education and public awareness; this is vital, since the public perception of risk from infrequent events naturally tends to fade over time, until the next catastrophe happens.

Geophysical risk assessment is fundamental to incorporate the wide spectrum of uncertainties from the different risk components (hazard, exposure and vulnerability). Satellite imagery and VGI are enabling the characterisation of the built environment with unprecedented temporal and spatial detail. Moreover, the development of risk-reduction strategies not only should rely on the direct (or physical) impact, but should also incorporate socioeconomic aspects, thus considering the capability of the society to recover from destructive events.

## 3.3 Geophysical risk: tsunamis

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