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Tsunami preparedness in Indonesia with special consideration of landslide and volcanic induced events

Characterization of the Threat

What do communities in risk areas need to be prepared for?

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1. Background

Two recent tsunamis in late 2018, in Sulawesi and Anak Krakatau, Indonesia, strikingly demonstrated the high vulnerability of communities to tsunamis induced by landslides and volcanic mechanisms. Both tsunamis were the result of a chain (cascade) of events: on 28 September in Palu, on the island of Sulawesi, the cascade consisted of a sequence of earthquake - landslide - tsunami, while on 22 December, after a prolonged period of volcanic activity, a flank failure occurred on Anak Krakatau, which in turn triggered a tsunami (Walter et al, 2019). In both cases, the resulting tsunamis caught the local population largely unprepared and caused a high number of fatalities. This has been attributed to the limited understanding of tsunami generation from mechanisms other than fault rupture and the lack of an effective tsunami warning system for non-seismic events.

Both events have raised questions in the Indonesian society and among the relevant authorities about appropriate strategies for improved preparedness, early warning and mitigation for such events. The German-Indonesian project "TsunamiRisk" aims to help answer these questions through applied geoscientific and social science research aimed at developing policy recommendations and enabling transfer into practice.

The perspective of local communities must be given special consideration, as it is ultimately they who are confronted with the direct impacts of such events on the one hand and who must implement better preparation and long-term mitigation on the ground on the other. Therefore, the project investigates the specific framework conditions as well as existing experiences in Indonesian communities with previous earthquake/tsunami events in order to support the discussion about adequate strategies and approaches for preparedness, early warning and mitigation of non-seismic tsunami hazards at the local level.

The starting point for all this is to have a better understanding of the tsunami threats that communities face. The present study is intended to make a contribution to this.

2. Scope and Objectives of the Study

The purpose and scope of this study on the characterization of the tsunami threat at local level can be boiled down to the question: "What do communities need to prepare for?"

Understanding the particular threats they are exposed to and the relevant characteristics of such phenomena will help communities to develop adequate strategies for preparedness, early warning and mitigation.

This includes knowing what types of tsunamis might affect them, where the source areas are, and how long the tsunamis are expected to take to reach them. Communities need to understand the possible range of magnitudes of such phenomena and the corresponding probabilities with which they may occur. Furthermore, it is of utmost importance to understand the possible extension of inundation areas, which in turn forms the basis for the evaluation of potential impacts and cascading effects. In order to develop appropriate early warning and evacuation strategies, communities need to understand possible precursors, natural warnings signs, timelines and warning information provided by the NTWC.

And it also requires some understanding about the “unknown” and the uncertainties which are related to these kind of hazards. Current knowledge on non-seismic induced tsunamis in general and its impact on a specific community in particular is still quite limited and future events are expected to bring further surprises with unexpected features and effects that have not yet been anticipated by the communities.

With this study it is intended to provide an overview on the different types of tsunami threat, it´s most important features and how they interact with preceding or subsequent hazards as part of a cascading process. The aim is to provide a better understanding of the main characteristics of the tsunami threat that communities face in order to develop general conclusions and recommendations for strategies that will help them to mitigate and prepare for such events.

With full intention, this study remains on a more generalized level and is only intended as a first orientation, but in no case replaces more detailed risk analysis. Sound hazard and risk analyses at the local level are an indispensable foundation for communities to effectively prepare for the scenarios that threaten them. Such analyses that consider all types of tsunami hazards are still largely lacking.

3. The multiple manifestations of the tsunami threat

The experience with tsunamis in Indonesia and worldwide shows a wide range of varying manifestations. The analysis of 19 recent events in Indonesia (2006-2021) confirms this clearly (Meta-Study WP 430). Each of the 19 events is unique and shows an individual pattern in terms of underlying source mechanism, timeline, response possibilities (based on natural warning signs and / or technical warnings) and impacts. Quite a number of these events had features that caught not only the communities, but also the experts by surprise. While more surprises are certainly to be expected in the future, a good understanding of the features already known will place communities in a better position to protect and prepare against this natural phenomenon.

Tsunamis may be triggered by different mechanism and sources, which can be located in the immediate vicinity or thousands of kilometres away. They are fast-onset events with short lead times, often only a few minutes. Most often, Tsunamis are preceded by perceivable or measurable precursors, but they can also take the population by complete surprise without any precursor or natural warning sign/technical warning.

The range of potential impacts extends from catastrophic with global consequences to minor and more localized ones. While high-impact events, which occur less frequently, usually draw a great deal of attention and media coverage, the more frequent, lower-impact events tend to have much fewer visibility and are often remembered less by the public.

Tsunamis can cause extraordinary casualties, affect the physical and mental health of survivors, and severely destroy property and ecosystems. Besides direct impacts which are largely a result of inundation and the flow velocity of a tsunami wave, indirect impacts through floating debris, damaged power lines and spills of harmful substances as well as salt water intrusion in freshwater reservoirs and groundwater aquifers can lead to long lasting consequences. Experiences such as that of Fukushima, Japan in 2011 show that additional severe impacts can be caused by cascading effects, especially when sensitive or critical infrastructure is affected.

Tsunamis are always triggered by primary natural hazards. Most common are cascades of hazards, in which tsunamis are triggered by earthquakes. Sometimes these are accompanied by landslides. In other cascades, volcanic eruptions are the initial trigger for tsunamis. Such multi-hazard events, especially if happening in the near-field, present a special challenge to communities as they must cope with the interaction and multiple impacts of different hazards at the same time.

4. The different types of tsunamis communities may face in Indonesia

Communities in Indonesia may face tsunamis caused by different generation mechanism (Figure 1). The most frequent source mechanism (> 80%) is a vertical displacement of the seabed during tectonic earthquakes. Less frequent, but not less dangerous, are tsunamis caused by landslides and volcanic eruptions.

Tsunamis through meteorite impact are theoretical possible, but remain out of consideration here because of their extremely rare occurrence. Meteo-tsunamis, which are a tsunami-like phenomena triggered by meteorological or atmospheric disturbances, are also not considered in this study.

Type of Tsunami	Meteo-Tsunami	Earthquake induced tsunami	Landslide induced tsunami	Volcano induced tsunami	Meteorite impact
Triggering mechanism	Rapid changes in barometric pressure	Vertical displacement of the seabed	Mass movements in the water body: submarine landslides or subaerial land slumping into the ocean Causes are sudden, atmospheric (heavy rainfall) or seismic triggered slope failure or volcanic flank collapse. Landslides are often secondary phenomena and can amplify earthquake or volcano induced tsunami	Submarine eruption or phreatomagmatic explosion, pyroclastic flows and lahars entering the water, flank failure, collapse of lava domes, caldera subsidence and shock waves in the atmosphere from large explosions	Impact of extra-terrestrial objects in the ocean
Monitoring		InaTEWS	No monitoring yet (except recently around Krakatau: sea-level changes by tide gauges)		
Risk Assessment		Risk assessment available	No risk assessment yet		
Special features		Splay faults, Slow earthquakes, Outer rise events, Far Field		Mud volcanoes	
Relative frequency of occurrence	Less frequent	80+ % of all tsunamis	Less frequent	Relatively infrequent	Very rare
Timescales (impact after its origin)		Minutes to Hours	Usually Minutes In particular cases up to several hours		
Reach	Short range	From short range to trans-oceanic	Usually short range (near-field) In particular cases also trans-oceanic (far-field)		Trans-oceanic

Figure 1: **Spectrum of possible categories of Tsunami in Indonesia (TsunamiRisk - WP 430)**

The attribution of a tsunami to one of the three outlined categories is not always clear-cut. Landslide induced tsunamis are often interlinked to tectonic earthquakes or volcanic eruptions. It can also be assumed that tsunamis generated by tectonic earthquakes are sometimes amplified by accompanying submarine landslides. However, this is often not recognized at all.

Landslide and volcanic induced tsunamis occur much less frequent compared to earthquake induced tsunamis, but represent also a major challenge to the communities at risk. In the period from 2006-2022 they caused more fatalities than earthquake triggered tsunamis (Figure 2). Since there are no comprehensive and nationwide hazards and risk analyses for landslide and volcanic induced tsunamis available yet, it is currently hardly possible for the communities at risk to determine their actual exposure to these threats. It must also be assumed that such events will continue to take communities by surprise, as these kind of tsunamis are not always preceded by clear natural warning signs (like a strong earthquake) and there are hardly any warning systems in place yet that can detect these phenomena on time. This applies in particular to all events that take place in the near-field area.

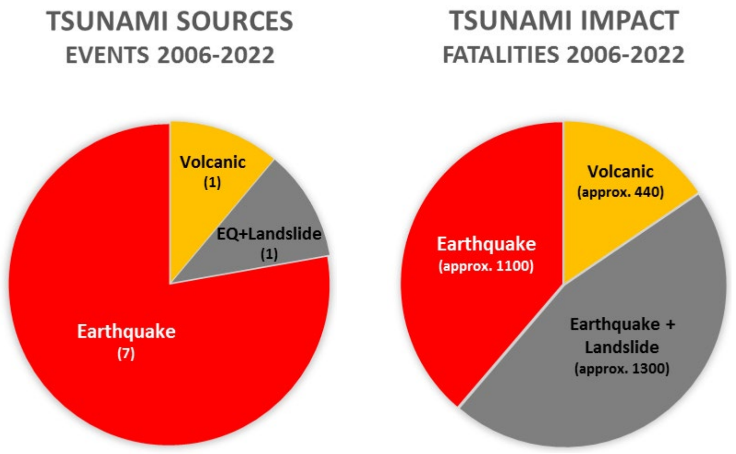

Figure 2: **Sources of tsunamis (left) and number of fatalities from tsunamis triggered by different source mechanism (right) in Indonesia during the period 2006-2022 (TsunamiRisk - WP 430)**

In Indonesia, tsunamis can be triggered by all sources or combinations of them in areas that are close to inhabited coastal areas. In these cases, the tsunami travel times are often in the range of minutes. Most events in the past fall into this category. In addition, there are occasional far-field events which, at least in recent times, have all originated in the Pacific Ocean, and from this point of view only pose a threat to coastal areas in eastern Indonesia. Latest experiences show that such far field tsunamis are being detected and monitored on time and should not come as a surprise to local communities. In any case, knowing the expected travel times for the different types of tsunamis that might affect a particular community is another key factor for community preparedness.

3.1. Earthquake induced tsunamis

The majority of coastal communities in Indonesia is facing threats from earthquake induced tsunamis (Figure 3). Most of those tsunamis are generated in the near field, which not only results in short tsunami travel times, but also in possible impacts caused by the associated earthquake and further cascading effects. Since the 2004 Indian Ocean tsunami, communities in Indonesia have become more aware and knowledgeable about the tsunami hazard from tectonic earthquakes.

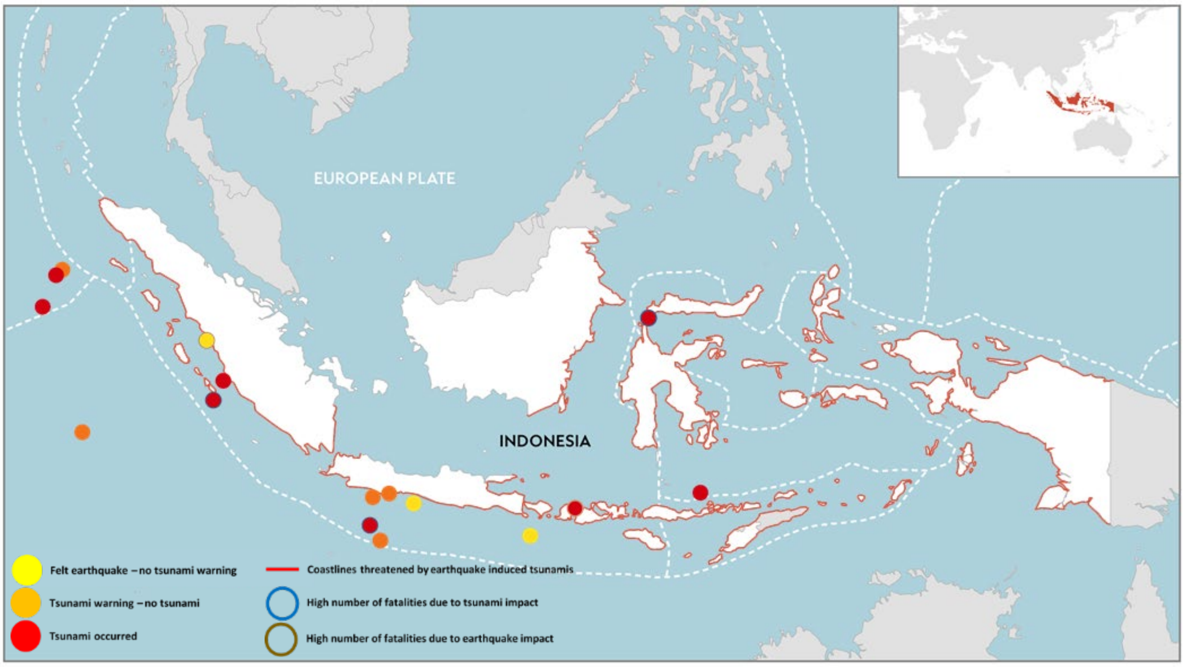

Figure 3: **Coastal regions where earthquake induced tsunamis pose a substantial threat and recent tsunami related events in Indonesia during the period 2006-2022 (compiled by WP 430, see Figures 4 and 5)**

Earthquake-triggered tsunamis occur relatively frequently in Indonesia, and one can expect such a tsunami about every 2 years. If one adds the earthquakes that are strongly felt in coastal communities but do not trigger a tsunami, the number of events is actually much higher. Even if the tsunami threat from tectonic earthquakes is, in principle, well understood, experience shows that each event is unique and often good for a surprise. At local level, the interaction of earthquake and tsunami hazards can show very different patterns. An analysis of seventeen recent events in Indonesia from 2006 to 2021 has provided interesting insights into these features (Figures 4 and 5):

- **All earthquake induced destructive tsunamis were generated in the near-field**. Tsunami arrival times can vary significantly by location, but are mostly on the order of about 30 to 60 minutes. In two events, the travel time of the tsunami to the shorelines closest to the source was only a few minutes. (Mentawai 2010, Lombok 2018)
- **Most of these tsunamis were preceded by strong ground shaking**. Duration and intensity of ground shaking are important natural warning signs of a possible tsunami. Earthquakes in the near field may cause significant destruction (Padang 2009) which can hamper tsunami evacuations.
- **Less than half of the locally strongly felt earthquakes actually triggered a tsunami**. Of the 14 events in which coastal communities felt a strong earthquake, only six actually resulted in a tsunami. For five of the eight events that did not trigger a tsunami, a tsunami warning had been issued (based on the analysis of earthquake parameters). Noteworthy in this regards are three outer-rise earthquakes (Aceh 01-2012 and 04-2012, Mentawai 2016) which were strongly felt by the communities but did not pose a significant tsunami threat due to their focal mechanism. Those three earthquakes triggered tsunami warnings, which were subsequently the subject of public controversy.
- **Near-field tsunami events, with no or no clear natural warning signs from the initiating earthquake, are particularly dangerous**. Two tsunamis (Pangandaran 2006, Mentawai 2010), both classified as so-called "slow earthquake" events, were preceded by only minor or swaying ground movements which were difficult for the local population to interpret properly.

- **Far field tsunamis so far had minor or no impact on Indonesian communities**. The threat of far-field tsunamis originates essentially in the Pacific Ocean (Japan 2011 and Chile 2014). Other source areas in the Indian Ocean (Makran Subduction Zone) are unlikely to impact Indonesia.
- **As far as the extent of the impact is concerned, completely different scenarios may arise**. From 2006 to 2021 Indonesia suffered six events with a high number of fatalities. In two events these were due solely to the effects of earthquakes (Padang 2009, Lombok 2018), while in two other events the fatalities were related only to the effects of the tsunami (Pangandaran 2006, Mentawai 2010). The complex Palu event in 2018 resulted in a high number of casualties from both phenomena. The Krakatau tsunami in 2018 was caused by a volcanic flank collapse.
- **In addition to direct impacts from earthquakes and tsunamis, communities may face additional seismic triggered cascading effects** like soil liquefaction and mass movements on land (Palu 2018).
- **Aftershocks are a common feature and can further complicate the situation**. Aftershocks can collapse buildings already pre-damaged by the main earthquake or the subsequent tsunami and can trigger or intensify panic reactions in the population. In exceptional cases aftershocks can reach a magnitude that is high enough to result in another tsunami threat and makes a further tsunami warning necessary (Aceh 04-2012).

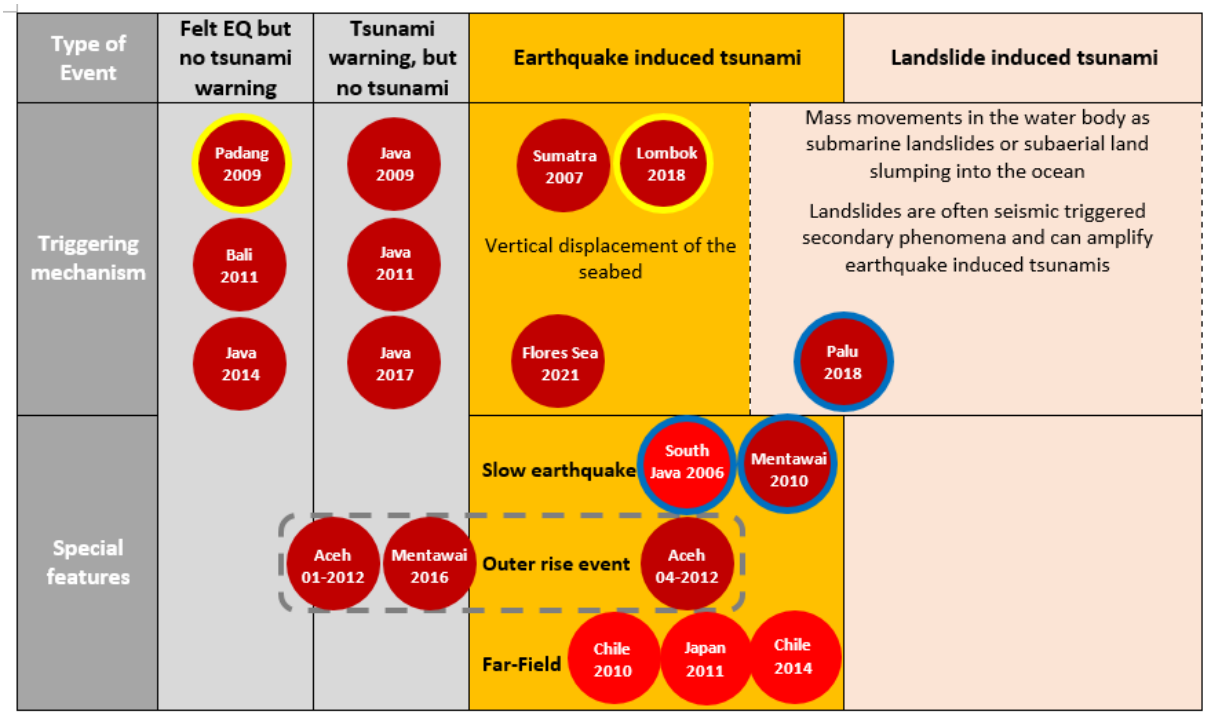

Figure 4: **Types and special features of recent tsunami related events in Indonesia (2006-2022). Events with a high number of fatalities due to tsunami impact are marked by blue circles, those due to the earthquake by yellow circles. (TsunamiRisk - WP 430)**

Date of the Event & Location of the Case		Type of Event	Earthquake Magnitude	NTWC Warning	Natural Warning	Tsunami Impact	Earthquake Impact
Earthquake location within the Indonesian archipelago							
2006-07-17	Pangandaran	Slow EQ	7,7	No Warning		High	
2007-09-12	Sumatra/Padang	EQ	8,0	Warning		Medium	High
2009-09-02	Java/Bantul	EQ	7,3	Warning			High
2009-09-30	Padang	EQ	7,7	No Warning			Very high
2010-10-25	Mentawai	Slow EQ	7,0	Warning		High	
2011-04-04	Southern Java	EQ	6,7	Warning			
2011-10-13	Bali	EQ	6,1	No Warning			Medium
2012-01-11	Aceh	Outer Rise	7,1	Warning			
2012-04-11	Aceh	Outer Rise	8,6	Warning		Low	Low
2014-01-25	Java	EQ	6,1	No Warning			
2016-03-02	Mentawai/Sumatra	Outer Rise	7,7	Warning			
2017-12-15	West-Java	EQ	6,7	Warning			Medium
2018-08-05	Lombok	EQ	6,9	Advisory		Low	Very high
2018-09-28	Palu/Sulawesi	EQ / Landslide	7,5	Warning		High	Very high
2021-12-14	Flores Sea	EQ	7,3	Warning		Low	Medium
Earthquake location outside the Indonesian archipelago							
2010-02-27	Chile Tsunami (Maule)	Far Field	8,8				
2011-03-11	Japan Tsunami (Tohoku)	Far Field	9,0	Warning		Low	
2014-04-02	Chile Tsunami (Iquique)	Far Field	8,2	Advisory			

Figure 5: **Characteristics and impacts of recent earthquake-tsunami related events (2006-2022) in Indonesia (TsunamiRisk - WP 430)**

3.2. Landslide induced tsunamis

Knowledge of the source areas and coastlines threatened by landslide-induced tsunamis in Indonesia is yet rather sketchy, so the actual magnitude of the threat to coastal communities still remains a major unknown.

There are a number of historical known landslide tsunamis as well as geophysical evidence for landslides which might have been tsunamigenic. Studies on the Sunda Arc and Makassar Strait provide insights on these locations.

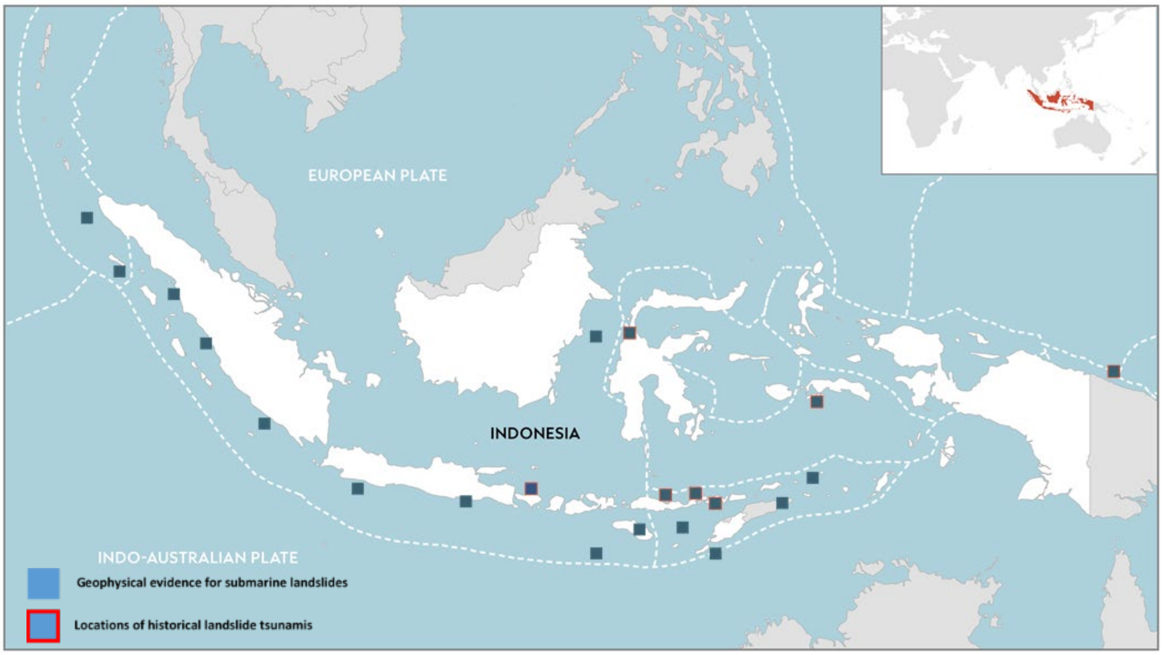

Figure 6: **Locations of historical landslide tsunamis in Indonesia and places of geophysical evidence for submarine landslides (based on Brune et al. 2010, Brackenridge et al. 2020)**

Landslide induced tsunamis are often interlinked to tectonic earthquakes or volcanic eruptions. Constellations in which tsunamis triggered by tectonic movements are amplified by collateral submarine landslides certainly play an important role. Such contribution of landslides to earthquake induced tsunamis is usually difficult to detect and therefore often disputed. Also critical and difficult to detect are cases where the earthquake is below the tsunami warning threshold but causes a landslide, which in turn triggers a tsunami. Furthermore, the interactions between landslides and earthquakes can be very complex, as demonstrated by the Palu tsunami (2018). Its mechanism is still uncertain but has been proposed to be the result of a combination of earthquake-related seafloor rupture and subaerial/submarine landslides (Schambach et al. 2021).

Due to the variable and complex generation mechanisms of landslide tsunamis, their manifestation at local level can vary greatly. From a number of past events, some relevant characteristics can be derived to describe the threat to communities from landslide-induced tsunamis. These events include Bali (1815), Seram (1899 and 2021), Lomblen Island (1979), Flores (1992), Papua New Guinea (1998), and Palu (2018). The flank slide movement during the Krakatau event (2018) has been excluded here but is considered in the following chapter on volcanic induced tsunamis. Based on documented historical and recent experience, which of course do only represent a small subset of past events, it is possible to make the following assumptions:

- **Landslides that generate tsunamis are mostly triggered by earthquakes** and can occur in form of submarine land sliding (Papua New Guinea 1998) or subaerial land slumping (Bali 1815, Seram 1899) into the sea. Tsunamis generated under such circumstances are most likely caused by a combination of triggering mechanisms that include both tectonic and mass movements (Flores 1992, Palu 2018). The interaction between an initial earthquake and the resulting tsunamis, whether or not they are triggered by landslides, is multifaceted and has already been described in the previous chapter.
- **Landslide tsunamis can even be caused by minor earthquakes that do not themselves have the potential to trigger a tsunami**. In such situations, if the ground motions are only weakly or not at all felt by the local population, the tsunami hazard may be unrecognized or underestimated. Serious problems can arise in this constellation if the National Tsunami Early Warning System, which is exclusively designed for tectonically induced tsunamis, excludes a tsunami hazard in such a situation and communicates this to the authorities and population (Seram 2021).
- **The strength of a felt earthquake does not provide conclusive indications about the occurrence and magnitude of an imminent threat from a landslide triggered tsunami**. Nevertheless, a strongly felt earthquake should always be viewed by the public as the ultimate natural warning sign of an impending tsunami threat, regardless of the underlying triggering mechanism.
- **In rare cases a landslide tsunami can occur without a preceding earthquake**. Those events will most probably always take the affected communities by surprise. Such a spontaneous landslide from the north-western flank of the Iliwerung volcano has been documented in Flores (Lomblen Island 1979) and the resulting tsunami inundated areas up to 1500 m inland leading to a high death toll in several villages.
- **The documented historical landslide tsunamis all occurred in the near field**. For these cases, tsunami travel times are in the order of minutes. Therefore, if natural warning signs can be observed or technical warning mechanisms are in place, warning times would be extremely short.
- **They are usually localized events**. The documented cases show that the impact and damage were limited to a relatively small area. The primary tsunami hazard is to coastal communities within a few tens of kilometres of the source mechanism.
- **Whether tsunamis from landslides originating in the far field could pose a threat to Indonesian communities remains to be determined**. Based on the current state of knowledge, however, this appears to be a rather unlikely scenario.
- **Landslide tsunamis often have catastrophic consequences for the immediate vicinity**. Tsunamis from submarine landslides can attain wave heights of up to 15 m (Papua New Guinea 1998) and even much higher run-ups on land. Of the eight events which have been considered in this study, five events resulted in a high number of fatalities in the nearby communities (Bali 1815, Lomblen Island 1979, Flores 1992, Papua New Guinea 1998, Palu 2018).

3.3. Volcano induced tsunamis

Volcanogenic tsunamis are rather infrequent hazards. Only about 5% of all tsunamis fall into this category. The distinction from earthquake and landslide induced tsunamis is sometimes not clear-cut, especially when earthquakes occur preceding or during a volcanic eruption (Tambora, 1815) or landslides from quiescent volcanoes (Lomblen Island 1979) are involved. Unlike an earthquake induced tsunami that displaces ocean water from the seafloor up, along a fault line that can be hundreds of kilometres long, a volcano induced tsunami is more like a point source.

The **locations of volcanoes in Indonesia that may trigger tsunamis** are widely known and are mostly concentrated in the eastern part of the Sunda trench, the Maluku Islands, and North Sulawesi (Fig. 6). Outside of these areas, Krakatoa in the Sunda Strait must be also taken into account. More difficult, however, is a comprehensive hazard assessment providing more detailed information for threatened coastal communities. There are relatively few scientific studies dealing with the tsunami hazard from individual volcanoes. Unfortunately, the existing findings have so far failed to find their way into disaster risk management strategies, as was evident in the case of the 2018 Krakatau tsunami. In this particular case, a study (Giachetti et. al 2012) provided a detailed analysis of the tsunami hazard related to a possible flank collapse of Anak Krakatau, which then occurred in 2018 almost exactly as described.

The reach of tsunami-waves generated by volcanic activities depends very much on the specific volcanic source mechanism (see below), the volume of displaced masses and the energy which is released. Except waves produced by very large flank failure and air waves that can reach very far, impacts are usually limited to a radius of 300 km around the source.

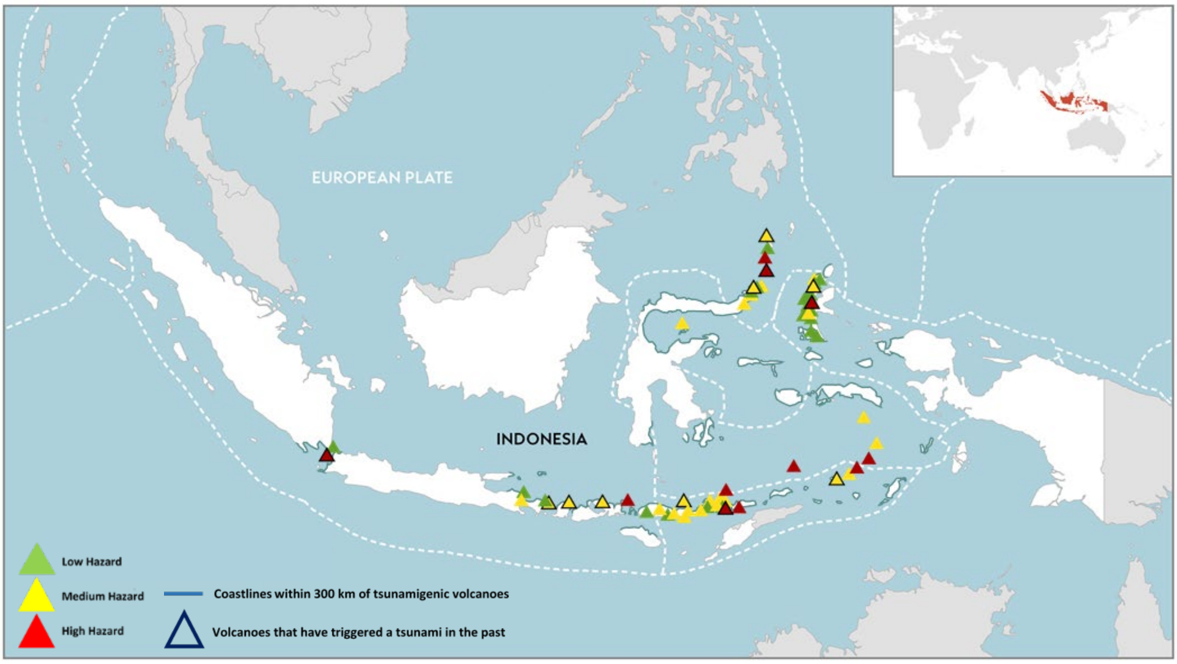

Figure 7: **Location and categorization of tsunamigenic volcanoes and regional impact zone (300 km) (based on Zorn et al., 2022)**

Volcanic induced tsunamis are characterized by **variable and complex source mechanism** (Figure 8). These include underwater explosions, pyroclastic flows and lahars entering the water, flank failure (from rock falls to massive debris avalanches), collapse of lava domes and coastal lava benches, caldera collapse (resulting in rapid subsidence of the sea floor) and shock waves in the atmosphere from large explosions (by coupling between shock wave and sea surface). Sometimes multiple mechanisms are involved, which can further complicate the situation. Unfortunately, the precise nature and dynamics of the interactions and processes that generate waves during eruptions often remain unclear. The source of the different tsunamis observed during the 1883 eruption of Krakatoa have long been debated and may be due to combination of pyroclastic flows, underwater explosions, caldera subsidence and failures of the caldera walls as well as air waves.

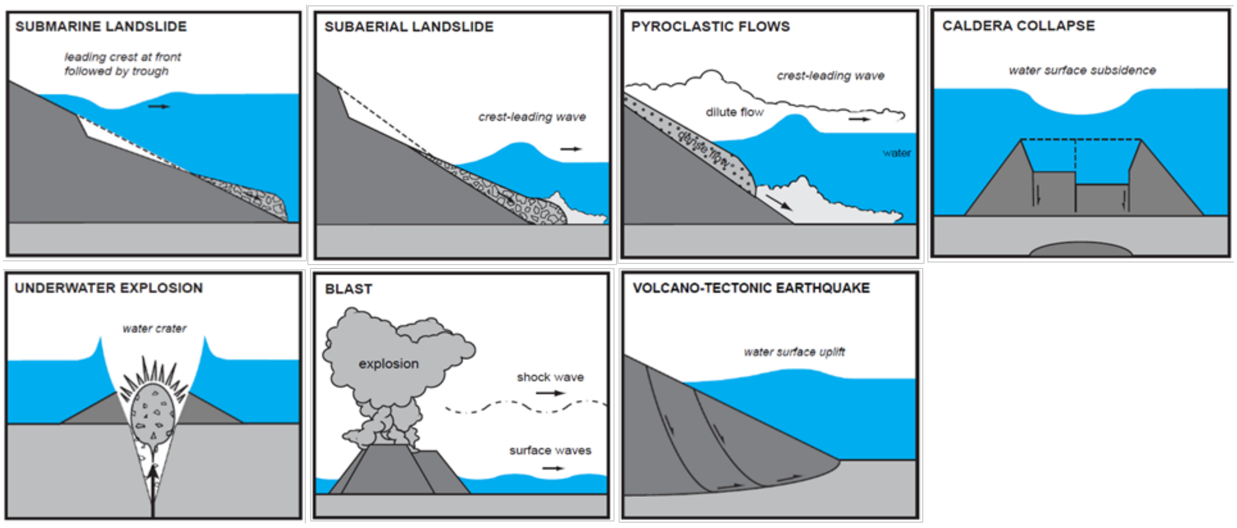

Figure 8: **Principal volcanic source mechanisms of tsunami: underwater explosions, air wave generated by blast, pyroclastic flow, caldera collapse and flank failures (updated version from Paris, 2013)**

For more than one-third of the volcanically triggered tsunamis recorded in Indonesia in the past, the source mechanism of origin remains unclear, and in many other cases the identified source mechanism is still subject to a considerable degree of uncertainty (Figure 9).

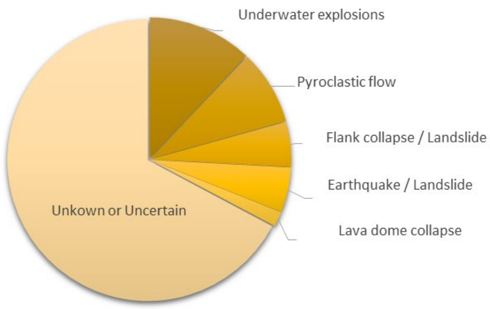

Figure 9: **Source mechanism of historical volcanic induced tsunamis (GFZ, 2022)**

The reach and impact of volcanic induced tsunamis depend very much on the source mechanism. Their hazard is mainly to coastal communities within a few tens of kilometres of active volcanoes, although large explosive eruptions and flank collapses can generate hazard at greater distances of hundreds of kilometres. Based on past experiences (Paris, 2014), it is unlikely that shock waves, lahars and collapses of lava benches can create tsunamis with wave heights of more than 3 meter (Figure 10).

In the absence of more detailed hazard and risk assessments, for the time being, one can only rely on lessons learned from previous events to outline the threat situation for communities at risk. However, it must be taken into account that the description of previous events is by no means complete and is often also subject to high uncertainties. Nevertheless, a number of rather general assumptions can be derived that may be helpful for a first characterization of the threat:

– **The vast majority of volcanic induced tsunamis occur during an eruption phase** and their impacts are mostly confined to local or regional surroundings within a radius of up to 300 km. The strongest impacts are usually in the immediate vicinity of the respective volcano (< 60 km).

- **A special case are volcano flank failures.** They might also occur during quiescent phases (Lomblen Island 1979) as volcanic edifices are by their nature unstable (i.e. due to structural discontinuities or hydrothermal alteration). In rare cases, tsunamis triggered by a volcano flank failure can have a longer range and, depending on the coastal structure, extreme run-ups.

Main source mechanism	**Frequency of occurrence**	**Potential for damaging tsunami** (wave heights > 3m)	**Wave heights** (m) at shoreline	**Travel distance** (km)
Underwater explosions	Most frequently	High	High (< 10 m)	Regional (< 200 km)
Pyroclastic flow	More common	High	High (< 30 m)	Regional (< 300 km)
Flank failures	More common	High	Extreme (some 10s of metres)	Ocean wide (< 6000 km)
Caldera subsidence	Rather rarely	Moderate	Moderate -High (< 10 m)?	Regional (< 200 km)
Air wave generated by blast	Rarely	Unlikely	Moderate (< 3 m)	Global (> 1000 km)
Lahar / collapse of lava bench	Very rarely	Low	Moderate (< 3 m)	Local (< 10 km)

Figure 10: **Characteristics of volcanic tsunamis generated by different source mechanism (based on Paris, 2014)**

- **Increased volcanic activity should always be taken as a general warning, but usually does not provide conclusive indications of the likelihood and magnitude of an imminent tsunami hazard.** The Sunda Strait tsunami (Krakatoa 2018) was preceded by a prolonged period of volcanic eruption activity of varying intensity over several months and there was no significant change in this eruption pattern that indicated the imminent triggering of a tsunami. In the case of Tagulandang Island (Ruang Volcano, 1871), the tsunami occurred just at the beginning of the eruption.
- Based on several criteria such as location, slope steepness, distance to coast and past activity, a number of **volcanoes with a higher tsunami hazard** have been be identified. These include Anak Krakatau in the Sunda Strait, Gamalama, Serua, Nila and Wetar in the Maluku Islands and Banda Sea, Karangetang and Ruang on the Sangihe Islands in North Sulawesi as well as Iliwerung, Batu Tara, Sirung and Sangeang Api in the Lesser Sunda Islands (Zorn et al., 2022).
- **Each volcano is different** and usually has its own eruption pattern. However, it is not possible to infer from this when a volcano will erupt next. Periods of quiet can vary from a few years to thousands of years. Due to the variable and complex source mechanisms and limited options for direct monitoring, **volcanic induced tsunamis are hard to forecast**. It is important to be aware that several tsunamigenic processes can be associated and may even trigger numerous tsunamis during a single event (Krakatoa 1883).
- Except around Anak Krakatau no mechanism for detection and forecasting of volcanic induced tsunami are currently in place. With this in mind, it is therefore extremely important for communities to **monitor and understand the possible natural warning signs** (explosions offshore, increasing travel distance of pyroclastic flows, rock falls, water oscillations or withdrawal at the shoreline). How this can save lives was illustrated during the recent tsunami event in Ha'atafu (Tonga 2022). Quick reaction is always necessary, as travel time of the waves from the volcano to a distance of 20 km is typically less than 15 min.

- In the immediate vicinity of Indonesia, especially **in Papua New Guinea and the Philippines, there are other volcanoes** to keep an eye on. Whether these could pose a threat to Indonesian communities remains to be determined. However, due to the distance and based on previous experience, the risk can be considered relatively low.
- As volcanic induced tsunami are closely associated in time and space with volcanic eruptions, communities will often **not only suffer the impact of the tsunami but also from the eruption** (Awu 1856, 1892) and further cascading effects. Extreme volcanic eruptions (Tambora 1815, Krakatoa 1883) can have devastating effects over large areas and time periods. At the contrary, population not suffering the direct impact of the eruption could be threatened by a tsunami.

5. The spatial distribution of the tsunami threat in Indonesia

The threat to Indonesia from tsunamis triggered by earthquakes, volcanoes, landslides, or a combination of these sources is shown in Figure 11.

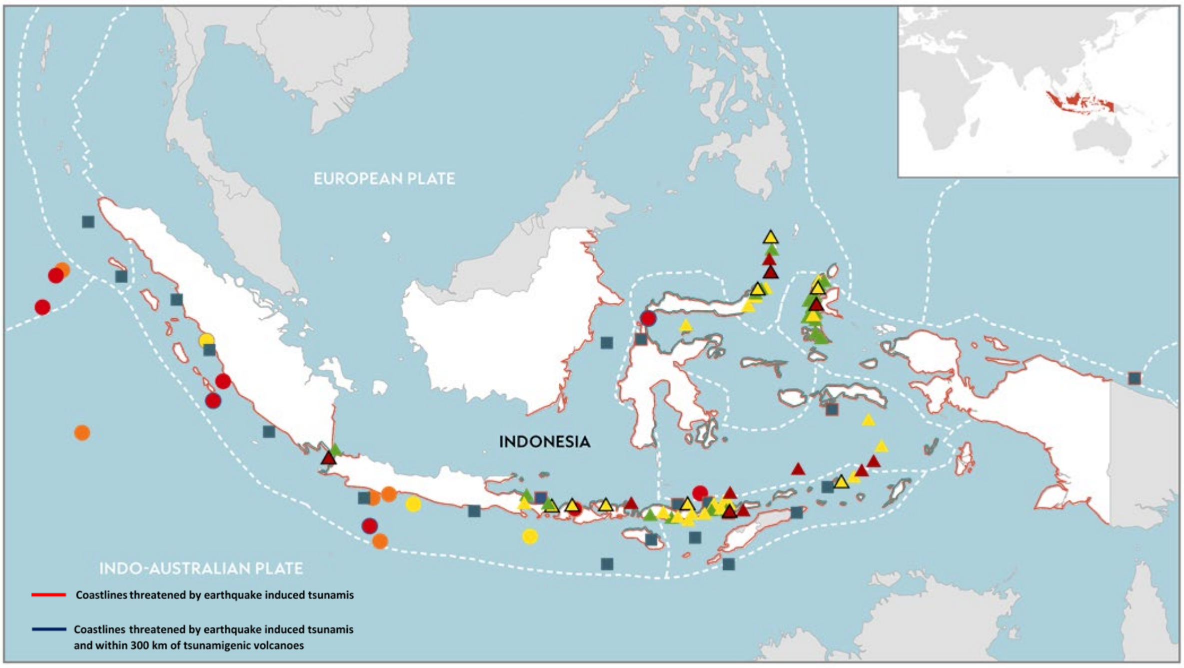

Figure 11: **Map of the different tsunami sources (earthquakes, landslides, volcanoes) and affected coastline in Indonesia (for meaning of symbols and colour codes see figures 3, 6 and 7)**

For tsunamis triggered by earthquakes, almost all of Indonesia is at risk due to the major thrust zones in the Indian Ocean that run almost parallel to the coastline, several faults in north-eastern Indonesia, and the far field threats from the Pacific Ring of Fire. The threat from the Indian Ocean is limited to near field tsunamis generated along the Sunda Arc.

Since earthquakes often trigger submarine landslides, it must be assumed that the threatened coasts may experience tsunamis that are amplified or even triggered by such landslides. Since knowledge of areas with significant hazard potential for submarine landslides is patchy to date, it must be assumed that this can happen anywhere along the Indonesian tsunami prone areas. One prominent example of this mechanism is the tsunami which hit Palu in 2018.

The threat by volcano generated tsunami is mainly concentrated on the eastern part of Indonesia. The only exception is the Krakatoa volcano in the Sunda Strait.

Overall, Indonesia can be divided into two major regions. The western part, with exception of the Sunda Strait, mainly faces near field threats from earthquake and landslide triggered tsunamis that are generated along the Sunda Arc thrust zone. Far-field sources, such as the Makran Subduction Zone and the volcanic source at Heard Island in the southern Indian Ocean, can be considered a minor threat to the Indonesian coastline. The eastern part faces a more diverse threat situation, which additionally include volcanic induced tsunamis and far field threats from large earthquakes around the Pacific Rim.

This overall picture should lead to a differentiated monitoring and warning strategy in the western and eastern part of Indonesia which will be discussed in the next chapter.

6. Preliminary conclusions for possible strategies

The previously described types of tsunami hazard pose multiple challenges to local communities. New approaches and strategies must be found to deal with these threat scenarios. These cannot be handled by communities alone, but require enhanced warning concepts and preparedness strategies developed jointly with national and regional authorities and the scientific community.

In the following, some preliminary ideas for such strategies are outlined.

6.1. Monitoring strategy

A monitoring strategy is proposed which takes the hazard potentials and their geographical distribution over Indonesia into account.

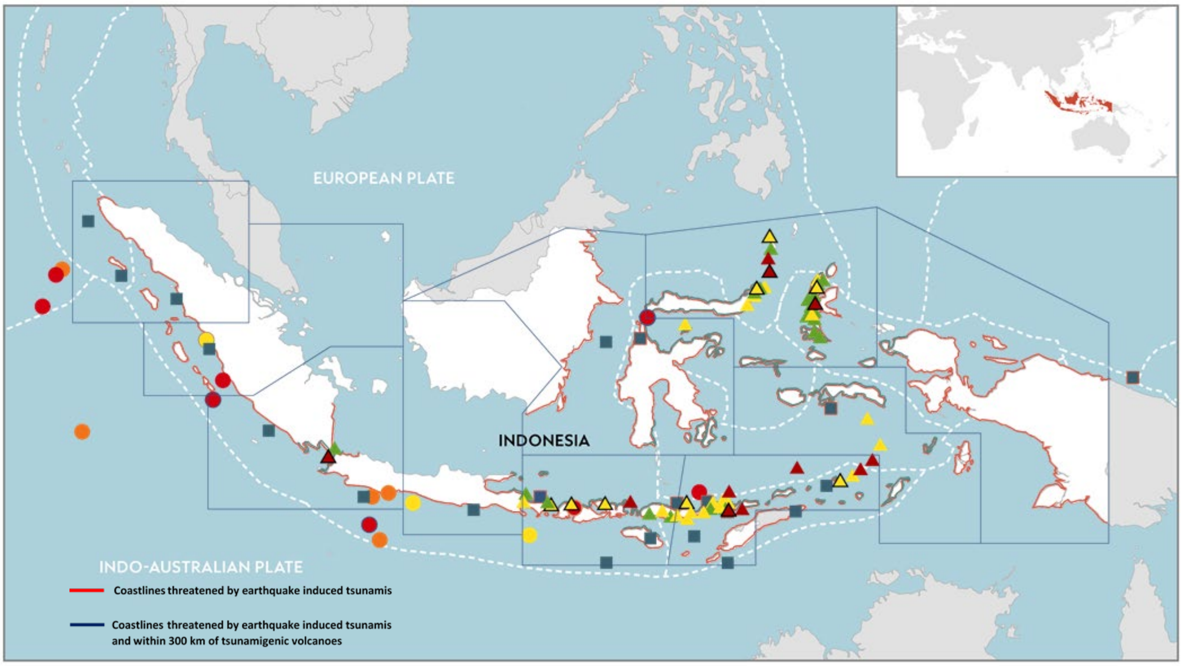

Figure 12: **Map of the different tsunami sources (earthquakes, landslides, volcanoes) and affected coastlines. Also shown are the borders of the 10 BMKG Regional Centres (for meaning of symbols and colour codes see figures 3, 6 and 7)**

Earthquakes

Earthquakes cannot be predicted but due to the fast travelling of seismic waves they can be measured and located very quickly and this information is used to generate an initial situation picture and warning messages for tsunami warning. The monitoring infrastructure is in essential parts already available and well working (Lauterjung et., 2014). The monitoring is organized nationwide and centralized. Dependant on the location of a strong tsunamigenic earthquake the warning message is regionalized, means that only those parts of the coast are warned which turn out to be tsunami endangered after first modelling runs based on the earthquake parameters. This earthquake monitoring network could be upgraded by a GPS network along the coastlines to monitor co-seismic crustal deformations. Such GPS networks could be used in a multipurpose arrangement for geodetic national tasks of land survey and/or meteorological purposes for weather forcast.

Landslides

Landslides are difficult to monitor, especially when it comes to measuring characteristic parameters such as the geometry of the slide, its volume, and slide velocity. Landslides, both subaerial and submarine, can be triggered by earthquakes well below the threshold magnitude for tsunamigenic earthquakes, making it dangerous to use earthquake parameters for warning. Possibly larger landslides can be detected by a seismic signature they produce but this is still under scientific investigation.

For ***submarine landslides***, our only option is to directly measure the tsunami generated by a landslide. This would require dense sea-level monitoring using submarine instruments and technologies. Since these technologies are expensive and require intensive and costly maintenance, they can only be installed in high-risk regions, meaning that we have to map regions with a high landslide potential and highly vulnerable coastal regions. One possible technology could be submarine fiber-optic cables that can be used as a backbone for numerous sensors or as the sensor itself (smart cable approach). In terms of geographic distribution, this approach argues for regionalization of the operation of the monitoring systems, which can be oriented to the BMKG regional center (see Fig. 12).

In Indonesia, there are some initiatives aiming at establishing a local tsunami warning mechanism at the community level with land-based sea level monitoring devices. Whether and how these can be usefully applied should be further investigated.

For ***subaerial landslides*** we have the possibilty to use satellite deformation measurements (i.e. InSAR) or direct field observations for monitoring purposes. This involves a two-stage monitoring approach. First, there is non continuous monitoring and measurement of deformation or destabilisation trends. When this trend reaches a critical value (to be determined by regional experts) a permanent monitoring (i.e. with cheap GPS sensors) can be installed and operated. This approach also argues for regionalization of the operation of the monitoring systems, which can be based on the BMKG regional centers.

Volcanoes

As the vast majority of volcanic induced tsunamis occur during an eruption phase and volcanoes do not erupt without precursors it is essential to develop a joint monitoring strategy between the volcanic (Centre of Vulcanology and Geological Hazard Mitigation - PVMBG) and geophysical (BMKG) services. For this purpose, it should be possible to use already existing monitoring infrastructure installed by PVMBG and BMKG. Additionally, remote sensing data from satellite observations could be employed. In this case one can develop a flexible monitoring strategy: basic non-continuous monitoring below a given threshold (e.g. deformation by satellite monitoring), densified continous monitoring by temporary deployed instruments in the field above a given threshold. In Indonesia, volcano emergency levels 1-4 have been defined and implemented by PVMBG (Figure 13). These levels must be synchronized with tsunami warnings for tsunamigenic volcanoes.

Normal level	Visual observations and instrumental records show normal fluctuations, but no change of activity Hazards in the form of poisonous gas may take place near vents according to the volcano's characteristic activity
Waspada level (advisory)	According to visual observations and instrumental records there are indications of increasing of volcanic activity
Siaga level (watch)	According to visual observation and instrumental records there are prominent indications of increasing volcanic activity. Eruptions may take place but do not threaten settlements and/or activities of communities near the volcano.
Awas level (warning)	According to visual observations and instrumental records, there are significant indications of volcanic activity, which are followed eruptions and potentially threaten settlements and or community activities around the volcano

Figure 13: **Level of volcanic activity in Indonesia (Andreastuti, S. et al., 2017)**

In addition, a regional monitoring approach should be considered. This is supported by the fact that most volcanoes with some potential to trigger a tsunami are located in the eastern part of Indonesia and that each volcano has its individual characteristics. Therefore and taking into account the diversity of source mechanism it is important to have local/regional knowledge available and to discuss necessary monitoring strategies with those experts, i.e. the extension of local and regional sea level monitoring. On the part of the BMKG, the regional offices (regional centers 2, 3, 8, 9, 10) could take over the volcanoes in their area of responsibility (see map in fig. 12 above) in agreement with PVMBG.

6.2. Disaster risk management strategies

From the point of view of the communities, in addition to knowledge of the different tsunami source areas, information about the coastal areas at risk is particularly relevant. In this regard, it is essential that communities understand which sections of the coast are at risk from which types of tsunami. The spatial distribution of the different types of tsunami hazard along Indonesian shorelines is outlined in Figure 13.

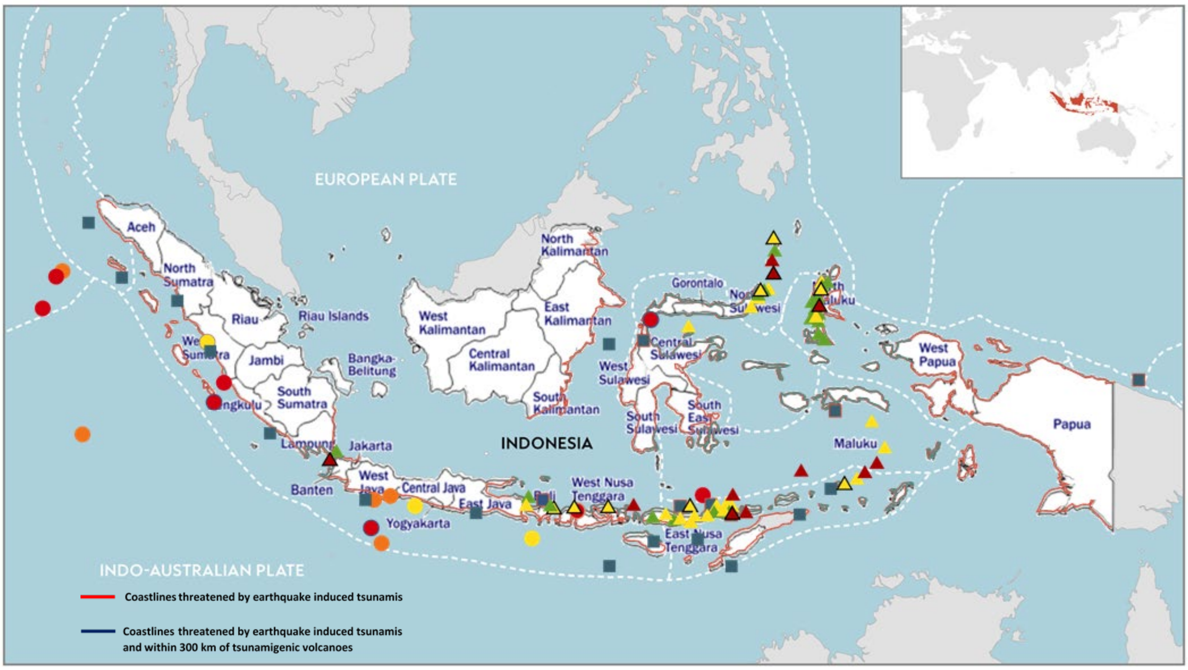

Figure 13: **Map of the different tsunami sources (earthquakes, landslides, volcanoes) and affected coastline. Also shown are the borders of the Indonesian provinces (for meaning of symbols and colour code see figures 3, 6 and 7)**

The spatial distribution of the different types of tsunami threat to coastal areas in Indonesia reveals quite clear patterns, as described in chapter 5. From this pattern, three basic types of tsunami threat scenarios for communities can be deducted:

Scenario 1 Communities that primarily face earthquake induced tsunamis from the near field. The originating earthquake can also trigger submarine landslides, which in turn can amplify tsunami waves or even generate them themselves. In addition, a minor threat from volcanically induced tsunamis from the far field cannot be completely ruled out in these communities.

Scenario 2 Communities that besides earthquake induced tsunamis with landslide effects face a higher risk of volcanic induced tsunamis. Those communities are located within a radius of 300 km around tsunamigenic volcanoes. Although these are predominantly near field tsunamis, these communities might also experience some minor threats from the far field.

Scenario 3 Communities that mainly face earthquake induced tsunamis with possible landslide effects originating from the near field and, in addition, have a lower risk of being affected by tsunamis originating from more distant earthquake or volcano sources.

Since these scenario types each require their own approaches, it seems appropriate to first discuss possible risk management strategies in more general terms and thus develop a framework for action for communities with similar threat situations.

When overlaying the spatial distribution of the threat with the political administrative units that are ultimately responsible for developing and implementing disaster risk management strategies (Fig. 13), it is possible to determine the possible threat scenarios for each province in Indonesia, which then could form the basis for the development and implementation of adapted strategies. Those provinces that have the same threat scenarios could then be interlinked and strengthened through joint learning on regional decentralized approaches for tsunami preparedness strategies and experience sharing.

Scenario	**EQ** Near-field	**EQ** Far-field	**Land-slide**	**Volcanic** < 300 km	**Volcanic** > 300 km	**Provinces**
1					Minor threat	Aceh, North Sumatra, West Sumatra, Bengkulu, West-Java, Central Java, Yogyakarta,
2		Minor threat			Minor threat	Lampung, Banten, East-Java, Bali, West Nusa Tenggara, East Nusa Tenggara, West Papua, Maluku, North Maluku, North Sulawesi, Gorontalo, Central Sulawesi, South East Sulawesi, South Sulawesi
3		Minor threat			Minor threat	Papua, West Sulawesi, North Kalimantan, East Kalimantan, South Kalimantan

Figure 14: **Features of the outlined tsunami threat scenarios for local communities and the affected provinces (own compilation)**

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