Bulletin of the Geological Society of Malaysia, Volume 70, November 2020, pp. 1 - 15
DOI: https://doi.org/10.7186/bgsm70202001

Assessment of tsunami hazard in Sabah – Level of threat, constraints and future work

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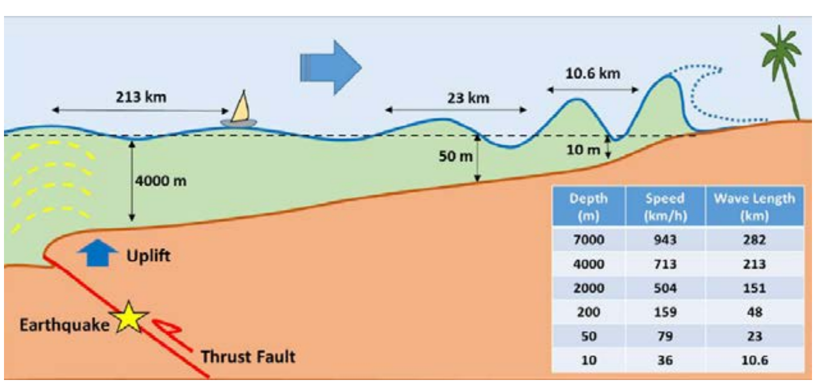
Abstract: The coastal areas of Sabah are exposed to far-field earthquake-induced tsunamis that could be generated along the trenches of Manila, Negros, Sulu, Cotabato, Sangihe and North Sulawesi. Tsunami simulation models from these trenches indicated that tsunami waves can reach the coast of Sabah between 40 and 120 minutes with tsunami wave heights reaching up to 3 m near the coast. The level of tsunami threat is high in southeast Sabah due to its narrow continental shelf and proximity to tsunami source in the North Sulawesi Trench. The level of tsunami threat is moderate in north and east Sabah due to their proximity to tsunami source in the Sulu Trench. The level of tsunami threat is low in west Sabah due to its distant location to tsunami source from the Manila Trench. While tsunamis cannot be prevented, its impact on human life and property can be reduced through proper assessment of its threat using tsunami simulation models. Unfortunately, constraints remain in producing a reliable tsunami inundation models due to the lack of high-resolution topography and bathymetry data in Sabah and surrounding seas. It would be helpful if such data can be acquired by the relevant government agencies, at least first, in high threat-level areas, such as Tawau and Semporna districts. In order to properly plan mitigation measures tsunami risk mapping should be intensified in high threat-level areas. The locations of settlements (including water villages), population concentrations, types of buildings and houses, road system, drainage system, harbours, jetties and vegetations (including mangroves) need to be mapped in great detail. Based on the detailed tsunami risk map, targeted vulnerable communities could be given continuous and intensive education and awareness on basic tsunami science and tsunami hazard preparedness.

Keywords: Tsunami assessment, tsunami threat, tsunami simulation, tsunami preparedness

INTRODUCTION

Tsunamis are waves caused by the sudden movement of the ocean surface due to earthquakes, landslides on the sea floor, land slumping into the ocean, large volcanic eruptions or meteorite impact in the ocean. However, most tsunamis are generated by earthquakes where there is subduction along tectonic plate boundaries. When the plates move past each other, they can tilt or displace large areas of the ocean floor, thus disturbing the ocean surface and generating tsunamis. Not all earthquakes, however, generate tsunami for it is usually those shallow earthquakes (less than 70 km depth) with a Richter magnitude exceeding 7.5 Mw that have produced destructive tsunami (ITIC, 2020). Tsunami arrive at a coastline as a series of successive crests (high water levels) and troughs (low water levels) - usually occurring 10 to 45 minutes apart. As they enter the shallow waters of coastlines, bays, or harbours, their speed and wavelength decrease, though their heights are considerably increased (Figure 1).



Depth (m)	Speed (km/h)	Wave Length (km)
7000	943	282
4000	713	213
2000	504	151
200	159	48
50	79	23
10	36	10.6

Figure 1: Tsunami wave propagation from deep to shallow waters. As it enters the shallow waters of coastlines, bays, or harbours, their speed and wavelength decreases, though their heights are considerably increased (based on ITIC, 2020).

Depending on the water depth and coastal configuration, the waves may also undergo extensive refraction. Tsunami waves may thus smash into the shore like a wall of water or move in as a fast-moving flood or tide - carrying everything in their path. Either way, the waves become a significant threat to life and property. If the tsunami arrives at high tide or if there are concurrent storm waves, the effects will be cumulative and the inundation and destruction even greater. The maximum height a tsunami reaches on shore is called the run-up and is the vertical distance between the maximum height reached by the water on shore and the mean sea level surface. Tsunami run-up at the point of impact will depend on how the energy is focused, the travel path of the tsunami waves, the coastal configuration, and the offshore topography (ITIC, 2020).

While the occurrence of tsunami cannot be prevented, their impact on human life and property can be reduced through proper planning. In this respect, assessment of potential tsunami threat to coastal areas are very useful as they provide a base on which early tsunami warning and evacuation systems can be developed. Since the destructive tsunami event on 26 December 2004 in the Indian Ocean, the Malaysian Government through the Malaysian Meteorology Department (MMD) has taken initiatives to equip the country and its people with better methods of advanced warning, coastal defence and creating awareness among the members of the public. One of the responses is the establishment of the Malaysian National Tsunami Early Warning System (MNTEWS), which comprises three major components; Monitoring and Detection, Data Processing and Data Dissemination (Malaysian Meteorological Department, 2013). Monitoring and detection involves the use of Seismic Network, Tide Gauge Network and Coastal Camera Network while the dissemination of warning is made electronically and also through announcements relayed by relevant agencies at the local level. In ensuring that this system can meet its objectives, the authorities carried out various awareness campaigns and simulation exercises with communities exposed to this threat.

This paper provides an overview of tsunami threat to the coastal areas of Sabah based on a synthesis of available literature on the current state of knowledge concerning potential tsunami threat. A review of the tectonic setting, historical earthquakes and historical tsunamis around Sabah as well as its coastal morphology and bathymetry is presented in order to appreciate how the tsunami threat is conceived. Some constraints in assessing tsunami hazard and future work to mitigate this hazard are also highlighted. It is hoped that some of these suggestions can be incorporated in the disaster risk reduction (DRR) program on tsunami hazard in Malaysia.

PLATE TECTONIC SETTING OF SABAH

Sabah is located on the semi-stable South China Sea and to a certain extent is influenced by the active mobile belts in Sulawesi and Philippines (Figure 2). The subduction zone along the Sulu Trench (ST) continues into East Sabah (Tongkul, 1991). Similarly the movement along the Palu-Koro Fault (PKF) in Sulawesi appears to affect Southeast Sabah (Rangin *et al.*, 1990). GPS measurements

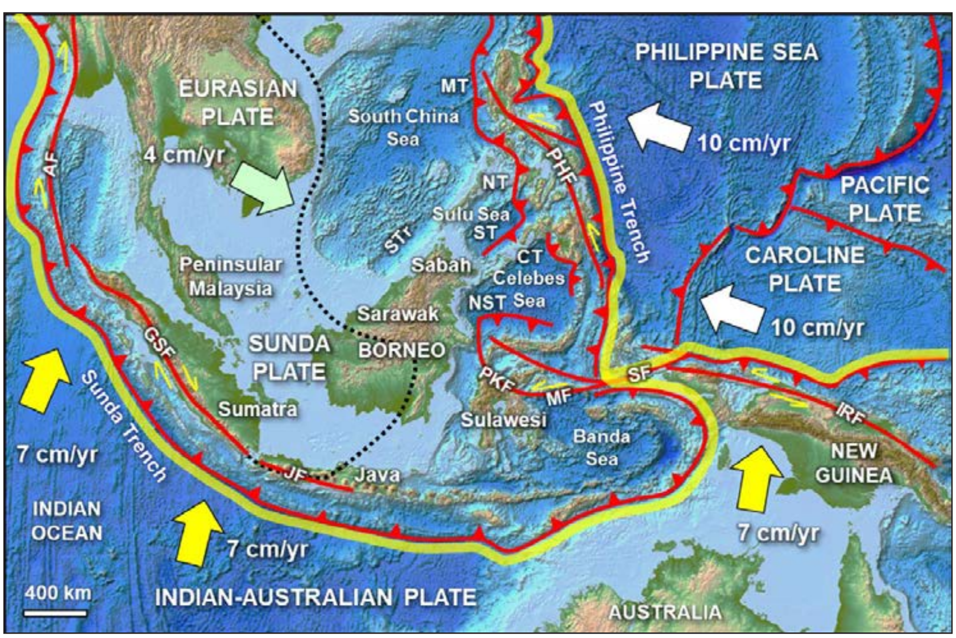


Figure 2: Sabah is surrounded by three major plate boundaries (thick yellow line). The Eurasian Plate is moving southeast (4 cm/yr) against the Philippine-Caroline-Pacific Plate which is moving relatively faster towards the west (10 cm/yr). The Indian-Australian Plate is moving northwards (7 cm/yr). MT: Manila Trench, NT: Negros Trench, ST: Sulu Trench, CT: Cotabato Trench, NST: North Sulawesi Trench, STr: Sabah Trough, PHF: Philippine Fault.

of movement across the Palu-Koro Fault showed 3.4 cm/yr left-lateral strike-slip movement (Walpersdorf *et al*., 1998). In the South China Sea, the Sabah Trough (STr) which was probably once associated with subduction zone is not seismically active. Active thrust faults found along the trough are probably associated with sedimentary loading and slumping or crustal shortening (Sapin *et al*., 2013; Hall, 2013; King *et al*., 2010; Hesse *et al*., 2009).

OCCURRENCE OF LARGE EARTHQUAKES AROUND SABAH

Earthquakes in the South China, Sulu and Celebes seas are sometimes felt as slight tremors in Sabah. The USGS earthquake databases shows a total of 90 shallow earthquakes (focal depth at less than 70 km) with magnitude larger than 7.0 (Mw) occurred within 1000 km from the coast of Sabah since 1900 (Figure 3). Based on earthquake databases from USGS, IRIS and NOAA a total of 38 earthquakes with magnitude more than 7 (Mw) are located within the South China, Sulu and Celebes seas (Table 1). The maximum earthquake magnitude recorded in the South China Sea, Sulu Sea and Celebes Sea are 8.4 (Mw), 8.3 (Mw) and 8.4 (Mw), respectively.

HISTORICAL TSUNAMIS AROUND SABAH

The main cause of tsunami in the Southeast Asian region is shallow earthquakes with magnitudes of more than 7 (Mw) produced by plate subduction and collision (Figure 4). Records of tsunami event from the National Geophysical Data Centre / World Data Service (NGDC/WDS) of the National Oceanic and Atmospheric Administration (NOAA) show that there are some 249 tsunami events in Indonesia and 92 such events in the Philippines. In the South China Sea eight tsunami events were recorded (1677, 1852, 1872, 1924, 1928, 1931, 1934 & 1994) along the Manila Trench (Figure 5). In Sulu Sea six tsunami events were recorded along the Negros Trench (1922, 1925, 1932 & 1948) and Sulu Trench (1897 & 1978). In Celebes Sea, there were at least 13 tsunami events recorded along the Cotabato Trench (1856, 1871, 1889, 1902, 1908, 1917, 1918, 1928, 1976 & 2002) and North Sulawesi Trench (1848, 1907, 1991 & 1996). The tsunamis are mostly generated by large earthquakes with minor occurrence of volcanic eruptions. Apart from the 2018 submarine landslide-generated tsunami in Sulawesi (Nakata *et al*., 2020), there is no other record of tsunami generated by submarine landslide in this region. A statistical study of historical tsunamis in the Philippines by Nakamura (1978) showed that the southern Mindanao area which includes the Sulu and Cotabato Trenches has the highest probability of tsunami occurrence, once in 10 years with waves reaching 7.8 m in height.

Three of the most devastating tsunamis occurred in the Sulu Sea and Celebes Sea in 1897, 1976 and 1996. The 21 August 1976 tsunami (9 m high) generated by 8.1 Mw earthquake in the Gulf of Moro resulted in the death of around 8000 people, injured 10,000 people and left about 90,000 people homeless. The 1 January 1996 tsunami (3.4 m high) generated by a 7.9 Mw earthquake north of Sulawesi killed 9 people, injured 63 people and destroyed 400 buildings. The 21 September 1897 tsunami (7 m high) generated by

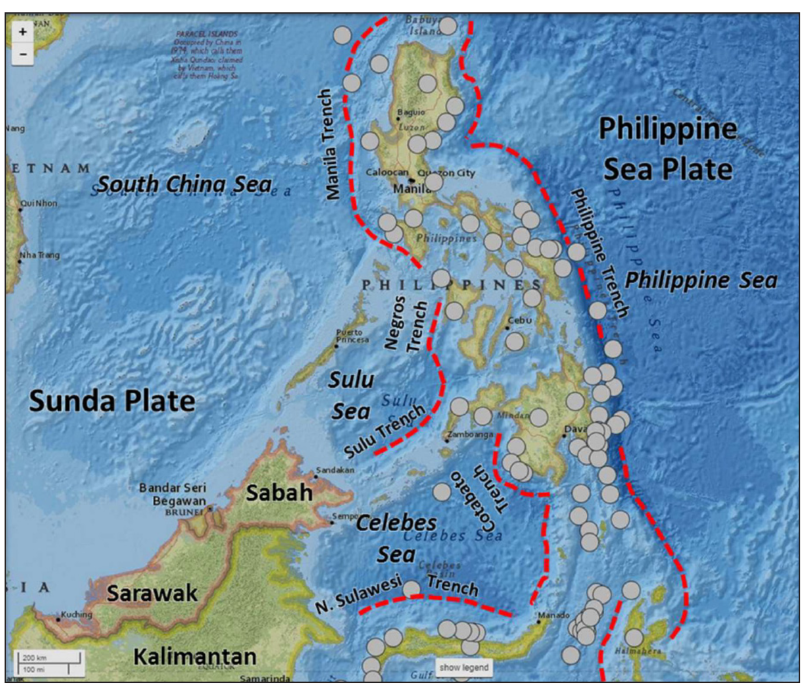


Figure 3: Distribution of shallow (focal depth less than 70 km) regional earthquakes (magnitude more than 7 Mw) along the active subduction zones of the Philippines and North Sulawesi, Indonesia. Earthquakes ploted from USGS Database (1900-2020).

Table 1: Shallow earthquakes (focal depth less than 70 km) with magnitude more than 7 Mw recorded in South China Sea, Sulu Sea and Celebes Sea. Some of the earthquakes triggered tsunamis. Data from USGS, IRIS and NOAA earthquake databases.

(a) Earthquake in South China Sea (Manila Trench)					
No	Date (UTC)	Magnitude (Mw)	Depth (km)	Location (latitude & longitude)	Tsunami Occurrence
1	1934-02-14	7.5	15.0	17.463, 119.199	Yes
2	1938-05-23	7.1	15.0	18.000, 120.045	Yes
3	1942-04-08	7.4	15.0	13.061, 120.483	-
4	1948-03-03	7.0	15.0	18.790, 118.915	-
5	1972-04-25	7.5	25.0	13.402. 120.275	Yes
6	1999-12-11	7.3	33.0	15.766, 119.740	-
7	2006-03-03	7.0	36.0	13.640, 120.150	-
8	2006-06-01	8.4	13.0	19.050, 120.880	-
(b) Earthquake in Sulu Sea (Negros and Sulu Trenches)					
1	1897-09-20	8.1	33.00	6.000, 122.000	Yes
2	1897-09-21	8.2	33.0	6.000, 122.000	Yes
3	1948-01-24	8.3	33.0	10.500, 122.00	Yes
4	1990-06-14	7.1	18.1	11.760, 121.899	-
5	2006-02-15	7.9	2.0	9.620, 121.950	-
(c) Earthquake in Celebes Sea (Cotabato and North Sulawesi Trenches)					
1	1902-08-21	7.3	33.0	7.500, 123.500	Yes
2	1905-01-12	8.4	90.0	1.000, 123.000	
3	1918-08-15	8.3	20.0	5.967, 124.377	Yes
4	1928-12-19	7.5	25.0	7.000, 124.000	Yes
5	1932-12-04	7.2	15.0	2.451, 121.005	-
6	1976-08-16	8.0	33.0	6.262, 124.023	Yes
7	1990-04-18	7.8	25.7	1.186, 122.857	-
8	1991-05-19	7.0	33.0	1.156, 122.957	-
9	1991-06-20	7.5	31.4	1.196, 122.787	-
10	1996-01-01	7.9	24.0	0.729, 119.931	Yes
11	1996-07-22	7.0	33.0	1.000, 120.450	-
12	1997-11-25	7.0	24.0	1.241, 122.536	-
13	1999-03-04	7.1	33.0	5.397, 121.937	-
14	2002-03-05	7.5	31.0	6.033, 124.249	Yes
15	2008-11-16	7.4	30.0	1.271, 122.091	Yes

8.2 Mw earthquake north of Zamboanga resulted in 13 deaths, 14 injuries and 33 houses destroyed.

Based on record from the Philippines (Bautista *et al*., 2006), the 21 September 1897 tsunami produced a 2 m high tsunami in east and north Sabah (Figure 6). This tsunami was also mentioned in the British North Borneo Herald (Anon, 1897). The following interesting letter is from Mr. Hastings, the Officer-in-Charge at Darvel Bay (18th Nov, 1897):

I forward the following particulars of an occurrence which must evidently be taken as having been caused by recent earthquake: The report comes to hand from Krani Salleh, Government clerk, Tunku (Tungku), and is as follows:

… Some rattan and gutta hunters return to Tunku and reported that the Ulu (head water of) Tunku River where a hill once stood is now flat and that several salt water springs have sprung up whether in place of the hill or in different places is uncertain. I asked the clerk to look up the guides, as I hope shortly to visit the places and ascertain the truth. The clerk states that, leaving Tunku at 6 am one can reach the salt springs by 6pm the same day.

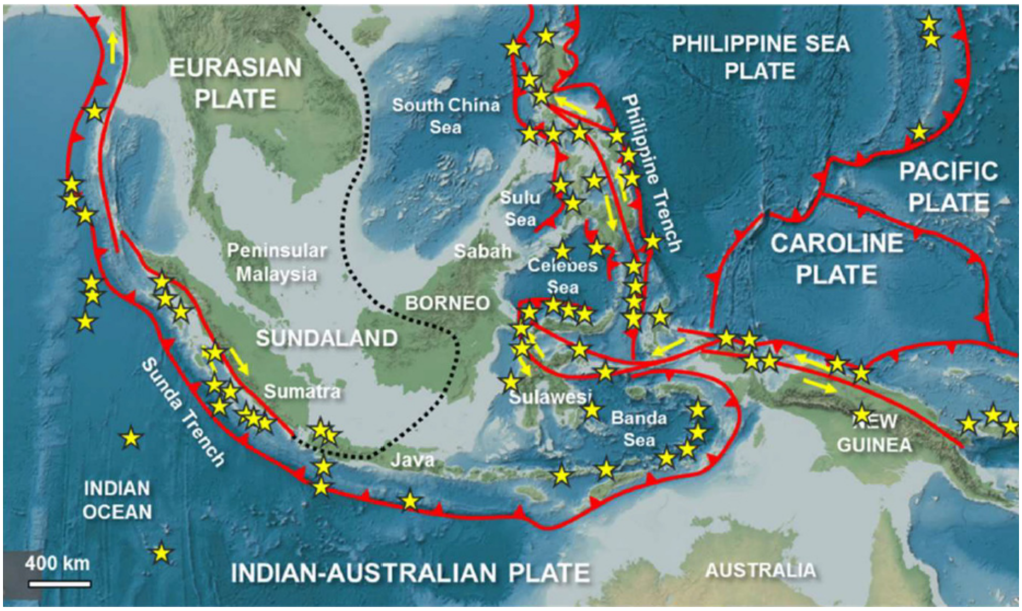


Figure 4: Distribution of tsunamis in Southeast Asia (from NCEI/WDS Global Historical Tsunami Database) which are closely associated with plate tectonic boundaries where large earthquakes (> 7 Mw) occurred.

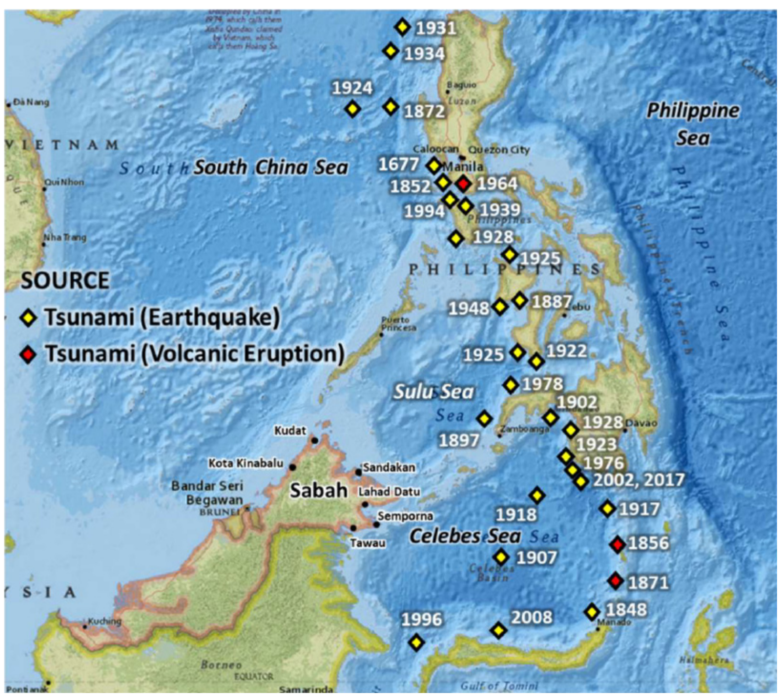


Figure 5: Historical tsunamis around Sabah due large earthquakes and volcanic eruptions in the Philippines and Indonesia during the last 200 years. Data from NCEI/WDS Global Historical Tsunami Database.

Ibrahim Salleh also states that the tidal wave visited Tunku some 8 to 10 feet high, washing through his house and doing considerable damage at Dungan; happily, no lives were lost.

Based on a report from Japan (Kumizi, 1984), the eastern part of Sabah, specifically Labuk area was hit by a 2 m high tsunami during the 15 August 1918 tsunami, following an 8.3 Mw earthquake in the Celebes Sea (see Figure 5). The tsunami, up to 7.2 m in height resulted in 52 deaths in the Philippines (Mindanao) and also affected the north coast of Sulawesi, Indonesia.

The most recent tsunami in the Celebes Sea occurred on the 29 April 2017 generated by magnitude Mw 6.8 earthquake from the Cotabato Trench. This tsunami which occurred at 4.23 in the morning with a maximum wave height of 0.2 m (PHILVOCS, 2017) was felt in southeast Sabah. According to a local newspaper, the sea level at the fish landing jetty in Kg. Pangkalan, Kunak rose up to the knee early Saturday morning on 29 April 2017 (Anon, 2017). Tsunami simulations by Tohoku University estimated the arrival of this tsunami in Sabah occurred 2 hours after the earthquake event, around 6.30 in the morning (Figure 7).

REVIEW OF TSUNAMI STUDIES AND SIMULATIONS IN SABAH

Following the destructive 2004 Tsunami event in the Indian Ocean, several studies on the threat of tsunami on the coastal areas of Sabah were carried out. Some of the key findings of these studies are presented here.

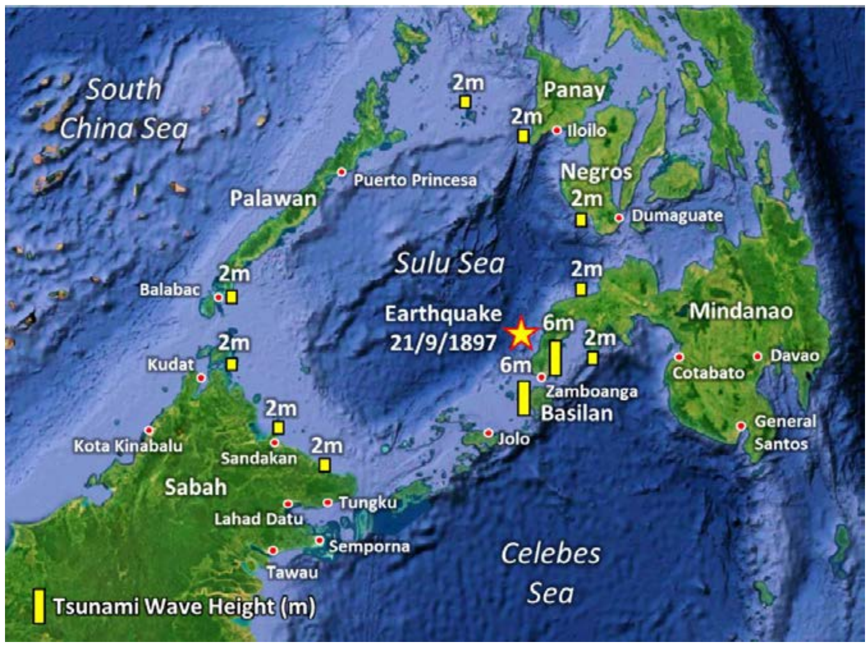


Figure 6: About 2 m high tsunami affected the coast of East Sabah during the 9 September 1897 earthquake in the Philippines (based on Bautista *et al.*, 2006).

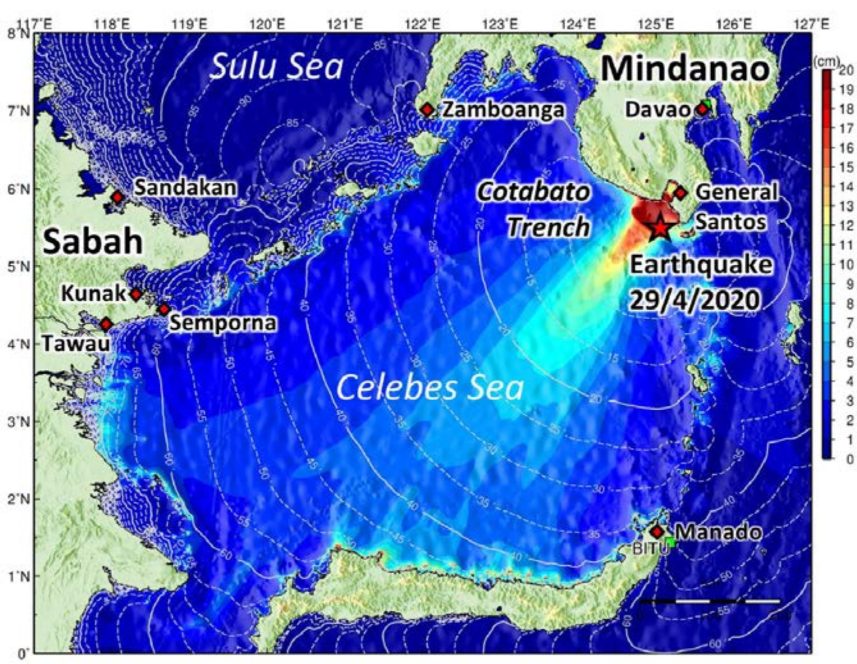


Figure 7: Simulation of the 29 April 2017 tsunami caused by magnitude 6.8 Mw earthquake from the Cotabato Trench, Philippines. The tsunami waves took about 2 hours to arrive in Sabah. Image provided by Bruno Adriano from the International Research Institute of Disaster Science (IRIDS), Tohoku University, Japan immediately after the tsunami event.

Based on regional tectonic setting and a review of historical data on earthquakes and tsunami, Raj (2007) concluded that there is no threat from local tsunami to the coastal areas of Sabah fronted by the South China Sea in the west, Sulu Sea in the northeast and east and Celebes Sea in the southeast. Distant tsunamis from Manila, Negros, Cotabato and North Sulawesi trenches will have insignificant run-ups (<0.5 m) except for areas in the Dent and Semporna Peninsulas which have significant run-ups (>0.5 m). This is primarily due to the relatively wide continental shelf surrounding Sabah. Tongkul *et al.* (2015) carried out paleo-tsunami studies on 13 sites along the coast of east and southeast Sabah, but did not find any potential tsunami deposits. While this study also did not identify tsunami deposits, it does not mean that tsunami waves did not affect Sabah. The limited number of sites investigated may have missed tsunami deposits.

Tsunami simulations in the Sulu Sea generated by earthquakes from the Sulu Trench (Tongkul *et al*., 2009; Aziz, 2012; Nurashid *et al*., 2013; Mardi *et al*., 2017) shows a range of values of tsunami wave heights arriving in Sabah (Table 2). The tsunami wave heights generally correspond to the magnitude of earthquakes used in the simulation. Near Sandakan, a magnitude 8.1 Mw earthquake produces tsunami wave height of less than a metre, whereas a magnitude 8.5 Mw earthquake produces up to 2.2 m tsunami wave height and 2.78 m tsunami run-up height. The arrival time of tsunami waves near Sandakan is about 100 minutes. This arrival time is not affected by the magnitude of earthquake. Large earthquake with magnitude 9 Mw produces tsunami wave heights up to 10.5 m. However, it must be noted that the future occurrence of magnitude larger than 8.5 Mw in this region is quite remote based on its tectonic setting and past earthquake record.

Tsunami simulations in the Celebes Sea generated by earthquakes from the North Sulawesi Trench and Cotabato Trench (Tongkul *et al*., 2009; Ahmad Khairut *et al*., 2019) also shows a range of values of tsunami wave heights arriving in Sabah (Table 3). Near Tawau, a magnitude 8.1 Mw earthquake from the North Sulawesi Trench produces tsunami wave height of about 1.3 m. The tsunami wave height increase to about 3 m when the magnitude of earthquake is increased to 8.4 Mw. A magnitude 9.5 Mw earthquake produces up to 5 m tsunami wave height. The arrival time of tsunami waves is about 50 minutes and does not change very much with increase in earthquake magnitude. A magnitude

Table 2: Summary of tsunami simulations results in the Sulu Sea.

No	Researchers	Modelling Code	Tsunami Source	Magnitude (Mw)	Earliest Tsunami Arrival Time (min)	Maximum Tsunami Wave Height (m)	Maximum Tsunami Run-Up Height (m)
1	Tongkul *et al*., 2009	TUNAMI-N2	Sulu Trench	8.1	100 (Near Sandakan)	0.8	-
2	Aziz, 2012	TUNAMI-N2	Sulu Trench	8.3	100 (Near Sandakan)	0.73	-
3	Nurashid *et al.*, 2013	TUNAMI-N2	Sulu Trench	8.2 8.5 8.8	90 (Near Sandakan)	1.0 2.2 3.8	1.36 2.78 4.75
4	Mardi *et al.*, 2017	TUNA-M2	Sulu Trench	8.0 8.5 9.0	33 (Offshore Sandakan)	0.3 1.8 10.5	- - -

Table 3: Summary of tsunami simulations results in the Celebes Sea.

No	Researchers	Modelling Code	Tsunami Source	Magnitude (Mw)	Earliest Tsunami Arrival Time (min)	Maximum Tsunami Wave Height (m)	Maximum Tsunami Run-Up Height (m)
1	Tongkul *et al.*, 2009; Tongkul & Saleh, 2010	TUNAMI-N2	North Sulawesi Trench	8.0 8.2 8.4	50 (Near Tawau)	1.3 2.0 3.0	- - -
			Cotabato Trench	8.0 8.2 8.4	80 (Near Tawau)	0.8 1.0 1.2	- - -
2	Ahmad Khairut *et al.*, 2019	TUNAMI-N2	North Sulawesi Trench	9.5	60 (Near Tawau)	5.0	-
			Cotabato Trench	9.5	80 (Near Tawau)	2.0	-

8.1 Mw earthquake from the Cotabato Trench produces tsunami wave height of about 0.8 m whereas a magnitude 9.5 produces 2 m. It must be noted that the probability of a magnitude 9.5 Mw in this region is unrealistic based on its tectonic setting and past earthquake record.

Tsunami simulations in the South China Sea generated by earthquakes from the Manila Trench and from the Brunei Slide (Okal *et al.*, 2010; Teh *et al.*, 2011; Mardi *et al.*, 2015, 2017; Koh *et al.*, 2016 & Tan *et al.*, 2017) shows a huge contrast in values of tsunami wave heights arriving in Sabah (Table 4). Tsunami waves generated by magnitude 8.5 Mw earthquakes from the Manila Trench produces less than a metre tsunami wave height offshore Kudat. Suppasri *et al.* (2012), who also carried out tsunami simulations from a source along the Manila trench pointed out that Sabah is quite safe because it is located at shallow sea depth. The extremely high tsunami wave height (5.3 m) produced by magnitude 9 Mw earthquake (Mardi *et al.*, 2017) is uncertain. The tsunami wave heights produced by the Brunei Slide (Gee *et al.*, 2007) ranges from 5 to 19 metres in Sabah. The simulated high waves hitting west Sabah should be taken with caution considering that the parameters used for the giant landslide modelling may not be geologically realistic (Madon, 2018).

BATHYMETRY AND COASTAL MORPHOLOGY OF SABAH

Sabah is surrounded by shallow continental shelf and deep oceanic seas, reaching up to 6000 m in water depth. The 200-m water depth marking the continental shelf edge shows variable width. In the South China Sea and Sulu Sea the continental shelf is quite wide, with the edge located around 80-100 km offshore (Figure 8). Further south, however, towards Tungku and Darvel Bay the shelf becomes narrower with its edge located around 20 km offshore. In the Celebes Sea the continental shelf is narrow located around 30 km offshore Tawau and Semporna areas. The distance from the shoreline to the 2000-m isobath marking the deep ocean regions also varies. In the Sulu Sea the deep ocean is located quite a distant away from the shoreline, around 150 km offshore, whereas in the Celebes Sea the deep ocean is only about 50 km from the shoreline. The water depth near the coast ranges in depth from 5-20 m only. Near Kota Kinabalu, Kota Belud, Kudat, Sandakan, Lahad Datu and Kunak, water depth less than 20 m extends several kilometres seaward. Near Semporna, where numerous coral islands occur, the water depth is much shallower (2-5 m).

Sabah has a long coastline stretching from Sipitang in the southwest to Kudat in the north, Sandakan in the east and Tawau in the southeast. The coastline is quite irregular with the occurrence of several bays, estuaries, islands and headlands. The most prominent bays are the Brunei Bay in southwest Sabah, Kimanis Bay in west Sabah, Marudu Bay in north Sabah, Paitan Bay in northeast Sabah, Labuk Bay in east Sabah, Darvel Bay in Lahad Datu and Cowie Bay in Tawau. Grouped around Semporna Peninsula coast are several islands, the largest of which are Pulau Timbun Mata and Pulau Bum-Bum. Both erosional and depositional landform are present. Erosional landform is characterised by rocky coastlines, sea cliffs and sea caves. Depositional landforms are characterized by beaches that occur as pockets in between the rocky headlands. The beaches are mostly narrow with gentle gradients. Mangroves occur in river estuaries and bays (Figure 9).

The major town area mostly sits on low lying coastal plain in front of hilly areas. Some of the coastal plains are narrow (e.g. Kota Kinabalu, Sandakan, Lahad Datu) whereas some are quite wide (e.g. Kudat, Kota Marudu, Kunak, Semporna, Tawau). Apart from shops, hotels and housing buildings, most settlements along the coast of Sabah comprise water villages, where houses are built on stilts (Figure 10). Some of the prominent water villages occur

Table 4: Summary of tsunami simulation results in the South China Sea.

No	Researchers	Modelling Code	Tsunami Source	Magnitude (Mw)	Earliest Tsunami Arrival Time (min)	Maximum Tsunami Wave Height (m)	Maximum Tsunami Run-Up (m)
1	Teh *et al.*, 2011	TUNA	Manila Trench	9.0	140 (Offshore Kudat)	0.4	-
2	Basri *et al.*, 2013	TUNAMI-N2	Manila Trench	8.6	150 (Kudat Airport)	0.8	0.9
3	Mardi *et al.*, 2017	TUNA-M2	Manila Trench	8.0 8.5 9.0	120 (Offshore Kudat)	0.16 0.9 5.3	- - -
4	Okal *et al.*, 2010	MOST	Brunei Slide	-	-	5	-
5	Koh *et al.*, 2016	TUNA-M2	Brunei Slide	4 degrees slope	24 (Kudat) 55 (Penampang)	11.2 18.9	- -
6	Tan *et al.*, 2017	TUNA	Brunei Slide	4 degrees slope	24 (Kudat) 54 (Kota Kinabalu)	11.0 19.0	20.3 26.1

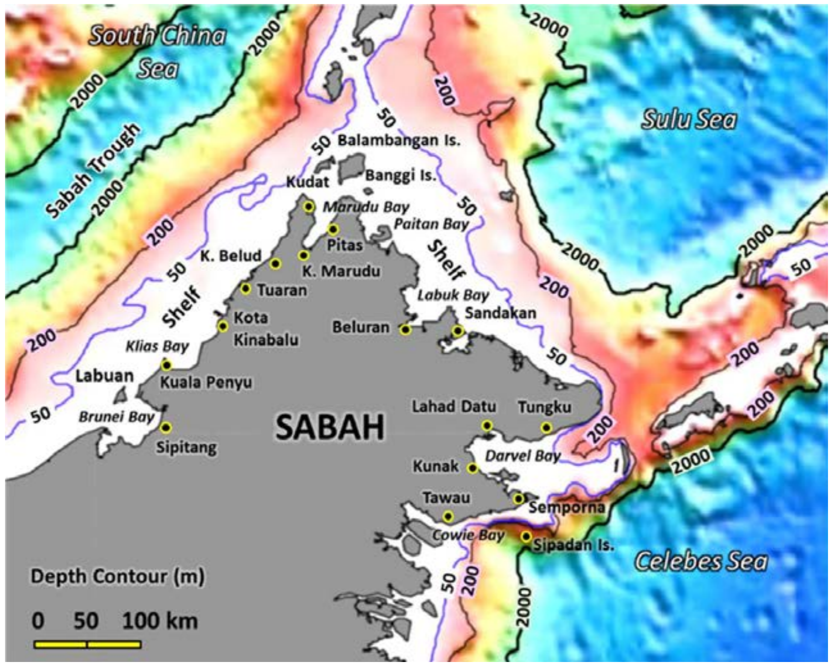


Figure 8: Coastal morphology and bathymetry of Sabah. Note the wide continental shelf around Sabah except in Tungku, Semporna and Tawau areas.

Figure 9: Coastline of Sabah comprised diverse coastal features: (a) steep cliff, (b) rocky coastline, (c) sandy beach, (d) mangrove flats.

Figure 10: Water villages in Sabah, (a) Kg. Tinosa, Sandakan, (b) Kg. Sim-sim, Sandakan, (c) Kg. Pasir Putih, Tawau, (d) Kg. Titingan, Tawau.

in Sandakan town area (e.g. Kg. Tinosa, Kg. Sim-sim, Kg. Bokara, Kg. Pelabuhan, Kg. BDC at Sim-sim, Kg. Bahagia, Kg. Sundang, Kg. Istimewa, Kg. Lupak Meluas, K. Forest, Kg. Muhibbah and Kg. Sentosa Jaya), Lahad Datu town area (e.g. Kg. Tabanak, Kg. Sabah Baru), Semporna town area (Kg. Bangau-Bangau, Kg. Sri Jaya, Kg. Balimbang) and Tawau town area (Kg. Hidayat, Kg. Titingan, Kg. Pukat and Kg. Pasir Putih).

SOURCES OF TSUNAMI THREAT IN SABAH

The main source of tsunami threat comes from large earthquakes (>8.0 Mw) located along the Manila Trench (MT) in the South China Sea, the Negros Trend (NT) and Sulu Trenches (ST) in the Sulu Sea, and the Cotabato Trench (CT), Shangihe Trench (ShT) and North Sulawesi Trench (NST) in the Celebes Sea (Figure 11). The earthquake record shows that large earthquakes with magnitude up to 8.4 Mw have occurred in these trenches. Minor tsunami threat may also come from potential giant submarine landslides along the edge of the continental shelf in the Sabah Trough (STr) off western Sabah.

LEVEL OF TSUNAMI THREAT IN SABAH

Based on the tectonic and geological setting, historical tsunamis and the results of several tsunami simulations reviewed earlier, the relative level of threat to the coastal areas in Sabah can be assessed. The tsunami threat in west coast of Sabah is considered low where tsunami waves originating from the Manila Trench due to magnitude 8.4 Mw earthquake is predicted to arrive near the coast after 2 to 2.5 hours with wave heights of less than a metre (Figure 12). The long distant source and wide continental shelf fronting west Sabah described earlier, result in the drastic reduction of speed and strength of the incoming tsunami waves, thus making them less impactful. The likelihood of occurrence for a giant submarine landslide-triggered tsunami is also extremely low. The tsunami threat in north and east Sabah is considered moderate whereby tsunami waves originating from the Sulu Trench due to magnitude 8.4 Mw earthquake is predicted to arrive near the coast after one hour, with wave height of between 1.5 and 2 m. Although the continental shelf is quite wide, the proximity to the potential tsunami source is of concern here. In southeast Sabah, tsunami waves originating from the North Sulawesi Trench due to magnitude 8.4 Mw earthquake is predicted to arrive at the coast just after 40 minutes of generation, with wave height up to 3 m. The narrow continental shelf in this area and its proximity to the tsunami source makes the southeast part of Sabah a region with the highest level of threat. The level of threat in east and southeast Sabah correlates with the tsunami hazard map for eastern Indonesia and southern Philippines (Figure 13) produced by Løvholt, *et al*. (2011).

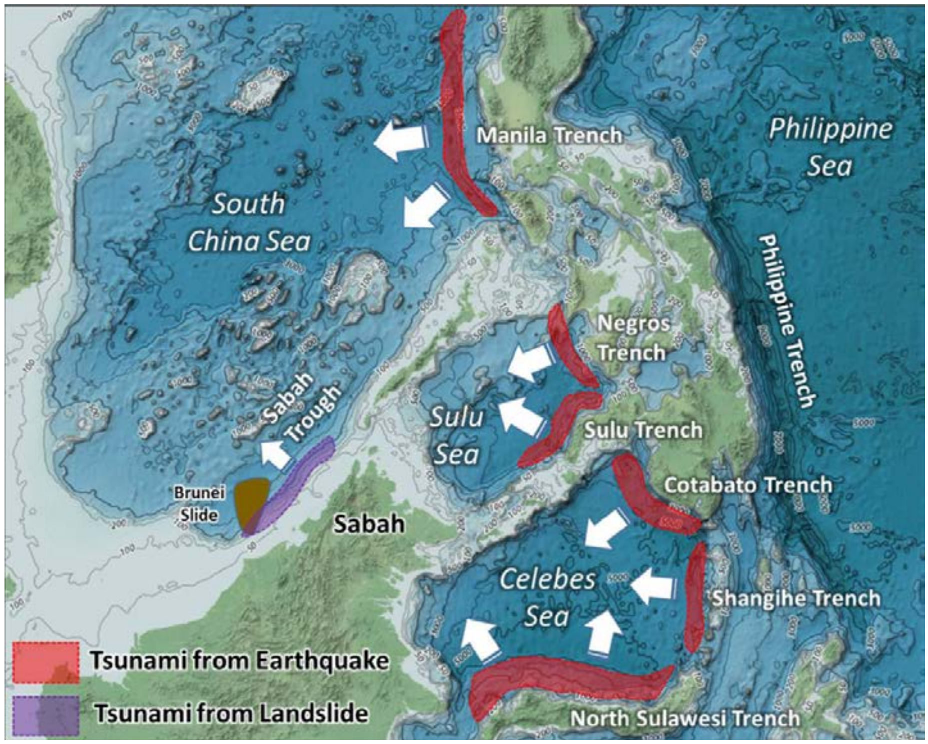


Figure 11: Potential distant sources of tsunami for Sabah, generated by large earthquakes (magnitude Mw >8.0) in the South China Sea, Sulu Sea and Celebes Sea.

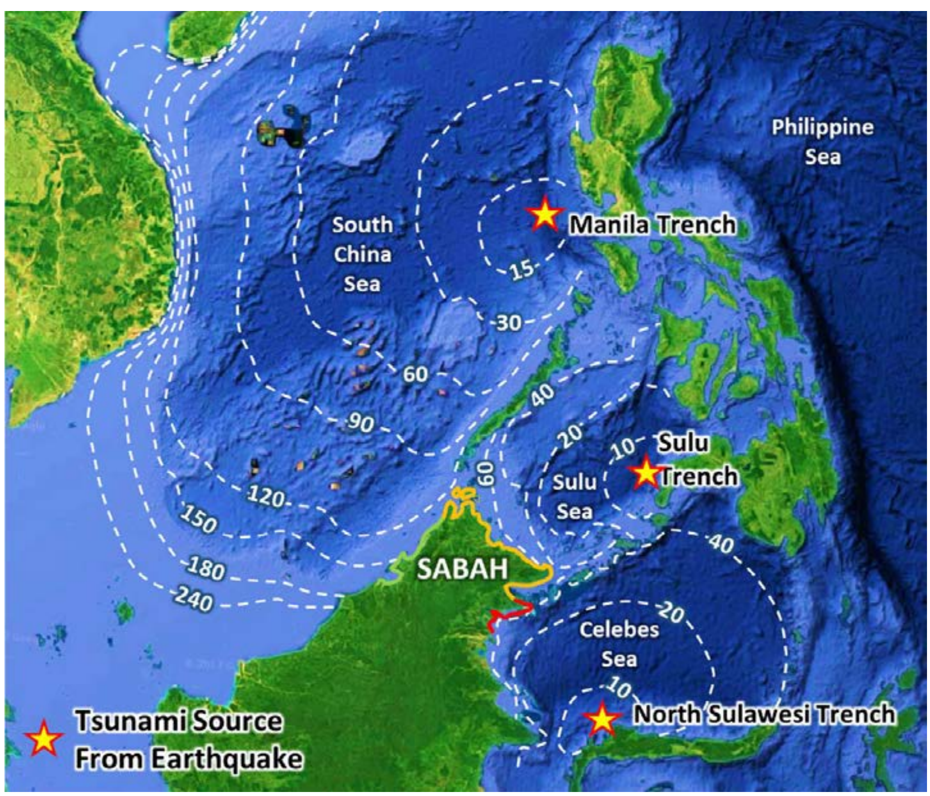


Figure 12: Simulation of tsunamis generated by magnitude 8.4 Mw from the Manila, Sulu and North Sulawesi trenches shows that all of Sabah's coast face tsunami threats. However, the level of threats varies. Tsunami waves arrives at the coast between 40-120 minutes with wave height between 1-3 meters. Level of threat are shown in green (low) in west Sabah, orange (moderate) in north and east Sabah, and red (high) in southeast Sabah.

TSUNAMI THREAT IN TAWAU AND SEMPORNA DISTRICTS

The coastal area around Tawau and Semporna face the highest levels of threat for tsunamis generated by large earthquake (8.4 Mw) from the North Sulawesi Trench. The continental shelf is rather narrow, between 10-20 km only. The narrow shelf will have limited dissipating impact on incoming tsunami waves. Tawau area is also more exposed to the open sea compared to Semporna which is partially sheltered by numerous small islands such as Sipadan, Ligitan, Dinawan, Mabul, Menampilik, Nusa Tengah, Sipanggau and Karindingan islands (Figure 14). The narrow Cowie Bay between Tawau City and Sebatik Island will have the effect by concentrating the tsunami wave power and may result in waves much higher than the predicted 3 m tsunami waves near the coast. The tsunami wave is expected to have adverse impact on coastal settlements, mostly water villages in Tawau area (Figure 15). In Semporna, the strength of the incoming tsunami wave is also expected to be amplified as it enters the strait between Semporna Town area and Bum Bum Island (Figure 16).

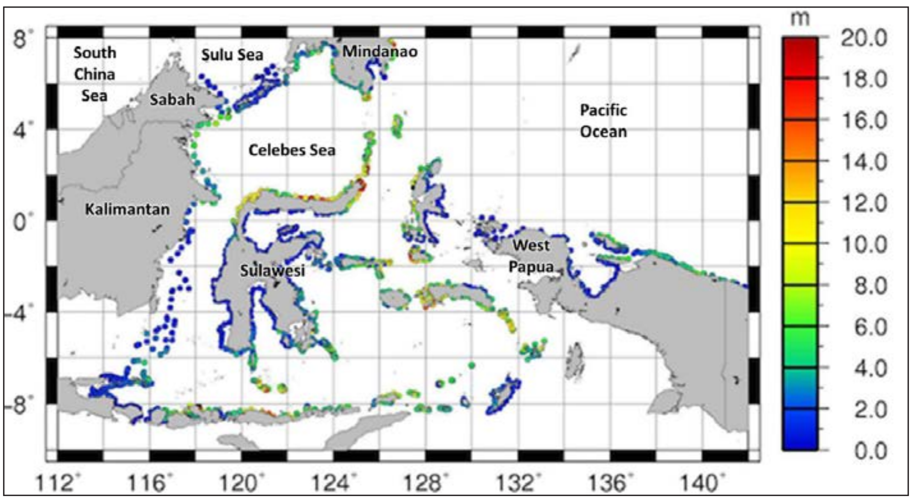


Figure 13: Merged tsunami hazard map for eastern Indonesia and southern Philippines (from Løvholt, *et al*., 2012). The area around southeast Sabah shows tsunami wave heights around 4 metres indicating a high level of tsunami threat in this region.

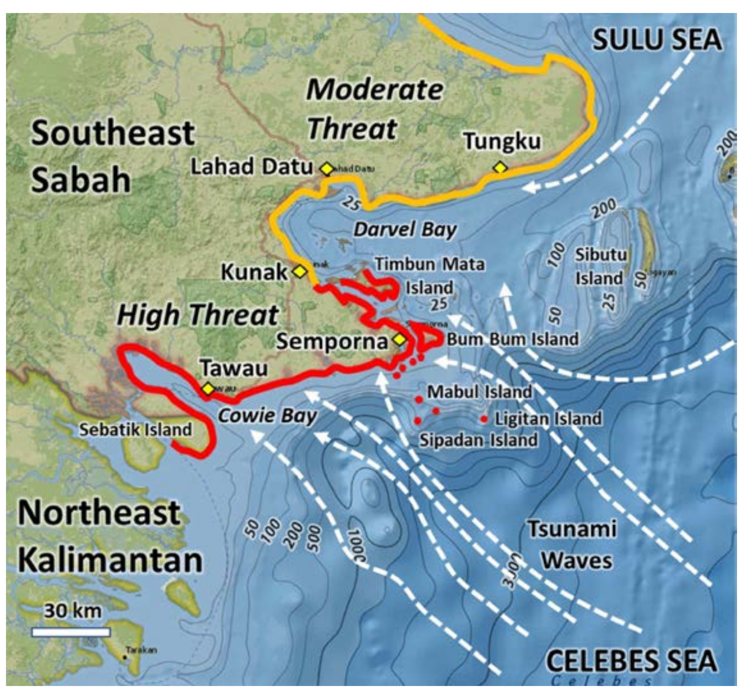


Figure 14: Possible tsunami pathways towards southeast Sabah. Tawau is directly exposed to tsunami waves from North Sulawesi. The small islands off-Semporna are also directly exposed (e.g. Sipadan, Ligitan and Mabul Islands). These islands provide partial protection to Semporna. Kunak is protected by Timbun Mata Island whereas Lahad Datu is protected by the shallow Darvel Bay. Level of threat shown in red (high) for Tawau and Semporna, and orange (moderate) for Kunak and Lahad Datu.

CONSTRAINTS IN ASSESSING TSUNAMI THREATS IN SABAH

Tsunami threat are usually assessed using tsunami simulation models. However, if the parameters used in the simulations are unrealistic, then the results are meaningless. One of the key constraints in producing a reliable tsunami numerical model in Sabah is the lack of high-resolution topographic and bathymetric data along the coastline. Most of the available tsunami simulations reviewed earlier use the regional bathymetric data from the General Bathymetric Chart of the Ocean (GEBCO) and local bathymetry from the nautical charts, whereas the topography data are from the 30-m resolution Shuttle Radar Topographic Mission (SRTM) and from 5-m resolution Interferometric Synthetic Aperture Radar (IFSAR). Available topographic maps and digital model (DTM and DSM) are too coarse (10 m contour intervals) and the nautical charts are at different scales, incomplete, mostly outdated (made in 1940's, 1960's, 1970's and 1980's) and limited to the deeper part of the sea. A lot of work is required to use the nautical charts to obtain a good representation of the coral reefs. Pederson *et al.* (2010) clearly pointed out this problem as one of the modelling challenges they faced. Therefore, at best, the present tsunami inundation models in Sabah only provide a general idea of the potential threat. Detailed and accurate bathymetry data at shallower regions and near

Figure 15: Low lying and densely populated coastal area in Tawau Town area. Numerous water villages (e.g. Kg. Pasir Putih, Kg. Pukat, Kg. Titingan, Kg. Hidayat) located along the coast. Tsunami waves amplified as it enters the Cowie Bay.

Figure 16: Low lying and densely populated coastal area in Semporna Town area. Numerous water villages (e.g. Kg. Bangau-Bangau, Kg. Sri Jaya, Kg. Balimbang) located along the coast. Tsunami waves amplified as it enters the Semporna Strait.

the coast are important to obtain reliable and much better results for tsunami computations such as tsunami wave heights, travel time, inundation height and run-up distance. Accurate representation of inland vegetation and structures such as buildings, roads and drains may also produce better computation results in terms of the tsunami inundation height and distribution.

FUTURE WORK

In order to properly identify and quantify the threat of tsunamis in Sabah, continuous improvement in tsunami propagation and inundation modelling should be carried out using more realistic tsunami source parameters and higher resolution bathymetry and topography. It would be helpful if high-resolution data on topography (e.g. using LiDAR or drones) and bathymetric data were acquired by the relevant government agencies (e.g. JUPEM, JLM), as a priority at least, in the high threat-level areas, such as Tawau and Semporna. These data could then be made available to researchers for use in various other types of study. Expertise on this specialised field of study in local institutions should be strengthened and researchers should be encouraged to work together.

In order to properly plan mitigation measures (e.g. appropriately located evacuation routes, evacuation centres, sirens, signages) tsunami risk mapping should be intensified in high threat-level areas. The locations of settlements (including water villages), population concentrations, types of buildings and houses, road system, drainage system, harbours, jetties and vegetations (including mangroves) should be mapped in great detail. Again, this is where availability of modern high-resolution topographic map is very useful. Based on the detailed tsunami risk map, targeted vulnerable communities (including young people) could be given continuous and intensive education and awareness on basic tsunami science and tsunami hazard preparedness. Where possible, mangroves should be conserved and where they are already destroyed, they should be re-established in strategic areas, as a natural defence for incoming tsunami waves.

CONCLUDING REMARKS

Although no significant recent tsunamis have occurred in Sabah, the threat of earthquake-generated tsunami is real, based on historical tsunami records. The threat is highest in the coastal area of east Sabah, especially around Tawau and Semporna Districts. More attention should be given to these areas. While tsunamis cannot be prevented, the levels of risk can be reduced or eliminated with proper understanding of how tsunamis interact with the surroundings. Detailed tsunami inundation modelling and mapping of high-risk areas are urgently needed. Current tsunami hazard preparedness is quite low among coastal communities and needs to be addressed urgently by the relevant agencies or NGOs.

ACKNOWLEDGEMENTS

We would like to thank Universiti Malaysia Sabah for providing logistic support for this research. This study was made possible with financial support from the Malaysian Ministry of Science and Innovation (SCF0015-SEA-2006 & SCF0079-SEA-2012) and Universiti Malaysia Sabah (STD0008). We would also like to thank the two reviewers for their constructive comments on the paper.

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Manuscript received 12 June 2020
Revised manuscript received 8 July 2020
Manuscript accepted 13 July 2020