Post-event Field Survey of 28 September 2018 Sulawesi Earthquake and Tsunami

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Abstract. An earthquake with a magnitude of M_W = 7.5 that occurred in Sulawesi, Indonesia on September 28, 2018, triggered liquefaction and tsunamis that caused severe damage and many casualties. This paper reports the results of a post-tsunami field survey conducted by a team with members from Indonesia and Taiwan that began 13 days after the earthquake. The main purpose of this survey was to measure the runup of tsunami waves and inundation and observe the damage caused by the tsunami. Measurements were made in 18 selected sites, most in Palu Bay. The survey results show that the runup height and inundation distance reached 10.7 m in Tondo and 488 m in layana respectively. The arrival times of the tsunami waves were quite short and different for each site, typically about 3-8 minutes from the time of the main earthquake event. This study also describes the damage to buildings and infrastructures, and coastal landslides.

1 Introduction

On Friday, September 28, 2018, at 18:02:44 Central Indonesia Time (UTC + 8), Palu Bay was hit by a strong earthquake with magnitude M_W = 7.5. The epicenter was located at -0.22°N 119.85°E at a depth of 10 km and 27 km northeast of Donggala City (BMKG, 2018). The major phenomena following the earthquake were liquefaction and tsunamis. As of October 21, 2018, as many as 2,113 people were killed, 1,309 missing, and 4,612 injured (Hadi and Kurniawati, 2018). The source of the earthquake was the shift of the Palu-Koro strike-slip fault, one of the most active structures around Sulawesi island. After the earthquake, a series of tsunami waves hit Palu City and Donggala Regency. Low-amplitude tsunami waves were also detected in Mamuju, a city overlooking the Makassar Strait and outside Palu Bay. The tsunami hit the coast, leveled houses, washed away various objects and destroyed the coastal area of Palu Bay, Central Sulawesi Province.

Within the territory controlled by Indonesian authorities, the 2018 Sulawesi Tsunami was the most devastating since the 2004 Indian Ocean Tsunami. There were 8 tsunami events after the December 26, 2004 Indian Ocean Tsunami, namely 2005 Nias (M_W = 8.6;1,314 victims), 2006 Buru Island (M_W = 6.7; 4 victims), 2006 Java (M_W = 7.7; 668 victims), 2007 Bengkulu (M_W = 8.4; 23 victims), 2009 Manokwari (M_W = 7.6; 4 victims), 2009 Tasikmalaya (M_W = 7.3;79 victims), 2010 Mentawai (M_W = 7.8; 413 victims), and 2018 Sulawesi (M_W = 7.5;2,113 victims). These tsunami events are distributed in tsunami zones that cover all parts of Indonesia except Kalimantan island. Refering to the tsunami catalog and zones in Indonesia (Latief et al., 2000), the 2018 tsunami was on the border between zone D, which includes the Makassar Strait, and zone E, which includes the Maluku Sea. Zones D and E accounted for 9% and 31%, respectively, of the total tsunami events in Indonesia between 1600 and 2000. The Palu-Koro fault where the 2018 tsunami occurred is a very active source of earthquakes and tsunamis in zones D and E. The movement of rock formations is 35-44 mm/year (Bellier et al., 2001). The Sulawesi region has a long history of earthquakes and tsunamis (Prasetya et al., 2001). On January 30, 1930, an earthquake occurred on the West Coast of Donggala that caused a tsunami with a height of 8-10 m, 200 deaths, 790 houses damaged, and the flooding of all villages on the west coast of Donggala. On January 1, 1996, an earthquake in the Makassar Strait caused a tsunami that swept the west coast of Donggala and Toli-Toli Districts. In the same year, an earthquake occurred in Bangkir Village, Tonggolobibi, and Donggala, causing a 3.4-m-high tsunami that carried sea water 300 m inland, 9 people were killed and buildings in the three locations were badly damaged. On October 11, 1998, another earthquake occurred in Donggala, severely damaging hundreds of buildings. In 2005 and 2008, earthquakes also occurred, but did not cause many casualties. The most recent earthquake occurred in Sigi Regency and Parigi Moutong Regency in August 2012, which left 8 people dead.

The disaster area of the September 2018 tsunami includes Palu Bay, a bay on Sulawesi island, and Central Sulawesi Province. This bay has a length of 30 km, a width of 7 km, and a maximum depth of 700 m. Although the epicenter was at the outer boundary of Palu Bay, the most severe damage suffered in Palu City was at the end of the bay, about 70 km from the epicenter. Palu City, the capital of Central Sulawesi Province, has a population of 379,782 (BPS-Statistics of Palu Municipality, 2018). Most of the victims came from this city. In addition to Palu City, the disaster area also included Donggala Regency, with a population of 299,174 (BPS-Statistics of Donggala Regency, 2018), and Sigi District, with a population of 234,588 (BPS-Statistics of Sigi Regency, 2018). Sigi Regency did not suffer damage from the tsunami, but large-scale liquefaction led to a significant number of deaths and disappearances in this area.

This disaster in Central Sulawesi has surprised scientific community. For a strike-slip fault, the plates move horizontally and thus do not usually cause enough vertical deformation to trigger a huge tsunami. It is still in discuss whether the tsunami caused by co-seismic deformation or non-tectonic sources. Ulrich et al. (2019) assume that a source related to earthquake displacements is probable and that landsliding may not have been the primary source of the tsunami. On the contrary, Takagi et al. (2019), Sassa and Takagawa (2018), Arikawa et al. (2018) tend to assume that landslides produced the tsunami. Field surveys play an important role to support seeking answer for question arised.

The focus of post-tsunami surveys depends on the data of interest (e.g., hydrodynamic, geological, geophysical, environmental, ecological, social, or economic). The field survey reported in the present study focuses on hydrodynamic data that includes measurements of runup height and inundation distance. Tsunami flow depth on land was also measured in some sites. In addition, tsunami arrival time was analyzed and observation of buildings and infrastructures damage was conducted. The data can be used for the simulation of tsunamis caused by plate movements or underwater landslides. For instance, Lynett et.al (2003) employed the field survey data of the 1998 Papua New Guinea tsunami as validation for a numerical model, i.e. Boussinesq model and a nonlinear shallow water wave model. Yalciner (2001) conducted field survey and modeling of the 1999 Izmit tsunami which the location had similarity in geographycal feature, earthquake magnitude and tsunami mechanism with recent Sulawesi case. More broadly, these data can be used for disaster mitigation and rebuilding of the affected areas by the 2018 Sulawesi Tsunami.

Many groups have carried out field surveys of the Sulawesi tsunami event or also known as Palu tsunami. Muhari et al. (2018) investigated wave height and inundation depth at several points with a focus around the end of the bay. A UNESCO international tsunami survey team surveyed 125 km of coastline along the Palu Bay up to the earthquake epicentre region. The team performed 78 tsunami runup and inundation height measurements throughout the surveyed coastline (Omira et al., 2019; Yalciner et al., 2018). Putra et al (2019) focus more on tsunami deposits. Meanwhile, Arikawa et al. (2018), Sassa and Takagawa (2018), and Takagi et al. (2019) each conducted a survey related to coastal subsidence, coastal liquefaction or submarine landslide detected in Palu Bay. This survey data can be combined with data from other groups, especially we contribute to provide data of runup height, inundation distance, flow depth, and damage at different points and coordinates.

2 Survey Details

A team from National Cheng Kung University, Taiwan, and Universitas Jenderal Soedirman, Indonesia, arrived at Sis Aljufri Airport in Palu City at 06:00 a.m. Central Indonesia Time on October 11, 2018, thirteen days after the tsunami event. Studies have shown that surveys can be carried out successfully within two to three weeks of an event (Synolakis and Okal, 2005). Starting from the afternoon of October 11, a field survey was conducted until October 19 evening, for a survey period of 9 days. The emergency response period for the disaster area was determined by the Indonesian government to be one month (September 28 to October 26, 2018). The victim evacuation period was two weeks (September 28 to October 12). This means that the survey was conducted in the emergency response stage, one day before the victim evacuation period ended. During this period, cleaning of area impacted by tsunami was still in progress, so that debris could be seen in the disaster area.

Our survey covered the following activities: 1) gathering information about disaster-affected locations, collecting videos and photos of tsunami events from the news, websites, social media, and personal collections of residents that had experienced the disaster; 2) tracing the road along the coast in Palu Bay to get an overview of the affected area; 3) choosing some sites that had significant impact caused by the tsunami; 4) looking for evidence of runup boundaries, inundation limits, and tsunami water level elevation from the subgrade; 5) measuring the profile of the beach at each site; 6) observing and documenting damage and specific phenomena; and 7) interviewing eyewitnesses.

Because many people have smartphones, documentation in the form of photos and videos is abundant. Such documentation was collected from the internet. Unfortunately, many people with valuable documentation did not upload it to the internet. Therefore, our team searched for video recordings and photographs made by local residents while conducting the measurement survey.

The disaster location was located in Palu Bay. The survey area covers the entire coastal area in the bay, which falls under the authority of Central Sulawesi Province. The coastline in the bay is around 70 km. The road connecting the provinces on Sulawesi island, called the Trans Sulawesi Road, is mostly parallel to the coastline of the bay. The team traced the road from Donggala City to Sirenja Village, which is the limit of the tsunami disaster in Palu Bay. Tracing the Trans Sulawesi Road to see an overview of the impact of the tsunami is possible because the road is mostly located 50 to 200 m from the coastline, so the coastline can almost always be seen from the road. A camera on a moving car was operated to record the situation around the beach area. It produced a number of videos describing the damage (contained in supplement).

Eighteen sites were selected for measurement (Fig. 1). At each site, the beach profile was measured using 1 to 4 transects or cross sections, for a total of 28 cross sections. Site selection was based on consideration of the level of damage, significance of runup height and length of inundation, administrative boundaries as well as resources and time. The measurement times and locations of the 18 sites are shown in Table 1. The table gives the runup height and inundation distance, which are explained in section 3.

Finding evidence of runup heights, boundaries of inundation, and elevation of tsunami water levels is challenging. Some detective work is often necessary. October is the beginning of the rainy season in Indonesia, including Sulawesi. Palu City is located near the equator, as shown by latitudes in Table 1. It is one of the driest areas in Indonesia, with rainfall recorded at the Mutiara Meteorology Station in 2017 of 774.3 mm. Since the earthquake incident until the date of the end of the survey, it rained four times, three of which occurred during our survey period, with a duration of less than 2 hours and with low to moderate intensity. It was a challenging work to look for tsunami footprint on surfaces that were exposed to surface runoff caused by rains. The team collected hundreds of traces and water marks left by the tsunami. The tracks were in the form of: a) debris lines, b) debris left on trees, c) broken branches, d) sand trapped in buildings, e) damaged building elements, and f) brown leaves (submerged in salt water during tsunami event). Fig. 2 shows some evidence of runup and inundation traces.

In addition to physical evidence that could be seen and documented in the field, eyewitnesses are important because of their information and confirmation. Very often interviews provide unique information that cannot be obtained by any other means and are therefore much more than an auxiliary tool (Maramai and Tinti, 1997). In this survey, interviews were conducted on 56 people throughout the disaster area. Some of the interviews were recorded in video so the testimonies can be heard again. The authors obtained important information from the surveys, such as the arrival time of the tsunami, the number of waves coming in, the boundaries of runup and water level, the situation in the area before and after the tsunami, and how to survive themselves from the tsunami. Witnesses told that there were 3 tsunami waves. The first wave had the smallest amplitude. Then, two waves followed it. The first wave acted as a trigger for evacuation with many people starting to escape from the coastline. Without this first low-amplitude wave, there may have been more casualties.

After the physical evidence and/or witnesses confirmed the position of the entry of tsunami water inland, measurements were carried out using conventional measurement instruments. Several laser and optical instruments for terrestrial surveys were operated. The instruments included a total station, a water pass, a prism, a handheld GPS device, a laser distance meter, and some assistance tools. These tools were used to measure height differences and the distance from a point and position.

Runup heights were corrected to calculate heights above sea level at the time of survey by using WXTide software version 4.7, available at www.wxtide32.com/index.html. We use Donggala station, the closest station listed in the software, for correcting and assume no significant variations on the sea level inside Palu Bay.

Damage observation was carried out at each site of surveys. We focus on damage of building and infrastructures although other kind of damage are interesting, such as vegetation, shoreline, and properties (cars, boats, fisherman tools, etc.). Videos and photographs were produced to assess the damage. Video recorded along trans Sulawesi Road were compared to Google Street View, Google Map, and Google Earth in order to assess the distance of damage from coastine. In addition, detail measurement of dimension was done for special object (for instance bridge) which is useful for tsunami force analysis.

3 Inundation and Runup Measurements Result

Runup is the maximum ground elevation wetted by the tsunami on a sloping shoreline. In the simplest case, the runup value is recorded at maximum horizontal inundation distance (IOC Manuals and Guides No. 37, 2014). The measurement results are shown in Table 1 and Figs. 3-5. The measurement values in the table has been corrected with tides. Runup height and inundation distance vary from site to site.

Western coast of Palu Bay comprises of Site 1 to 6. Site 1 (Donggala City) is located at the mouth of the bay. Runup height and inundation distance at this site were not significant. Site 2 and 3 namely Loli Dondo Village and Loli Saluran Village where had runup height for both sites is relatively the same, 2.53 m and 2.18. Inundation distance were short due to steep hills towards the mainland. Site 4 and 5 (Watusampu Village and Tipo Village) had height of runup, 6.63 m and 7.79 m. The inundation distances were 71.51 m and 91.11 m. High runup with short inundation was influenced by steep topography. The highest runup for western coast was found in Tipo (7.79 m), followed by Watusampu (6.63 m).

The site at the southern coast of the bay (end of Palu Bay) consists of sites 7 to 9 (Lere, Besusu Barat, and Talise). The runup heights at these site were low at 1.40 m and 1.12 m for Lere and Besusu Barat. Talise had a higher runup of 3.02 m, but all the three had almost the same inundation distance between 200 to 250 m. The density of buildings in this area seems to have prevented the tsunami from reaching further inland. Flat topography caused runup elevation that did not differ much from sea levels.

Survey sites in the eastern coast area of Palu Bay consists of Site 10 to 16. Site 10 was located in Tondo. The topography of this area is relatively steep with a slope of 0.06 (6%). Evidence of tsunami water rise was in the form of debris on top of buildings, truncated building elements, collapsed walls, trash carried away, and fixed debris. A survivor also showed the highest places of tsunami water in this area. A total of 4 cross sections of these coast were measured by our team. The measured runup heights were 10.73, 7.97, 10.14, and 8.50 m, respectively, as shown in Table 1. The runup height of 10.73 m is the highest in this survey (Fig. 5) caused a few building surviving. Omira et al. (2019) shows that the highest runup from their field survey was in Benteng Village with height of 9.1 m. Benteng Village (in western coast) is viz-a-viz with highest runup location of our survey in Tondo (in eastern coast).

North of Tondo is Site 11 (Layana). The topography of this site is relatively flat with a slope of 0.013 (1.3%). Because of this sloping topography, the tsunami wave reached as far as 488 m inland. It was the longest distance among others. The runup points reached 6.57 m and 2.78 m in this site. Both varied greatly because many buildings have long and wide walls that stemmed the tsunami flow further inland.

Site 12 and 13 are Mamboro and Taipa. Runup height of 3.5 m and flow depth of 5.36 m caused severe damage houses and casualties in Mamboro. In Taipa, runup of 4.88 m reached the roof of passenger terminal of Taipa port. North of Pantoloan port is Wani port (Site 15). Runup, inundation and flow depth were significant at this site, 3.58 m and 5.12 m respectively. Site 16 (Lero) is northernmost of survey site inside Palu Bay. This site is face-to-face with Site 1 where are also lies in mouth of Palu bay. The two last sites were Tanjung Padang and Lende. These site located outside of Palu Bay and close to the epicenter. Around 1 m runup hit the both site. Coastal area between site 16 and 17 is steep slope of hilly area and no tsunami footage existed.

4 Tsunami Arrival Time

Arrival time of a tsunami wave is one of the main parameters calculated in tsunami modeling. The time needed for the tsunami wave to propagate from earthquake source location to the coast is defined by the estimated time of arrival (ETA) (Strunz et al., 2011). It is important related to early warning system.

Tidal records may provide a clue on tsunami arrival time. The tidal station closest to the disaster site is Pantoloan Tidal Station. This station is located inside Palu Bay, on a pier in Pantoloan Port and operated by the Agency of Geospatial Information. When the earthquake and tsunami occurred, the recording equipment was not damaged but the data transfer stopped because the communication network was interrupted. Fig. 8 and Fig. 9 shows the water level recorded when the tsunami arrived. The maximum low tide (6.74 m) was at 18:08 local time and the maximum tide (10.55 m) was at 18:10 local time. This means that the tsunami wave height recorded at the station was 3.8 m. This wave height can be seen more clearly in Fig. 9, which is from the same source as that for Fig. 8. In addition, the first tsunami wave arrived at 18:07, with the wave trough at 18:08 and the wave crest at 18:10 local time (UTC+8).

Other hint regarding tsunami arrival time are based on videos on social media, internet, and television, as well as eyewitnesses. More than one tsunami wave hit the coastal zone in Palu Bay. Most witnesses stated that three tsunami waves had arrived. The first was less than 1-m high. The second and third waves were much higher, and were quantified by measurements in this survey. The number of tsunami waves and their height order were similar to the 17 July 2006 Tsunami in Java. That event also had three tsunami waves which the first one was of little magnitude and was followed by the second wave which was the highest one (Lavigne et al., 2007). Witnesses did not give an exact arrival time of the tsunami wave on the coastal zone in Palu Bay. Generally, they referred to prayer times as a guide. Indonesia is majority Muslim. The time of the earthquake and tsunami is close to one of the Muslim worship times in the afternoon, which coincides with a sunset called “maghrib” prayer. The prayer schedule circulated by the Ministry of Religion of the Republic of Indonesia for the area of Palu City and Donggala Regency indicates that the starting time of “maghrib” prayer period on September 28, 2018, was 17:58 local time. Normally, there are two call sounded from a mosque as starting time sign for praying. The first call is called “adzan” and the second call is called “iqamah”. The period between the two call is 10 minutes. Some news, videos, and witnesses show that the tsunami came when people were preparing to pray, between “adzan" and “iqamah". The M_W = 7.5 earthquake occurred at 18:04. This shows that the tsunami waves came less than 10 minutes after the earthquake or between 18:05 and 18:15 local time, different for each site in the disaster area. Thus, the testimony of the witnesses was consistent with the detection of tidal gauges at the Pantoloan station. The important note from the September 2018 event is that the tsunami arrival time was very short.

5 Buildings and Infrastructures Damage

We identified damages to buildings and structures caused by the Sulawesi event 2018 into 3 types, namely damage due to earthquakes, liquefaction, and tsunamis. Damage caused by earthquakes is characterized by horizontal collapse, cracking, and fracture structures. Damage due to liquefaction can be characterized by objects and buildings being turned over, rotated, gone, sunk in water, or sunk in mud. Damage due to tsunamis is characterized by objects, buildings, or structures being washed away from the shoreline by a water current.

Survey sites in the western coastal area of Palu Bay included Site 1 to 6. Site 1 (Donggala City) is located at the mouth of the bay. There are a fishing port and an inter-island port on this site. A survival fisherman told that he was on a ship when the tsunami struck. He saw tempestuous seawater not far from the position of the ships in the vicinity of the port of Donggala. The water propagated from the tempestuous seawater towards warfs in the ports caused a fishing boat rose to the dock floor.

Move south towards site 2 and 3 namely Loli Dondo Village and Loli Saluran Village. Both of these sites have the same characteristics, where many resident houses built on the right and left side of the Trans Sulawesi road. The part of the housing that is closer to the beach is mostly destroyed, while the part of the housing that is closer to the hill side has moderate damage.

Site 4 and 5 (Watusampu Village and Tipo Village) also have similar characteristics. Topography in the form of a steep surface due to a row of hills on the west coast of Palu Bay. These hills are a source of sand for building materials. So there are a lot of sand mining activities at these two sites. In Watusampu site, measurement was carried out around the naval base of Indonesian Navy, where a navy patrol boat was lifted from its mooring site to the mainland. Approaching the tip of Palu Bay on the west side is the Site 6 (Silae) which is an urban area with a dense population. The main road on this site is very close (20-30 m) to the coastline. Settlement around the road was badly damaged. A 4-star hotel suffered serious structural damage but did not collapse.

The sites in the southern coast of the bay consists of sites 7 to 9 (Lere, Besusu Barat, and Talise), lie in the end of Palu Bay, have a sloping topography, the highest population, the most fatalities, and the worst damage. In Besusu Barat, a steel bridge with a span of 300 m was collapsed. The density of buildings in this area seems to have prevented the tsunami from reaching further inland. Witnesses who were on the banks of the Palu River during the earthquake and tsunami event said that the bridge collapsed during the earthquake and before the tsunami arrived. Amateur videos taken from the bridge abutment provide clues to the depth of flow. Measurements of trees and small buildings around the bridge indicate the depth of the tsunami flow around 3.25 m. Most of the victims came from this site because it is a densely populated area, with many offices and business activities as well as open public spaces. In addition, there was the Palu Nomoni festival, a public party that invited large crowds, at the time of the tsunami on Besusu and Talise beach and its surroundings.

Survey sites in the eastern coast area of Palu Bay consisted of Site 10 to 16. Site 10 was located in Tondo. This area has many private boarding houses for students of the University of Tadulako, the biggest university in the city of Palu. The topography of this area is relatively steep with a slope of 0.04 (4%). The runup height of 10.73 m is the highest in this survey (Fig. 5) caused a few building surviving. This area was very crowded when the earthquake and tsunami event. Most students were in their boarding houses during the earthquake because it occurred after working hours. Surprisingly, fewer than 10 deaths were recorded. This is likely due to most of the young residents have agility to save themselves when the tsunami arrived.

North of Tondo is Site 11 (Layana). This site is a trade complex that supports the economic activities of Palu City in particular and Central Sulawesi Province in general. The buildings damaged at this site functioned as shops, warehouses, and corporate offices.

Site 12 and 13 are Mamboro and Taipa. High flow depth of 5.36 m caused severe damage houses and casualties in Mamboro village. A stream covered fully by debris. In Taipa village, runup and flow depth reach 4.88 m and devastated passenger terminal, ferry crane, and navigation control building. Taipa is passenger port serves Sulawesi Island to others. Site 14 (Pantoloan) is the biggest port in the bay where containers floated off and port crane collapsed. North of Pantoloan port is Wani port (Site 15). Here, we found terrible damage especially houses of fisherman community, collapsed coastal structures, and a ship lifted to land. Runup, inundation and flow depth were significant at this site. Site 16 (Lero) is northernmost of survey site inside Palu Bay. This site is face-to-face with Site 1 (western coast) where are also lies in mouth of Palu bay. Small harbour and its facilities totally destroyed. The two last sites were Tanjung Padang and Lende. These site located outside of Palu Bay and close to the epicenter. Tsunamis were felt just like tide wave. They destroy a little part of housing and agricultural field. Coastal area between site 16 and 17 is steep slope of hilly area, very few houses and no tsunami impact found.

We made videos to document damage along Trans Sulawesi Road. Then those are compared to Google Street View® before the tsunami occurrence. From the videos, it can be seen that the severe damage was limited in 150 m from coastline. Impact of the tsunami towards structures and coastal environment summarized in Table 2.

A detail measurement was done to a special phenomenon. A reinforced concrete bridge with simple support beam type on Cumi-cumi Road, Palu City (Fig 6b) shifted as far as 9.7 m. It gives a clue regarding the tsunami's strength. This bridge is made of reinforced concrete with a bridge span of 5.0 m and a width of 19.1 m. It passed over an open channel which had a width of 4.1 m and a depth of 1.6 m. It had 14 beam girders with dimensions of 0.25 m × 0.30 m with a girder distance of 1.35 m. Its plate had a thickness of 0.20 m. Based on these dimensions, the surface area of the bridge was 244.7 m^2, the volume was 23.4 m^3, and the mass was approximated to be around 56 tons. The bridge was estimated to have been submerged by tsunami water as deep as 2.5-4.0 m based on the tsunami marks around it. Debris caught in the bridge fence (Fig. 6b) was evidence of the tsunami water soaking the bridge. The shift stopped because the bridge body was stuck in the wall of a building. Furthermore, we can investigate this case with the help of Google Earth, as shown in Fig. 7, where Figs. 7a and 7b show satellite images taken on September 26, 2017, and October 2, 2018, respectively. As shown, the asphalt layer of the road was broken and the bridge over the open channel was shifted away from the coast by the tsunami. The position of this bridge is at the end of Palu Bay (-0.88123°S; 119.83907°E).

6 Coastal Landslides

Total coastal landslides in Palu Bay related to 28 September 2018 event occurred at 7 locations (Sassa and Takagawa, 2018), 6 locations (Arikawa, 2018) or 10 locations (Omira et al., 2019). Our team found two locations of coastal landslides. These add landslide locations which have been found by other survey team. The two locations are around the river mouth in Donggala City (Figs. 11 and 12) and around the river mouth in Lero Village (Figs. 13 and 14). Landslides in Donggala were indicated by the loss of land around the Donggala River. Around 30 houses were reported to have suddenly sunk along with some of the residents. The wharf in the port of Donggala dropped by about 80 cm. The pile that was being installed for the foundation of a large building sank deep into the soil layer suddenly and was no longer found.

In Lero village, some houses and their inhabitants drowned when the tremor struck. Figure 12 shows a house going down so that the ceiling was in the previous floor position. A typical house in Indonesia has a ceiling height of 3 to 4 m. This is an indication that the landslide in Lero village has reduced the land surface in the range of 3 to 4 m. In addition, an eyewitness reported that seabed around 10 m from coastline changed from 1 m deep to “invisible” depth seen by naked eyes. He heard roaring sound a minute after the main earthquake.

7 Conclusions

This study reported the results of a post-tsunami field survey conducted after the 2018 Sulawesi Tsunami. The results show that the runup heights reached 10.73 m in Tondo and the inundation distance was 488 m in Layana. Tondo area has a steep slope coast whereas Layana area has a flat topography. Flow depths were detected more than 2 m for sites which had significant damage. Tsunami events are concentrated in the bay, this indicates the type of local tsunami. Most informans in the survey site testified that there were three main tsunami waves that reached the coastal zone in Palu Bay. The second was the highest. The arrival time of waves varied according to location. It is around 3 minutes in Donggala City and Lero Village, and around 10 minutes in the end of Palu Bay (Lere, Besusu Barat, and Talise) after the $M_W = 7.5$ main earthquake event.

The tsunami waves that hit the coastal zone in Palu Bay were very strong as indicated by massive damage at each site we surveyed. The severe damage was limited within 150 m from coastline. These include the shifting of a 38-ton bridge. Coastal landslides detected by our team in Donggala City (lost surface area of 10,068 m^2) and Lero Village (lost suface area of 22,971 m^2) gives additional evidence towards coastal landslides found by other team as reported by Arikawa et al. (2018) and Omira et al. (2019). Multiple landslides event may motivate to the development of a tsunami model that is capable of simulating tsunamis generated by consecutive earthquake and landslide events, or simultaneous landslide events. Furthermore, landslides should be included in probabilistic tsunami hazard assessment, as done by Horspool et al. (2014) for Indonesia and for earthquake sources. The data and analysis from this survey and those from other teams will lead to a comprehensive and complete understanding of the September 2018 Sulawesi Tsunami.

Data availability. All photos were taken by author's team. Tide image was obtained from Geospatial Information Agency (BIG).

Author contribution. All authors contributed to the preparation of this paper.

Competing interest. The authors declare that they have no confllict of interest.

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Table 1 Measured sites (see also Figures 1 and 2)

No.	Site name	Measurement time	Coordinates		Inundation distance (m)	Runup height (m)	Flow depth (m)	Watermark
			Longitude	Latitude				
1.	Donggala City	12-Oct-18 4:34:08PM	119.741313	-0.663054	31.20	1.58		BL, SD
2.	Loli Dondo	16-Oct-18 3:27:28PM	119.776100	-0.731612	65.40	2.53	2.38	BB, BV, DS
3.	Loli Saluran	16-Oct-18 2:16:54PM	119.794095	-0.783867	118.49	2.18		BB, BV, DS
4.	Watu Sampu	16-Oct-18 12:48:04PM	119.810032	-0.822144	71.51	6.63	4.19	BL, BV, DD, EW
5.	Tipo	17-Oct-18 10:25:41PM	119.829355	-0.864574	91.11	7.79		DS, EW
6.	Silae	17-Oct-18 3:08:35PM	119.834315	-0.874580	80.13	4.53		DD, DS, GD
7.	Lere	15-Oct-18 2:30:19PM	119.843401	-0.885372	228.22	1.40	3.90	DD, DS, GD
8.	Besusu Barat	16-Oct-18 8:20:46AM	119.860210	-0.887457	250.35	1.12	3.25	BB, DD, DS, GD
9.	Talise				254.23		2.18	
	Talise 1	15-Oct-18	119.873739	-0.876266		2.79		BB, DS, GD, EW
	Talise 2	8:12:18AM	119.874616	-0.873833		2.94		DD, DS, GD
	Talise 3		119.874389	-0.874440		3.02		DD, DS, GD
	Talise 4		119.874294	-0.875004		2.71		DD, DS, GD
10.	Tondo				270.27		7.30	
	Tondo 1	14-Oct-18	119.881499	-0.844691		10.73		DC, DD,DS, EW
	Tondo 2	12:58:26	119.880688	-0.843981		7.97		DC, DD, DS, EW
	Tondo 3		119.881253	-0.845850		10.14		DC, DD, DS, EW
	Tondo 4		119.880854	-0.846571		8.5		DC, DD, DS, EW
11.	Layana	14-Oct-18			487.84		5.20	
	Layana 1	7:45:14	119.887135	-0.822159		6.57		DD, DS, GD, WW
	Layana 2		119.883472	-0.823863		2.78		DD, DS, GD
12.	Mamboro	13-Oct-18			164.08		5.36	
	Mamboro 1	13:43:47	119.879074	-0.801753		3.48		DC, DD, DS, EW
	Mamboro 2		119.878349	-0.800542		3.68		DC, DD, DS, EW
13.	Taipa:				110.94		6.19	
	Taipa 1	17-Oct-18	119.858686	-0.778698		3.15		BV, DS, EW
	Taipa 2	8:56:31	119.859367	-0.779472		4.52		BV, DS, EW
	Taipa 3	17-Oct-18 9:01:46 17-Oct-18 9:55:28	119.859542	-0.779995		4.88		BV, DS, EW
14.	Pantoloan	17-Oct-18 13:33:12	119.857660	-0.710840	166.70	2.30		DS, EW, GD
15.	Wani	17-Oct-18 12:34:23	119.841543	-0.693099	185.13	3.58	5.12	BL, DD, EW, MO
16.	Lero	17-Oct-18	119.812422	-0.629011	75.80	1.77		DS, EW, WW

		11:27:51						
17.	Tanjung Padang	18-Oct-18 12:43:01	119.803220	-0.231612	95.80	1.22		DS, EW, GD
18.	Lende	18-Oct-18 14:11:29	119.817232	-0.185461	36.60	1.17		EW, GD

BB: broken tree branch; BL: boat on land surface; BV: brown vegetation; DC: debris caught; DD: debris deposition; DS: damaged structures; EW: eye witnesses; GD: garbage deposition; MO: marine-origin objects; SD: sediment deposition; WW: watermark on wall.

Table 2 Land use and damage for each site

No.	Site name	Land use	Damage
1	Donggala City	Fishing port, passenger and cargo port, urban area	Damaged houses, fisherman boat lifted to land
2	Loli Dondo	Settlement, fishery	Damaged houses
3	Loli Saluran	Settlement, stone mining	Damaged houses
4	Watu Sampu	Indonesian Navy harbour, agriculture	Navy vessel lifted to land
5	Tipo	Settlement	Damaged houses
6	Silae	Urban area, settlement	Damaged houses,
7	Lere	Urban area, business	Damaged mall, campus, offices
8	Besusu Barat	Urban area, offices, business	Collapsed 300-msteel bridge
9	Talise	Urban area, sightseeing, aquaculture	Damaged coastal garden, restaurants
10	Tondo	Settlement, sight seeing	Damaged houses
11	Layana	Warehouse, stores complex	Damaged warehouses and stores
12	Mamboro	Settlement	Damaged houses
13	Taipa	Passenger port, sight seeing	Damaged passenger terminal
14	Pantoloan	Passenger and cargo port	Washed away container
15	Wani	Fishery port, aquaculture	Ship lifted to land, severely damaged houses
16	Lero	Settlement, agriculture	Houses sunk by liquifaction
17	Tanjung Padang	Agriculture	Damaged houses and crops
18	Lende	Agriculture	Damaged houses and crops

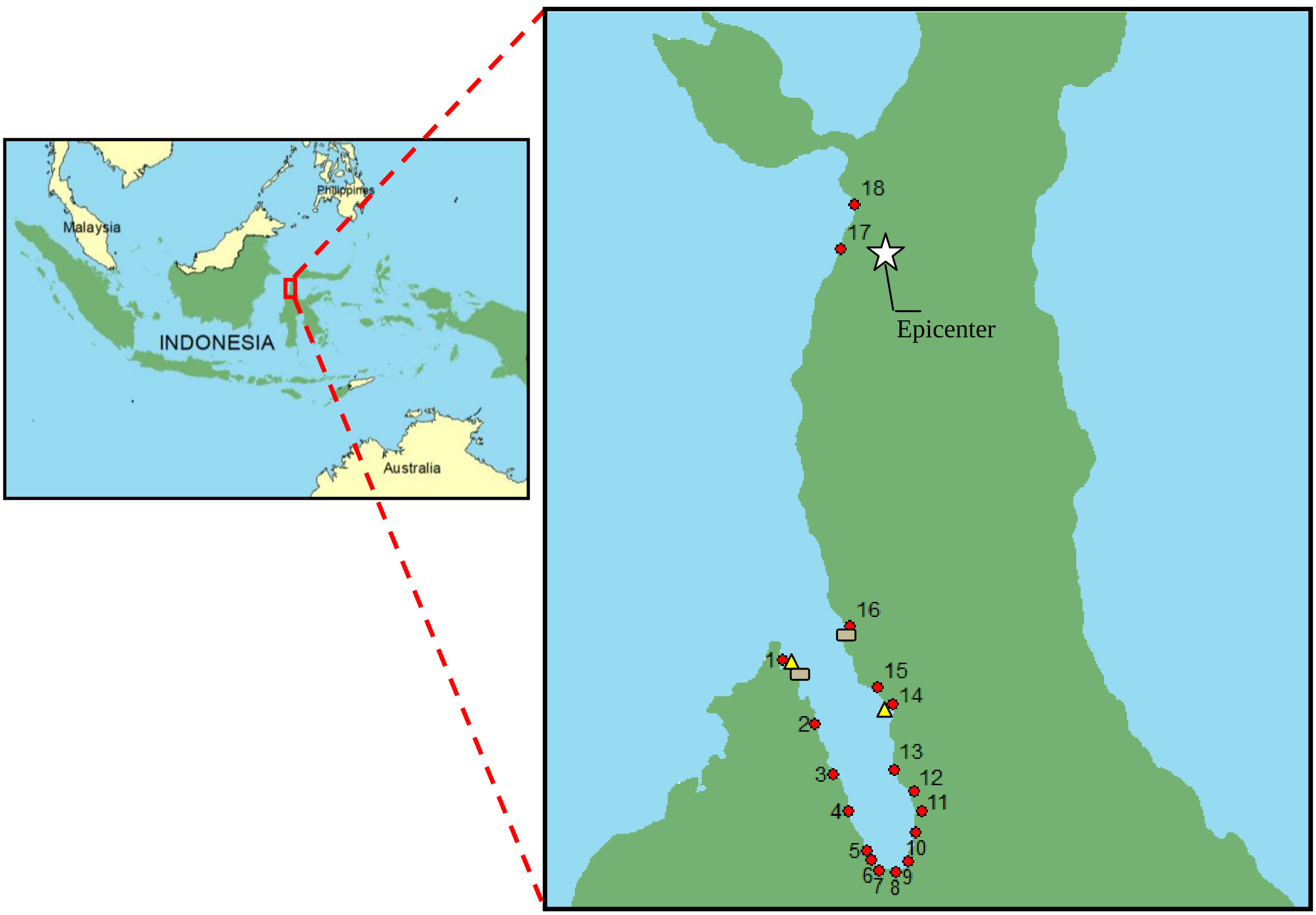


Figure 1: Survey area of Palu Bay located on Sulawesi island. A camera in a moving car was used to record the tsunami-affected area following the Trans Sulawesi Road paralleled Palu Bay coastline from Site 1 to Site 18. Tidal station were at Site 1 and Site 14. Coastal landslides detected were located at Site 1 and Site 16.

Figure 2: Evidence of tsunami runup and inundation. (a) Debris left behind in the residential area of Tondo, (b) debris caught in a tree in Mamboro, (c) and (d) debris stuck in a tree in Tondo, (e) leaves turned brown due to being submerged in salt water, (f) a tree had green leaves at the top and brown at the lower part, indicating the tsunami inundation height (flow depth) limit in Layana, (g) debris lodged on top of a building, (h) broken house element showing tsunami water level, (i) watermark on a house wall in Lero village, (j) sand deposit on building floor in Donggala City, (k) a 45-m-long ship moved to land in Wani harbour, (l) interview with an survivor in Mamboro.

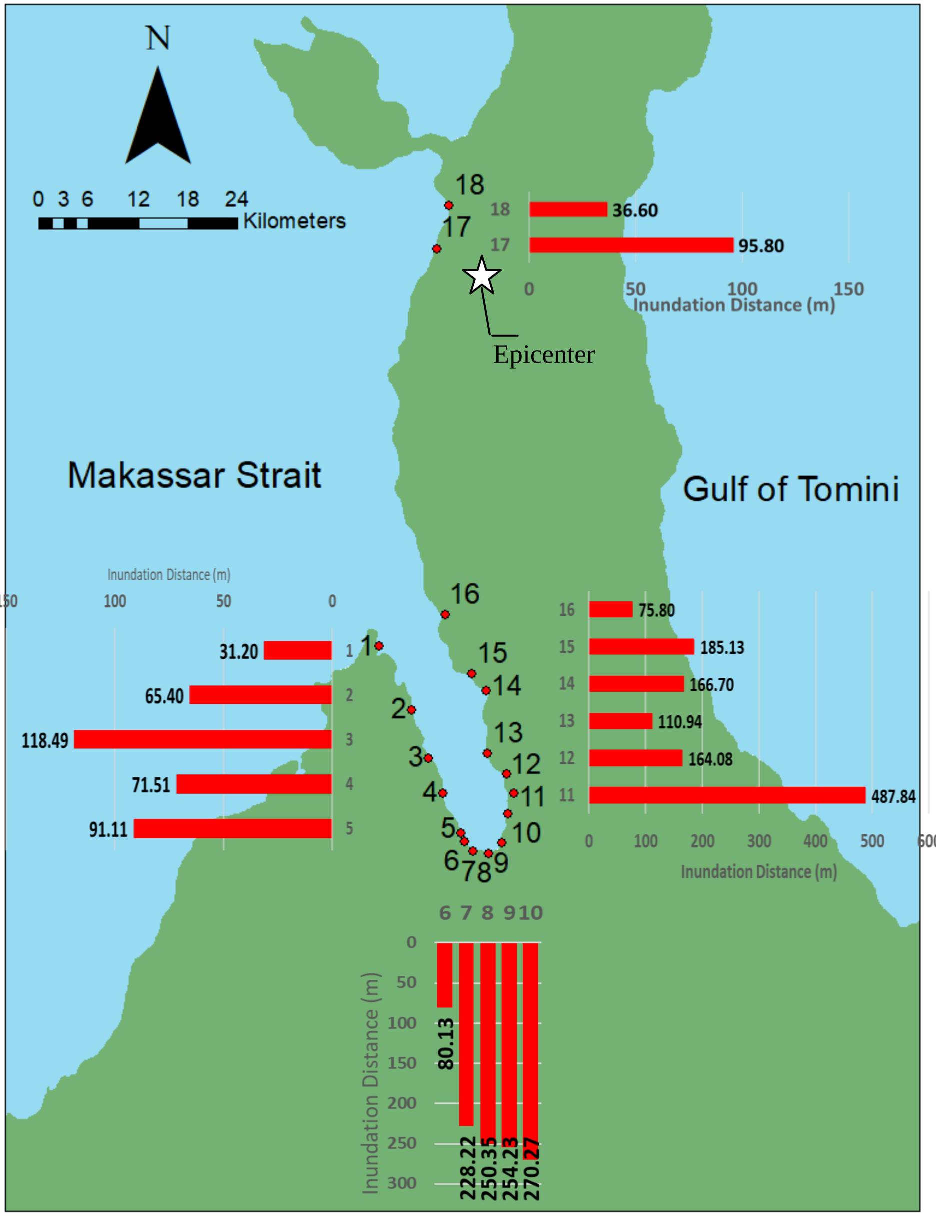


Figure 3: Measurement results of inundation distances.

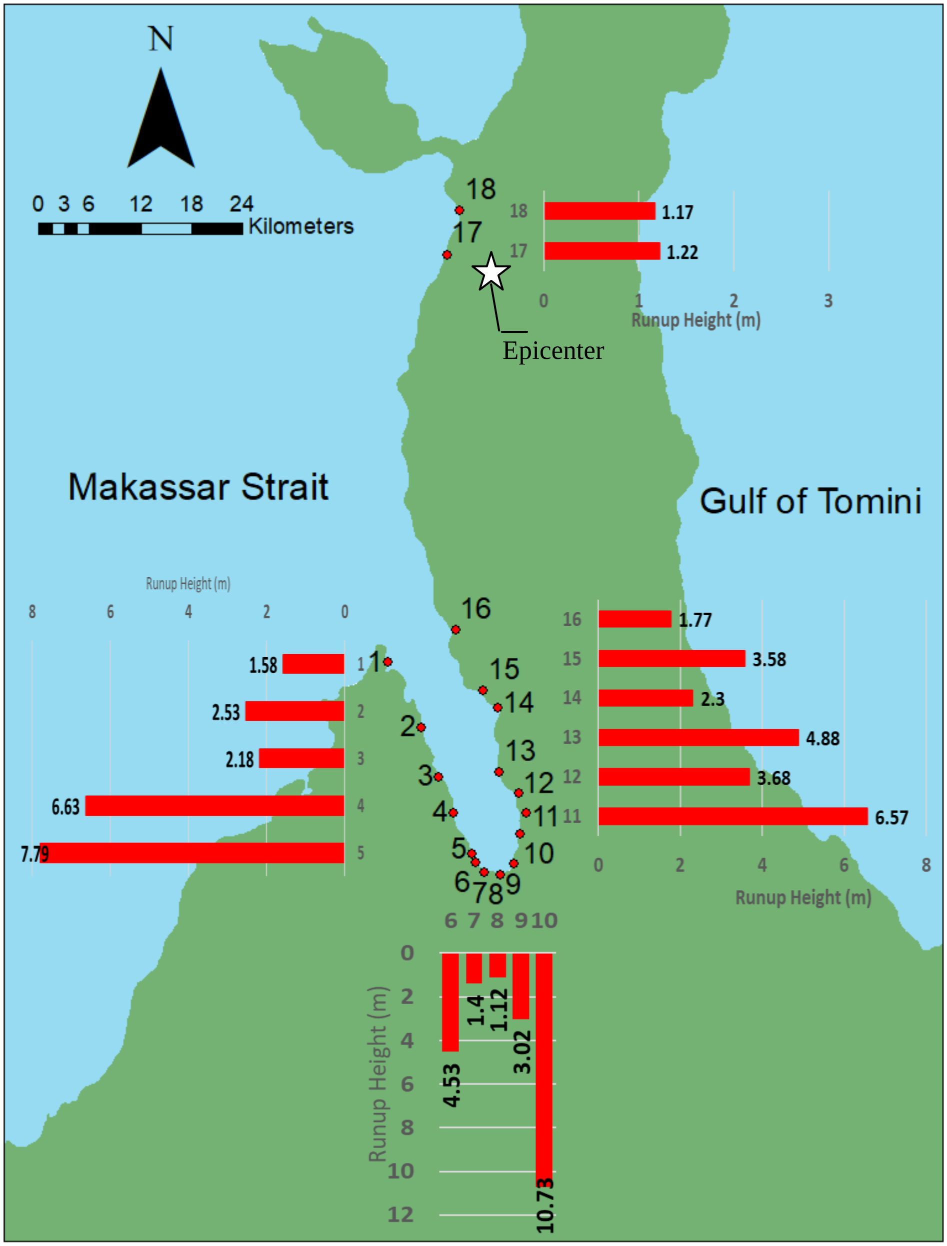


Figure 4: Measurement results of runup heights.

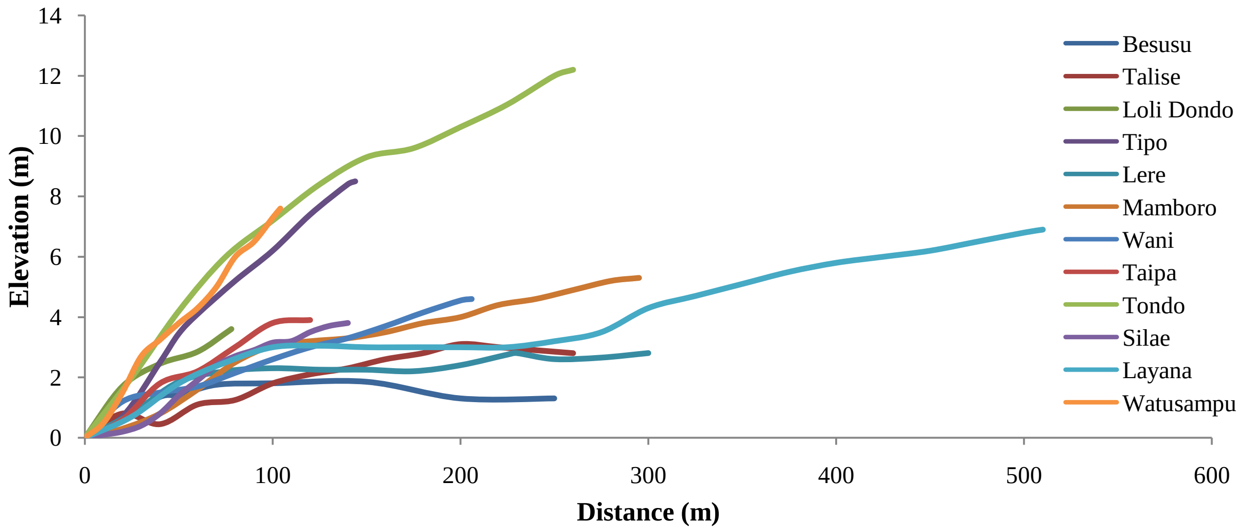
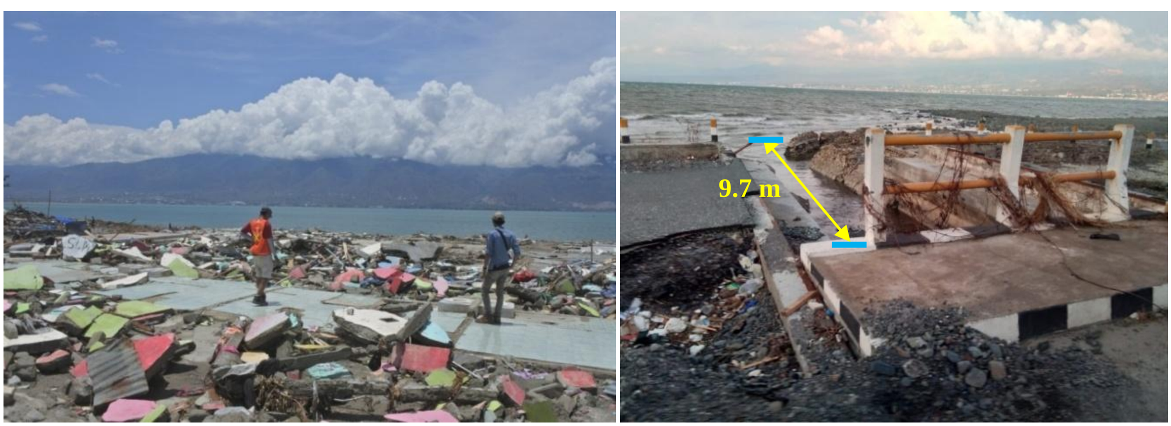


Figure 5: Transects of beach where tsunami wave arrived. The longest inundation distance is at the Layana site and the highest runup is at the Tondo site.



(a) (b)

Figure 6: (a) Damage caused by the tsunami in Tondo, a residential complex where a lot of private boarding houses were inhabited by students at the University of Tadulako, and (b) a reinforced concrete bridge on Cumi-cumi Road Palu City shifted by 9.7 m by the tsunami.

(a) (b)

Figure 7: Satellite images taken on (a) September 26, 2017 and (b) October 2, 2018, showing the bridge shift.

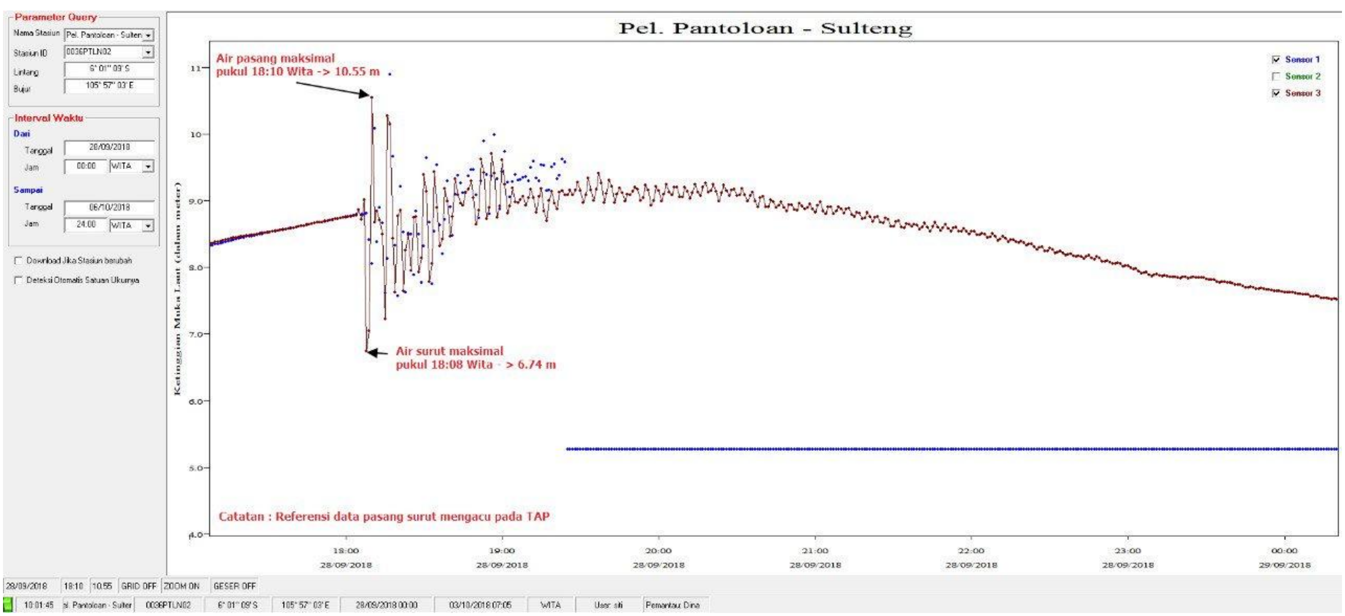


Figure 8: Water level recording at the Pantoloan tidal station managed by Geospatial Information Agency (Sudibyo, 2018).

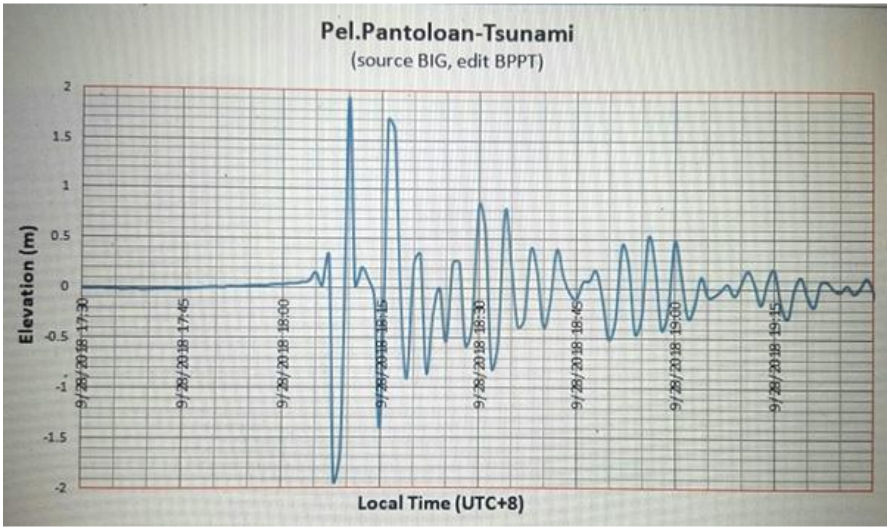


Figure 9: Magnified view of Fig. 9, sourced Geospatial Information Agency (Sudibyo, 2018).

(a) (b)

(c) (d)

Figure 10: Landslide in Donggala City. (a) A trestle dropped 0.8 m in Donggala Port, (b) a building on the seaside slip down significantly, (c) the surface of an alley in a settlement dropped 0.4 m, and (d) a layered courtyard with paving blocks dropped around 1.5 m.

(a) (b)

Figure 11: Possible landslide areas in Donggala (yellow dotted lines). Images were obtained from Google Earth. Satellite images taken on(a) 6 July, 2016 (more than a year before the earthquake) and (b) 2 October, 2018 (4 days after the earthquake and tsunami). The yellow bounded area is around 10,068 m^2 or 1 hectare. Number 1, 2, 3 and 4 in Fig. 12 b corresponds to Fig. 11 (a), (b), (c), and (d).

Figure 12: Quick landsubsidence in Lero Village. Photograph taken two weeks after the event. Some houses dropped suddenly, around 3-4 m, when the earthquake occurred. Residents of these houses, especially that indicated by the oval, could not save themselves. The yellow dotted line is the former coastline.

Figure 13: Quick land subsidence in Lero Village. Satellite images taken on (a) 7 April, 2016, and (b) 2 October, 2018, from Google Earth, showing conditions after the earthquake and tsunami. The area of land that dropped is 22,971 m^2 or almost 2.3 hectares.