Authors Response

Referee 1 – Anonymous

We would like to thank Referee 1 for the constructive comments and suggestions towards improving our manuscript.
We summarize comments from Referee 1, author's response, and author's changes in manuscript as follows. At the end of this authors response, we provide a manuscript showing highlights to mark referee comments. Then follow by a marked-up manuscript showing highlight to mark modification by author. Final form without highlight is available as revised manuscript.

Comment 1:
Overall This is an interesting paper that describes the results of field work after the2018 Sulawesi tsunami. The paper follows the general pattern of field work papers, and is important that such events are properly documents, so that modellers can then attempt to reproduce them. However, the paper suffers from lower than expected writing quality. The English is ok in some places, and poor in others. Also, the authors often repeat themselves. The more serious problem, however, comes from its unclear focus. Most of the paper deals with the tsunami damage, but at times the authors randomly include other information relating to aftershocks or landslides that are not related to the tsunami. Thus, several parts of the paper should be deleted, and the message should become more focused. Instead, the authors might want to describe the mechanisms of tsunami damage in more detail at each location (currently they only superficially describe some locations).

Response 1:
Thanks for very detailed and constructive comments from Referee1. We are improving our writing quality, including English. An native at an English proofreading service center would handle our manuscript. That's right we often repeated ourselves (23 times), now we already reduced it. We modify the writing in order to more focus by removing several parts you suggest, e.g aftershock and earth-surface landslide. Nevertheless, we preserve part about coastal landslides since we feel to have contribution on it. We strongly agree with your advice on description of the mechanism of tsunami damage. So that we add description on runup, inundation, and damage at each site in our text.

MAJOR COMMENTS

Comment 2:
By now a number of other field work papers have been published. Please find these, and cite them. Also, please explain what differences there are between your work and other papers.

Response 2:
Alright. We are adding other field work papers, i.e Omira et al (2019),Mikami et al. (2019), Muhari et al. (2018),Yalciner et al. (2018), Putra et al. (2019), Sassa & Takagawa (2019), Takagi (2019), Arikawa et al. (2018). The last three papers focus on coastal landslides, while Putra et al. evaluate runup based on tsunami deposit. Muhari et al. was probably the first team coming in disaster area. They gave early report as direction for other team coming later. Their results are preliminary and limited around Palu City, in the end of Palu Bay. The most close topic with us is by Omira et al. (UNESCO international team) and Mikami et al.. They measured more points than ours. Our several points intersect with their points. Nevertheless, they did not measure inundation distance as done by our team. We cite them and explain it in the manuscript.

Change in manuscript 2:

P3 L6-15 marked-up/revised manuscript

Many groups have carried out field surveys of the Sulawesi Tsunami event, also known as the Palu Tsunami. Muhari et al. (2018) investigated the 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 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). Mikami et al. (2019) measured runup height and inundation depth of 22 places and disscussed damage to coastal communities around Palu Bay. Putra et al. (2019) focused on tsunami deposits. 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 landslides detected in Palu Bay. These survey data can be combined with data from other groups. In this study, we provide data of runup height, inundation distance, flow depth/inundation depth, and damage at different points and coordinates.

Comment 3:

P3, L24. In what way did the authors do this? How can they choose one point that can be representative for a tsunami that was as complicated as the one in this case?

Response 3:

P3 L24 version 1 manuscript. We modify the sentence. We mean that we chose some sites (not only one point) which had significant impact caused by the tsunami. We measured runup, inundation, and flow depth at 18 sites. On the first day of our survey we recorded situations along the Palu Bay. From these recordings we can roughly estimate sites with high runup and the long inundation. These points usually also have a severe level of damage. Besides, important places such as ports and densely populated areas are our priority. Measuring a coastal cross section at each certain distance, for example, every 1 km along 70 km of Palu Bay, might provide more representative data, but we have difficulty doing that mainly because it will take a long time. In addition, the areas affected by the tsunamis were also fragmented, not connected.

Change in manuscript 3:

P3 L28-29 marked-up/revised manuscript

..... 3) choosing sites that were significantly impacted by the tsunami; .....

Comment 4:

The English in the paper needs to be improved. In places the sentences are correct, and in others they are pretty poor.

Response 4:

Thanks for the assessment. We are trying to meet referee's suggestion, improving English in the manuscript thoroughly, and it was be checked by English proofreading service center.

Comment 5:

P4 L4-5 what kind of camera was used? Did the authors obtain a 360 degree view? Otherwise, in what way is this similar? Isthis going to be opened to other researchers? (if not, what is the point of writing this?)

Response 5:

P4_L4-5 version 1 manuscript We delete "This method is similar to that used by Google Street View®, but we used simpler equipment." We do not have adequate reason to claim similar with

Google Street View. Only the idea may be similar with Google Street View® but the method and camera used was different. However, we think our video collections are useful. We plan to put them in the supplement in order to be opened to other researchers. We use Google Street View® for comparing with our videos to evaluate damage along Trans Sulawesi Road.

Changes in manuscript 6:

P4 L10-11 marked-up/revised manuscript

..... 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 the supplement).

P5 L10-11 marked-up/revised manuscript

.....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. ....

Comment 6:

P4 L19 and onwards. What is the point of talking so much about the rain, if the authors then dismiss the importance of it?

Response 6:

P4_L19 version 1 manuscript We replace "Fortunately, from the point of view of conducting a survey, surface runoff due to rain seems insignificant and does not erase the tsunami footprint." with "It was a challenging work to look for tsunami footprint on surfaces that were exposed to surface runoff." In additon, we also shorten the paragraph containing about rain.

Change in manuscript 6:

P4 L18-22 marked-up/revised manuscript

..... October is the beginning of the rainy season in Indonesia, including Sulawesi. Palu City is located near the equator, as shown 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. From the earthquake incident until 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 challenging to find tsunami footprints on surfaces exposed to surface runoff caused by rain. .....

Comment 7:

P5 L2. Where all these measurements corrected for tide? Using which software? Are the datasets given in this paper those corrected for tide, or the original measurements? Also P5 L7-9, the location of these tidal stations needs to be shown in some figure. See also P5 L22, which indicates both corrected and uncorrected, making it unclear what the other numbers in the paper actually are.

Response 7:

P5 L2 version 1 manuscript 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 used Donggala station listed in the software for correcting and assume no significant variations on the sea level inside Palu Bay. We modified that all number (runup and inundation) shown in the paper are corrected for tide. Thanks for rigorous comments.

P5_L7-9 version 1 manuscript OK, we show Donggala and Pantoloan tidal stations in Fig. 1. We remove Mamuju station from the text.

P5_L22 version 1 manuscript We modified that all number (runup, inundation, water elevation) shown in the paper are corrected for tide.

Changes in manuscript 7:

P5 L5-7 marked-up/revised manuscript

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

P5 L15-17 marked-up/revised manuscript

..... The measurement results are shown in Table 1 and Figs. 3-5. The measurement values in the table are corrected based on the tides. Runup height and inundation distance vary from site to site.

P5 L32 - P6 L1-2 marked-up/revised manuscript

..... 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. .....

Comment 8:

P6 L16. What is the point of this section? You are talking about earthquake damage,but this paper up to now is mostly about tsunami damage. Hence, it feels rather odd. I suggest just focusing on the damage by the tsunami, and delete this section.

P6 L24 If the bridge was shifted, it was damaged. Not sure what the authors are trying to say here: : : Also, how can the authors say the area is only 3.4m2, given the description earlier? This part feels rather confusing.

Response 8:

P6_L2-6 and L12-16 version 1 manuscript. We delete these parts and try to focus on the damage by tsunami as you suggesting.

P6_L24 version 1 manuscript. We revise its area = 244.7 m2, thanks for the precise comment. We measured size of bridge which moved from original position with intention to give data about bridge dimension that may be used by modeler to assess tsunami force (drag force, lift force, etc.). We provide sketch of the bridge and put it on supplement.

Change in manuscript 8:

P9 L8-10 marked-up/revised manuscript

..... Based on these dimensions, the surface area of the bridge was 244.7 m2, the volume was 23.4 m3, and the mass was estimated to be around 56 tons. .....

Comment 9:

P7 L2. From which sites? What is the point the authors are trying to make here?

P7 L4-10. What is the point of this talk of aftershocks? I suggest all this is deleted, and the authors focus just on the tsunami damage.

Response 9:

P7_L2 version 1 manuscript. We mean it from our measuring sites, Palu bay area. Additional data were documented beside runup and inundation measurement. But, we deleted it.

P7_L4-10 version 1 manuscript. We deleted section about aftershock in order to be more focused. Thanks.

Change in manuscript 9:

Please see marked-up/revised manuscript.

Comment 10:

Same for P8 L10-19 P8 L20-30 What is the point the authors are making here? The authors don't seem to conclude anything, and merely state conjecture. This might be ok if it was in the discussion section of the paper, but this is not it.

Response 10:

P8_L10-19 and P8 L20-30 version 1 manuscript. It has been removed to make more focused.

Change in manuscript 10:

Please see marked-up/revised manuscript.

Comment 11:

P9 L1-5 version 1 manuscript. What is the point in a scientific paper of stating that surveys are being carried out? The authors should provide details or analysis, or let others do so. Reporting thatsomething is happening is journalistic.

P9 L19-22 version 1 manuscript. There are already papers that are describing the location of landslides. Also, it is strange that the authors conclude this when they did not talk about this at length in their own paper (they should focus on the conclusions that can be derived from their own work).

Response 11:

P9_L1-5 version 1 manuscript. Thanks for the advice. We deleted "Therefore, the Indonesian Navy deployed the KRI Spica Ship, ... to conduct a bathymetry survey of Palu Bay after the tsunami." .

P9_L19-22 version 1 manuscript. We modified this part "Land subsidence in Donggala City (10,068 m^2) and Lero Village (22,971 m^2) gives evidence for underwater landslides. However, it does not mean there were only two underwater landslides; more landslide locations may be found in the disaster area. " to be "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)."

Change in manuscript 11:

P10 L12-14 marked-up/revised manuscript.

..... The coastal landslides detected by our team in Donggala City (lost surface area of 10,068 m2) and Lero Village (lost suface area of 22,971 m2) are additional evidence of the coastal landslides found by other teams. .....

MINOR COMMENTS

Comment 12:

P2 L26 "Most of the victims came from": : :

P2 L30 astonished should not be used in academic literature.

P2 L30, by now you said many times that the earthquake took place due to an activestrike-slip fault in Indonesia. Please delete

P2 L32, again, you repeated many times that the earthquake destroyed many buildings.

Response 12:

P2_L26 version 1 manuscript. We revised it to be"Most of the victims came from..."

P2_L30 version 1 manuscript. We replaced “astonished” with“surprised”
P2_L30 version 1 manuscript. We removed "The Palu-Koro fault which divides Sulawesi into two parts, has quite active tectonic activity...." ; Moved "the movement of ..." ; and “This is the second most active fault in Indonesia after the Yapen fault inPapua." .....
P2_L32 version 1 manuscript. We deleted it and reduce repeated words or sentences.

<u>Changes in manuscript 12:</u>
P2 L20 marked-up/revised manuscript
..... Most of the victims came from this city. .....
P2 L24 marked-up/revised manuscript
.....
This disaster in Central Sulawesi surprised the 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 uncertain whether the tsunami was caused by co-seismic deformation or non-tectonic sources. Ulrich et al. (2019) believe that a source related to earthquake displacements is probable and that landsliding may not have been the primary source of the tsunami. In contrast, Takagi et al. (2019), Sassa and Takagawa (2018), and Arikawa et al. (2018) believe that landslides produced the tsunami. Field surveys are important for determining the actual cause.
.....
P2 L6 marked-up/revised manuscript
..... The movement of rock formations is 35-44 mm/year (Bellier et al., 2001). .....

<u>Comment 13:</u>
P3 L11 “for a numerical model”
P3 L12 “rebuilding of the affected areas by the 2018: : :”
P3 L30 what is the point of saying that the authors took videos. Are these provided inthe present research or any additional information? Otherwise delete: : :

<u>Response 13:</u>
P3_L11 version 1 manuscript. OK. We change it.
P3_L12 version 1 manuscript. OK. We change “..... rebuilding the affected areas of the 2018 Sulawesi Tsunami” with "rebuilding of the affected areas by the 2018..."
P3_L30 version 1 manuscript. We deleted "We also recorded videos and took photographs."

<u>Changes inmanuscript 13:</u>
P2 L35 - P3 L1-2 marked-up/revised manuscript
..... For instance, Lynett et.al (2003) employed the field survey data of the 1998 Papua New Guinea tsunami as validation for numerical models, namely the Boussinesq model and a nonlinear shallow water wave model. .....
P3 L4-5 marked-up/revised manuscript
..... More broadly, these data can be used for disaster mitigation and rebuilding of the affected areas by the 2018 Sulawesi Tsunami....
P4 L3-4 marked-up/revised manuscript
..... Therefore, our team searched for video recordings and photographs made by local residents while conducting the measurement survey.

<u>Comment 14:</u>
P4 L1 you repeated already that this road runs parallel to the coastline.
P4 L9-10, delete these lines.
P4 L17 “until the date of the end of the survey: : :”

P4 L28 “The authors obtained important information from the surveys”: : :
P4 L31 “The first wave acted as a trigger for evacuation, with many people starting to escape from the coastline”. The technical word is “trigger”. Please read other papers about evacuation triggers for tsunamis

Response 14:
P4_L1 version 1 manuscript. We reduced the repeated phrase “parallel to the coastline” and now only one.
P4_L9-10 version 1 manuscript. We deleted these lines “Many locations with steep cliffs and tsunami trails were not easily visible. We did not take measurements in such locations. Likewise, we did not measure places not significantly affected by the tsunamis.”
P4_L17 version 1 manuscript. We modified “Since the earthquake incident until the date of our team's return " to be “Since the earthquake incident until the date of the end of the survey"
P4_L28 version 1 manuscript. We modified“We got some important informationfrom the interviews to be"The authors obtained important information from the surveys"
P4_L31 version 1 manuscript. We modified“The first wave was a warning so many people went away from the coastline immediately” to be "The first wave acted as a trigger for evacuation, with many people starting to escape from the coastline".

Changes in manuscript 14:
P4 L6-7 marked-up/revised manuscript
..... The road connecting the provinces on Sulawesi island, called the Trans Sulawesi Road, is mostly parallel to the coastline of the bay. .....
P4 L20-21 marked-up/revised manuscript
..... From the earthquake incident until 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. .....
P4 L30 marked-up/revised manuscript
..... The authors obtained important information from the surveys, ...
P4 L33-34 marked-up/revised manuscript
..... The first wave acted as a trigger for evacuation, with many people escaping the coastline. Without this first low-amplitude wave, there may have been more casualties. .....

Comment 15:
P5 L5 “is recorded at the maximum horizontal inundation distance”. (Delete “the horizontal distance flooded by the wave)
P5 L10 what do the authors mean by tsunami border?
P5 L 12 Delete sentence starting by “The items scattered”
P5 L17 what is “tsunami creeping”? run-up?
P5 L23 “This area was flattened by the tsunami (Fig 6a), with no buildings surviving”?
P5 L26 Rephrase “being quite nimble” P5L27 what exactly is this important observation? Be specific.
P5 L32 tsunami risk managers know they can use this data for run-up modelling. Please delete this sentence, it is obvious.

Response 15:
P5_L5 version 1 manuscript. Done. We deleted"the horizontal distance flooded by the wave"
P5_L10 version 1 manuscript. It is meant limit of inundation. We deleted "from coastline to tsunami border on land", and made new sentences.
P5_L12 version 1 manuscript. Done. We delete the sentence and made new sentences in Part 5 about damage observation.

P5_L17 version 1 manuscript. Right. We mean “creeping” was runup. We replaced “creeping” by “runup”.
P5_L23 version 1 manuscript. We deleted "This area was flattened by tsunami (Fig. 6a), buildings collapse." And added “caused a few building surviving” in Part 5 about damages.
P5_L26 version 1 manuscript. We replaced "being quite nimble" by "have agility to save ..."
P5_L27 version 1 manuscript. We deleted "This is an important observation for future mitigation efforts."

Changes in manuscript 15:
P5 L14-15 marked-up/revised manuscript
..... In the simplest case, the runup value is recorded at maximum horizontal inundation distance (IOC Manuals and Guides No. 37, 2014). .....

P6 L5-6 marked-up/revised manuscript
.....
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. .....

P8 L20-22 marked-up/revised manuscript
..... 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.

P6 L1-2 marked-up/revised manuscript
..... The runup height of 10.73 m is the highest in this survey (Fig. 5) caused a few building surviving. .....
P8 L18-19 marked-up/revised manuscript
..... This is likely due to most of the young residents having the agility to save themselves when the tsunami arrived.

Comment 16:
Same for P6 L31-32.
P6 L18 check reference, not shown
P8 L23 the words “impacted areas with a relatively narrow width” are unclear. Revise.
P8 L28 “Ulrih et al. (2019) assume that a: : :”

Response 16:
P6 L31-32 version 1 manuscript. We deleted “This phenomenon can be further analyzed to determine the tsunami force.”
P6 L18 version 1 manuscript. OK, it refers to Fig 6b.
P8_L23 version 1 manuscript. We removed part 5.5 about underwater landslides so that we deleted paragraph contained "This suspected source should be located near the impacted areas with a relatively narrow width (Muhari et al., 2018).".
P8_L28 version 1 manuscript. We revised and move this part "Ulrich et al. (2019) assume that a ..." to introduction part.

Changes in manuscript 16:
P9 L15-16 marked-up/revised manuscript
..... The position of this bridge is at the end of Palu Bay (-0.88123°S 119.83907°E). .....
P9 L4-6 marked-up/revised manuscript
.....

Detail measurements were taken of a reinforced concrete bridge with simple support beams on Cumi-cumi Road, Palu City (Fig. 6(b)). This bridge shifted by as far as 9.7 m. It provided clues regarding the strength of the tsunamis. ....

P2 L26-27 marked-up/revised manuscript

..... Ulrich et al. (2019) believe that a source related to earthquake displacements is probable and that landsliding may not have been the primary source of the tsunami. .....

Referee 2 – Prof. Ahmet Cevdet Yalciner

We would like to thank Prof Ahmet Cevdet Yalciner for the constructive comments and suggestions towards improving our manuscript. We summarize comments from Referee 2, author's response, and author's changes in manuscript. At the end of this authors response, we provide a manuscript showing highlights to mark referee comments. Then follow by a marked-up manuscript showing highlight to mark modification by author. Final form without highlight is available as revised manuscript.

Comment 1:

Page-1

Line 14: Indicating the name of the university mentioned would provide more clear information.

Line 22-23: Do the authors have any reference for the earthquake parameters given?

Line 23-24: Do the authors have any reference for the numbers reported?

Response 1:

Page-1

P1 L14 version 1 manuscript. The name of the university is Tadulako University. We move it from abstract to paragraph in section 5 page 8 line 13-14.

P1 L22-23 version 1 manuscript. The earthquake parameters given are from Meteorological, Climatological and Geophysical Agency (Indonesian: Badan Meteorologi, Klimatologi, dan Geofisika, BMKG) (http://inatews.bmkg.go.id/?act=tsuevents and https://www.bmkg.go.id/press-release/?p=gempabumi-tektonik-m7-7-kabupaten-donggala-sulawesi-tengah-pada-hari-jumat-28-september-2018-berpotensi-tsunami&tag=press-release&lang=ID). The parameters are also available in BMKG's earthquake catalog.

P1 L23-24 version 1 manuscript. The numbers reported are from the Indonesian National Disaster Management Agency (Indonesian: Badan Nasional Penanggulangan Bencana, BNPB) which was broadcasted by media. We took one of them from https://nasional.tempo.co/read/1138400/jumlah-korban-tewas-terkini-gempa-dan-tsunami-palu-2-113-orang/full&view=ok

We add these references in the manuscript.

Changes in manuscript:

P8 L13-14 marked-up/revised manuscript.

"... This area has many private boarding houses for students of the University of Tadulako, the biggest university in the city of Palu." ...

P1 L19-21 marked-up/revised manuscript

.....

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). .....

P1 L21-22 marked-up/revised manuscript

..... As of October 21, 2018, as many as 2,113 people were killed, 1,309 missing, and 4,612 injured (Hadi and Kurniawati, 2018). .....

Comment 2:

Page-3

Line 2-5: "For tsunamis, post-incident surveys are often carried out. Major tsunamis such as: : :." Only stating some of the tsunami post-event surveys like "giving examples" may not be appropriate. Two suggestions: Either state the importance and relation of them with this study OR delete these sentences.

Line 9: "Observation of damage was also conducted." Too general sentence. What kind of damage data is collected? Any details on the data collection processes?

Response 2:

P3 L2-5 version 1 manuscript. We delete these sentences "For tsunamis, post-incident surveys are often carried out. Major tsunamis such as: : :."

P3 L9 version 1 manuscript. We emphasized damage to buildings and infrastructures. We identified the difference about damage by earthquake, liquefaction and tsunami. We made videos to document damage along Trans Sulawesi Road, compared them to Google Street View®, Google Map and Google Earth and concluded that the severe damage was limited in 150 m from coastline. We also measured dimension of a bridge because we assume it was special case we found. We add about this in paragraphs of the manuscript.

Changes in manuscript 2:

P2 L31-31 marked-up/revised manuscript

...... 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. .....

P5 L8-12 marked-up/revised manuscript

.....

Damage observation was carried out at each site of surveys. We emphasized on damage to buildings 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.

.....

Comment 3:

Page 9:

Line 14: “There were three main tsunami waves that reached the beach.” Which beach? Not clear.
Line 14: “The first wave was relatively low.” With respect to what? You should State it more clearly and in an understandable way.
Line 18: “The wave that hit the beach was quite high.” This sentence by itself does not provide any meaningful information.

Response 3:

P9 L14 version 1 manuscript. We modify “There were three main tsunami waves that reached the beach.” to be “Most people interviewed in the survey area testified that there were three main tsunami waves that reached the coastal zone in Palu Bay. The second was the highest.”.
P9 L18 version 1 manuscript. We replace “The wave that hit the beach was quite high” with “The tsunami waves that hit the coastal zone in Palu Bay were very strong, as indicated by massive damage at each site we surveyed. Severe damage was limited to within 150 m from the coastline. These include the shifting of a 56-ton bridge.”

Changes in manuscript 3:

P10 L5-7 marked-up/revised manuscript

..... Most people interviewed in the survey area testified that there were three main tsunami waves that reached the coastal zone in Palu Bay. The second was the highest. .....

P10 L1-2 marked-up/revised manuscript

..... The tsunami waves that hit the coastal zone in Palu Bay were very strong, as indicated by massive damage at each site we surveyed. Severe damage was limited to within 150 m from the coastline. These include the shifting of a 56-ton bridge. .....

Comment 4:

General Comments: - A brief summary and citation of previously published papers on 2018 Palu Event field survey is necessary. - Section 5.1, Aftershock information is not related with the focus of this study and the work done. - The conclusion section should be rewritten by clear sentences and providing a comprehensive summary of the results obtained. For example, Giving ranges such as “2 to10 m and the inundation distances were 80 to 500 m.” Or “The arrival time of waves varied from 3 to 10 minutes..” does not provide satisfying information. The authors, at least, may add the locations of these measurements.

Response 4:

Thanks for the suggestions. We provide a brief summary and citation of previously published papers e.g. Omira et al (2019), Mikami et al (2019), Yalciner et al. (2018), Muhari et al (2018), and Arikawa et al. (2018).
We remove section 5.1 about aftershock information which is also suggested by Referee 1.

We modify the sentences, the ranges of numbers are replaced by the maximum and significant run up height and inundation distance with mentioning the locations.
Your comments and suggestions are accomodated in our revised manuscript.

Changes in manuscript 4:

P3 L6-15 marked-up/revised manuscript

Many groups have carried out field surveys of the Sulawesi Tsunami event, also known as the Palu Tsunami. Muhari et al. (2018) investigated the 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 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). Mikami et al. (2019) measured runup height and inundation depth of 22 places and disscussed damage to coastal communities around Palu Bay. Putra et al. (2019) focused on tsunami deposits. 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 landslides detected in Palu Bay. These survey data can be combined with data from other groups. In this study, we provide data of runup height, inundation distance, flow depth/inundation depth, and damage at different points and coordinates.

P1 L13-15 marked-up/revised manuscript

The survey results show that the runup height and inundation distance reached 10.7 m in Tondo and 488 m in Layana, respectively. Inundation depth of 2 to 4 m were common at most of the site and the highest was 8.70 m in Taipa.

Version 1 manuscript. The red texts are parts with referee comments.

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 ranged from 2 to 10 m and that the inundation distance was between 80 and 510 m. The highest runup (10.5 m) was recorded in Tondo, a complex that has many boarding houses near a university. The longest inundation distance (511 m) was found in Layana, a marketplace. 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 earthquake event. The characteristics of the damage to buildings, facilities, and structures are also summarized. Several indicators of underwater landslides are described. The survey results can be used for the calibration and validation of hydrodynamic models for tsunamis. They can also be used for regional reconstruction, mitigation, planning, and development.

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 0.18°N 119.85°E at a depth of 11 km and 27 km northeast of Donggala City. 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. In addition, 66,238 houses were damaged. The source of the earthquake was the shift of the Palu-Koro strike-slip fault, one of the most active structures around Sulawesi. 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 Palu-Koro fault, which divides Sulawesi into two parts, has quite active tectonic activity. The movement of rock formations is 35-44 mm/year (Bellier et al., 2001). This is the second most active fault in Indonesia after the Yapen fault in Papua. 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 Bangkir, Tonggolobibi, and Donggala villages 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). The most 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 astonished earthquake and tsunami experts and researchers. Geologically, the area of the earthquake includes the Palu-Koro fault, an active strike-slip fault in Indonesia. For this type of fault, the plates move horizontally and thus do not usually cause enough vertical deformation to trigger a huge tsunami. However, the tsunami in Central Sulawesi destroyed property and caused many casualties. Several hypotheses have been proposed. One is that there was an underwater landslide, which was the driving force for the tsunami wave. To answer such questions and other questions that arise from a tsunami event, field surveys play an important role. For tsunamis, post-incident surveys are often carried out. Major tsunamis such as the 2004 Indian Ocean Tsunami and the 2011 Tohoku Tsunami require many teams to conduct surveys. Field surveys for the Indian Ocean Tsunami have been reported by Borrero (2005), Fritz and Borrero (2006), and Goff et al. (2006). Field surveys for the 2011 Tohoku Tsunami have been reported by Mori et al. (2011), Mikami et al. (2012), Liu et al. (2013), and Suppasri et al. (2013).

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 water depth on land was also measured in some areas. Observation of damage was also 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 numerical model, i.e. Boussinesq model and a nonlinear shallow water wave model. More broadly, these data can be used for disaster mitigation and rebuilding the affected areas of the 2018 Sulawesi Tsunami.

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 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.

Our survey covered the following activities: 1) gathering information about disaster-affected locations, collecting videos and photographs 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 a measurement site that can represent the impact of 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 hit by the tsunami; 6) observing and documenting specific damage and phenomena; and 7) interviewing eyewitnesses.

Because many people have smartphones, documentation in the form of photographs 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. We also recorded videos and took photographs.

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. Our 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. We operated a camera on a moving vehicle to record the situation around the beach area. This method is similar to that used by Google Street View®, but we used simpler equipment.

We chose 18 locations to measure (Fig. 1). These locations were used to represent runup and inundation data in Palu Bay. 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, as well as resources and time. Many locations with steep cliffs and tsunami trails were not easily visible. We did not take measurements in such locations. Likewise, we did not measure places not significantly affected by the tsunamis. 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 our team's return, 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. Fortunately, from the point of view of conducting a survey, surface runoff due to rain seems insignificant and does not erase the tsunami footprint. Our 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). Figure 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 they directly experienced the earthquake and tsunami. 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). Our team interviewed 56 people throughout the disaster area. Some of the interviews were recorded in video form so the testimonies can be heard again. We got some important information from the interviews, 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, the magnitude of earthquake shocks, and how to save themselves from the tsunami. We were told that there were 3 tsunami waves. The first wave had the smallest amplitude. Then, two waves followed it. The first wave was a warning so many people went away from the coastline immediately. 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. Our team operated several laser and optical instruments for terrestrial surveys. The instruments were a total station, a water pass, a prism, a handheld GPS device, laser distance meter, and some assistance tools. These tools were used to measure height differences and the distance from a point and position.

3 Runup and Inundation Observation

Runup is the maximum ground elevation wetted by the tsunami on a sloping shoreline. In the simplest case, the runup value is recorded at the maximum inundation distance, the horizontal distance flooded by the wave (IOC Manuals and Guides No. 37, 2014). Because of the difficulty of using a benchmark on land, we measured runup height to the local sea level at the time of measurement and then corrected it to above sea level on average using astronomical pairs of data collected from tidal stations in Mamuju and Pantoloan. Mamuju is located outside the bay, on the west coast of Sulawesi overlooking the Makassar Strait. Pantoloan is located inside Palu Bay. The measurement results are shown in Table 1 and Figs. 3-5.

From Table 1 and Fig. 3, the farthest inundation distance from coastline to tsunami border on land is at the Layana site. 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. The items scattered in the tsunami were predominantly manufactured goods of economic value. This site is thus monitored closely by security forces to prevent looting. 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 511 m inland. The farthest point reached in this area varies greatly because many buildings have long and wide walls that stemmed the tsunami flow further inland.

The highest point of the tsunami creeping was found at the Tondo site (Fig. 5). This area has many private boarding houses for students of the University of Tadulako, a state university in the city of Palu. 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. Eyewitnesses 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 12.20, 9.44, 11.61, and 9.97 m, respectively, as shown in Table 1. The runup height of 12.2 m (10.5 m after correction based on astronomical tides) is the highest at the Palu disaster area site. This area was flattened by tsunami (Fig. 6a), buildings collapse. This area is very crowded. 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 being quite nimble and able to save themselves when the tsunami arrived. This is an important observation for future mitigation efforts.

Records are also shown for sites 7, 8, and 9 (Lere, Besusu, and Talise, respectively). The area of these sites is at the end of the bay, has a sloping topography, the highest population, the most fatalities, and the worst damage. The runups were not very high (less than 2 m), but the inundation distance was relatively long (270-290 m). The density of buildings in this area seems to have prevented the tsunami from reaching further inland. Runup data from this survey can be utilized to support runup modeling especially for densely populated areas as promoted by Muhari et al. (2011).

4 Damage due to Tsunami

The Meteorological, Climatological and Geophysical Agency (BMKG) stated that the Sulawesi 2018 earthquake had a scale of Modified Mercalli Intensity (MMI) VIII (severe). Scale VIII MMI is characterized by minor damage to specially designed structures; major damage to ordinary large buildings with partial collapse; major damage to poorly constructed structures; the fall of chimneys, piles of factories, columns, monuments, and walls; and heavy furniture being turned over. Our team documented much of the scale VIII MMI evidence that could be seen in disaster areas. Some areas even had scale IX MMI. Damage to buildings and structures at the disaster site can be divided 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.

Liquefaction was a significant event in the disaster in Central Sulawesi. There are 3 locations of liquefaction with a large area and damage, namely Petobo and Balaroa in Palu City and Jono Oge in Sigi Regency. The corresponding areas of liquefaction were180 hectares, 48 hectares, and 202 hectares, and the numbers of houses damaged or destroyed were 2050, 1045, and 366, respectively. The land dropped by 3 m and rose by 2 m. Before the September 2018 incident, an investigation of potential liquefaction in Palu City and its surroundings was carried out by Widyaningrum (2012).

A reinforced concrete bridge on Cumi-cumi Road, Palu City (**Error! Reference source not found.**b), 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. This bridge has a relatively small span because it passes over a sewer from the city of Palu, not a large river. The sewer has a width of 4.1 m and a depth of 1.6 m. The width of the bridge is relatively large (two lanes). The bridge has14 beam girders with dimensions of 0.25 m × 0.30 m with a girder distance of 1.35 m. The bridge has simple support. The bridge plate has a thickness of 0.20 m. Based on these dimensions, the mass of the bridge was estimated to be around 38 tons. A large and perpendicular direction of the tsunami's velocity shifted the bridge by as far as 9.7 m without damage. The surface area of the bridge perpendicular to the direction of arrival of the tsunami is 3.4 m^2, including the area of the projected bridge fence. 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. 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 sewer 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). This phenomenon can be further analyzed to determine the tsunami force.

5 Additional Relevant Information

Several types of data obtained directly from sites or collected from agencies may serve as significant information for further analysis.

5.1 Aftershock

The aftershock data were collected from the Meteorological, Climatological and Geophysical Agency (BMKG). Figure 8 shows the distribution of aftershocks updated on October 18, 2018, at 09:00 West Indonesia Time. It can be seen that there were 561 earthquakes events for 20 days after the main earthquake with magnitudes of M_W 2.5-6. The frequency of the earthquakes decreased over time, 21 of the earthquakes could be felt by people. Among them, on the day of event, September 28, 2018, from main earthquake time to 06:21 p.m. there were aftershocks with magnitudes of M6.3, M6.2, M6.2, M4.7, M5.6, M5.0, and M6.1, respectively.

5.2 Tide

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. Figure 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 in Fig. 10, which is from the same source as that for Fig. 9. 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).

5.3 Tsunami Arrival Time

The time of arrival 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. Based on videos on social media, internet, and television, as well as eyewitnesses, more than one tsunami wave hit the beaches 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). Eyewitnesses did not give an exact arrival time of the tsunami wave on the beach. 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. These results can be used to verify the arrival time estimated by models using tidal data. The important thing from the September 2018 event is that the tsunami arrival time was very short.

5.4 Surface-earth Landslide

Our team found 16 locations for earth-surface landslides. Their locations are summarized in Table 3. These locations are in hilly areas, where the slope is 60°-80°. Locations 1 and 2 are in Oti Village, locations 3 and 4 are in Batusuya Village, and locations 5 to 16 are in Sindue Tombusabora sub-district. The landslides were caused by a series of earthquakes that occurred from 13:00 local time to the largest earthquake (magnitude: 7.5), which triggered the tsunami. Our team only recorded the coordinates of the locations of the surface landslides, not the landslide volumes. In addition, our team also only inventoried landslides that occurred along Jalan Toli-toli to Palu. Further investigation on geology or geotechnics may be needed to find a relationship between surface-earth landslides and underwater landslides. The detection of submarine landslidesis being conducted by various agencies, including the Indonesian Navy on board the KRI Spica 934 and the Technology Assessment and Application Agency (BPPT) with the Baruna Jaya 1 survey ship.

5.5 Underwater Landslide

A strike-slip fault earthquake with magnitude M_W = 7.5 should not have produced the large observed tsunami. The 2018 Sulawesi tsunami might have been generated by a mechanism other than the strike-slip earthquake. This suspected source should be located near the impacted areas with a relatively narrow width (Muhari et al., 2018). It is possible that a large submarine landslide contributed to and intensified the Sulawesi tsunami. The southern part of the Palu Bay, around latitude-0.82°S, is the most likely location of a potential landslide (Heidarzadeh et al., 2018). Sassa and Takagawa (2019) estimated that less than 20% of the Sulawesi tsunami height was related to tectonic processes, and that the majority was caused by coastal and submarine landslides, as characterized by liquefied gravity flows. On the contrary, by using coupled earthquake-tsunami physical-base model, Ulrih et al. (2019) resume that a source related to earthquake displacement in the strike-slip system is probable and that landsliding may not have been primary source of the tsunami in Sulawesi 2018 event. So far, source of tsunami in Sulawesi is still in discussion.

Some evidence from videos and eyewitnesses indicates that landslides or coastal land subsidence occurred inside Palu Bay area. Therefore, the Indonesian Navy deployed the KRI Spica Ship, a new survey vessel equipped with a multibeam echosounder, to record underwater data on October 15, 2018, after the tsunami. The Agency for the Assessment and Application of Technology (BPPT) sent a Baruna Jaya 1 survey ship to conduct a bathymetry survey of Palu Bay after the tsunami. Although the focus of our team was to measure runup and inundation, we also obtained evidence that might be related to underwater landslides. Total collapses and flows of coastal land due to liquefaction occurred in at least nine locations (Sassa and Takagawa, 2019). We found two of them with indicators of land subsidence on the coast. The two locations are around the river mouth in Donggala City (Figs. 11 and 12) and around the river mouth of Lero Village (Figs. 13 and 14).

6 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 ranged from 2 to10 m and the inundation distances were 80 to 500 m. The highest runup (10.5 m) was in the Tondo area, which has a steep slope coast. The farthest inundation (503 m) was in the Layana area, which has a flat topography. There were three main tsunami waves that reached the beach. The first wave was relatively low. Almost all beaches in Palu Bay were hit by tsunami waves. The arrival time of waves varied from 3 to 10 minutes after the $M_W = 7.5$ main earthquake event (between 18:05 and 18:15 local time). The worst damage was at the end of Palu Bay. The results of this field survey can be used for the calibration and validation of hydrodynamic models for tsunamis.

The wave that hit the beach was quite high. A reinforced concrete bridge weighing 38 tons at the end of the Palu bay was shifted by 9.7 m without damage. This indicates that the tsunami wave in Palu has great momentum. The tsunami force needs to be further analyzed to provide valuable data for reconstruction. Land subsidence in Donggala City (10,068 m^2) and Lero Village (22,971 m^2) gives evidence for underwater landslides. However, it does not mean there were only two underwater landslides; more landslide locations may be found in the disaster area. This event is motivation for 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 for Indonesia by Horspool et al. (2014). 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. Earthquake after shock graphics was from Meteorological Climatological, and Geophysical Agency (BMKG). Tide data 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.

Acknowledgement

This research was financially supported by the Ministry of Science and Technology, Taiwan, under grants MOST 107-2221-E-006-080 and Water Resources Agency, MOEA, under grants MOEAWRA 1080412. Thanks to Universitas Jenderal Soedirman, Indonesia, especially the Department of Civil Engineering and the Community Service Institution (LPPM Unsoed), which mobilized surveyors, students, and instruments to the disaster area. In addition, we highly appreciate Mr. Arvandi from the Agency of Public Works and Community Housing, Division of Municipal and Water Resources, Central Sulawesi Province for special assisstance during our activities in the Palu Bay area.

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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. Inundation depth of 2 to 4 m were common at most of the site and the highest was 8.70 m in Taipa. 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 infrastructure 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°S and 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 surprised the 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 uncertain whether the tsunami was caused by co-seismic deformation or non-tectonic sources. Ulrich et al. (2019) (Ulrich et al., 2019) believe that a source related to earthquake displacements is probable and that landsliding may not have been the primary source of the tsunami. In contrast, Takagi et al. (2019), Sassa and Takagawa (2018), and Arikawa et al. (2018) believe that landslides produced the tsunami. Field surveys are important for determining the actual cause.

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 observations of damage to buildings and infrastructure were 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 numerical models, namely the Boussinesq model and a nonlinear shallow water wave model. Yalciner (2001) conducted a field survey and modeled the 1999 Izmit tsunami, which is similar in terms of geographical features, earthquake magnitude, and tsunami mechanism compared with the recent Sulawesi Tsunami. 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, also known as the Palu Tsunami. Muhari et al. (2018) investigated the 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 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). Mikami et al. (2019) measured runup height and inundation depth of 22 places and disscussed damage to coastal communities around Palu Bay. Putra et al. (2019) focused on tsunami deposits. 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 landslides detected in Palu Bay. These survey data can be combined with data from other groups. In this study, we provide data of runup height, inundation distance, flow depth/inundation 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 October11, 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, the cleaning of area impacted by the tsunami was still in progress, and thus 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 sites that were significantly impacted 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 the 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 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. From the earthquake incident until 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 challenging to find tsunami footprints on surfaces exposed to surface runoff caused by rain. 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 people survived the tsunami. Witnesses stated that there were three 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 escaping 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 the survey using WXTide software version 4.7, available at www.wxtide32.com/index.html. We used Donggala station, the closest station listed in the software, for corrections and assumed no significant variations in sea level inside Palu Bay.

Damage observations were carried out at each site of the survey. We emphasized damage to buildings and infrastructure, although other kinds of damage were noted, such as that to vegetation, the shoreline, and property (e.g., cars, boats). Videos and photographs were produced to assess the damage. Videos recorded along Trans Sulawesi Road were compared to Google Street View, Google Maps, and Google Earth data to assess the distance from damaged regions to the coastine. In addition, detail measurements of the dimensions of special objects (e.g., bridge) was done to facilitate tsunami force analysis.

3 Inundation and Runup Measurements Results

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 are corrected based on the tides. Runup height and inundation distance vary from site to site.

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

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

The eastern coast area of Palu Bay included Sites 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 that was carried away, and fixed debris. A survivor showed us the highest places of the tsunami water in this area. A total of four cross sections of the 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. The highest runup found in the field survey of Omira et al. (2019) was in Benteng Village, with a height of 9.1 m. Benteng Village (on the western coast) is viz-a-viz with the highest runup location found in our survey (Tondo, on the 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. This was the longest distance recorded. The runup points reached 6.57 and 2.78 m at this site. Both points varied greatly because many buildings have long and wide walls that stemmed the tsunami flow further inland.

Sites 12 and 13 are Mamboro and Taipa. A runup height of 3.5 m and a flow depth of 5.36 m caused severe damage to houses and casualties in Mamboro. In Taipa, a runup of 4.88 m reached the roof of the 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, 185.13 and 5.14 m respectively). Site 16 (Lero) is the northernmost survey site inside Palu Bay. This site faces Site 1, which also lies at the mouth of Palu Bay. The last two sites were Tanjung Padang and Lende. These sites are located outside Palu Bay and close to the epicenter. A runup of around 1 m was found at both sites. The coastal area between Sites 16 and 17 has steep slopes (hilly area). No tsunami footage was found for this area.

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 9 show 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 for 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 sunsetcalled "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" (or "adhan", "azan", "athan") and the second call is called "iqamah" (or "iqama", "iqamat"). 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. It was around 3 minutes in Donggala City and Lero Village, and around 10 minutes at the end of Palu Bay (Lere, Besusu Barat, and Talise) after the main earthquake. The testimony from the witnesses was consistent with the tidal gauge data at Pantoloan station. The important note from the September 2018 event is that the tsunami arrival time was very short.

5 Building and Infrastructure Damage

We categorized damage to buildings and structures caused by the Sulawesi Tsunami into three 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 Sites 1 to 6. Site 1 (Donggala City) is located at the mouth of the bay. This site has a fishing port and an inter-island port. A fisherman who survived the tsunami told us that he was on a ship when the tsunami struck. He saw turbulent water not far from the position of the ships in the vicinity of the port of Donggala. This water propagated towards the warfs in the ports, causing a fishing boat to rise to the dock.

Sites 2 and 3, namely Loli Dondo Village and Loli Saluran Village, have the same characteristics, with many houses built on the right and left sides of the Trans Sulawesi Road. The housings closest to the beach were mostly destroyed, and those closest to the hillside had moderate damage.

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

The sites on the southern coast of the bay, Sites 7 to 9 (Lere, Besusu Barat, and Talise) at the end of Palu Bay, have a sloping topography and the highest population. They had the most fatalities and the worst damage. In Besusu Barat, a steel bridge with a span of 300 m collapsed. 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 that the depth of the tsunami flow reached 4.89 m. The density of buildings in this area seems to have prevented the tsunami from reaching further inland. Most of the victims were at this site because it is a densely populated area, with many offices and a lot of business activity as well as open public spaces. In addition, the Palu Nomoni festival, which attracted large crowds, was taking place at the time of the tsunami on Besusu and Talise beaches and surrounding areas.

Survey sites in the eastern coast area of Palu Bay were Sites 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) because few buildings survived in this area. This area was very crowded during 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 having the agility to save themselves when the tsunami arrived.

North of Tondo is Site 11 (Layana). This site is a trading 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.

Sites 12 and 13 are Mamboro and Taipa, respectively. A high flow depth of 7.79 m caused severe damage to houses and casualties in Mamboro Village. A stream was covered fully by debris. In Taipa Village, the runup (4.88 m) and flow depth (8.40 m) devastated the passenger terminal, ferry crane, and navigation control building. Taipa is a passenger port that connects Sulawesi island to other islands. Site 14 (Pantoloan) is the biggest port in the bay. Here, containers floated off and the port crane collapsed. North of Pantoloan Port is Wani Port (Site 15). Here, we found terrible damage, especially to the houses of the fishing community, collapsed coastal structures, and a ship that was lifted onto land. Runup, inundation, and flow depth were significant at this site. Site 16 (Lero) is the northernmost survey site inside Palu Bay. This site faces Site 1 (western coast), which also lies at the mouth of Palu Bay. A small harbor and its facilities were totally destroyed. The last two sites were Tanjung Padang and Lende. These sites are located outside Palu Bay and close to the epicenter. The tsunamis were similar to tide waves. They destroyed some houses and agricultural land. The coastal area between Sites 16 and 17 has steep slopes (hilly area). It has very few houses. No tsunami impact was found.

We made videos to document the damage along the Trans Sulawesi Roadand compared them to Google Street View® data recorded before the tsunami occurrence. The videos showed that severe damage was limited to within 150 m from the coastline. The impact of the tsunami on structures and the coastal environment is summarized in Table 2.

Detail measurements were taken of a reinforced concrete bridge with simple support beams on Cumi-cumi Road, near Palu Grand Mall, Palu City (Fig. 6(b)). This bridge shifted by as far as 9.7 m. It provided clues regarding the strength of the tsunamis. 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 and a girder distance of 1.35 m (its sketch is available in the supplement). 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 estimated to be around 56 tons. The bridge was estimated to have been submerged by tsunami water as deep as 3.0-4.5 m based on the tsunami marks around it (Site 7 / Lere). Debris caught in the bridge fence (Fig. 6(b)) 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 investigated this case with the help of Google Earth, as shown in Figs. 7(a) and 7(b), which 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 the 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 additional locations of coastal landslides. These are landslide locations not found by other survey teams. 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 lost.

In Lero Village, some houses and their inhabitants drowned when the tremor struck. Fig. 12 shows a house going down, with the ceiling at the position of the original floor. A typical house in Indonesia has a ceiling height of 3 to 4 m. This indicates that the landslide in Lero Village lowered the land surface by 3 to 4 m. In addition, an eyewitness reported that the seabed around 10 m from the coastline changed from 1 m deep to a depth that made the seabed invisible to the naked eyes. He heard a 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 height reached 10.73 m in Tondo and the inundation distance was 488 m in Layana. The Tondo area has a steeply sloped coast where as the Layana area has a flat topography. Flow depths of more than 2 m were found at sites that had significant damage. Tsunami events were concentrated in the bay, which indicates local tsunamis. Most people interviewed in the survey area 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 the waves varied according to location. It was around 3 minutes in Donggala City and Lero Village, and around 10 minutes at 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. Severe damage was limited to within 150 m from the coastline. These include the shifting of a 56-ton bridge. The 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) are additional evidence of the coastal landslides found by other teams. 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.

Acknowledgement

This research was financially supported by the Ministry of Science and Technology, Taiwan, under grants MOST 107-2221-E-006-080 and Water Resources Agency, MOEA, under grants MOEAWRA 1080412. Thanks to Universitas Jenderal Soedirman, Indonesia, especially the Department of Civil Engineering and the Community Service Institution (LPPM Unsoed), which mobilized surveyors, students, and instruments to the disaster area. Authors highly appreciate Mr. Arvandi from the Agency of Public Works and Community Housing, Division of Municipal and Water Resources, Central Sulawesi Province for special assisstance during our activities in the Palu Bay area. In addition, the authors also highly appreciate Mrs. Sanidhya Nika Purnomo for our disscussion on geographical information.

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Table 1 Measured sites (see also Fig. 1 – 5)

No.	Site name	Measurement time	Coordinates		Inundation distance (m)	Runup height (m)	Inundation depth (m)	Watermark
			Longitude	Latitude				
1.	Donggala City	12-Oct-18 16:34:08	119.741313	-0.663054	25.60	2.25	-	BL, SD
2.	Loli Dondo	16-Oct-18 15:27:28	119.776100	-0.731612	65.36	2.50	-	BB, BV, DS
			119.776664	-0.731339	-	-	2.10	
3.	Loli Saluran	16-Oct-18 14:16:54	119.794095	-0.783867	118.49	2.18	-	BB, BV, DS
4.	Watu Sampu	16-Oct-18 12:48:04	119.810032	-0.822144	71.51	6.63	-	BL, BV, DD, EW
			119.810746	-0.821815	-	-	7.63	
			119.810484	-0.821851	-	-	3.68	
5.	Tipo	17-Oct-18 10:25:41	119.829355	-0.864574	91.11	7.79	-	DS, EW
6.	Silae	17-Oct-18 15:08:35	119.834315	-0.874580	80.13	4.53	-	DD, DS, GD
7.	Lere	15-Oct-18 14:30:19	119.843401	-0.885372	228.22	1.40	3.90	DD, DS, GD
			119.843921	-0.883389	-	-	3.71	
			119.845245	-0.884549	-	-	4.64	
8.	Besusu Barat	16-Oct-18 8:20:46	119.860210	-0.887457	250.35	1.12	3.25	BB, DD, DS, GD
			119.862034	-0.885743	-	-	4.89	
			119.860762	-0.885652	-	-	2.22	
			119.860110	-0.885546	-	-	3.28	
9.	Talise	15-Oct-18 8:12:18	119.873739	-0.876266	254.23	2.79	-	BB, DS, GD, EW
			119.874616	-0.873833	-	2.94	-	DD, DS, GD
			119.874389	-0.874440	-	3.02	-	DD, DS, GD
			119.874294	-0.875004	-	2.71	-	DD, DS, GD
			119.873755	-0.874115	-	-	2.48	
			119.872371	-0.874472	-	-	2.68	
10.	Tondo	14-Oct-18 12:58:26	119.881499	-0.844691	270.27	10.73	-	DC, DD,DS, EW
			119.880688	-0.843981	-	7.97	-	DC, DD, DS, EW
			119.881253	-0.845850	-	10.14	-	DC, DD, DS, EW
			119.880854	-0.846571	-	8.5	-	DC, DD, DS, EW
			119.880408	-0.844700	-	-	7.39	
			119.880640	-0.846648	-	-	4.20	
11.	Layana	14-Oct-18 7:45:14	119.887135	-0.822159	487.84	6.57	-	DD, DS, GD, WW
			119.883472	-0.823863	-	2.78	-	DD, DS, GD
			119.883352	-0.823840	-	-	4.44	
			119.883470	-0.823864	-	-	4.35	
			119.884453	-0.820980	-	-	4.18	
12.	Mamboro	13-Oct-18 13:43:47	119.879074	-0.801753	164.08	3.48	-	DC, DD, DS, EW
			119.878349	-0.800542	-	3.68	-	DC, DD, DS, EW
			119.877522	-0.801852	-	-	5.52	
			119.877164	-0.801229	-	-	7.79	
			119.877384	-0.800166	-	-	2.44	
13.	Taipa:	17-Oct-18 8:56:31	119.858686	-0.778698	110.94	3.15	-	BV, DS, EW
			119.859367	-0.779472	-	4.52	-	BV, DS, EW

			119.859542	-0.779995	-	4.88	-	BV, DS, EW
			119.858177	-0.778752	-	-	8.40	
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	-	BL, DD, EW, MO
			119.841150	-0.694111	-	-	5.14	
			119.842266	-0.694969	-	-	2.84	
16.	Lero	17-Oct-18 11:27:51	119.812422	-0.629011	75.80	1.77	-	DS, EW, WW
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 (photos are available in supplement)

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, bridge
8	Besusu Barat	Urban area, offices, business	Collapsed 300-m steel 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, damaged port area
16	Lero	Settlement, agriculture	Houses sunk by liquifaction
17	Tanjung Padang	Agriculture	Damaged houses and crops
18	Lende	Agriculture	Damaged houses and crops

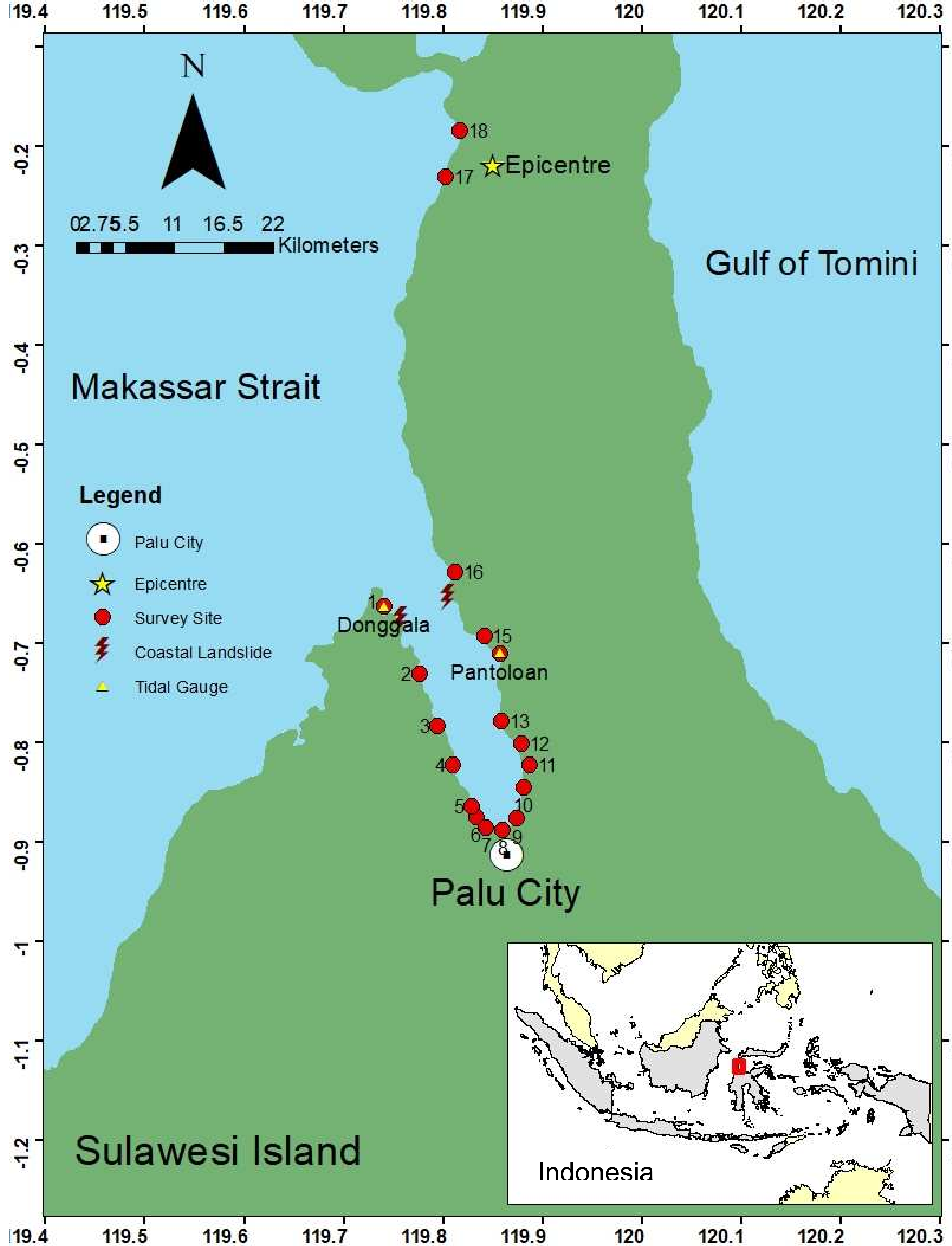

Figure 1: Survey area of Palu Bay located on Sulawesi island. Survey sites followed the Trans Sulawesi Road paralleled Palu Bay coastline from Site 1 to Site 18. Tidal stations were at Site 1 (Donggala) and Site 14 (Pantoloan). Coastal landslides were detected at Site 1 (Donggala) and Site 16 (Lero).


(a)
10.14.2018
(b)
10.13.2018
(c)
10.14.2018
(d)
(e)
(f)
6 m
(g)
(h)
10.14.2018
(i)
10.14.2019
(j)
Sediment deposit
(k)
(l)

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 a survivor in Mamboro.

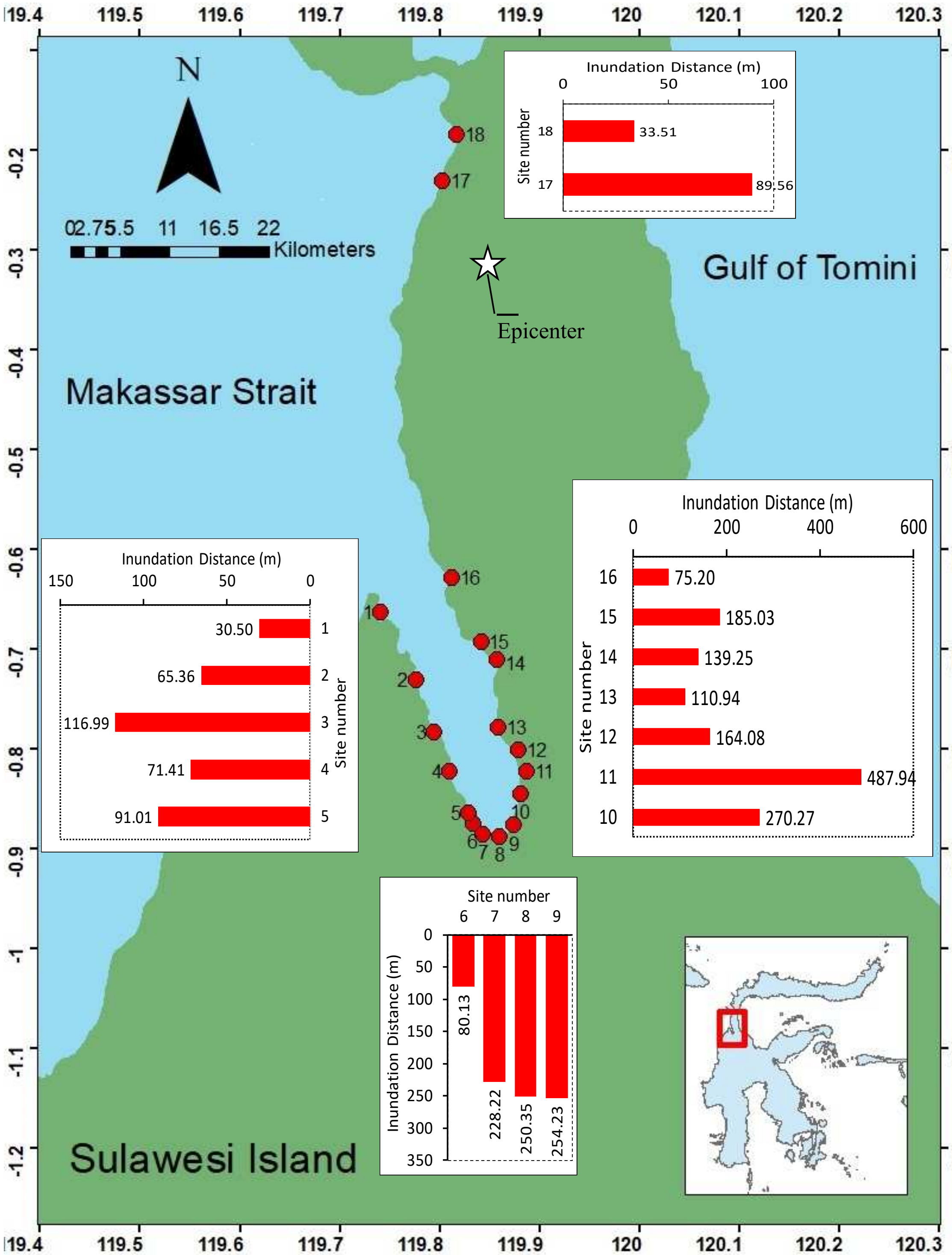

Figure 3: Measurement results of inundation distances.

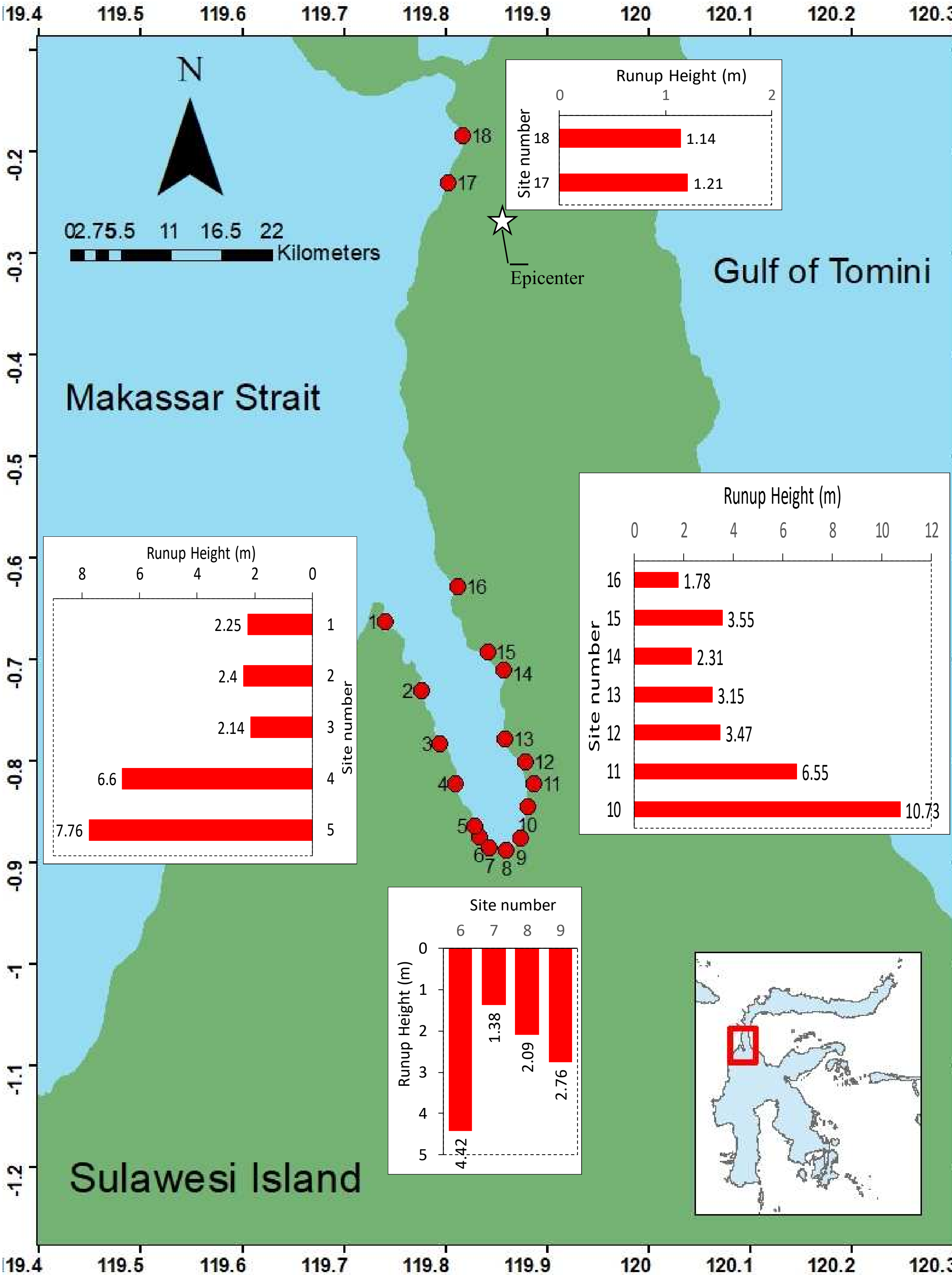

Figure 4: Measurement results of runup heights.

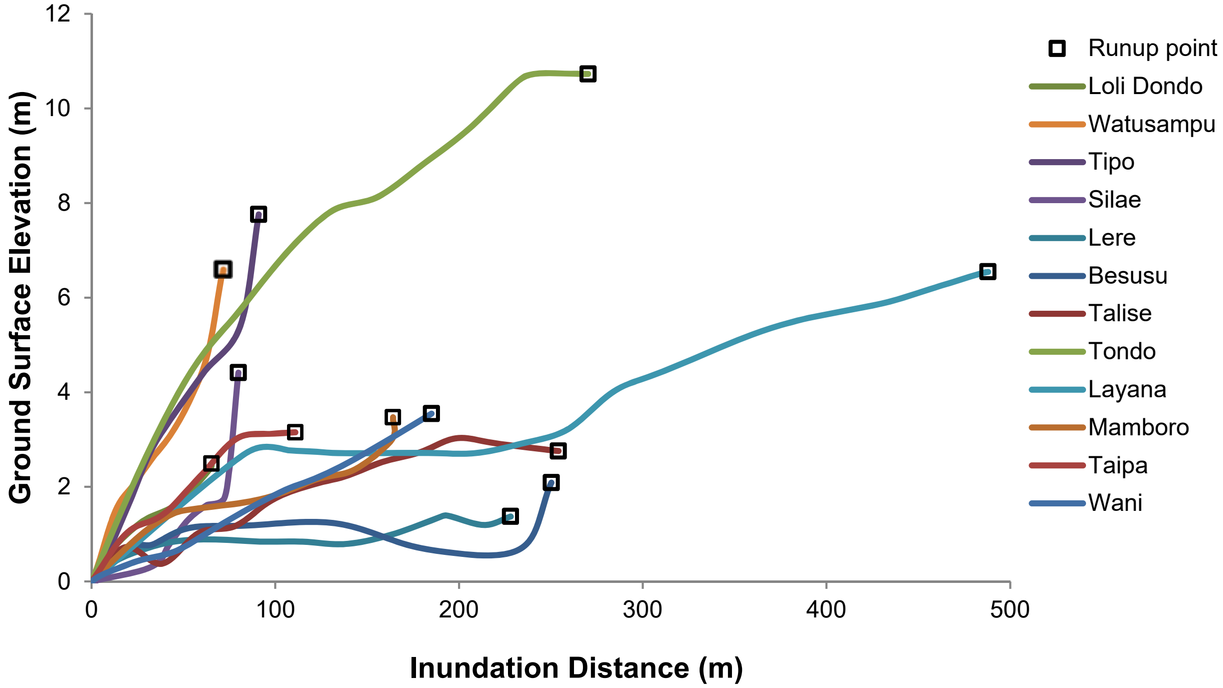

Figure 5: Transects of beach where tsunami wave arrived. The longest inundation distance is at the Layana site and the highest runup is at the Tondo site.

(a) (b)

(c) (d)

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, (b) a reinforced concrete bridge on Cumi-cumi Road Palu City shifted by 9.7 m by the tsunami,(c) Mamboro Village with 90% of houses destroyed, and (d) asphalt layer of small road turned 90° in Tondo.

(a) (b)

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

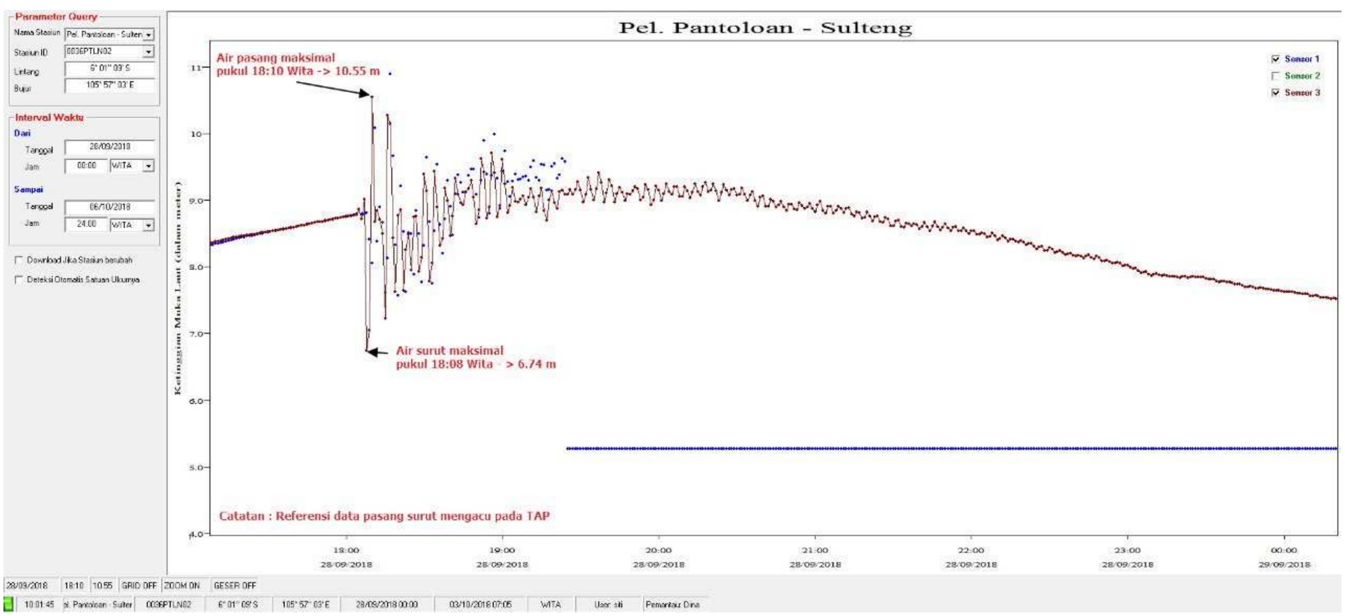

Figure 8: Water level recording at the Pantoloan tidal station managed by the Geospatial Information Agency (Sudibyo, 2018).

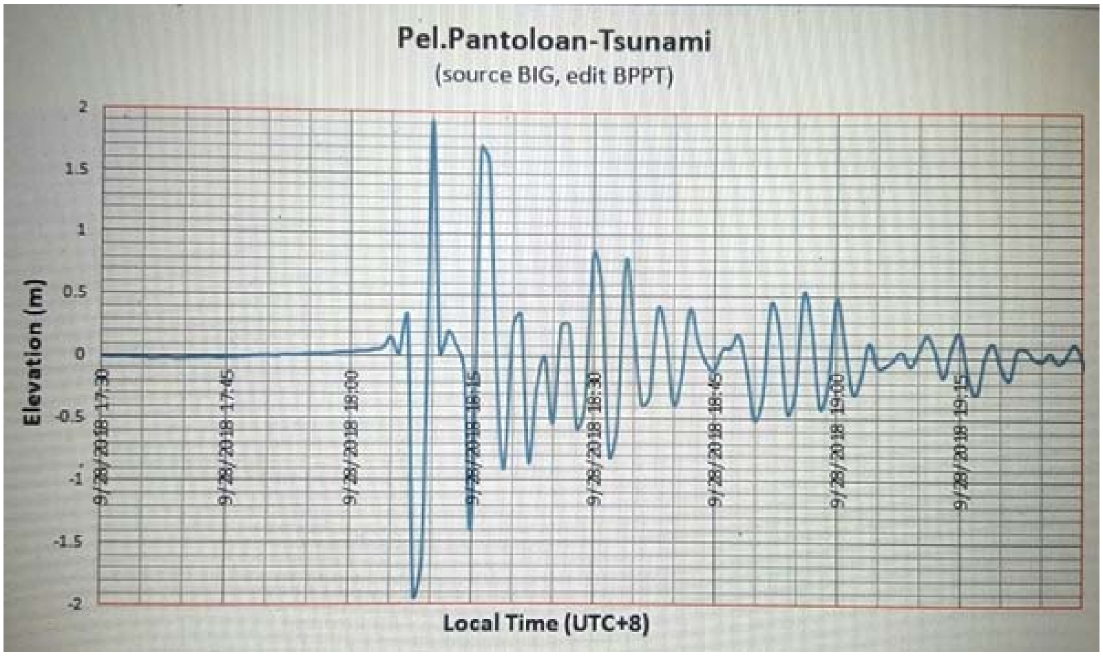

Figure 9: Magnified view of Fig. 8, sourced from the Geospatial Information Agency (Sudibyo, 2018).

(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.