

The manuscript submitted by Dr. Zorn and the colleagues shows the potential of tsunami hazards with volcanic origins in Southeast Asia (Indonesia, Papua New Guinea, Philippines, India, etc.). The authors focused on various factors of 131 volcanoes, such as topographic features, recent volcanic activity, tsunamigenic history in the past, which are considered closely related to tsunami potential, and used a Multicriteria Decision Analysis (MCDA) for the hazard assessment. Then, they found 19 with particularly high tsunami hazard potential, some of which less known and monitored.

While their assessment could not avoid their subjectivity in their definitions of the weights and the points in MCDA, the presented assessment that widely covers major volcanoes in this region is useful to consider tsunami potentials and for further consideration of volcanic tsunami potential at each volcano. I think this manuscript still has some parts to be improved, as listed below, but I believe that this manuscript has the potential to become suitable for publication from NHESS after major revisions.

Reply: We thank the reviewer for this assessment.

[Major comments]

1. The objectivity of each factor used in MCDA

In MCDA, the authors considered different factors (H/D-Ratio, Volcanic activity, Tsunamigenic history, Slope angle, and Hazardous Features [Underwater extent, Morphological features, Vegetation, Hydrothermal alteration, Topography between an edifice and the sea]). I suppose that these factors are different in terms of objectivity and uncertainty; in other words, some are objective, while others contain error or subjectivity. For example, H/D-Ratio, slope angle, volcanic activity (if limited to recent activity), and underwater extent are based on rather reliable data. On the other hand, tsunamigenic history should contain many missing events (as the authors mentioned), morphological features cannot be simply quantitatively related to the hazard assessment, the effects of vegetations on edifice stability would depend on their type, etc... I recommend that the authors first use only "more objective" factors, and then add "less objective factors" (at least, please show results only with "more objective" factors, in the supplementary). It would be very helpful for readers' understanding of what are the main factors determining the potential of volcanic hazards.

Reply: We agree with this comment and now firstly separate both objectivity and subjectivity more clearly:

Page 6 line 138: "We consider the following five factors and point systems for the ranking. Each represents a set of data that can be recorded or quantified objectively, which is then assigned a subjective but consistent point scale in order to create a comparable hierarchy:"

Secondly, we also comment on the reliability or uncertainty of the factors the reviewer pointed out:

Page 8 line 228: “Morphometry, here meaning H/D-ratio and slope angle, measure both the feasibility of gravitational mass movements (flank collapses or PDCs) reaching the sea, as well as quantify oversteepening of individual flanks. This data also represents the most reliable quantitative data in our ranking as it can be precisely measured.”

Page 8 line 232: “In turn, we decided to weigh the Hazardous Features less since these are not quantitatively determined and more prone to human subjectivity and misjudgement. Thus they are less reliable.”

Thirdly, we go on to use these separations as a justification for our (still subjective) choices for the factor weights. We can weigh factors less if we do not trust them and give this factor less importance. This is why e.g. the hazardous features were only weighted at 10%. We add a short explanation:

Page 8 line 228: “For the factor weights, we have to choose values based on the importance of the factor data. A higher weight of a factor will result in a larger impact of this factor on the final score and thus make it more important. Here too, these choices are largely subjective, but allow reducing the impact or importance of e.g. less reliable factor data and in-turn raise the impact of more reliable factors. We decided to favour morphometry and eruptive activity over the other factors.”

Finally, for the separate list the reviewer requests here using only reliable factors, we would refer to our interactive excel sheet which can be freely adjusted for that purpose. If e.g. the hazardous features (as the least reliable factor) should be removed, its weight could simply be set to 0% while increasing the others (see instructions on the sheet).

Page 15 line 323: “A complete, more detailed, and interactive version of this list with individual entries relating to how the points were counted can be found in supplementary material B.”

2. Similar factors in MCDA

Factors of morphological features and hydrothermal alteration seem to be related to the factor of volcanic activity. It seems that these related factors increase the scores for volcanoes that recently erupted. Please show how these factors are correlated with each other. If the correlations are large, some of the factors might be removed.

Reply: We fully agree that further clarifications and an improved explanation is needed. The factors we used are, in fact, largely independent and do not correlate on the scoring. We specifically pick up the reviewer example of hydrothermal alteration and volcanic activity and add a statement highlighting this point in the limitations as follows:

Page 14 line 290: “Conducting a comparative ranking can be more challenging if there are major dependencies between the used factors. As an example for our case, it would be reasonable to assume that recent eruptive activity would more likely cause hydrothermal alteration, thus making the eruptive history and hazardous features factors interdependent. However, in our catalogue, only few volcanoes are recorded to have extensive hydrothermal alteration on their flanks and for many of these, no eruption occurred for decades to centuries (e.g. Manuk, Teon, Serua). Hence, we think that these issues are unlikely to significantly affect our results. The only exception is a direct dependence between the H/D-

ratio and the slope angle as it is essentially the same value if the volcano is close to the coast, however the separation does allow for a more distinct look at volcanoes that may be far from the coast, but still have steep slopes on a local level.”

3. Potential spatial impact of volcanogenic tsunamis

The map in Fig. 7 does not add any important information, since the heat map of the volcanic tsunamis' spatial impact shows high density around the high-hazard volcanoes, which is obvious. Also, the assessment of the spatial impacts only based on the tsunami travel times is disappointing. To consider the hazard, tsunami amplitudes on coasts should be taken into account. I understand that it is difficult to assume complex volcanic tsunami sources, the authors are recommended to conduct numerical simulations using linear long-wave models, at least with a simple tsunami source model (for example, a Gaussian-shape uplift on the sea surface).

Reply: We appreciate this comment and make multiple improvements and clarifications to the text and figures. Indeed, we do not include information on tsunami amplitudes or run-up on coasts. This is intentional as a reliable assessment of volcano-generated tsunami wave amplitudes requires knowledge of many of yet unknown source parameters. Specifically, there are multiple potential processes at volcanoes which may generate a tsunami (explosion, flank collapse, PDC etc.). Each of them has a specific set of parameters describing magnitude, direction, etc. and each of them would result in highly different wave amplitudes. Reliable modelling of volcanogenic tsunamis requires thorough collection and evaluation of these specific source parameters, in addition to the advanced numerical techniques beyond classical nonlinear shallow water (NLSW) algorithms, and is usually applied to specific singular (historical) events. Incorporating such modelling for multiple volcanoes at once (in a ranking study like present) would not only be highly demanding, but, without constraining all the principal source parameters, also highly speculative. This also holds true for simpler Gaussian-shape uplifts as the magnitude of uplift would have to be defined based on speculation. Also, a Gaussian-shape source cannot account for any wave directivity which is typical for flank collapses, which is an issue that would become relevant when specific wave heights are considered.

Instead, we would like to avoid producing highly unconstrained results and pursue a more meaningful approach by limiting our models to the spatial tsunami extent in time and the length of the potentially affected coast. Note that these simple tsunami travel time models have the advantage that they are independent from the wave height and the generation mechanism (as long as it is a point source), so we can make meaningful assessments without assuming a yet unknown tsunami source.

Firstly, we address this issue by clarifying the aim of the modelling. We particularly emphasise that predictive models (e.g. Giachetti et al. 2012) require in-depth understanding of specific local factors::

Page 24 line 451: “Consequently, predictive studies remain rare (Giachetti et al. 2012; Paris et al. 2019) and are only possible because the specific local circumstances leading to the tsunami are very well understood, which is knowledge that is lacking for most coastal volcanoes. Here, we provide multiple

predictive models for the volcanoes we classified as posing a high tsunamigenic hazard. As volcanogenic tsunamis are caused by a large variety of mechanisms (Fig. 6) we contribute to this aspect by providing a simplified and broader view at the travel times of potential future tsunamis that are unspecific to the mechanism of tsunami generation and their magnitude (with the possible exception of meteotsunamis as seen at Hunga Tonga Ha'apai in 2022, which appear to have different wave propagation properties). We mainly account for the potential spatial impact of volcanogenic tsunamis and extend our tsunami hazard evaluation by assessing the total length of a coastline affected within one and two hours of tsunami propagation for the volcanoes categorised as high hazard in our ranking (except Didicas)“

Secondly, we highlight that the amplitudes and wave heights cannot be considered, but that comes with the advantage of the tsunami source independence.

Page 24 line 455: “This means that we can simulate the travel and arrival times of specific volcanoes independent of how the tsunami was generated (as long as it is a point source), but we also cannot consider specific wave heights or runup as these depend strongly on the specific source mechanism and magnitude of the event and require additional and much more specific modelling data for individual sites.”

Page 26 line 475: “While our models are limited to the travel time, they can be used to estimate the warning time for shores in case a tsunami occurs at one of the considered volcanoes.“

Thirdly, we agree with the reviewer and recognize the value of models with specific wave heights. While we prefer our simplified broader models, we instead provide an additional paragraph summarising some previous studies specific to single volcanoes and historical events:

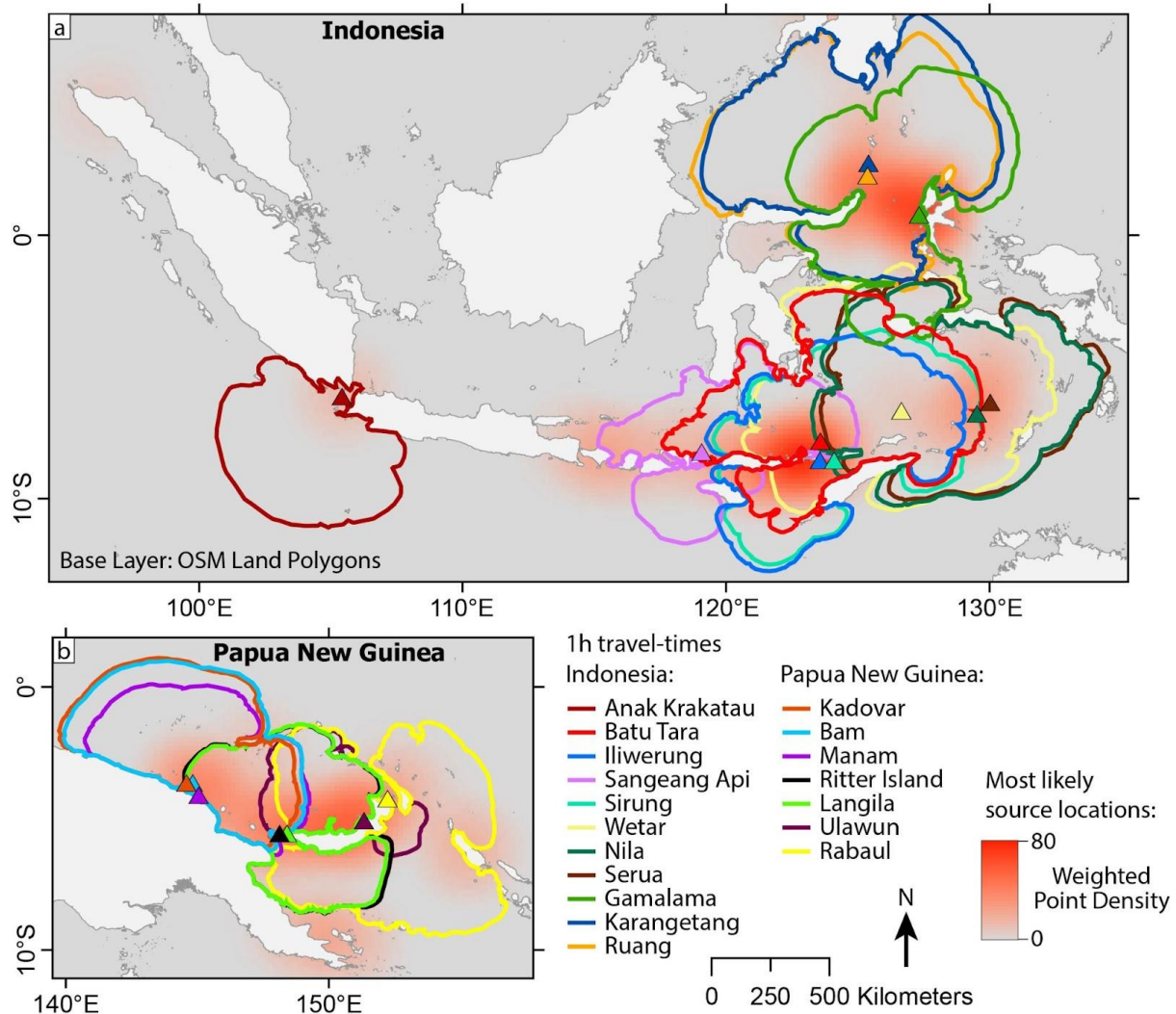
Page 23 line 444: “In order to assess the risks and impacts of volcanogenic tsunamis, numerical simulations are commonly used, both for distinct future scenarios and in retrospect for past events. For Southeast Asia, a large number of such studies had been conducted. Most models were done for Anak Krakatau looking specifically at the 2018 flank collapse with some using the known event to calibrate and confirm the quality of current simulation methods (Grilli et al. 2019; Borrero et al. 2020; Mulia et al. 2020; Omira and Ramalho 2020; Paris et al. 2020; Zengafinnen et al. 2020), some using the known tsunami data (e.g. from tide gauges) to identify source parameters (Heidarzadeh et al. 2020; Ren et al. 2020; Grilli et al. 2021) and some testing variations in the source parameters to characterise potential future events (Dogan et al. 2021). In general, the consensus is that a landslide between 0.1 and 0.3 km³ volume that occurred both with a subaerial and a submarine component is mostly consistent with the observed and modelled runup heights at the adjacent shores. Similar models also exist for the 1883 tsunami at Krakatau, with the main purpose being the identification of its generation mechanism (Maeno and Imamura 2011) and how such a tsunami propagates in the far-field (Choi et al. 2003). Predictive studies only considering possible future events are not as abundant, but have been done for Anak Krakatau before the 2018 tsunami (Giachetti et al. 2012; Badriana et al. 2017), with Giachetti et al. (2012) making a remarkably close prediction to the later event. Other volcanoes in Southeast Asia are not as commonly considered. Pranantyo et al. (2021) test the tsunami propagation from Ruang volcano, Indonesia, using and comparing both historical observations and data from the 2018 Anak Krakatau event and reproducing a 25 m runup in the near-field. In Papua New Guinea numerical tsunami models have almost exclusively been considered for the Ritter Island tsunami in 1888 and the reconstruction of its generation (Ward and Day 2003; Karstens et al. 2020). Similarly, numerical tsunami models in the Philippines are mostly limited to Taal volcano, where models are based both on a past tsunami in 1716 (Pakosung et al. 2020) and a predictive study considering scenarios with different explosion sites and energies (Paris et al. 2019). Considering these works, it is clear that tsunamis sourced by volcanoes can be well explained with numerical models, but the considered volcanoes remain limited to a few select sites and scenarios. These

models are also typically restricted to one particular volcano and one specific mechanism of tsunami generation as a retrospectively investigation.”

We also make a brief point that our travel-time models could be supplemented with more specific scenario models in future studies.

Page 26 line 489: “For future hazard and risk assessments, we thus recommend supplementing the knowledge from our TTT-models with specific detailed scenario calculations using established numerical modelling approaches, particularly for those high-hazard volcanoes where no such models exist (e.g. Batu Tara, Iliwerung, Nila).”

Lastly, regarding the heat-map in Fig. 7, while it may seem obvious, highlights the most likely areas for tsunamis to occur. We think this is important to keep as many of the hazardous volcanoes in the highlighted areas have received little attention and study, which is what we point to with our figure. Here we improve the figure by combining it with Fig. 8 to create a more condensed version and to avoid confusion with our travel-time modelling



[Minor comments]

Title: As the authors mentioned, submarine volcanoes are not considered in this study. Hence, it would be better to add such as subaerial volcanoes, volcanoes on land, or equivalent words to the title

Reply: Agreed, we adjust the title accordingly. In SE Asia, there are only 4 known submarine volcanoes which could not be included here, which we also include in the text.

The title now reads: "Identification and ranking of subaerial volcanic tsunami hazard sources in Southeast Asia"

Page 14 line 287: "Here, these are Banua Wuhu, Indonesia, and Hankow Reef, Papua New Guinea as well as two unnamed seamounts."

L35: causing some 26% of all volcano induced fatalities

This part is unclear. Do you mean “26% of all volcanoes causing tsunamis”? or 26 % of all volcanoes in the world (irrespective to tsunami generation)?

Reply: We agree that this statement is confusingly phrased and clarified. Volcanic eruptions cause fatalities by PDCs, lava flows, lahars, etc. and 26% of all are from tsunamis caused by volcanoes.

Page 2 line 35: “...and 26% of all fatalities recorded at volcanoes since 1800 have been due to such tsunamis (Brown et al. 2017).”

L88: although in some circumstances

In what circumstances do volcanoes inland exceed such a distance? Please mention some examples.

Reply: A very good suggestion, we added some examples in text.

Page 3 line 89: “Deposits of debris avalanches from sector failures of stratovolcanoes, e.g. the Gotemba deposit from Fuji volcano, Japan, were found as far as 24 km from the summit (Yoshida et al., 2012), or 35 km at Shiveluch, Kamtchatka (Belousov et al. 1999). Pyroclastic flows at Mt St. Helens, USA, also reached more than 25 km from the vent (Kieffer, 1981). However, these distances are exceptional and likely limited to very large volume collapses or highly energetic lateral eruptions.”

Figure 2:

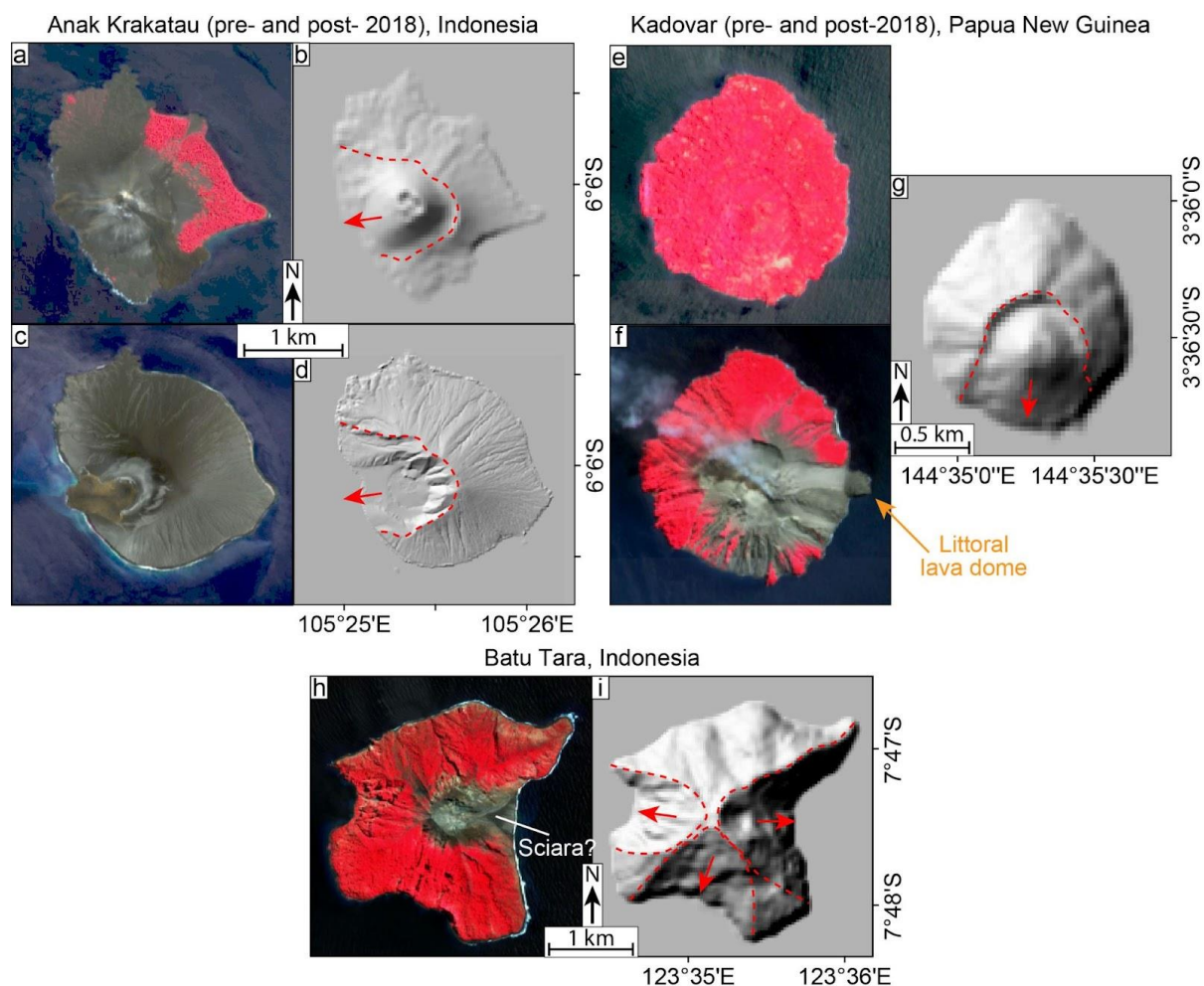
Here the authors show only a case of Nila volcano in the high hazard category. At least, please show volcanoes in the other two categories for comparison.

We agree that it is helpful to have a few more examples and have added further figures as suggested. However, because volcanoes in the categories are defined by our scores and not morphological archetypes it would not really be representative to just have one example from either category. Figure 2 mainly served to illustrate the way we measured and recorded our data and Nila happened to have a wide variety of features and thus made for the best showcase example.

Instead, we accommodate this suggestion by providing figures with further volcanoes in the discussion and supplement, although focusing more on the high-hazard ones as we consider these to be more important to showcase. Here we added one for Krakatau and Kadovar as a main figure along with Batu Tara. We further present figures of all other high-hazard volcanoes in the supplement, together with the final section of this manuscript, which we also moved to the supplement.

Page 23 line 443: “A brief feature of individual high-hazard volcanoes can be found in the supplementary material C.”

New Figure:



L606– Conclusions

I recommend that the authors add one or a few sentences stating the limitations of this analysis (containing subjectivity and/or errors more or less).

Reply: We fully agree and thoroughly improve the conclusions of the manuscript and now also state the limitations of this analysis. The new conclusion now reads as follows:

Page 31 line 607: “Based on our MCDA analysis considering 131 volcanoes in SE-Asia we identify 19 that pose a high tsunami hazard and another 48 with moderate tsunami hazard. We find our ranking system to be robust for the higher scoring volcanoes, meaning that we can reliably identify the most likely volcanoes to produce a tsunami in the future. For volcanoes with moderate to low scores the ranking is less robust and more susceptible to subjective judgement. The main limitations remaining are (1) a lack of knowledge how much individual factors contribute to the tsunami hazard of a volcano, instead requiring subjective assumptions, (2) erroneous, incomplete or insufficient data availability for many volcanoes

(e.g. bathymetry or historical data), and (3) the multitude of different mechanisms which may cause a volcanic tsunami (i.e. PDCs, landslides, explosions), making a clear scenario assessment challenging.

Our results show that the Indonesian Lesser Sunda Islands and northern Molucca Sea as well as the southern Bismarck Sea in Papua New Guinea are areas with a high number of hazardous volcanoes and may thus be particularly prone to tsunamis sourced by volcanoes. Many of these volcanoes such as Batu Tara, Indonesia, are not commonly considered for this type of hazard. We therefore emphasise the need to reconsider the current state of monitoring and risk assessment in these areas. Since tsunami warning systems are mostly not designed to detect volcanogenic tsunamis, our results highlight the importance of a reassessment of the current network and additional suitable equipment on the ground and through earth observation satellites. Due to the inherently short warning times of these events, we also recommended increased pre-emptive measures on a local level, such as increased public education programs for coastal communities and the marking evacuation routes along populated coasts.”