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Discussions

Interactive comment on "High accuracy coastal flood mapping for Norway using LiDAR data" *by* Kristian Breili et al.

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Note: All line and figure numbers refer to submitted manuscript

General comments

This is a generally well-written, informative description of a new dataset and suite of tools for coastal management activities for the country of Norway. Thank you for affording me the opportunity to review! The analysis is thorough and description of input data, results, and related uncertainties is sufficient. I, however, would prefer to see this presented as a brief communication, as I believe the major contribution of this work lies

more in its presentation of the dataset and availability of management tools and less so in any analyses of coastal risk, adaptations, or impacts. For example, I feel like the conclusions section (L450 – 473) can mostly represent the results section without any significant loss of interpretative value, and the remaining lines (to L493) appropriately represents sufficient discussion of uncertainties and overarching themes.

This opinion is not strong enough, however, to merit a major revision or rejection. I believe it's still an important contribution. Additionally, the assigned editor has looked over the manuscript and deemed it appropriate as a research article, so I will defer to their judgement here.

> **Author comment:** Firstly, many thanks for your review which has improved the quality of our manuscript. We don't agree that the work should be presented as a short communication. It is certainly true that one of the main contributions of this work lies in the presentation of the dataset and availability of online management tools. However, there are also important results showing Norway's vulnerability to coastal flooding; including specific examples, regional differences, and detailing what is at risk. There is also an important assessment of the DEM accuracy. We feel there is more than enough analysis here to warrant keeping this paper as a research article. Reducing the work to a short communication (2-4 pages) would mean so much of the analysis would be lost. Furthermore, much of this analysis and the results go above and beyond what is available from our online tool Se-Havnivå. It is also the case that this work aims to document Norway's present vulnerability to coastal flooding. As this work is, therefore, an important benchmark. As new knowledge and data sets become available then the numbers of what is at risk will change - including what is available online. We will keep this work as a research article, as long as the editor does not require a complete rewriting of the manuscript to a brief communication.

Other general notes

For the uncertainty analyses

- With confidence intervals (or upper/lower limits of uncertainty) expressed for 9 of 10 metrics in Table 7, I'm not sure why there was no utilization of these in the results. At the least, one figure could have shown the difference in inundation extent using an upper and lower limit, and at most, all results could have been expressed as their appropriate ranges incorporating all relevant uncertainties

    Author comment: This is a preliminary assessment of the uncertainties - the purpose of which is to indicate that the uncertainties are generally smaller than the projected sea level rise. Also, to give the reader an idea of the different uncertainties involved in the mapping method. There are also smaller errors associated with the different vertical datums and transformations that have not been assessed for the entire coast.

    We agree that it would be very useful to show confidence intervals. However, as the other reviewer suggests, this could be highlighted as something to be addressed in future work. We therefore had added the following text to show that we will aim, in future, to perform a more complete uncertainty analysis, and to try and build that into our mapping.

    Text added at line 369: "In summary, a preliminary assessment indicates that the elevation model (RMSE 0.26 m) is the largest source of uncertainty in our mapping method. There are also smaller errors associated with different vertical datums and transformations between datums that have not been assessed for the entire coast. However, we believe that the sum of these mapping errors are generally smaller than the projected sea-level rise, which gives us confidence in our results. Future work should look at how these uncertainties can be incorporated into our mapping and web tool (Gesch,

2013, 2018; Cooper and Chen, 2013; Cooper et al., 2013)."

- One of the greatest sources of uncertainty as discussed was the bias introduced by engineered structures over water. I'm curious as to why the authors did not attempt to crop out these structures using a coastline mask. Was it because of discussed issues with the coastline not agreeing between datasets?

    Author comment: This is a problem we have struggled with but unfortunately there is no obvious solution. Lines 266 onwards already explain the issue: "We can not, however, simply subtract the numbers calculated for present MHW from the numbers for higher water levels for buildings, because an unknown number of these buildings will truly be affected by higher levels of flooding. We suggest that the numbers of buildings erroneously mapped as affected will decrease for higher water levels. The numbers calculated for present MHW for buildings form a basis estimates for other water levels can be compared to. They can also be considered as a measure of the precision of the current methods and data used in our analysis. Note that because the coastal climate service Sehavnivå i kart presents numbers including the MHW-bias, the numbers for affected areas and roads given in Table 2 and 4 will differ from those of Se havnivå i kart."

    Using a coastline to crop out engineered structures over water will not solve this problem. We do not know the height of these structures, and, as explained in lines 266 onwards, many of them will be affected by coastal flooding for water levels above MHW. In our work, we have chosen to include structures over water in the numbers for present MHW, for reasons explained above. But it is clearly something the reader should keep in mind when interpreting the results.

- A DEM accuracy of <0.1m (Table 7) is not really true, is it? That refers to the accuracy of the processed lidar point data, and not the interpolated DEM. As stated in the text, an accuracy of 0.26m is more appropriate. So why is it presented as such in the table, and elsewhere in the text?

Author comment: Yes, it is correct that the project goal standard deviation applies to the laser data and not the interpolated DEM. To make this clearer, we have changed the order of Section 4.1 (deals with all uncertainties) and Section 4.2 (deals specifically with the DEM) and made several minor changes to the text to distinguish more clearly between accuracy of LiDAR data and interpolated DEM.

Updates to manuscript:

* Table 7: 0.26 m is added as DEM's estimated RMSE
* Line 162: The vertical accuracy of the LiDAR data has a production goal root mean square error (RMSE) of 0.1 m for well-defined solid areas (Kartverket 2014).
* Line 348: The project goal uncertainty (RMSE) of the LiDAR data, from which the DEM is interpolated from, is 0.1 m (Kartverket, 2014).
* Line 351: The actual accuracy of the interpolated DEM depends on...
* Line 356: We therefore consider the project goal uncertainty of the LiDAR data as an optimistic error estimate for the DEM in the coastal zone.
* Line 406-407: Our tests suggest that the interpolated DEM used to calculate the inundation maps, does only achieve the project goal uncertainty of the LiDAR data in flat terrain. Considerably lower accuracies must be expected in steep areas and along much of the coast.

For the figures:

- I would like to have seen combination figures – pictures inset, side-by-side, or multi-panel with the representative inundation maps (e.g. 5 & 6, 7 & 8). Larger,

too.

  Author comment: Please see new figures in supplementary document. Figure 6 and 8 are now insets of Figure 5 and 7. Figure 4, 5, 7, and 9 will be two-column figures in order to make the maps larger and easier to read. Cross references and figure-captions are changed accordingly.

- Clear graphs showing the results from tables 2-6 more clearly would increase the impact of these findings. The bar graphs in Figures 10, 13, 14 are informative, but I can't help but feel like more data could be incorporated into larger line graphs for more interpretive power, and showcase the infrastructure challenges facing Norway in the RCP8.5 scenario.

  Author comment: We agree that more could be made of these graphs. To address this, we have changed figure 10 to include the percentage increase between present and 2090. Figure 13 and 14 now show that percentage of the total area of the municipality affected. Figure 14 also shows the percentage increase from present to 2090.

- Figures 11/12 are hard to interpret, too much overlapping data. Perhaps colour-magnitude hexagons might more clearly convey the spatial patterns (e.g. see Figure 2, https://www.nature.com/articles/s41467-019-10762-4)

  Author comment: As long as the exact positions of the affected objects are not part of our data sets, we do not see how colour-magnitude hexagons can be used to map the impact of each municipality. So we have kept the bubbles, but made the figures larger and used small bubbles with a fixed size for municipalities with few structures affected. We have also reorganized the figures: in the revised manuscript Figure 11 and 12 are replaced by Figure 9, 10, and 11 that separately show the affected land areas, buildings, and roads for a 200-year storm surge at present and for 2090. This allows each theme to be visualized in larger figures and we believe they now are easier to interpret.

- References are minimal, and several are non-peer reviewed reports. A more thorough examination of the literature, particularly with regards to inundation mapping and DEM analyses/uncertainties, would really benefit this manuscript

  Author comment: We have added the following references to address this issue:

  Section 2.1: Olesen et al. (2013)

  Section 4.1: Gesch (2013), Gesch (2018), Cooper and Chen (2013), Cooper et al. (2013)

  Section 2.2: Sibson (1981), Passeri et al. (2015), and Roelvink et al. (2009)

Line by line comments as follows

- L13 - Adaption and adaptation are used interchangeably throughout the manuscript. Please pick one for readability.

  Author comment: OK, adaption changed to adaptation throughout manuscript

- L19 - The sentence beginning "The consequences ..." is awkward. Maybe remove "and many" as well as the "the" before coastal.

  Author comment: OK, done.

- L24 - is GIA the only component of VLM at play? No tectonics? I ask because I don't know and a cursory look turned up no information. Just curious!

  Author comment: This is somewhat addressed on line 105: ". The VLM field used in the projections is based upon permanent GPS observations and repeated levelling (see Simpson et al., 2015). The presence of small-scale anomalies, e.g., urban subsidence or neotectonics (e.g. Olesen et al., 2013), may cause VLM to deviate significantly from this field at the local level."

  In other words, the VLM field is based on observations, it is entirely possible that a component of this motion is tectonic. Also, as stated, there will be local deviations from the field. However, the general pattern of vertical motion is clearly GIA. We have added a reference to neotectonics (Olesen et al., 2013) to address this a little more clearly.

- L78 - See point above, how this manuscript may be better suited as a short communication, describing the tool and its applications, inviting the reader to go and perform their own analyses.

  Author comment: See first comment.

- L128 - I recognize that it's an even more complicated variable than those already left out from your analyses, but I would have appreciated some mention of a reduction in sea ice and associated coastal effects on arctic communities. In Canada the highest rates of coastal retreat and impact on communities/infrastructure due to SLR is in arctic areas impacted by a loss of sea ice and associated increased wave activity. . . I'm sure there are some similar effects being witnessed in northern parts of the study area.

  Author comment: Mainland Norway is essentially free of sea ice. Although situated quite far north, the Gulf stream means the coast remains free of sea ice throughout the year.

- L161 - is that a definitive statement – every grid cell has at least 2 datapoints? Or is that an average. Also, interpolation method?

  Author comment: The product specifications of the LiDAR data says ”at least two datapoints per m^2”.

  Text added at line 162: ”Two methods are applied to interpolate the LiDAR data to a regular DEM. In a first try, natural neighbor interpolation (Sibson, 1981) was used. If this failed, empty spaces were binned with an average value.”

- L168 - Some discussion of alternatives to the bathtub methods (e.g. modeling approaches using XBeach)?

  Added at line 169: ”The ”bathtub” approach is favored for several reasons. Firstly, mapping results from this approach are consistent with how current guidelines on coastal planning are applied in Norway. Secondly, the approach is straightforward, computationally inexpensive, and has been widely used in large-scale coastal flooding analyses. However, there are known limitations of the “bathtub” method. For example, the response of hydrodynamics, morphology, and ecology as sea level rises is not accounted for (see Passeri et al. (2015) for a review). Some of these effects could be important on local scales along the Norwegian coast.”

  Added at line 440: ”The ”bathtub” approach applied in the present study results in maps that are consistent with national guidelines on how to account for future sea-level change and storm-surge in coastal planning. Currently, there are no regulations for modelling the effects of waves, which may increase mean sea level during a storm and introduce geomorphological changes due to erosion and transport of sediments. Modelling the effects of waves should be addressed in future work and will require a more advanced

  framework than the ”bathtub” approach. A more advanced framework is provided by the open-source numerical model XBeach (Roelvink et al., 2009), which is developed to simulate the effects of storms on sandy coasts with domain size of kilometers. The XBeach model is not a tool for analyzing the entire Norwegian coast, but is suitable for case studies of vulnerable areas like beaches and coasts covered by soft sediments (e.g., southwest of Norway).”

- L193 - Again, unless this is a short communication introducing the tool, this kind of discussion isn’t really necessary in a scientific paper

  Author comment: Ok, removed

- L202 - See general comments for sections 3 and 4. Generally I think that sections 3.1 and 3.2 could be thinned significantly, particularly if more detailed and interpretive figures and maps are presented. 3.3 is a good section – this is the level of interpretation I’d personally like to see in the results.

  Author comment: We have moved line 251-272 (discussing the MHW bias) from Section 3.2 to Section 2.3. This makes Section 3.2 considerably shorter and more focused on the results. The figures have also been revised somewhat to include more information. However, we disagree that the level of interpretation is too detailed in Sections 3.1 and 3.2. Section 3.1 deals with specific examples, and the descriptions of those inundation maps are, we would argue, brief and light on detail. The purpose of these examples is to show how different geographic/landscape situations are at risk. And, furthermore, to show how Norway is at risk on local scales. Section 3.2 has been cut as the MHW-bias discussion has been removed. Otherwise we believe the level of interpretation is appropriate for this work.

- Sections 4.1 and 4.2 are great – but then none of these uncertainties so carefully outlined are included in the analysis!

  Author comment: Confidence intervals have not been calculated for the maps available in the coastal service, but future work should look at how these uncertainties can be incorporated into our mapping and web tool. See also comment above.

- L421 - ”... and future applications of this tool” or something to that effect?

  Author comment: Ok, header changed to ”Comparison to other studies and future work”

Other corrections applied by the authors

Table 1: The sub category is changed from ”Private” to ”Private industry” for ”factories, workshops, storage halls, power plants, and transformers”.

Table 5: Horizontal lines added between each category

Figure 3 has been improved. The new version is clearer and easier to interpret.

In the revised manuscript, we have replaced Figure 11 and 12 by Figure 9, 10, and 11 that separately show the affected land areas, buildings, and roads for a 200-year storm surge at present and for 2090. This allows each theme to be visualized in larger figures.

Line 52: objects of impact -> objects at risk

Line 72: line break added

Line 129: Reference updated from Nicholls and Cazenave (2010) to Bamber et al. (2018).

Line 179: correcting typos: ...the object's height is used determines whether...

Line 194 changed to: ”Furthermore, the maps and numbers presented in Se havnivå i kart will be regularly updated as new knowledge and data (e.g. new elevation data, better understanding of vertical datums, error corrections) becomes available.”

Line 203 changed to: ”...the three types of coastlines (strandflat, glaciofluvial deltas, and soft moraine coast)...”

Change at line 313: ”The municipalities with the largest land areas that are at risk of flooding are located in the middle of Norway (between Trondheim and Tromsø) and in the outer part of Oslofjorden.”

Added at line 314: ...evident by the upper left...

Line 383: solid bedrock -> exposed bedrock

References

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Please also note the supplement to this comment:
https://www.nat-hazards-earth-syst-sci-discuss.net/nhess-2019-217/nhess-2019-217-AC1-supplement.pdf

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