Response to the comments on the manuscript (HESSD-2019-415) " New flood frequency estimates for the largest river in Norway based on the combination of short and long time series" by Kolbjørn Engeland, Anna Aano, Ida Steffensen, Eivind Støren, Øyvind Paasche

This is the authors' answer to the interactive comment posted by Daniel Schillereff.

We are very grateful for the excellent review afforded by Daniel Schillereff which we believe will improve our paper.

Comment #1: Structure and content of the introduction

The suggestions for modifying the introduction are very useful and we will include changes in the revised manuscript.

We will, as suggested, provide more details on how paleo-data can help to reduce uncertainty associated with flood prediction (more data leads to smaller estimation uncertainty) and provide additional insight to flood variability on longer time scales, which can further advance our understanding of how climate change influence flood variability on multiple time scales.

We will also add more information about the time scales involved. Although we do not aim to give a review of different archives suitable for paleoflood reconstructions (e.g. Wilhelm et al., 2018), we will nevertheless in include info on the length of historical records (back to the 16th century) and lake sediment archives (Holocene) available in Norway.

Comment #2: Human modifications to the landscape and flood stationarity

Human modifications of the landscape are also important factors for future flood risk and we will add this information to the introduction.

The issue of human influence on the landscape is in this case two-fold and may or may not have sedimentological as well as hydrological influences on the system in question. Changes in land-use and deforestation can impact sediment availability in the catchment, but it can also change the buffering capacity and hence the run-off regime. We believe that the land-use changes caused by the removal of woodland cover that started in the 16th century may have influenced the local erosion and sediment transport of the upstream Glomma catchment (though, note that no data presently exists here), but because this is area represents only a fraction of the total catchment area we think that these 'excess sediments' would be diluted downstream. Another relevant point here is that the downstream gradient of the river Glomma is not steep so sediments can easily be deposited long before they reach the bifurcation point at Kongsvinger. A final point here is that the sediment source for the flood layers deposited in Flyginnsjøen is suggested to be mainly local, and the area around the lake and the location for the bifurcation events itself was not subject to removal of woodland for mining which would reduce the potential influence of anthropogenic influence on the sedimentary budget.

Having said that, we do not rule out the possibility that the removing of woodland since the 16th century amplified the size (and frequency) of floods since forests, in most cases, reduces flood peaks. This, however, require a more regional and systematic vegetation change than that related to mining in the upper Glomma catchment to affect the 154450 km^2 large catchment. The 2500-4000 yr BP flood-rich period coincidence largely to the bronze age (2500-3700 BP) when settlements and farming expanded in Norway. We see, however, similar flood rich period in other lake sediment records that certainly not are influenced by farming (shown in Fig. 18) and argue that the effect of land-use cannot explain the observed changes in flood frequency. Se also reply to comment #4 on this matter.

Comment #3: Evaluating the geochemical flood proxy

We agree that a more thorough sedimentary analysis of potential sediment sources in the catchment could add valuable information to the composition of the recorded flood deposits, and perhaps even denote source areas and thus also flood triggering mechanisms (see eg. Støren et al 2016). Given the size of the Glomma catchment, and the mixing process involved such an approach will require not only sediment samples from the are between the bifurcation threshold and the lake, but also representative samples from potential sedimentary sources in the 154450 km2 catchment for comparison. This would be an interesting exercise, but the workload would be enormous and is well beyond the scope of this paper.

Moreover, during bifurcation events the discharge in the Flyginnsjøen catchment increase with an order of magnitude, dramatically changing the erosion in the area. This change is deemed to mask subtle variability in sediment transport for the Glomma catchment.

Linking the sedimentary signal to specific individual flood events is, as the author recognizes, challenging, and its equally challenging to visualize this link in figure 12. We agree that the dashed vertical lines are not serving any good purpose and have removed these. The suggestion made by the reviewer to add color coding on peaks where we "are confident in their stratigraphic correspondence" is more problematic. Firstly, the plot is already busy, and more colors will add more clutter and probably not improve readability. Secondly, considering the uncertainties in the age-depth model we have not (yet) found a good way to estimate probabilities for correspondence either. Consequently, we rest on the assumption that our 23 recognized peaks in the sedimentary signal corresponds to the 24 bifurcation events over the same period. We argue that this, and the visual correspondence between peaks in K and Ti and peaks in discharge shown in fig 12 are sufficient show causality between bifurcation events and the observed sedimentary signal.

The discussion on uncertainties in the age-depth model and the correspondence between the historical flood events and the sedimentary signal have been elaborated on and we will all the same attempt to improve the aesthetics of figure 12.

Comment # 4

We agree with the summary of flood generating mechanisms given by the reviewer. What we see from the flood events in the current climate is

- The flood seasonality in Fig 1 shows that the main flood season lasts from May to June which is locally known as the snow melt season. There are a few floods in the autumn season when periods of sustained rain are the most important flood generating process.
- Investigations of recent large flood events suggest that the key process that generate the largest floods are:

    - Large amounts of snow over large areas available for snow melt. This require high winter precipitation and preferentially low winter temperatures. Several studies indicate a link between snow accumulation and snow melt flood peak/volume in Scandinavia (e.g. Olsson et al, 2018)
    - A cold spring followed by a sudden increase in temperature typically result in high melt rates. Note that the variability and sequence of temperature is important.
    - Large amounts of widespread precipitation combined with snow melt. This factor can be related to spring / summer precipitation.
    - The largest flood in 1789 is not typical for these conditions since it happened in late July in 1789 and intense rain over several days provided the main bulk of the flood water. Snow melt from high altitude areas certainly also contributed, but most likely not to the same extent as for instance the large flood that occurred in 1995 (referred to as 'Vesle-Ofsen')
- Our challenge is to relate these conditions to climatic variables. We speculate that the following climate conditions can enhance floods and boost the flood frequency:
    - high winter precipitation (more snow will be accumulated throughout the season and also build up perennial snowfields in high mountain areas)
    - high summer precipitation (especially when it occurs early in the season as such combines with melting of snow)
    - cold winter and spring temperatures (by pushing back the snow melting well into the summer season the probability of a sudden, substantial raise in temperatures can enhance the potential melting considerably, typically going from under 10 °C to over 20 °C.)

Climate change impacts on floods in Norway is examined in detail by Lawrence (2020), and for the catchment studied here, a decrease in flood magnitude is to be expected. This is in agreement with what paleodata suggests (Støren & Paasche, 2014).

Within Norway there are, however, a variable response of flood magnitudes in snow-dominated catchments and Lawrence (2020) suggests that this reflects the competing effects of increasing winter precipitation and temperature. This anticipated change can lead to either an increase or a decrease in winter snow storage, and/or to an increase in rain-on-snow events throughout the winter half year, depending on the latitude and the elevation of the catchment.

An increase in temperature will also lead to a shift in flood seasonality and flood generating processes (Vormoor et al, 2015, 2016). For Elverum we might expect more frequent autumn floods and less frequent and smaller spring floods.

When it comes to discussing the flood generating mechanisms during the Holocene, we have chosen to compare our results (in fig. 18) with mean reconstructed mean July temperature (Velle et al 2010), and a high-resolution glacier reconstruction (Kvisvik et al 2015) from the mountain areas in the upper Glomma catchment as well as a flood index (Støren et al., 2012) denoting the relative distribution of Holocene floods in Southern Norway. Indeed, comparison to winter, spring and autumn temperature and precipitation reconstruction would have been preferable, but as the reviewer also recognize, there is presently a lack of appropriate climate reconstructions available. We use the plotted paleoreconstructions to discuss the relative influence of changes in summer temperature, but also winter precipitation. We also utilize the flood index (Støren et al 2012) to briefly discuss the effect of changing atmospheric circulation distributing the winter precipitation e.g. causing a likely decrease in winter precipitation c. 2000-1000 cal. yr BP possibly explain the absence of floods recorded for this time interval (page 24 and 25).

We argue, however that summer temperature is highly correlated to winter temperature that can be considered as the main driver of Holocene flood frequencies in the Glomma catchment based on the observed variability both on instrumental and paleo-timescale. The explanation is likely to be linked to lower winter temperatures causing a higher potential for snow melt floods. In such a large catchment, with abundant perennial snow field in the mountains, and the potential for buildup of snowpack over several years, any changes in the flood frequency is deemed to be of regional nature. Consequently, it seems plausible that the effect of raising the 0-isotherm to a higher altitude, the effect of a warmer climate, will significantly change the potential storage of snow and thus flood frequency (see also Støren & Paasche, 2014).

We will to clarify this in the discussion (esp. 5.2)

Figure 3:

We do have good aerial photos of the bifurcation inflow zone. A photo will be included in fig. 3.

From the photos one can see the following:

- At Vingersjøen, unambiguous morphological evidence reveal that reverse flow occurs. Especially, since the river that flows out of the lake has actually an inflow delta. The size of this delta has also increased in size.
- For the flow path from Tavern to Flyginnsjøen, there is little geomorphological evidence. The area with intermittent flows is forested or grassland, and the forest cover has increased somewhat the recent years. The most clear evidence are road bridges that has been built across these occasional streams. Evidence of flooding from a bifurcation event is mainly seen as debris in the forested areas.

Figure 4 ad 5: The two inlets into Flyginnsjøen enter the lake at the northern shore and are separated by approximately 10 meters. Note that there is not a delta where Vrangselva enters Flyginnsjøen, indicating that the background sediment influx is low.

The sequence of maps is a bit difficult to follow.

Kongsvinger is a town! At least after Norwegian standards. We agree that the sequence of maps is a little difficult to follow. A major challenge is that the Elverum-site for streamflow data and the paleodata at Kongsvinger are located 80 km apart, which is why we think it useful to provide an overview map in Figure 1, detailed maps for the paleo-data in Figures 3 and 4, and detailed map for the historical data in Figure 7. We will give an effort to present details and names in the correct order to simplify the reading of the manuscript, and in Figure 3 we will follow the suggestion to make an zoom in on a smaller area such that Elverum is also visible in the inset map in the upper right corner.

Figure 6:

We will label the 1967 flood in Figure 6

Figures 14 and 15:

We will present ample detail he figure captions in Figs. 14 and 15. such that both figures can be interpreted on a standalone basis.

Table 3:

We will clarify the presentation of Table 3 by adding additional information to the caption and use typographic effects to highlight which correlations are from which core.

Minor comments

Section 3.3.1:

We will add a few sentences that explain the reasoning for using and integrating two cores.

Page 11, line 27:

The hydrometeorological basis for choosing a 9-month window is that in this catchment there is, on average, one major flood event per year. This typically occurs in May/June. Only rarely do we observe large flood events during autumn. Consequently, we expect to detect only one major flood event per year. For locations with more frequent floods, a smaller time window could be more appropriate.

Page 13, line 33:

The term "mm scale" is meant as a descriptive term rather than a measure of precise thickness. Given the peak detection algorithm-approach used to recognize flood deposits in the sediment stratigraphy, we have not measured the thickness of all flood layers. This is not a trivial task, since the start and stop of a deposit can be gradual and the signal to noise ratio increase when values are low. We prefer to keep the term "mm-scale" and avoid defining start and stop of individual flood deposits.

Page 19, Line 11:

Thanks for pointing this out. We agree that there is a more prominent step in flood occurrence rate at 700 yr BP rather than 600 yr BP, and will change the text accordingly.

Page 19, Lines 13-14:

We agree that the comment *"high flood frequency in the 18th century is also recorded in the historical flood data (Fig. 6)"* is speculative and we will delete it.

Page 20, Lines 18-20:

We will clarify the different approaches applied in section 4.3 when the paleoflood information is included in the flood frequency analysis.

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