Response to Referee 3

We are thankful for Referee 3's constructive and valuable feedback. We have assessed the Referee's concerns in the manuscript and detail our individual responses in the following. The Referee's comments are in a yellow background, and our responses are beneath.

The paper presents an interesting case study which aims at assessing the influence of culverts' blockage on flash flood inundations. The authors have used TELEMAC-2D (after implementing a specific culvert blockage module) to simulate different precipitation scenarios assuming different blockage conditions.

I think that the paper can be a relevant contribution, but some major revisions are required before it can be accepted for publication.

We thank the referee for reviewing our manuscript and providing valuable feedback that will help us improve our contribution.

Main points:

The title should be revised. First, it should explicitly reference "flash floods" instead of generic "floods". Besides, the paper just suggests how to find the most critical culverts, rather than giving practical guidance on how to design mitigation strategies. The authors should try to devise a new title that better reflects the main focus of the paper.

We thank the reviewer for pointing this out. Indeed, the title does not completely reflect the main focus of the paper. We have added "flash flood modeling" to the title and removed "design". The new title is:

"Culvert Blockages in 2D-Hydrodynamic Flash Flood Modeling: Quantifying the Impact on Flood Dynamics and Mitigation Strategies"

This reflects both on the main work, which is the quantification of the impact of the culvert blockages and the outcome that some individual culverts can have a larger impact than others.

Figure 1 should be enriched with more labels, e.g. outlet section, streams and locations that are referenced in the paper. The results description is currently hard to follow for readers that are not familiar with this area, due to the many geographical references.

Fig. 1 indeed lacked some necessary information. We have added the two referenced streams which should also indicate the flow direction. We thank the reviewer for these suggestions.

The study area lacks accurate observations that allow calibrating the model. However, I acknowledge that the paper mostly presents comparative results (e.g. blocked/non-blocked culverts, different blockage ratios, etc.) to show the relative importance of the culvert assumptions, and this may make the lack of calibration less relevant. My suggestion is therefore to treat the case study as if it was a synthetic case, although inspired by a real catchment. After acknowledging this hypothesis, the authors can completely remove any mention of real events (e.g. lines 118-129 and section 2.4) and just state that the parameters (CN, roughness, etc.) and precipitation scenarios are set to reasonable values for this area. The lack of calibration can then be discussed among the limitations.

We thank the referee for acknowledging the paper's results even though no calibration is possible. We still present background information on the catchment to show the motivation for the study. The catchment has experienced several minor flash floods in recent years and also observed blockages at culverts. We want to keep this information in the paper, to demonstrate to the reader that this issue is present in real-life cases.

The previous precipitation events are briefly analysed to see that the catchment does not only experience flooding for extreme precipitation events. Afterwards, the precipitation scenarios are selected so that their precipitation amounts exceed the thresholds of previous precipitation events that caused flooding. This information was added in the section "Precipitation Scenarios".

Still, we agree that the focus of the study, especially in terms of the lack of calibration data must be better highlighted in the paper. We have therefore rephrased and added statements in the introduction, limitation and conclusion. This should clarify that this paper does not aim to present a fully calibrated and robust flood model including blocked culverts, but rather assess the local and catchment scale impacts of blocked culverts.

Line 215. This sentence is the core of the proposed modification, but it is very cryptic: the residual discharge is distributed (how?) onto neighboring (of whom?) nodes. Please provide more information about this novelty, and maybe a simple sketch that clarifies the difference between the original and novel implementation. Moreover, did the authors perform any kind of validation of their novel implementation (e.g. for a simple test case)?

If the calculated discharge exceeds the maximum discharge available at the inlet node (based on the available volume / dt), then a node next to the inlet node is taken to provide the needed residual volume of water. If this node does not have enough water to provide the residual volume, then another node in vicinity to the inlet node assists, and so on. The largest set of potentially assisting nodes are predefined before the simulation, but it is assured that enough nodes for assistance are predefined. The implementation was tested and validated on individual culverts in the catchment. Since we do not see the main focus of our study in that implementation, we chose not to go into too much detail. However, we have added a few more aspects to our explanation in the manuscript to give more information about our implementation.

Section 2.6 presents details about the blockage method using the coefficient k_e. I think the authors should provide a better definition for this coefficient (e.g. by showing how the culvert discharge is computed at least for one flow type). This could help justify why the coefficient is set to 0.5 at line 240.

Culvert hydraulics are presented and discussed in multiple studies. We mention a few studies (e.g. Bodhaine (1968), Smolders et al. (2016), Fernandez-Pato et al. (2020), Weeks et al. (2013), Ollett et al. (2017) etc.), but numerous more studies could be referenced here. Therefore, we decide against presenting the equations for the discharge calculation at different flow types in the culvert.

We have added some more context to the selected value of k_e in our study, which is used for square-edged, concrete pipe or box culverts, which are the predominant forms of culverts in our catchment. We have furthermore added that the blockage ratio is in fact the dominant parameter for the calculation of the adapted energy loss coefficient k_e', and that the selection of the inlet loss coefficient without blockage plays a lesser role.

Results section. I think that this section should be re-organized and improved. Some suggestions are provided in the following points.

The global results (outlet hydrographs and flood extent) should be discussed first, since they are connected (i.e. blockage leads to a peak flow reduction due to increased flood extent).

Our study first discusses the outlet hydrographs. The conclusion here is that the impact from the blocked culverts is rather low, but the results also show that there might be some local differences that are more significant. Therefore, we then move on to hydrographs at specific locations, and see that there are local differences. Finally, we look at inundation, and also see here, that there are local differences, but total global differences are rather small.

We agree that hydrographs and inundation are connected, but argue that it does make sense to separate these results in this study, as hydrographs can only be assessed along a specific cross-section and inundation allows for a more spatial assessment of results.

As regards the inundation, I understand that the catchment size and relatively limited flood extent prevents displaying readable comparative maps. However, the authors should not only compare the total flooded areas, but also provide some quantitative metrics (e.g. ratio TP/(TP+FN+FP) or other metrics combining True/False Positives/Negatives) about the inundation overlapping (each scenario compared to the reference one). This could be useful to highlight if flooding occurs over different areas due to culvert blockages. Moreover, if the flooded area is overall similar but the max depths are different, another option could be to identify a limited number of classes of max depth intervals (e.g. 0-0.25 m; 0.25-0.5 m; 0.5-0.75 m; 0.75-1 m; >1 m) and compare histograms reporting the areas belonging to each class. This could also be useful to discuss variations among scenarios.

We thank the referee for suggesting additional statistical metrics that could improve the clarity of our study. We have calculated the CSI values and also done the statistical analysis with more max. depth intervals. We agree that presenting the CSI does add value to our study and therefore have added a table with the CSI values using thresholds of 3 cm and 30 cm for one blockage scenario across the return periods. This provides a good indication that flooded areas are generally very similar for blockages, but areas with larger water depths are affected by the blockage. This underlines the motivation to focus more on inundation with larger water depths.

Introducing more max depth intervals did not provide further insight into the processes of the blockages and we are afraid that introducing these into the paper would make the paper less comprehensive for the reader.

Section 3.3 is very descriptive but hard to follow without being familiar with the layout and conveyance capacity of streams and culverts. Moreover, all hydrographs look very similar, except at cross-section 3, so I wonder if the authors could just focus on a couple of interesting locations and two/three precipitation scenarios and make an effort to summarize only the relevant findings.

We agree that section 3.3 was very descriptive and hard to follow. Therefore, we have moved all descriptions of the cross-sections into the appendix, except for cross-section 3. This should improve clarity and put the focus on the more important findings.

Overall, the results of this case study seem to imply that the "impact" of the culvert blockage is not so large at the global scale (just a few percentage points in terms of flood extent and peak discharge), even by assuming different blockage configurations. This should be stated more explicitly in the conclusions. However, locally the impact can be more relevant: the revision of section 3.3 could give the opportunity to show an example and better discuss this point.

The referee is correct that the main outcome of the results of this study was not sufficiently stressed. We have changed some statements in the abstract and the conclusion that blocked culverts can have a significant impact locally, but the global impact remains small.

Lines 435-436. I was a bit astonished here. If there are numerical instabilities, the simulation results should not be included in the analysis.

The reviewer is correct that scenarios impacted by numerical instabilities should not be included in the analysis. We have re-checked this scenario and noticed an error in the simulation parameters. We fixed this error and reran the simulation. This scenario now aligns with the overall trend of the BR=0.2 scenarios.

Specific points:

- Table 1 can maybe be replaced by a figure.
- Figure 7. Check captions. Cross section 3 or 4?
- Line 351 and similar. I don't understand the implication that flooding occurs when the discharge in the culvert is larger than zero. Is this culvert supposed to remain dry even during precipitation events?
- Line 358. Typo.
- Line 422. Please report here at least the absolute values of the flood extent for the reference scenario, so that the reader can grasp its magnitude without having to jump to the appendix.

We also thank the reviewer for pointing out these specific points. We have decided against showing the precipitation events in a figure, so that the exact precipitation values are more accessible. This also supports giving more context to the historical events in that study area.

Line 351 and similar. The presented cross-section lies at a location, where the Reichenberger Bach is tunneled beneath the surface (within a culvert). Therefore, any discharge in this cross-section is flooding. This was not well described and we have made adaptations in this section and in the description of the study area.

The other points have been taken into account in the new manuscript as suggested.