

Response to Referee 1

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We are thankful for Referee 1'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 authors present an interesting article on a topic which is well-known to most flood modelers, but what is under-researched so far. In that sense, this article is very welcome and the analyses are very systematic, well structured and well explained. I only have several minor points where the authors should comment on:

We thank the referee for his feedback and for acknowledging the importance of the study.

- Mitigation strategies are in the title, but only investigated a bit in chap. 3.5; the authors should check whether that should remain in the title; should they want to leave it in the title, a bit more investigations should be done

We thank the referee for this observation. We agree that the major focus is not about designing mitigation strategies. Still we argue that one of the main outcomes of this study is that individual culverts have a larger impact on flood dynamics than others, which allows for mitigation strategies. We have changed the title to:

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

- L. 31f: I suggest here to add that the 2 methods are for the computation of the losses or are runoff generation approaches

We have rephrased the sentence to clarify that the two stated methods are for the runoff calculation only.

- Fig 1: please show both creeks in Fig 1, also Würzburg; I suggest to use the English terms, eg Bavaria; please check whether the Reichenberger and Guttenberger Bach can be shown more clearly

Fig. 1 indeed lacked some necessary information. We have added the two creeks, changed the labels of the states into English and added the location of Würzburg. We thank the referee for these suggestions.

- L. 118: comparatively dry for Bavaria, eg in Berlin / Brandenburg the precipitation is ~500 mm; 800 mm is average for Germany -> rephrase

37 We thank the referee for pointing out this imprecision. The area is indeed only comparatively dry
38 for bavaria, and not for Germany. We have rephrased that the region is frequently affected by
39 droughts, but still the catchment experienced several minor flash floods in recent years.

40

41 - Chap 2.2: please comment on even larger events eg for the Starkregengefahrenkarten which
42 are currently produced in the federal states 90 or 100 mm in 1 hour is investigated; this can be
43 done here or in the discussion later, limitation part; how would more extreme events impact your
44 results ?

45 We have included more information on this issue in the limitation section. Since the effects of
46 the blocked culverts already decreases in the HN50 and the HN100 events, they are expected to
47 further diminish for even more extreme rainfall scenarios.

48

49 - L. 150: would you expect better results with a finer mesh ? grid convergence, please
50 comment on this

51 A finer mesh resolution only marginally changed the results, but resulted in significantly higher
52 computation costs. This information is added to the manuscript in the section “Mesh Generation
53 and Parameters”.

54 - L. 151: mention the resolution of the DEM

55 The DEM has a resolution of 1m. This information is added to the manuscript.

56

57 - Headline 2.4: wouldn't it be better to call this Plausibilisation of the Model or similar ? see
58 also line 491

59 We thank the referee for this suggestion. We agree that calling it a model plausibilisation is more
60 suitable in this context and have adapted the manuscript accordingly.

61

62 - Chap. 2.5: comment here or in the discussion; you could also link Telemac2D with a drainage
63 model; would that have advantages, possibly produce more realistic results ?

64 There are currently some developments in linking Telemac2D to drainage models. However, this
65 so far only accounts for vertical drains and overflows, and not for horizontal ones, as we have in
66 culverts. Therefore, this would first require further development to be applied here. Once
67 implemented, this would possibly enhance results, as it could represent the time lag between
68 inlet and outlet, as well as allows for modeling of bifurcations or changes in geometry. However,
69 the results in this study are not expected to change much when taking these into account. Most
70 culverts in the study are straight, rectangular or circular pipes and the time lags would most
71 likely only inflict changes in the timing of the inundation and less in the extent.

72 We have added this reasoning to the limitation section.

73

74 - Chap. 3.3: I suggest to include 1, 2 or 3 cross sections and the related figures from the
75 appendix here in the paper; the cross sections not shown and the related text then should occur
76 in the appendix

77 We thank the referee for this suggestion. We have moved the descriptions of the other cross-
78 sections to the Appendix and only present the critical cross-section 3 (now cross-section 2,
79 since the former cross-section 2 was removed from the study) in this section. This should
80 improve the clarity of this section.

81

82 - Could one think about some statistical approaches to determine when which culvert is
83 blocked to wish extent ? include that also in the manuscript

84 In our opinion, these statistical approaches would need to be based on laboratory experiments
85 and would be strongly dependent on different factors such as topography, flow characteristics at
86 the culvert, and debris availability. Especially debris availability is a parameter that can also vary
87 temporally within a catchment based on the season, agricultural period, or logging activities. We
88 have added some considerations about this in the Limitations section and in the Conclusion and
89 Outlook.

90

91 - Can't one overall say the impact of the blockage is not that big except some local effects ?
92 Should you agree, formulate that more clearly, especially in the conclusions and abstract; this
93 would not mean that the paper is not good or not novel, but would provide a valuable
94 information to readers and flood modelers

95 We agree that we should have more clearly formulated that the blockage causes more local
96 effects. We have added to both the abstract and the conclusion that the effects are more local,
97 but rather small at the catchment scale.

98

99 There are further minor points in a pdf attached; no need to comment on them

100 We thank the referee to also point out further points in the pdf and have made the necessary
101 changes.

102

Response to Referee 2

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104

105 We are thankful for Referee 2's constructive and valuable feedback. We have assessed the Referee's
106 concerns in the manuscript and detail our individual responses in the following. The Referee's
107 comments are in a yellow background, and our responses are beneath.

108

109 The manuscript examines the issue of modeling culvert blockage during flood events. This process is
110 significant in river reaches where culverts are numerous, often undersized, and susceptible to
111 clogging by material transported by the flow. The study builds on the TELEMAC-2D hydrodynamic
112 model, which already includes a routine for simulating culverts as one-dimensional elements. The
113 authors extend this routine by introducing an additional head-loss term defined as a function of the
114 blockage ratio (BR). This term is assumed to be activated dynamically when the ratio (TR) between
115 the upstream water depth and the culvert's height exceeds prescribed threshold values. The
116 influence of these two parameters on flood dynamics is investigated through a set of hydrological–
117 hydrodynamic scenarios developed for a small German catchment in which several culverts are
118 present.

119 In principle, the study is relevant and aligned with the topics addressed by the journal. However, in
120 my view, several aspects require further clarification before the manuscript can be considered for
121 publication in NHESS.

122 We thank the referee for providing valuable feedback and acknowledging the relevance of the study.

123

124 General comments

125 Choice of study basin. A general concern relates to the authors' selection of a reference catchment
126 for which hydrological information is extremely limited. There are no hydrometric measurements
127 available, either at the outlet or within the basin. Information on the channel network is also
128 incomplete; several culverts were missing from the initial dataset, and the authors acknowledge the
129 possible presence of additional undocumented structures (line 110). This lack of data has made
130 model validation essentially impossible, meaning that all scenarios are assessed only relative to a
131 reference simulation that may itself not reflect actual system behavior. The authors should provide a
132 clear justification for adopting such a poorly documented case study.

133 Unfortunately, it is rather rare for such catchments to have excessive calibration and validation data.
134 Even if these catchments have a gauging station at the outlet, this does tell little about the flood
135 dynamics in upstream parts of the catchment. A robust calibration data set would therefore include
136 not only multiple gauges across the catchment, but also detailed spatial inundation data, since
137 urbanized areas have particularly complex flow paths which can often not be linked to a temporal
138 gauge at individual locations.

139 Other studies have also acknowledged incomplete data sets of culverts – both in their parameters as
140 well as their location (e.g. Truhlar et al. (2020) <https://doi.org/10.1061/JSWBAY.0000900> , Lessard et
141 al. (2023), <https://doi.org/10.1080/07011784.2022.2160660> , both references now added to the
142 Introduction). Therefore, our study aims to highlight that culvert data sets are often incomplete which
143 is the source of errors and uncertainties in hydrodynamic flood modeling.

144 Finally, the motivation for this study comes from the fact that the study area is known to experience
145 culvert blockages, both triggered by floods, but also in dry conditions (see Figure 4). Therefore, we
146 argue that these points combined justify adopting this catchment for our study despite the lack of
147 validation data. We also want to point out that the study by Fallowfield & Motta (2024,
148 <https://doi.org/10.1111/jfr3.13021>), which similarly assesses culvert blockages in a modeling
149 framework, does not even look into validation of their model.

150 However, to further acknowledge that our study does lack data for calibration and validation, we have
151 added explicit statements in the introduction that the aim of this study is not to provide a fully
152 calibrated flash flood model, but to assess the relative impacts of culvert blockages by comparing
153 different blockage scenarios. This provides a framework for taking culvert blockages into account
154 when assessing flash flood hazards.

155 Furthermore, we have added in the conclusion that future research should focus on establishing
156 spatial monitoring systems for catchments to generate robust calibration data sets.

157

158 **Result interpretation.** In several sections, the discussion of results is excessively detailed yet does not
159 offer adequate interpretation, particularly where outcomes appear counterintuitive or anomalous.
160 The authors should make a more substantial effort to synthesize the findings and, importantly, to
161 explain and justify the behaviors observed rather than simply describing them. This issue is especially
162 relevant to my comment no. 11 below.

163 We address this comment in the specific comments, especially for comment 11.

164

165 **Specific comments**

166 In the following, I outline, point by point, the aspects that in my opinion require further clarification.

167 **1. Line 98.** The manuscript mentions here that “the study area has high gradients” yet no
168 quantitative information is provided regarding the channel slopes or, more importantly, the
169 slopes of the principal culverts (particularly the longer structures near the municipality of
170 Reichemberg). This omission is nontrivial because the culvert modelling approach
171 implemented in TELEMAC-2D - on which the entire study is based - excludes Type 1 flow
172 conditions, i.e., situations in which the control section is at the inlet and the culvert slope
173 exceeds the critical slope. The authors later refer (line 200) to Smolders et al. (2016), who
174 state that Type 1 operation is very rare; however, this statement pertains to a completely
175 different hydrodynamic setting, involving culverts between tidal basins with negligible slopes.
176 The authors should therefore verify, at least for the longest and hydraulically most relevant
177 culverts, whether their slopes can exceed the critical value for plausible discharge ranges, and
178 hence whether Type 1 operation can indeed be disregarded a priori.

179

180

181

182 We thank the referee for this very important comment!

183 The Reichenberger Bach starts at an elevation of around 290 m and has an elevation of 192 m at the
184 outlet of our study area. With a channel length of approximately 7.7 km, it has a slope of about 1.3 %.

185 The Guttenberger Bach starts at an elevation of around 356 m and has an elevation of 225 m at its
186 confluence with the Reichenberger Bach. With a channel length of approximately 5.3 km, the
187 Guttenberger Bach has a slope of about 2.5 %.

188 Based on these parameters, we consider that our study area is steep. We have added this information
189 to the manuscript.

190

191 The issues involving flow type 1 in the culvert implementation in TELEMAC-2D must indeed be
192 addressed in more detail. The referee is very correct to point out that Smolders et al. (2016) is based
193 on a different hydrodynamic setting. We have therefore conducted a thorough analysis on the
194 possible appearance of flow type 1 in our study area. In general, flow type 1 requires two conditions:
195 first, the slope of the culvert is steeper than the theoretical slope for critical conditions. Second, the
196 water depth at the outlet is small (e.g. $<2/3$ of the water depth at the inlet).

197 As the first condition was indeed met by some culverts for lower discharges, the water depths at the
198 inlets and outlets were investigated for the different scenarios of the study. Since we investigate flood
199 scenarios, water depths are large at the outlet and only in the less extreme scenarios (HN5 and
200 HN10), we possibly have flow type 1 during the rising limb of the flood wave at some culverts. These
201 culverts, however, are not located directly at the Reichenberger Bach, but at the end of minor creeks
202 with very low discharge that confluence to the Reichenberger Bach.

203 Furthermore, the scope of this study was not to investigate and benchmark culvert representation in
204 2D-flood modeling, which is still ongoing research in itself (e.g. Oberauer et al. (2026),
205 <https://doi.org/10.1016/j.jhydrol.2025.134728>). Culvert modeling will therefore still induce
206 uncertainty into the modeling framework. In our opinion, this uncertainty is more concerning when
207 the aim of a model is to accurately represent flood events and during possible model calibration.
208 Since our aim, however, was to compare the model results of inundation and discharge under
209 different blockage conditions, these uncertainties are of minor importance, since we mostly draw
210 comparative observations and conclusions.

211 We have added this information to the methodology section ("Culvert Modeling in TELEMAC-2D")
212 and furthermore added to the "Limitations" section.

213

214 **2. Figure 1 should be enhanced by clearly delineating the channel network, labelling the**
215 **streams referenced in the text, and indicating the flow direction.**

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

218

219 **3. (Section 2.2 – Precipitation scenarios). The manuscript does not specify whether rain gauges**
220 **are available, how many exist, or where they are located. Are they situated within the**
221 **catchment boundaries or outside? This information should be provided, and the locations**
222 **should be shown in Figure 1 if applicable.**

223 The referee is correct that we should include more information about the rain data in the manuscript,
224 besides just referencing the source. The rain data are from radar-based rasterized data sets with a
225 spatial resolution of 1 km x 1 km and a temporal resolution of 1 h. We have added these information
226 in the manuscript.

227

228 4. Lines 121–125. Given the relatively small size of the basin (33 km²) and its likely short
229 hydrological response times, it is not particularly informative to report, for example, that 60
230 mm of rainfall occurred over a 13-hour period on 9 July. What matters is the temporal
231 distribution of this event, especially the peak intensities. Additional detail on the hyetograph
232 should therefore be provided. Moreover, for Events 1, 3, and 4, the authors report total
233 precipitation amounts (e.g., 30 mm in 3 hours) and also state that values “locally reached 37
234 mm in 3 hours.” The meaning of this statement is unclear. Does spatially distributed rainfall
235 information exist for these events? If so, what is the data source - point rain gauges, radar-
236 derived products, or another dataset? Please clarify.

237 These rainfall events were obtained from a rasterized data set with a 1 km x 1 km spatial resolution
238 and 1 h temporal resolution. We have added this necessary information to the manuscript.

239 It is true that floods are defined by numerous parameters in the rainfall scenario, not just the total
240 amount of rainfall, but especially the peak intensity plays a crucial role. We have therefore added the
241 information that the peak intensity in the July 9th event was lower than 8 mm/h.

242 In general, we argue in this section that the catchment area is often affected by flash floods, which
243 can be seen by two factors. First, the characteristics of the rainfall events indicate that over the last 5
244 years, there were four events that exceeded at least HN3 on a catchment average, but also reached
245 HN30 locally. Second, these small flash floods caused multiple reactions by the fire department,
246 which demonstrates that it is well worth investigating the catchment.

247

248 5. (2.3 Mesh generation and parameters). At the beginning of this section, there is no
249 information on the topographic datasets used. Only later (lines 153–154) is there a brief
250 indication of the provider, but no details are given regarding DEM resolution or the
251 acquisition technique (e.g., LiDAR or another method). Considering that the channels in the
252 study area are relatively small, the quality and resolution of the DEM - along with any
253 supplementary field surveys - are critical for accurately representing the terrain. Similarly, the
254 main geometric characteristics of the culverts (width, height, length, slope, etc.) are not
255 reported. Please provide this information in a specific Table.

256 We agree that more details about the applied digital elevation model are necessary and we thank the
257 referee for pointing this out. We added that the digital elevation model is LIDAR-based and has a 1m
258 x 1m resolution to the beginning of this section.

259 We have added a table and a figure in the appendix, which provides information on the locations and
260 geometric characteristics of the culverts.

261

262 6. (Section 2.4 – Model validation). Given the very limited amount of observational data, I do
263 not consider it appropriate to refer to this step as “model validation”. The authors explicitly
264 acknowledge that the only available information consists of a few photographs which, due to
265 the lack of temporal metadata, do not necessarily correspond to the peak inundation extent
266 (line 168) and which cover only selected portions of the study area. Under these conditions,
267 true validation is not feasible. I recommend renaming this section to “Simulation of real
268 events” and avoiding the term “validation event”.

269 The referee is correct to point out that this should not be called a model validation and we thank the
270 referee for that remark. Based on the suggestion of another referee, we have changed the section
271 title to “Model Plausibilation” and use this term throughout the manuscript.

272

273 7. Lines 172–175. The manuscript compares the rainfall events of 9 and 15 July 2021, asserting
274 that the former was more severe because it produced 60 mm over 13 hours, whereas the
275 latter produced “only” 25 mm in two hours (although locally up to 43 mm in two hours, as
276 stated in line 124). As the authors will surely know, the severity of a rainfall event cannot be
277 assessed solely using its total depth; the temporal distribution and the mean intensity over
278 timescales comparable to the basin’s response time are far more relevant. For a basin of this
279 size, the response time is likely on the order of a few hours, not 13. I therefore ask the
280 authors to revise this paragraph and clearly state the criteria by which they consider the 9
281 July event to be more severe.

282 The referee is obviously correct that the severity of a rainfall event is not solely defined by the
283 amount of precipitation. The purpose of these lines was merely to state that the event on 9th of July
284 was still impacted by saturated soil from the event on 15th of July. However, our formulations were
285 misleading and we thank the referee for outlining this. We have adapted the manuscript so that this
286 section more clearly focuses on the event on 15th of July, and only mention the event on 9th of July
287 to explain the decision of increasing the runoff in the model.

288

289 8. Line 178. The manuscript states that “a spatially distributed precipitation” was used, but it is
290 not explained how this field was derived. Was it interpolated from point rain gauges,
291 obtained from radar-based products, or generated through another method? Please clarify
292 the data source and processing steps used to obtain this distributed precipitation input.

293 The spatially distributed precipitation was derived from 5-minute radar-based RADKLIM-YW
294 precipitation data set, which has a spatial resolution of 1km x 1km. This information is added to the
295 manuscript and the data source is referenced.

296

297 9. (Section 3.1). In my view, this entire section -including Table 3 and Figure 5 - introduces
298 unnecessary confusion and does not substantially contribute to the manuscript. The authors
299 themselves acknowledge that the inventory of culverts in the basin is incomplete, and there
300 is no hydrometric information available to calibrate or validate the various configurations.
301 Given these limitations, the analysis presented in this section does not appear to be
302 supported by verifiable evidence. Considering the manuscript’s overall length, this paragraph
303 could be omitted without loss of content.

304 Section 3.1 discusses the issue of incomplete data sets of culverts, which is a common problem, but
305 only rarely addressed (e.g. Truhlar et al. (2020) <https://doi.org/10.1061/JSWBAY.0000900>).
306 Therefore, we argue that this section is relevant and adds another layer to the study. Nevertheless,
307 we agree that the section does contribute less to the overall key outcomes of the study. For this
308 reason, we have reduced it to only one brief paragraph and moved the more in-depth analysis into
309 the Appendix.

310

311 10. Lines 322–327 and Figure A2. The delayed response observed at section 2 for the HN5 and
312 HN10 events requires explanation. This delay cannot be attributed to culvert blockage, as the
313 hydrographs show negligible differences across scenarios. Additionally, it is unclear why, for
314 the HN30 event, the peak flow in the br_08_tr_1.2 scenario is slightly higher than in the
315 reference case. The authors should provide a clear explanation for these behaviors. This issue
316 is closely related to the concerns raised in my subsequent point 11 and should be addressed
317 in that context.

318 We thank the referee for this very precise observation and we have reassessed this cross-section.
319 Cross-section 2 is at the Guttenberger Bach and affected by several effects. Downstream is the inlet to
320 a culvert, which can cause backwater effects, especially after triggered blockage. Upstream is a long
321 culvert, which is also overtopped in the simulation and therefore causes a flow path through a
322 complex urban regime. This flow path merges with the Guttenberger Bach briefly upstream of cross-
323 section 2. Directly after the triggered blockage of the upstream culvert, less discharge flows through
324 the culvert, but more into the urban flow path, which can cause very short term differences in the
325 hydrographs at cross-section 2. E.g., in the br_08_tr_1.2 HN30 event, the culvert upstream triggers a
326 blockage at around 6.25 h, so directly before the flood peak and the deviation between the reference
327 hydrograph.

328 As cross-section 2 is evidently not suitably located and an in-depth analysis would not contribute to
329 the key messages of our study, we have decided to remove cross-section 2 from the manuscript.

330

331 11. Lines 354–392. This entire section requires a more thorough explanation, as both the
332 comments provided and Figure 7 are unclear to me. Focusing on the HN5 case (5-year return
333 period, therefore a relatively frequent event), Figure 7 (first panel, top left) presents the
334 computed discharge hydrographs for the different culvert blockage scenarios. In the
335 reference case (no blockage) and in the br_08_tr_1.5 scenario (delayed blockage), the flow at
336 section 3 remains below 0.04 m³/s throughout the simulation period (over 9 hours). In
337 contrast, in the other scenarios, starting around the fourth or fifth hour, the discharge
338 increases sharply, reaching a peak above 0.4 m³/s around 6:20, before gradually decreasing,
339 yet remaining higher than in the reference and delayed-blockage cases. It is unclear why the
340 discharge in the presence of blocked culverts is up to ten times (!) higher than in the
341 unclogged scenarios. Given that rainfall excess input is identical across all simulations, one
342 would expect culvert blockage to reduce discharge through section 3 due to hydraulic
343 constriction, with the excess volume appearing as surface flooding. Indeed, Figure 8 confirms
344 that maximum water depths in flooded areas are greater under blocked culvert conditions
345 than in the reference scenario. However, this observation contradicts the trend in Figure 7,
346 where the discharge and conveyed volumes are higher in the blocked cases. The same
347 unexpected pattern, although less pronounced, occurs for higher return periods: in every
348 instance, the volume passing through section 3 is consistently higher when culverts are
349 blocked than when they are unobstructed. The authors need to provide a comprehensive
350 explanation for this behavior. Without such clarification, one might reasonably suspect that
351 the model does not preserve the mass continuity, which would call all results into question
352 and undermine the validity of the study. I also recommend that, at least for the HN5 case, the
353 authors calculate the ratio between the volume passing through section 3 and the rainfall
354 excess from the contributing sub-catchments. This would help identify the fate of the rainfall
355 excess volume and clarify whether surface retention or other processes are being properly
356 accounted for in the model.

357 Based on comment 10, we have decided to remove cross-section 2 from the manuscript. Therefore,
358 cross-section 3 is now cross-section 2.

359 The decision from us to first briefly describe the different cross-sections and then do an in-depth
360 analysis of cross-section 2 was rather poor, as it might confuse the reader and require a deeper
361 knowledge about the different locations in the catchment. Furthermore, we wrote cross-section 4
362 instead of cross-section 3 (now 2) twice (which the referee also pointed out). We apologise for these
363 circumstances and thank the referee for pointing this out.

364 We have restructured the section based on the comments of referee #1. Now, only cross-section 2 is
365 discussed in detail and the other cross-sections are moved to the Appendix.

366 Cross-section 2 lies within the municipality of Reichenberg. Within the municipality, the streams
367 (Reichenberger Bach and Guttenberger Bach) are fully conveyed beneath the surface. This means that
368 there is a culvert inlet for the Reichenberger Bach at the upstream border of the municipality and the
369 outlet is located at the downstream border of the municipality. Any discharge present at cross-section
370 3 is therefore from overloading of these culverts. Therefore, the results in Figure 7 align with the
371 effects of blocked culverts. Since a blocked culvert has a reduced discharge capacity, less water is
372 conveyed through the culvert. The water depth at the inlet increases, overtops the inlet structure and
373 flows through the municipality, reaching cross section 3. For earlier blockages (TR=0, TR=0.8), water
374 also enters the municipality earlier (seen clearly for HN5). TR=1.5 is not triggered for the HN5 event,
375 therefore, only minimal water flows through the municipality.

376 In addition to restructuring this section (3.3) in the manuscript, we have also rephrased some
377 sentences in the description of the study area in section 2.1, which should improve clarity about the
378 locations of the Reichenberger Bach above and beneath the surface.

379

380 12. Lines 370–372. The authors report a specific observation in these lines. How is this behavior
381 explained? Please refer to the issues raised in point 11 regarding the unexpected discharge
382 trends under culvert blockage scenarios.

383 We refer to the reply to comment 11.

384

385 13. Lines 376–377. Similarly, this observation requires clarification. How can the results be
386 interpreted in light of the anomalies noted in point 11?

387 We refer to the reply to comment 11.

388

389 14. Lines 414 and 417. The sentences “Increased inundation does not necessarily increase the
390 damage induced by the flood” and “As higher water depths are also linked to greater
391 damage” appear contradictory. The authors should clarify the intended meaning and ensure
392 consistency in their discussion of damage relationships.

393 The referee is correct that the sentences appear contradictory in its current state. We have rephrased
394 the section pointing out that inundation is more hazardous in settled areas and greater inundation
395 also carries larger risks.

396

397 15. Lines 427–428. The reported observation requires explanation. How do the authors account
398 for this behavior in the model results?

399 These lines compare the inundation extents of streets and combined residential and industrial areas.
400 Since streets are often located slightly lower than houses, or directly next to the streams, we think
401 that it makes sense that the inundation in streets already increases for lower return periods. We have
402 added this explanation to the manuscript.

403

404 16. Line 430. The meaning of “temporal trend” is unclear. Do the authors refer to changes with
405 respect to return period? This phrase should be clarified or corrected.

406 The word temporal trend is indeed unclear. We have replaced it with “trend along the return
407 periods”.

408

409 17. Lines 434–436. The authors acknowledge that numerical instabilities in the model may
410 explain anomalous behavior. This is concerning because such instabilities could potentially
411 affect other scenarios but remain undetected. The authors should comment on the
412 robustness of the simulations and any measures taken to verify stability.

413 The reviewer is correct that numerical instabilities could potentially affect other scenarios. We have
414 re-checked this scenario and noticed an error in the simulation parameters. We fixed this error and
415 reran the simulation. This scenario now aligns with the overall trend of the BR=0.2 scenarios.

416

417 18. Lines 477–478. The term “redistribution effects” is not clearly defined. Please provide a clear
418 explanation.

419 The term “redistribution effect” is indeed unclear and we thank the reviewer for that comment.

420 The reason for the slight increase in inundation when only omitting blockage at culvert 2 has different
421 facets. This slight increase in the inundation can be found at two different locations. First, there are
422 some pixels downstream of the culvert outlet, which have a water depth higher than 30 cm only
423 when culvert 2 is not blocked. This ever so slight increase can come from slightly different timings in
424 the flood dynamics behind the outlet of culvert 2. Furthermore, a slightly larger inundation is noticed
425 within the main square of Reichenberg. This can come from an untimely overlay from the two
426 hydrographs coming from the Reichenberger Bach (cross-section 4) and the Sichelsgrund (cross-
427 section 3). From the figures in the Appendix, C4 and C3, it is seen that for the HN10 event, the two
428 peaks from these cross-sections almost perfectly align at around 6.5 h. Since the two critical culverts
429 lie in direct vicinity of these cross-sections, slight changes in the culvert behavior can also slightly
430 change the inundation within Reichenberg.

431 However, we think that this analysis is too detailed for the paper and might only confuse the reader.
432 Therefore, we have rephrased the sentence that the increase in inundation increase is in fact almost
433 negligible.

434

435 19. Lines 520–522. The statement that “this study strongly cautions against deliberately inducing
436 blockage to reduce discharge as a basis for mitigation planning” underscores the concerns
437 raised in point 11. The model results in Figure 7 show an increase in flow rate under blockage

438 scenarios, which appears inconsistent with this recommendation. The authors should
439 reconcile these observations and clarify the implications for flood management.

440 We thank the reviewer for this observation. In theory, blocked culverts can reduce discharge
441 downstream and therefore be taken as mitigation measures. However, our study (and other studies,
442 e.g. Al-Whoane et al. 2025) show that this effect is very limited. Combined with the hazard of culvert
443 failure, dam erosion and releasing of a catastrophic debris-laden flash flood wave, culvert blockage
444 should be prevented. We agree, though, that our statement in these lines lacked context and
445 explanation; therefore, we rephrased our statement for clarity.

446

447 **Technical corrections (typing errors, etc.)**

- 448 • Line 193: Replace “diameter” with “height”.
- 449 • Line 195: Replace “before” with “upstream”.
- 450 • Line 317: Remove the repeated phrase.
- 451 • Lines 356 and caption of Figure 7: Correct “cross-section 4” to “cross-section 3” (if my
452 interpretation is correct).
- 453 • Line 357: Remove the duplicate phrase “a slight delay”.
- 454 • Line 368: Clarify whether it refers to cross-section 4 or cross-section 3.
- 455 • Line 443: Change “In general, the inundation...” to “In general, the relative increase of
456 inundation...”
- 457 • Line 468: Change “the resulting inundation extents...” to “the relative differences of
458 inundation extents...”
- 459 • Line 525: Replace “has demonstrated...” with a less assertive verb, such as “has shown...”

460 We also thank the referee for pointing out these technical errors. We have corrected them in the
461 manuscript.

462

463

Response to Referee 3

464

465

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

469

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

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

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

478

479 **Main points:**

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

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

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

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

491

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

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

497

498 The study area lacks accurate observations that allow calibrating the model. However, I acknowledge
499 that the paper mostly presents comparative results (e.g. blocked/non-blocked culverts, different
500 blockage ratios, etc.) to show the relative importance of the culvert assumptions, and this may make
501 the lack of calibration less relevant. My suggestion is therefore to treat the case study as if it was a

502 synthetic case, although inspired by a real catchment. After acknowledging this hypothesis, the
503 authors can completely remove any mention of real events (e.g. lines 118-129 and section 2.4) and
504 just state that the parameters (CN, roughness, etc.) and precipitation scenarios are set to reasonable
505 values for this area. The lack of calibration can then be discussed among the limitations.

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

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

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

520

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

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

535

536 Section 2.6 presents details about the blockage method using the coefficient k_e . I think the authors
537 should provide a better definition for this coefficient (e.g. by showing how the culvert discharge is
538 computed at least for one flow type). This could help justify why the coefficient is set to 0.5 at line
539 240.

540 Culvert hydraulics are presented and discussed in multiple studies. We mention a few studies (e.g.
541 Bodhaine (1968), Smolders et al. (2016), Fernandez-Pato et al. (2020), Weeks et al. (2013), Ollett et al.
542 (2017) etc.), but numerous more studies could be referenced here. Therefore, we decide against
543 presenting the equations for the discharge calculation at different flow types in the culvert.

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

549

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

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

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

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

562

563 As regards the inundation, I understand that the catchment size and relatively limited flood extent
564 prevents displaying readable comparative maps. However, the authors should not only compare the
565 total flooded areas, but also provide some quantitative metrics (e.g. ratio $TP/(TP+FN+FP)$ or other
566 metrics combining True/False Positives/Negatives) about the inundation overlapping (each scenario
567 compared to the reference one). This could be useful to highlight if flooding occurs over different
568 areas due to culvert blockages. Moreover, if the flooded area is overall similar but the max depths are
569 different, another option could be to identify a limited number of classes of max depth intervals (e.g.
570 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
571 belonging to each class. This could also be useful to discuss variations among scenarios.

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

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

582

583 Section 3.3 is very descriptive but hard to follow without being familiar with the layout and
584 conveyance capacity of streams and culverts. Moreover, all hydrographs look very similar, except at

585 cross-section 3, so I wonder if the authors could just focus on a couple of interesting locations and
586 two/three precipitation scenarios and make an effort to summarize only the relevant findings.

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

590

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

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

599

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

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

606

607 Specific points:

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

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

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

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

624

625

Response to Referee 4

626

627 We are thankful for Referee 4's constructive and valuable feedback. We have assessed the Referee's
628 concerns in the manuscript and detail our individual responses in the following. The Referee's
629 comments are in a yellow background, and our responses are beneath.

630

631 This paper presents a hydrological-hydraulic modelling framework aimed at simulating the effect of
632 culvert blockage in minor drainage networks. the main component is a modified version of TELEMAC-
633 2D model that can handle dynamic blockage conditions. The modelling framework is applied to a
634 drainage basin in Germany to simulate different scenarios of rainfall intensity and culvert blockage
635 conditions.

636 Overall this is an interesting work. It addresses an important problem that is often underestimated
637 both in scientific literature and in operational flood risk management.

638 We thank the referee for his valuable feedback and for reviewing our manuscript.

639

640 Main comments

641 1) My feeling is that the focus of the work is too narrow, resembling a technical report rather than a
642 scientific paper. There is little reference to importance of the problem on a bigger scale, and little
643 attention is given to the applicability of the proposed approach to other case studies. For instance,
644 would the TELEMAC 2D work well also for larger river networks, or under more complex hydraulic
645 conditions such as bifurcating culverts, underground confluences etc? Can it be coupled with
646 stormwater models? These are all issues that should be discussed by the authors.

647 Our study has shown that blocked culverts do not have significant impacts on a bigger scale, as the
648 outlet hydrographs of the catchment showed only little sensitivity to blockage. This is in agreement
649 with the study from Al-Whoane et al. (2025). Within our limitations section, however, we state that
650 blocked culverts can lead to failure of the culvert structure, which in turn can cause a catastrophic
651 event on a large scale. We have further elaborated this in the limitations section.

652 It would be premature to make generalizable statements from our specific case study, which may not
653 hold for other catchments. In this sense, yes, there is a rather narrow scope. Nevertheless, we argue
654 that our proposed approach can be directly applied to other case studies and also bigger catchments.
655 By applying a scenario-based modeling approach with varying degrees and timings of blockages,
656 critical culverts within a catchment can be identified. Additionally, targeted mitigation measures can
657 be assessed by modeling scenarios with some culverts prevented from blockage. We do agree though
658 that this was not strongly enough stated in the manuscript and have stressed this point more in the
659 introduction and the conclusion.

660 A coupling of TELEMAC-2D with a drainage network is currently under development. This does open
661 up new possibilities in modeling culverts, especially with bifurcations. A small section on this within
662 Limitations has been added to the manuscript.

663

664 Furthermore, we have rephrased statements in the introduction and the conclusion to provide more
665 context on the relevance of the study and the ability to transfer the methods on other study cases.

666

667 2) The reliability of the modelling framework is not sufficiently discussed in the manuscript. The
668 authors state that discharge measurements are not available for the study area, and therefore they
669 carried out a plausibility check using data from a reference flood event. However, the authors should
670 discuss if and how modelled flood extent and depth agrees with observations.

671 Furthermore, the plausibility of model results could be assessed by comparing the frequency of
672 simulated flooding due to culvert blockages with reported frequency of flooding. For instance, results
673 at cross-section 4 (figure 7) indicate that the study area is likely to be flooded at least once every 10
674 years, or more frequently in case of culvert blockage. Is this in agreement with reported flood
675 frequency, or is the model overestimating the occurrence of flood events?

676 We have revised the previous section "Model Validation" and renamed it "Model Plausibilisation", as
677 we cannot fully validate the model. This should now further clarify that the model in fact cannot be
678 validated, but the results at least match the observations from the photographs. The precipitation
679 scenarios for the culvert blockages exceed the threshold for experienced flooding from past events.
680 Therefore, flooding is expected for these scenarios, which is reproduced by the model. There is no
681 specific flood frequency data available for the catchment, and therefore we could only assess floods
682 based on reports by the fire department.

683

684 3) L116 "Without these culverts, the sub-catchments upstream of the culverts are disconnected from
685 the overall flood" and Lines 273-274: "Omitting culverts in hydrodynamic models can cause parts of
686 the catchment to become artificially disconnected from the flood dynamics,..." these two sentences
687 are not clear, do you mean that there is no hydrological connectivity? My understanding is that the
688 model can simulate surface runoff, so channel continuity is not a requisite to convey water
689 downstream. Can you please clarify and expand the description of the modelling framework on this?

690 No, we do not mean that there is no hydrological connectivity in the general sense. As the referee
691 points out, channel continuity is NOT a requisite to simulate a connected water volume downstream,
692 as the model is 2D and does not distinguish streams from the rest of the terrain. We do not mean
693 that the model simply disconnects upstream from downstream forever (as it would be in a 1D , or a
694 network model).

695 What these lines mean is that missing culverts in the model break the connectivity of water that
696 would flow through the stream if the culvert were present in the model. Connectivity may re-
697 establish itself after water ponds and finds some drainage direction or simply overtops. The reviewer
698 is right in that the model doesn't care, since water will flow wherever the gradients lead.

699 Whether this connectivity is re-established or not is an outcome of the simulation. As we wrote in the
700 manuscript, this incorrect and artificial disconnectivity can be expected to underestimate flow and
701 flooding downstream, or at the very least delays due to the artificial retention.

702

703 **Other comments**

704 Line 48-49: "However, these logjams at bridges usually show larger impacts at larger bridges, which
705 are present at large rivers and therefore not directly an issue for flash floods at smaller streams." I do

706 not agree here: also bridges over minor rivers are prone to debris jams, and the determine
707 backwater effects and consequent overflow upstream, especially in steep areas. I would say that such
708 events can be highly dangerous because of the quick onset of flood waves.

709 The referee is correct to point out that this statement neglects the danger that bridges can also play
710 an important role during flash floods. We have rephrased the lines that culverts play an important
711 role alongside bridges.

712

713 L118: "the Reichenberger Bach lies in a comparatively dry region with a mean annual precipitation of
714 712mm..." comparatively dry to what? To the rest of Germany?

715 We thank the referee for pointing out the lack of context. The area is only comparatively dry for the
716 state of Bavaria, and not for Germany. We have rephrased that the region is frequently affected by
717 droughts, but still the catchment experienced several minor flash floods in recent years.

718

719 Figure 1: please add the two water courses in the map

720 We have added the water courses to the map.

721

722 L120-125: what does NH means?

723 We have added context to the abbreviation HN.

724

725 L128: is KOSTRA 2020 a dataset of measurements, or something different? Is it at national scale?
726 Please explain

727 We have added more context about the KOSTRA 2020 dataset in the manuscript.

728

729 L193-194: "The flow types can be further grouped into inlet (flow types 1 and 5) and outlet control
730 (flow types 2, 3, 4, and 6)." If these flow types are relevant for the study you should provide at least a
731 short description of each. Otherwise, this can be omitted

732 The description of the different flow types of culverts has been done in multiple studies. Therefore,
733 we argue it is not necessary to detail this again in our study. We agree though, that these flow types
734 should not be stated in this context then and have omitted this now in the manuscript

735

736 Figure 10: the graph shows many simulations and most of them look similar, consider omitting some
737 of them

738 We agree that most of the blockage scenarios are rather similar, besides the TR=1.5 scenario, and the
739 TR=0 scenario. However, we prefer to keep the other blockage scenarios as well, to stress the
740 argument that the trigger point itself is only important, if triggering is either close to the flood peak
741 or triggering is prevented by a large TR. We have added some context on this in section 3.4.

742

743 Section 3.5 I would rename it as "Simulation of mitigation measures", there are no indications for the
744 design

745 We have renamed the section to "Simulation of mitigation measures".

746

747 L513: "backwater effects tend to be constrained by the bridge thickness." not fully clear: do you mean
748 that the bridge decks are relatively thin in the study areas and hence cannot block substantial amount
749 of floating debris?

750 Yes, the bridge decks in the study area are relatively thin and we have replaced "bridge thickness" to
751 "thickness of the bridge decks".

752

753 L526: "The results show that certain culverts can exert an large influence on flood dynamics,..." This is
754 perhaps an overstatement given the results, culvert blockage can increase flood depths and extent at
755 certain locations, but the effect is not so large

756 We have rephrased the statement to "can impact local flood dynamics".

757

758 L533-534: "Future research should further investigate the processes driving culvert blockage
759 formation. Laboratory experiments can provide insight into blockage mechanisms and thresholds,
760 which could then be translated into dynamic numerical models." Even though this might be useful, I
761 would first prioritize the installation of water level/discharge gauges in strategic points of the
762 drainage network. This would allow to measure the response of the basin to different rainfall events
763 and relate it with culvert blockages. Having real-time measurements could also allow for more timely
764 interventions to remove blockages

765 We agree that gauges throughout the catchment and within drainage infrastructure could provide
766 valuable insights into the mechanisms of culvert blockages and flood responses. We have added this
767 to the conclusion.

768