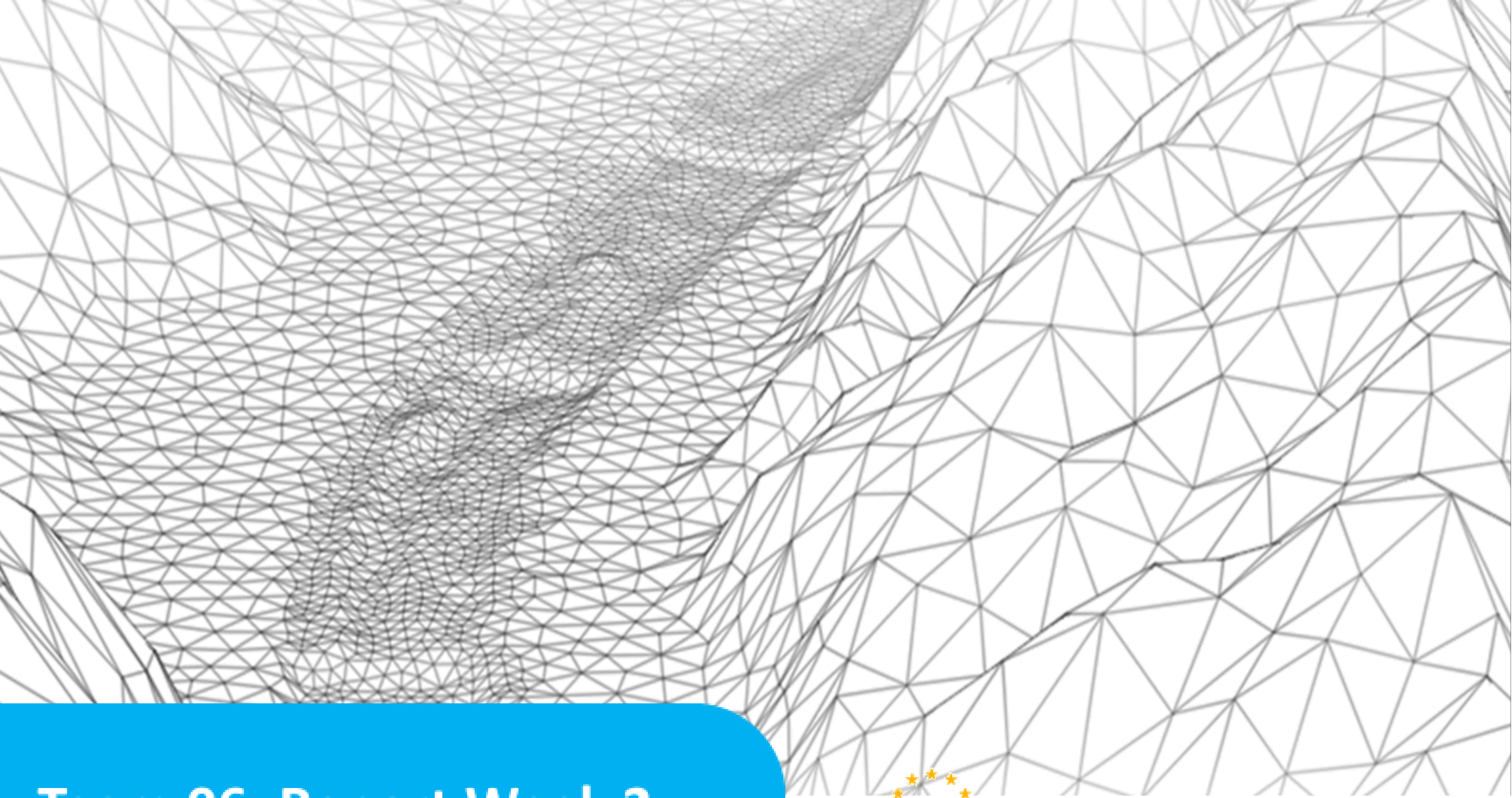

Team 06: Report Week 2

HYDROEUROPE

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HydroEurope

WP2: Uncertainty in Advanced Hydrological and Hydraulic Modelling
WP3: Climate Change Impacts on Flash Floods
Case Study Ahr Catchment (Germany)

Team 6 - Report Week 2: Development of 2D Model and Proposing Flood Adaptation Measures

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1 March 2024

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1 Two-dimensional modelling

After analysis of simulation results, it has been determined that the flood maps generated do not adequately represent the terrain features as per the Digital Elevation Model (DEM). To address this limitation, an alternative approach involving the analysis of simulation results has been pursued. Specifically, employing a method incorporating spatially distributed precipitation data appears more promising based on initial findings.

1.1 Pretreatment

To better represent reality, we decided to artificially hollow out the watercourse using the GRASS r.carve function. Indeed, the resolution of our DEM does not allow us to correctly represent runoff at stream level. Therefore, we decided to dig the river 15 m wide and 3 m deep. However, as the resolution of our DEM is 25 m, the river will be 25 m wide, which is not entirely representative of the Ahr river. However, as the main objective is to make a spatial analysis of precipitation and a comparison with the HEC-HMS results, it should not hold significant implications.

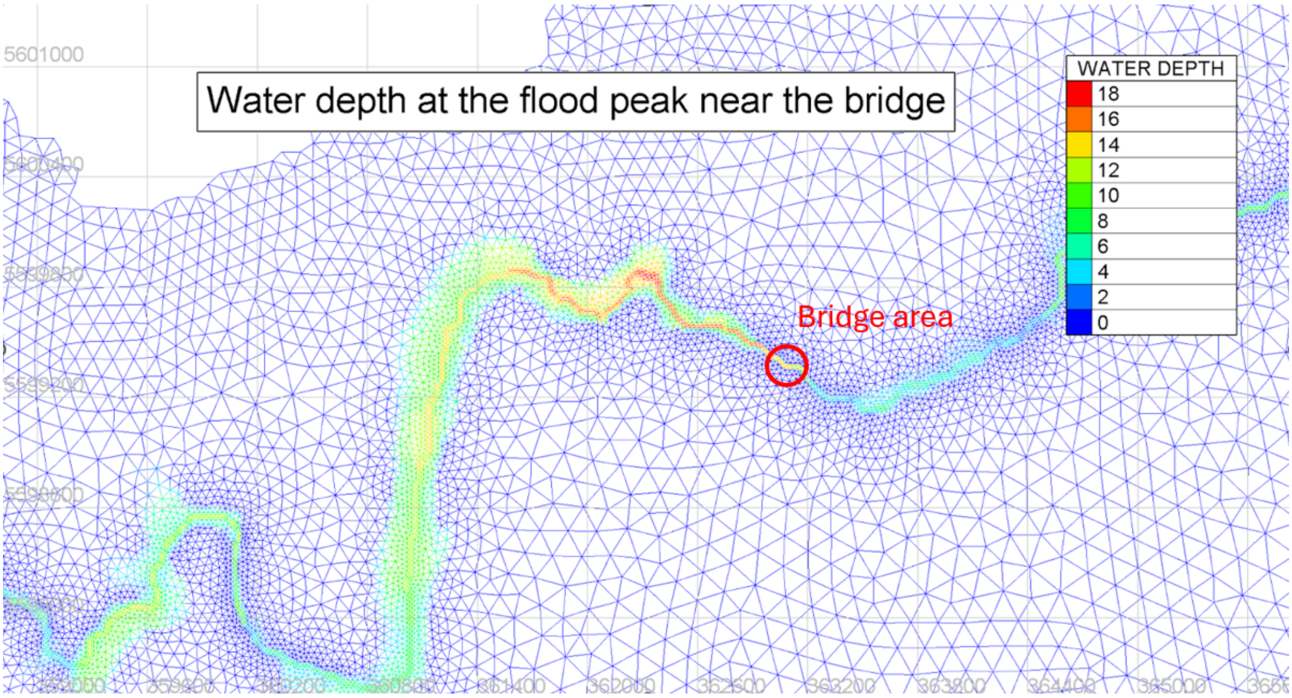

Figure 1. : Zoom on the area of the mesh where the bridge is located during the simulation (Bluekenue)

After this, we decided to run a simulation with a rainfall that is homogeneous in both time and space. The rainfall was defined as 150 mm/day over 72 hours, and the model was run for 6 days to allow the flood to subside. This, therefore, enables us to fill any troughs that may be present in the catchment. However, we note that the water is blocked at the downstream part of the bridge.

We used ‘Bluekenue’ software to remove bridges from the model as the presence of bridges would cause the flow to accumulate. The tool basically replaced the elevation values of the bridge level with the ground level.

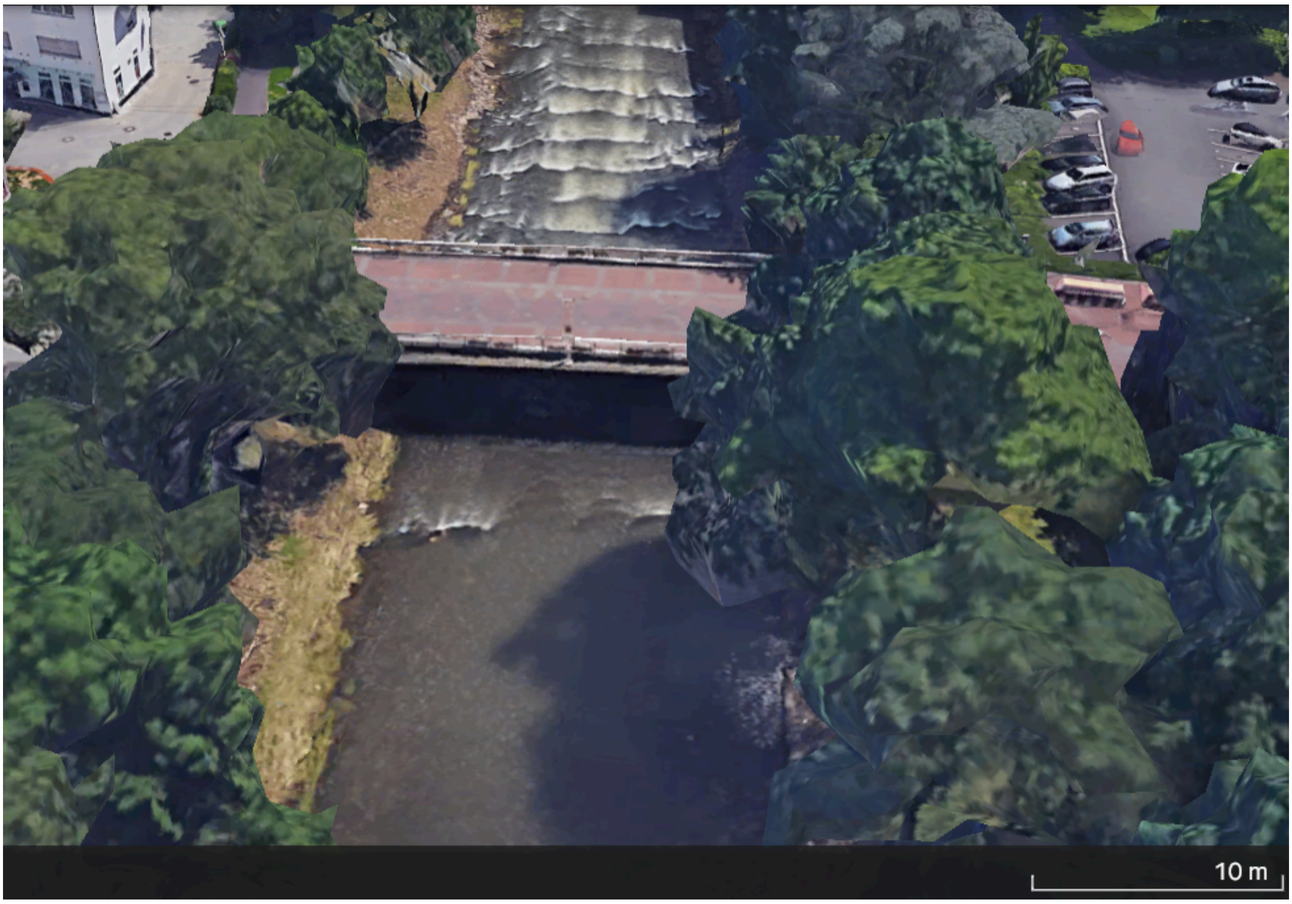

Figure 2. : The bridge removed from the DEM

Once this was completed, we ran simulations with the same parameters as the previous simulations, i.e. a 9-day simulation with homogeneous precipitation in time and space of 150 mm/hour for the first 3 days. This was done to create a hotstart, i.e. a simulation that we'll use as an input for our next simulations. The aim of this is to fill the depression zones with water so that the volume of precipitation at the input is equal to that at the output.

1.2 Methodology

There are various parameters to consider in the model to ensure it accurately reflects real conditions. Infiltration is accounted for using the curve number method. The runoff curve number is an empirical parameter utilized in hydrology to estimate direct runoff or infiltration resulting from rainfall excess. The Ahr watershed is predominantly composed of vegetation and forests. For this analysis, a curve number (CN) of 75 has been considered as a first approximation. In addition to this, for our first approach, the decision was made to maintain a uniform curve number across the whole catchment.

Precipitation is also a crucial parameter in the simulations of the 2D model. As a first step, we decided to spatialize the measured rainfall data. So, for each station, we input the precipitation measured with a time step of one hour. As the spatialization of rain does not exist in Telemac2D, we had to retrieve certain Fortran codes enabling this spatialization.

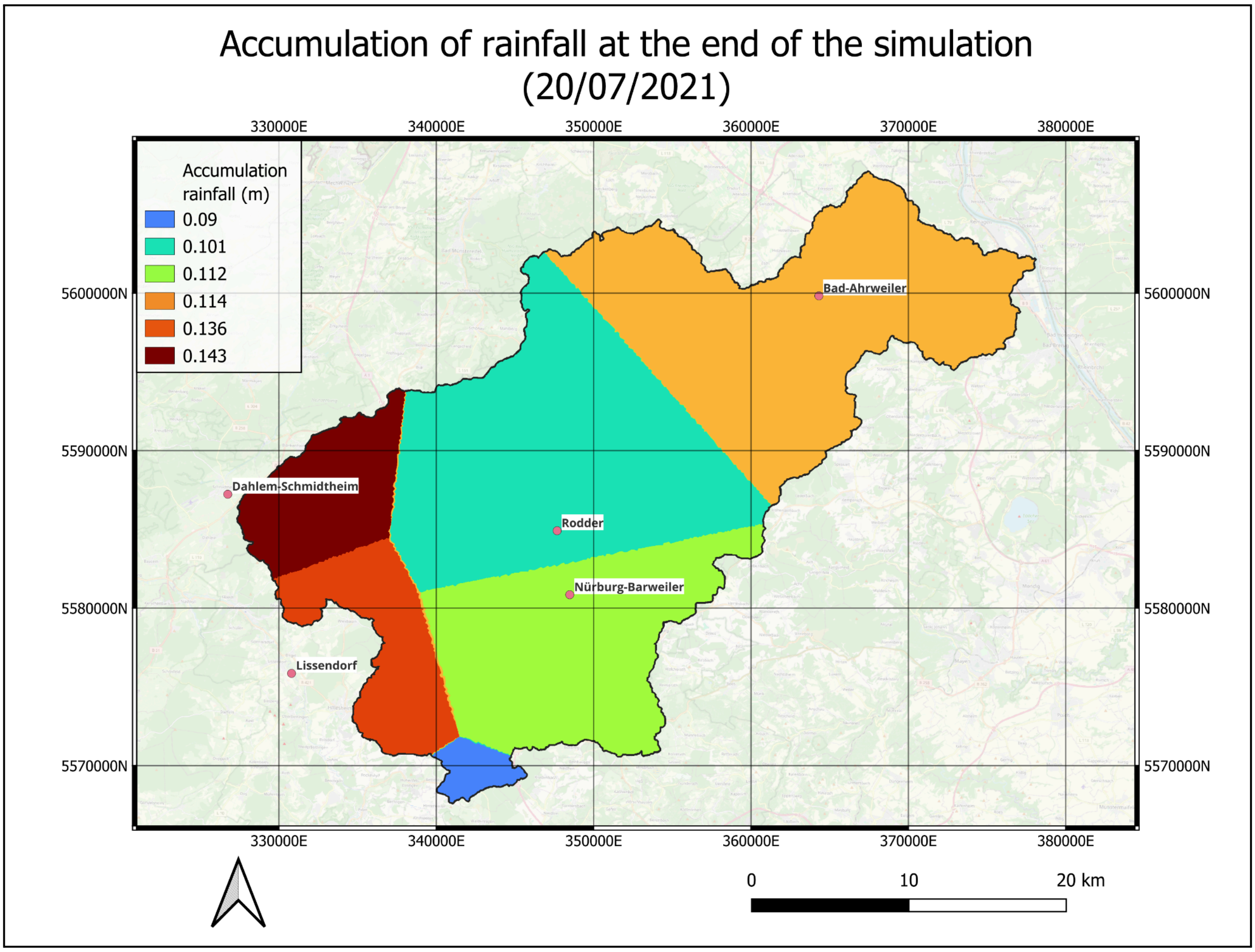

Figure 3. : Accumulation of the rainfall at the end of the simulation (20/07/2021)

We installed control sections at the stations for which we have data for the entire event, notably at the Kirmutscheid and Niederadenau stations. We also installed a control section at the outlet (Bad Bodendorf) to compare with HEC-HMS simulation results. Measured rainfall data has been directly used as the input because the model uses SCS Curve Number method to separate the effective rainfall. We also wanted to evaluate the impact of rainfall spatialization on our model, and in particular on the hydrograph at the outlet, but we ran out of time.

Regarding the initial abstraction (λ), its value directly determines the amount of runoff. The simulations were conducted using a default value of λ=0.2. The simulations are initiated using a previously computed file which abides by the law of water balance. Simulations are initiated from the hotstart described above, to avoid the effects of topographical depressions on our results.

1.3 Results

We thus obtain the following hydrographs at the Kirmutscheid gauging station.

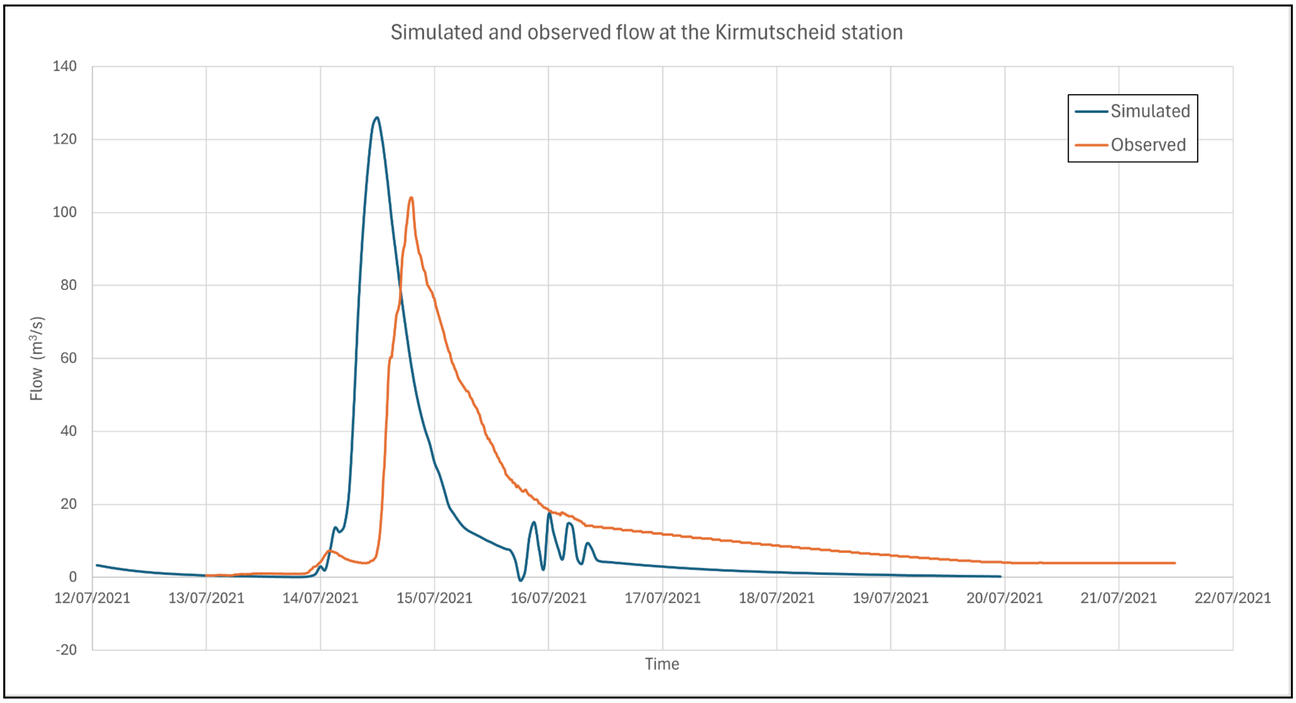

Figure 4. : Comparison of the flow simulated and observed at the Kirmutscheid Station

We can see that there are some differences in peak flood and time of peak. The simulated peak flood is higher and occurs earlier than that observed at the Kirmutscheid station. These two parameters are essential, as they can have a significant impact on the measures taken before and during an event.

As a result, it was decided to simulate a few other models by spatializing Curve Number and Strickler. The aim is to better represent the flow in our watershed. We therefore developed an R code based on the Corine Land Cover codification to spatialize these two parameters. For a first approach, we decided to take the values of hydrological soil group B, which corresponds to moderate infiltration.

CLC Code	Land cover	Curve numbers for hydrologic soil group			
		A	B	C	D
112	Discontinious urban fabrics	54	70	80	85
121	Industrial or commercial units	85	90	92,5	94
131	Mineral extraction sites	77	86	91	94
211	Non-irrigated arable land	65	76,5	84	88
231	Pastures	30	58	71	78
242	Comples cultivation patterns	30	58	71	78
243	Land principally occupied by agriculture	78	83	86	88
311	Borad-leaved forest	30	55	70	77
312	Coniferous forest	36	60	73	79
313	Mixed forest	30	55	70	77
321	Natural grasslands	39	61	74	80
324	Transitional woodland-shrub	30	55	70	77

Figure 5. CLC code for land-use shapefiles (Gilewski and Węglarz, 2018)

We did the same thing with the Strickler. The R code enabled us to add two columns to the Corine Land Cover layers, one for the Curve Number and the other for the Strickler. We then transformed these layers into raster by taking the values of these 2 columns as a reference. Finally, we interpolated these rasters onto our geometry file using Bluekenue software. We obtain the following results:

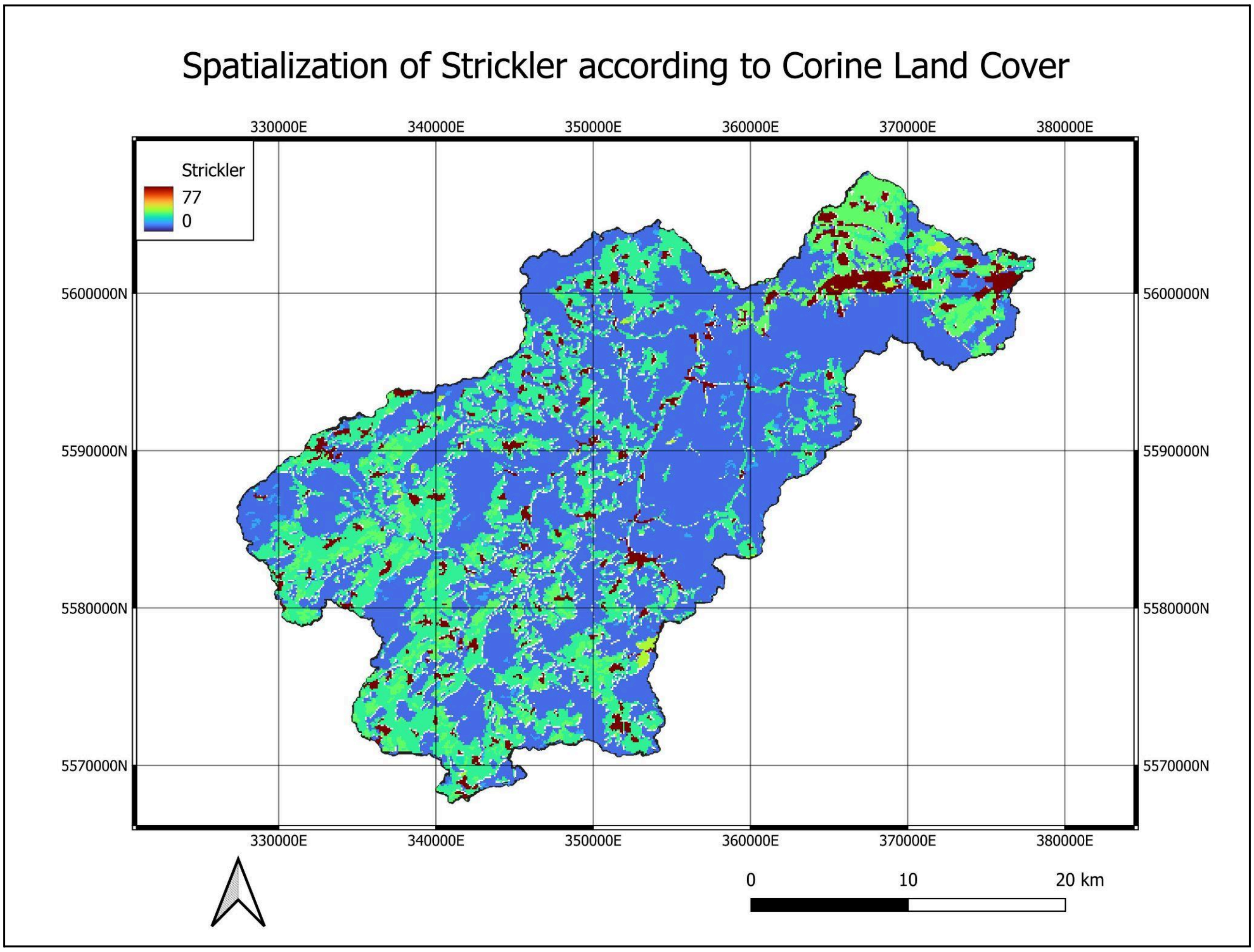

Figure 6. : Spatialization of Strickler according to Corine Land Cover

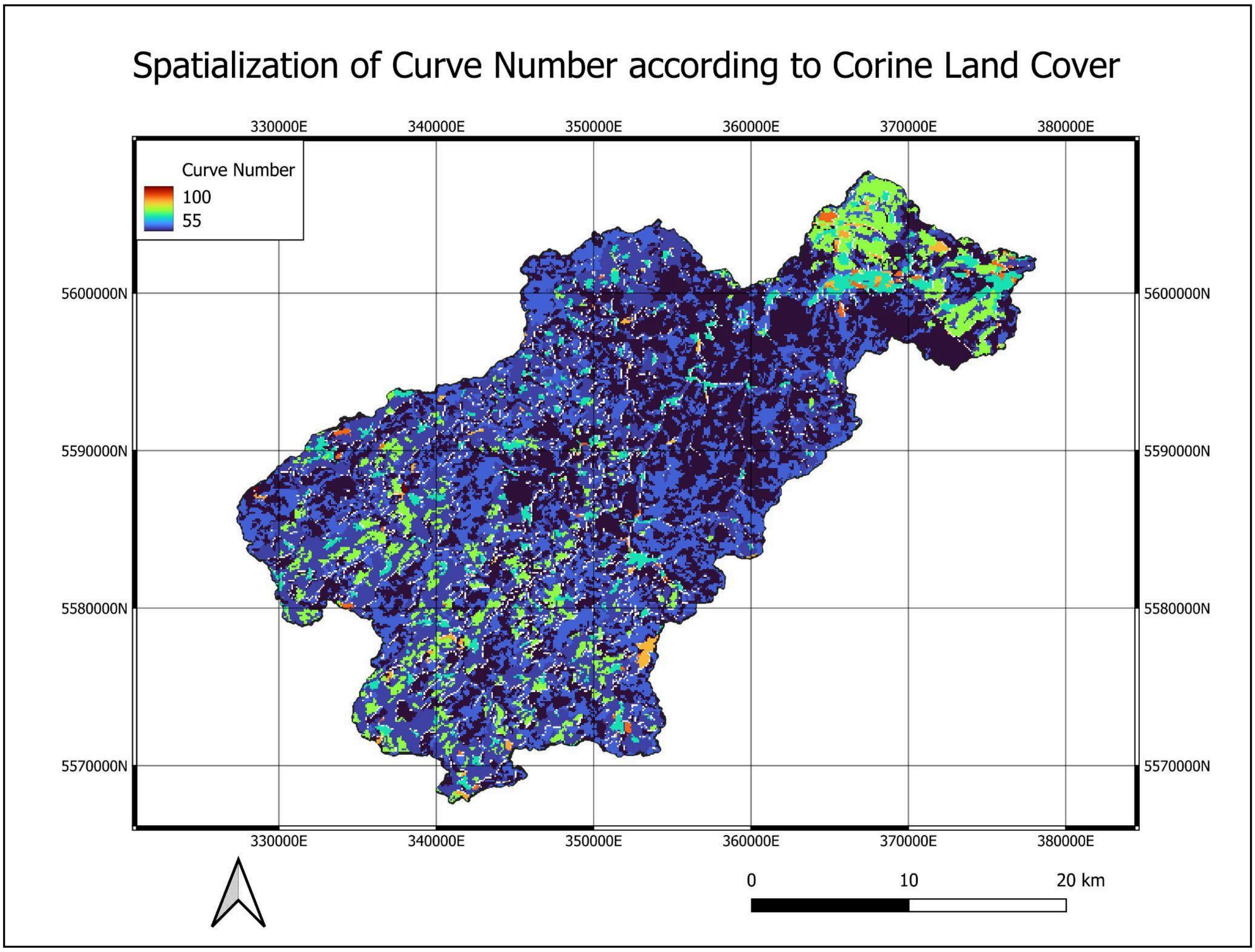

Figure 7. : Spatialization of Curve Number according to Corine Land Cover

We therefore performed the same simulations with these two parameters distributed spatially. However, we encountered instabilities when simulating with Curve Number spatialization. We therefore present here only the results for Strickler spatialization.

This gives us the following results at the Kirmutscheid gauge station:

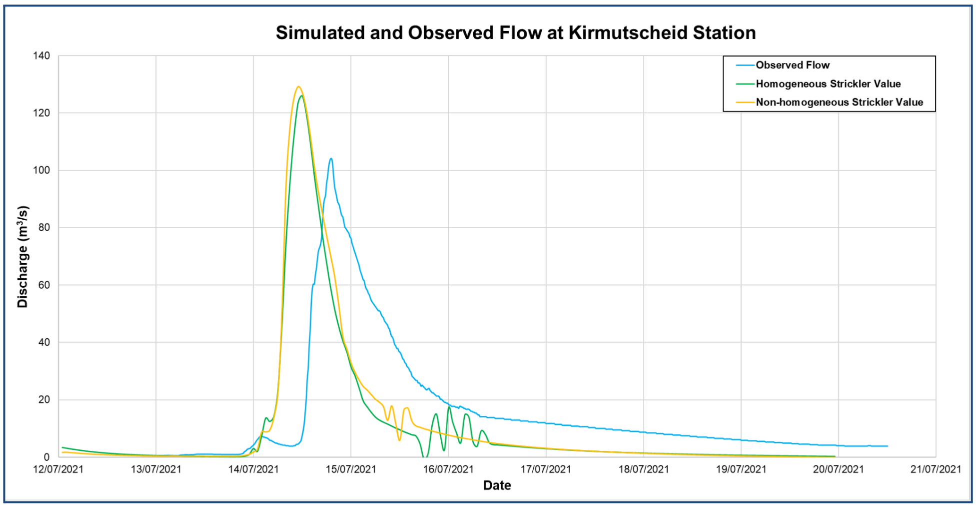

Figure 8. : Comparison of the flow simulated (with and without spatialization of Strickler) and observed at the Kirmutscheid Station.

We can see here that we obtain similar results for both simulations (with and without Strickler spatialization). However, we observe a reduction in oscillations due to numerical problems. However, we haven't had time to investigate these local oscillation problems further.

In order to improve our model, we would therefore need to modify other parameters to see their impact and thus calibrate the model. This could be done by modifying the Initial Abstraction factor, the Antecedent Moisture Condition, the Curve Number or other parameters.

We also decided to produce hydrographs at the outlet for comparison with our HEC-HMS model.

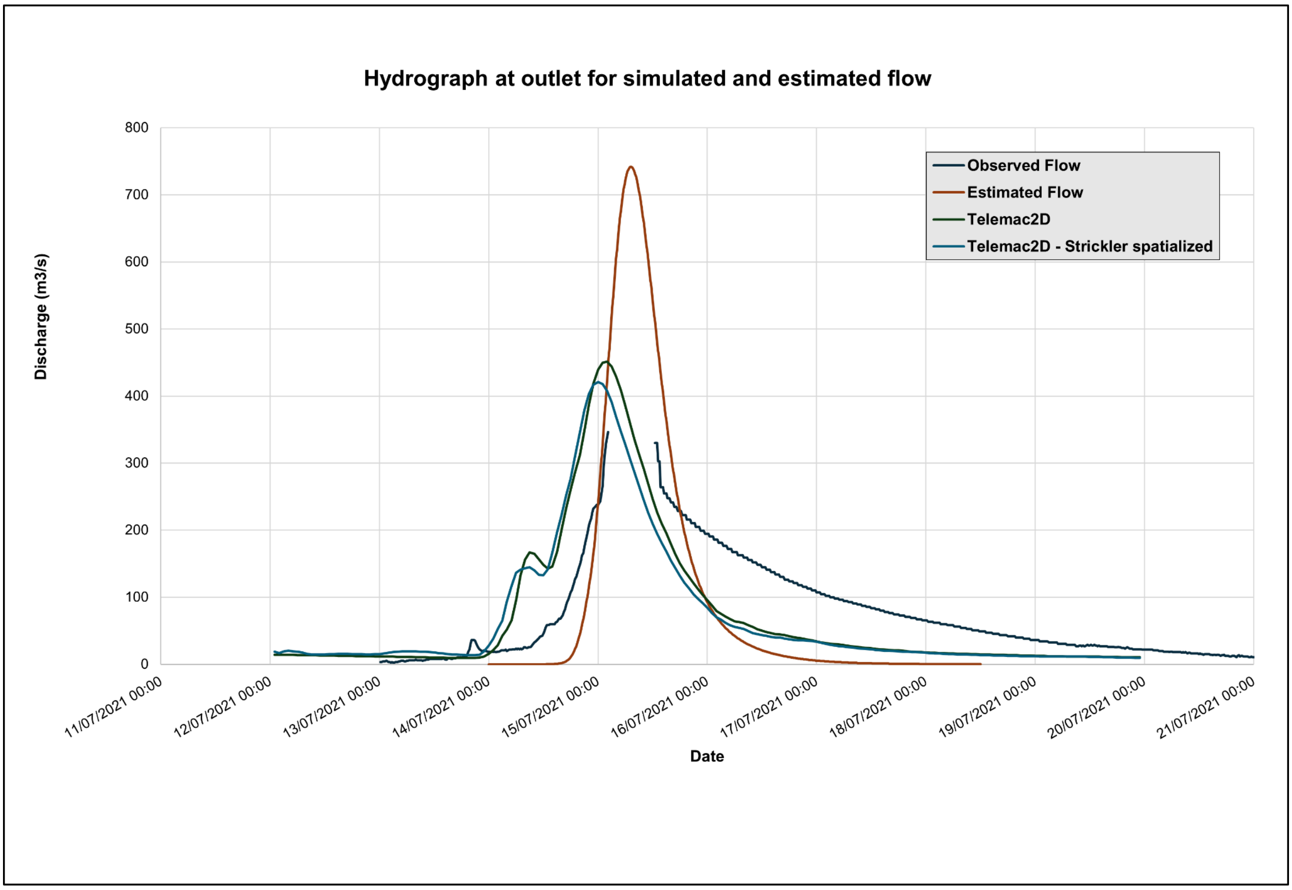

Figure 9. : Comparison of the flow hydrograph for Telemac2D simulation (with and without spatialization of Strickler), HEC-HMS model and observed data at the Bad Bodendorf gauge station.

We can see quite a difference between the results of the simulation with Telemac2D and that with HEC-HMS. These differences are particularly noticeable in the lower flood peak and the earlier peak time. We also note that our Telemac2D model has two flood peaks. However, it should be noted that the HEC-HMS model has been calibrated, whereas the Telemac2D model has not. We therefore need more time to go back to the problem and perform a calibration of our 2D hydrodynamic model in order to make a more in order to make a more relevant comparison.

1.4 Flood of the 14th July 2021

The website of the Ministry of Climate Protection, Environment, Energy, and Mobility of the Rhineland-Palatinate provides access to flood risk maps for the 2021 event.

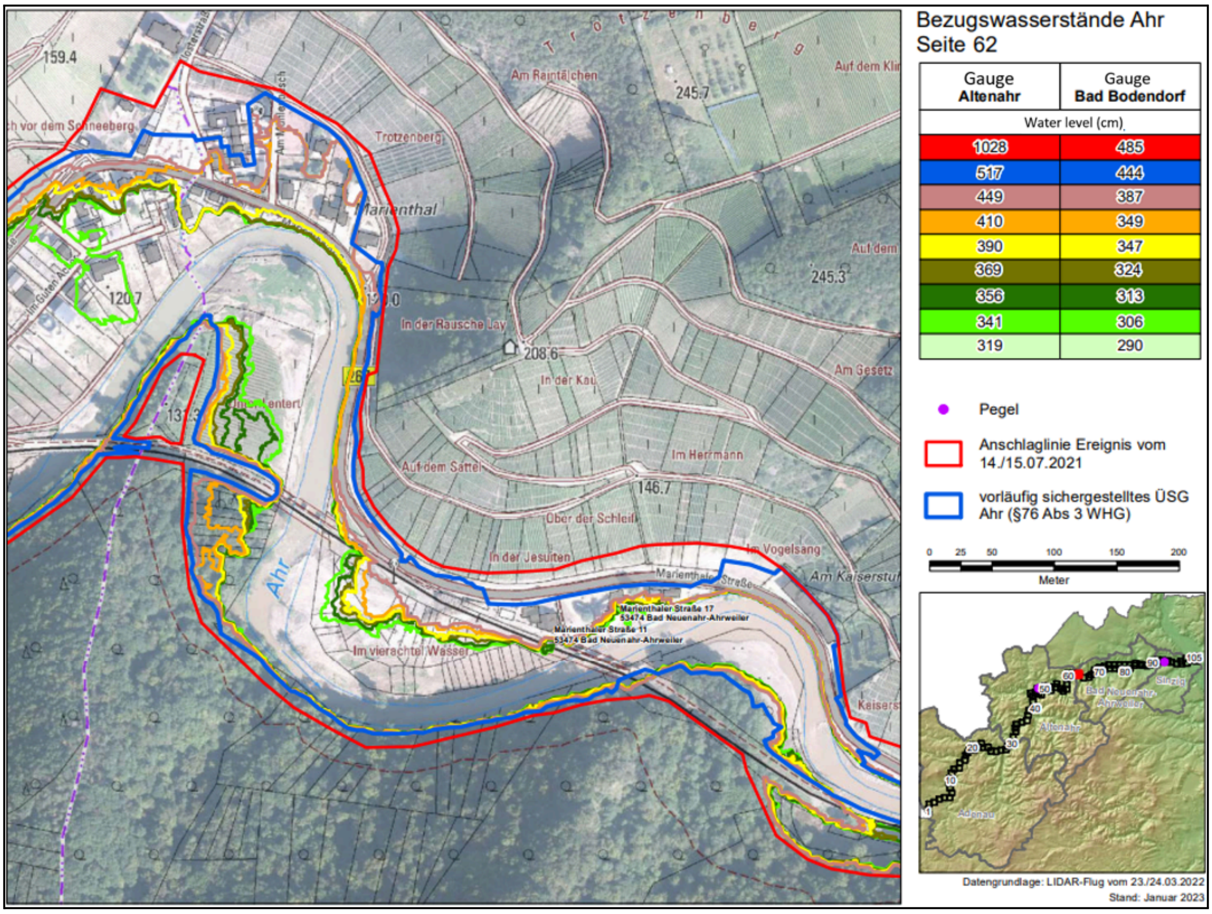

Figure 10. : Water level markers for the flood of July 15th, 2021, at Marienthal (Flood Stop Lines. Structure and Approval Directorate North, 2023)

This map, derived from government data, illustrates water levels during the floods of July 14th and 15th in the vicinity of Marienthal. We decided to choose this location because it has many houses/constructions and it has a rather particular river pattern with certain curvatures which could pose problems for our 2D model. The map reveals that the flood marker is significantly advanced within the village, indicating complete inundation. This observation underscores the severity of the flooding event and highlights the extent of its impact on the local community. Next, the comparison between this event and their corresponding simulation will be conducted.

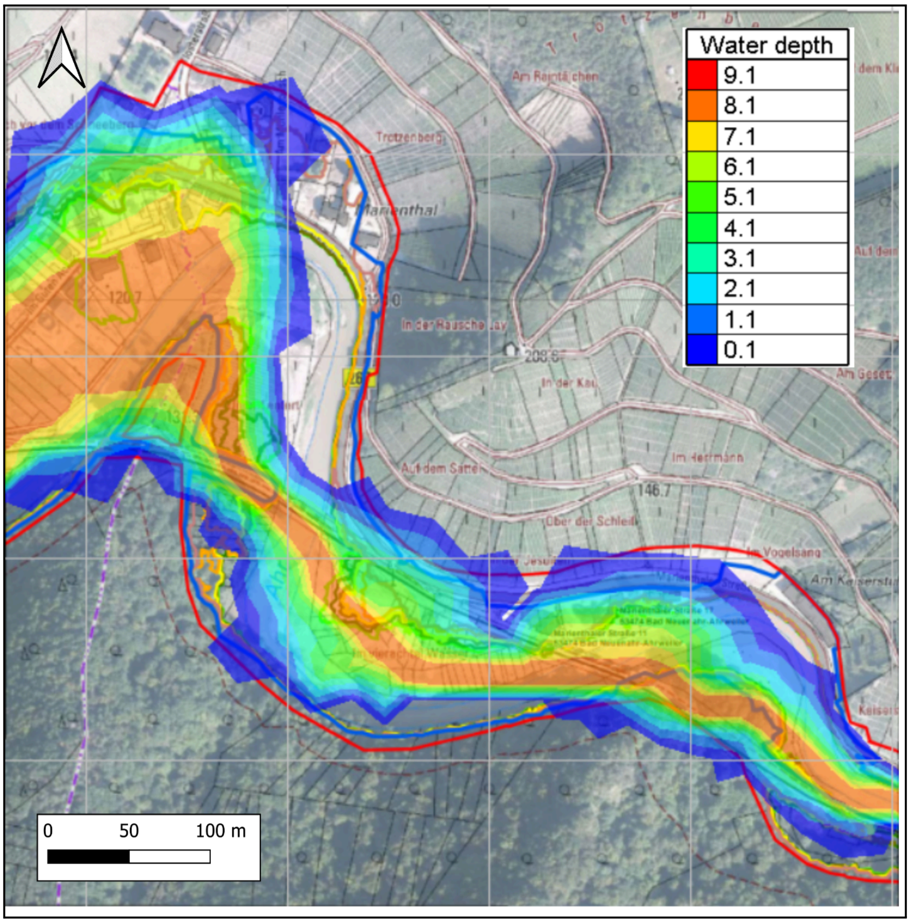

Figure 11. : map of simulation overlays and flood benchmarks at Marienthal

In the overlay, the simulation shows rather similar results. However, we can see that our model has difficulty following the curves of the river. What's more, the model underestimates the extent of flooding at certain locations. This is probably due to the resolution of our DEM, which is only 25 m. So, as we said before, we had to dig the river artificially, but as the resolution is 25 m, our river will be at least 25 m wide. This is not representative of reality, as our river is 10 m wide. So we're going to store a lot more water at river level in our model and reduce the extent of flooding.

2 Extreme storm analysis

2.1 Climatic Scenario - Duration and Frequency

Understanding the anticipated response of the catchment to projected future rainfall events becomes imperative for formulating effective flood mitigation strategies and interventions, particularly in the face of challenges posed by climate change. With the aim to estimate the implications of climate change on future flash flooding events, we have reviewed the Representative Concentration Pathways (RCP). Initially proposed by the IPCC, the RCP represents a method for capturing various future emissions trajectories, ranging from very low (RCP 2.6) to very high (RCP 8.5). After analyzing each of these projections, it was decided to focus our analysis on the RCP 8.5, as this scenario is reflective of the 'worst-case scenario' and as such allows for a comprehensive review of the proposed flood mitigation strategies and intervention.

In context of the Ahr catchment, it becomes of particular importance given its history of flash flood events, that changes in extreme flood scenarios due to the effects of climate change are able to be understood. For this reason, we have chosen to focus our analysis on two rainfall events of duration

6-hours and 12-hours as this is the most representative of flash flood storm durations. Through studying these durations, we are able to gain insight into the catchment's response to two flash flood events. Thus, improving our understanding of the catchment's response to future flash flooding and the implications of climate change on this matter. In addition to understanding how the duration of precipitation events are impacted by climate change.

2.2 Projected Climate Scenarios

In order to predict flood situations with different climate scenarios, the initial step involves determining a suitable climate change factor using existing literature. The climate change factor is sourced from the research conducted by Hosseinzadehtalaei, Tabari and Willems (2020) investigating climate change impact on short-duration extreme precipitation and Intensity-Duration-Frequency (IDF) curves over Europe. The IDF curves in figure 11 are derived and downscaled from EURO-CORDEX regional climate models for RCP scenarios 8.5 and 4.5 under different return periods and durations, and are for the period 2071-2100 using precipitation data from Central Europe.
The IDF curves show a larger change factor for shorter durations and longer return periods. The RCP 8.5 climate change factor (CCF) for a 50-year return period 6-hour and 12-hour durations of rainfall are 1.23 and 1.21 respectively.

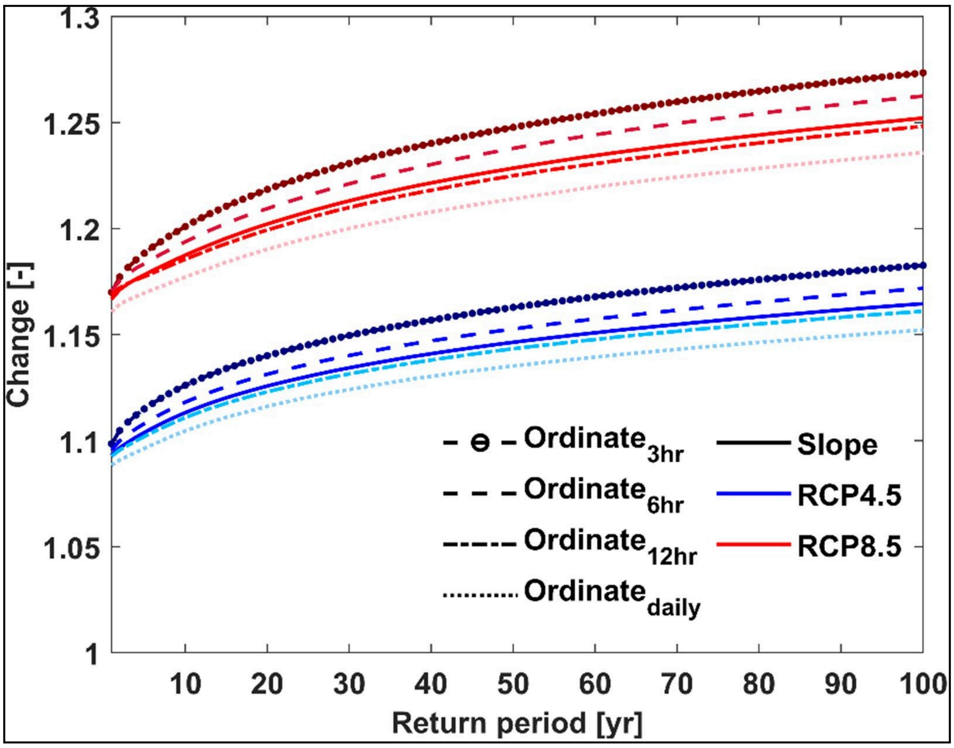

Figure 12. IDF curves for different durations, return periods and climate scenarios (RCP 4.5 and RCP 8.5) for the period of 2071-2100 (Hosseinzadehtalaei, Tabari and Willems, 2020).

Availability of a climate change factor has allowed the manipulation of the current estimations for total precipitation under the occurrence of a 50-year return period provided by the KOSTRA-DWD-2020 data set. By multiplying these values with the climate change factor, we have generated precipitation representative of a 50-year return period considering the effects of climate change. This approach allows us to account for the climatic scenario with RCP 8.5. The total precipitation is derived by averaging the cell values from the KOSTRA-DWD data set. Both the direct values and manipulation with climate change factor (CCF) for the RCP 8.5

scenario are shown in Table 1 and Table 2 for two duration rainfall events, 6-hour and 12-hour. Here, the precipitation data has been estimated across each sub-basin. Both tables exhibit a similar kind of pattern. The predicted 50-year and 100-year rainfall amounts are highest in sub-basin 1 and gradually reduces in sub-basin 2 and sub-basin 3 respectively.

An interesting thing is observed after multiplying the 50-year rainfall event with the RCP 8.5 CCF. The values have surpassed the rainfall amount of 100-year return period for each sub-basin. That means, with the effects of climate change, the approximation indicates that the rainfall event which is supposed to happen in every 100-year might happen in every 50-year.

Sub-basin	**6-hour Duration Rainfall Event (mm)**		
	50-yr Return Period	**100-yr Return Period**	**50-yr Return Period with RCP 8.5 Climate Change Factor**
Sub-basin 1	62.74	71.24	77.17
Sub-basin 2	60.9	69.10	74.91
Sub-basin 3	59.61	67.85	73.32

Table 1. Total Precipitation for 6-hr Duration Rainfall Event (with and without CCF)

Sub-basin	**12-hour Duration Rainfall Event (mm)**		
	50-yr Return Period	**100-yr Return Period**	**50-yr Return Period with RCP 8.5 Climate Change Factor**
Sub-basin 1	76.74	85.88	92.86
Sub-basin 2	72.65	82.40	87.91
Sub-basin 3	67.17	80.26	81.27

Table 2. Total Precipitation for 12-hr Duration Rainfall Event (with and without CCF)

2.3 Spatial variability

To gain a better understanding of climate change induced storms and the behaviour of the sub-basins to the storms, we have chosen to conduct a targeted analysis, applying two extreme rainfall events, a 6-hour event and a 12-hour event, spatially across the sub-basins within the catchment. This allows us to observe and understand how different parts of the catchment react to rainfall events of varying durations.

Subsequently, we applied these precipitation values individually to each sub-basin, excluding contributions from other sub-basins. For instance, in the first simulation, we applied precipitation solely from sub-basin 1. This, in turn, was ran for each sub-basin across the catchment, in addition to a simulation being ran in which every simulation has been run; each of the tests has been summarised inTable 2

No. of test	Total Precipitation across the sub-basin, for a 50-year event (mm)			Summary of the test
	Sub-basin 1	Sub-basin 2	Sub-basin 3	
Test 1	77.17	0	0	Using a climate projection representative of a climatic scenario RCP 8.5, for a **6-hour** storm for **sub-basin 1.**
Test 2	0	74.91	0	Using a climate projection representative of a climatic scenario RCP 8.5, for a **6-hour** storm for **sub-basin 2.**
Test 3	0	0	73.32	Using a climate projection representative of a climatic scenario RCP 8.5, for a **6-hour** storm for **sub-basin 3.**
Test 4	92.86	0	0	Using a climate projection representative of a climatic scenario RCP 8.5, for a **12-hour** storm for **sub-basin 1**.
Test 5	0	87.91	0	Using a climate projection representative of a climatic scenario RCP 8.5, for a **12-hour** storm for **sub-basin 2**.
Test 6	0	0	81.27	Using a climate projection representative of a climatic scenario RCP 8.5, for a **12-hour** storm for **sub-basin 3.**
Test 7	77.17	74.91	73.32	Using a climate projection representative of a climatic scenario RCP 8.5, for a **6-hour** storm across **all basins**
Test 8	92.86	87.91	81.27	Using a climate projection representative of a climatic scenario RCP 8.5, for a **12-hour** storm across **all basins**
Test 9	77.17	74.91	0	Using a climate projection representative of a climatic scenario RCP 8.5, for a **6-hour and 12-hour** storm for **sub-basin 1 & 2.**
Test 10	77.17	0	73.32	Using a climate projection representative of a climatic scenario RCP 8.5, for a **6-hour and 12-hour** storm for **sub-basin 1 & 3.**
Test 11	0	74.91	73.32	Using a climate projection representative of a climatic scenario RCP 8.5, for a **6-hour and 12-hour** storm for **sub-basin 2 & 3.**

Table 3. Different scenarios for modelling with climate change factor

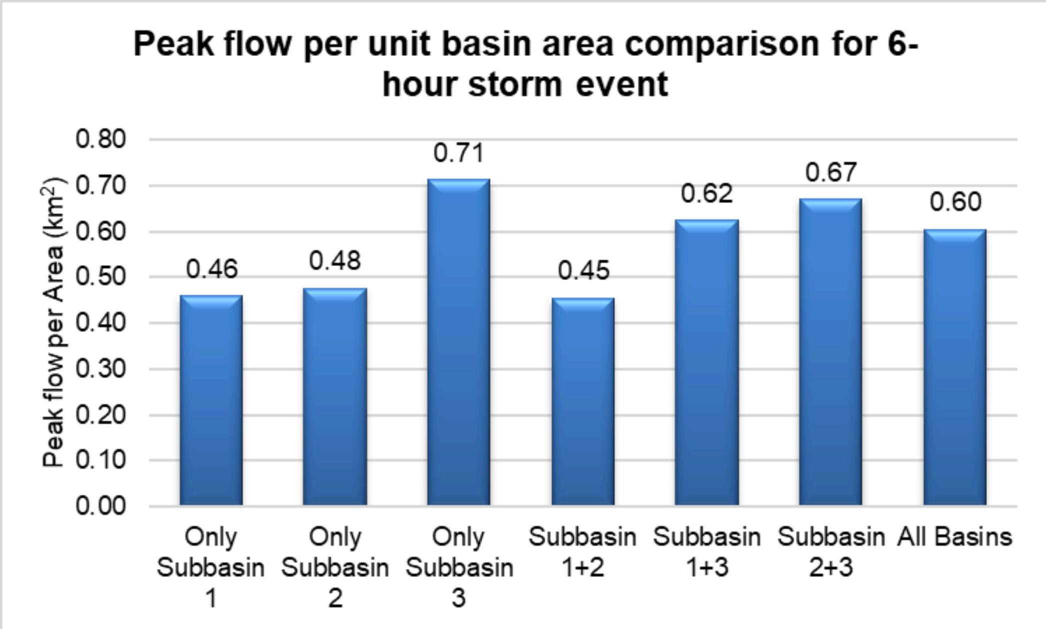

Figure 13. Peak flow per unit basin area comparison for 6-hour storm event

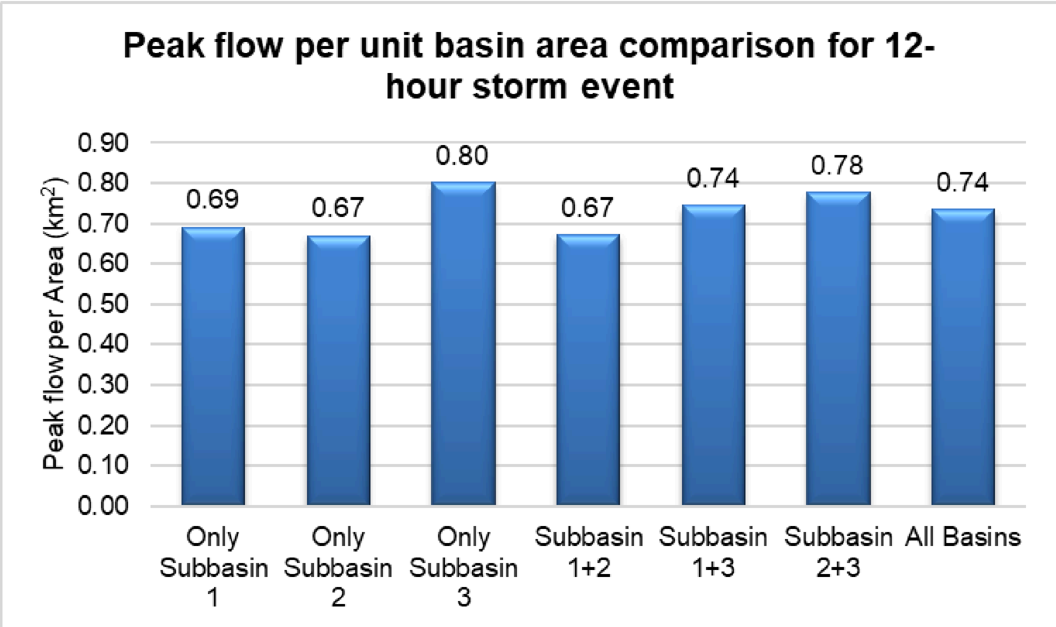

Figure 14. Peak flow per unit basin area comparison for 12-hour storm event

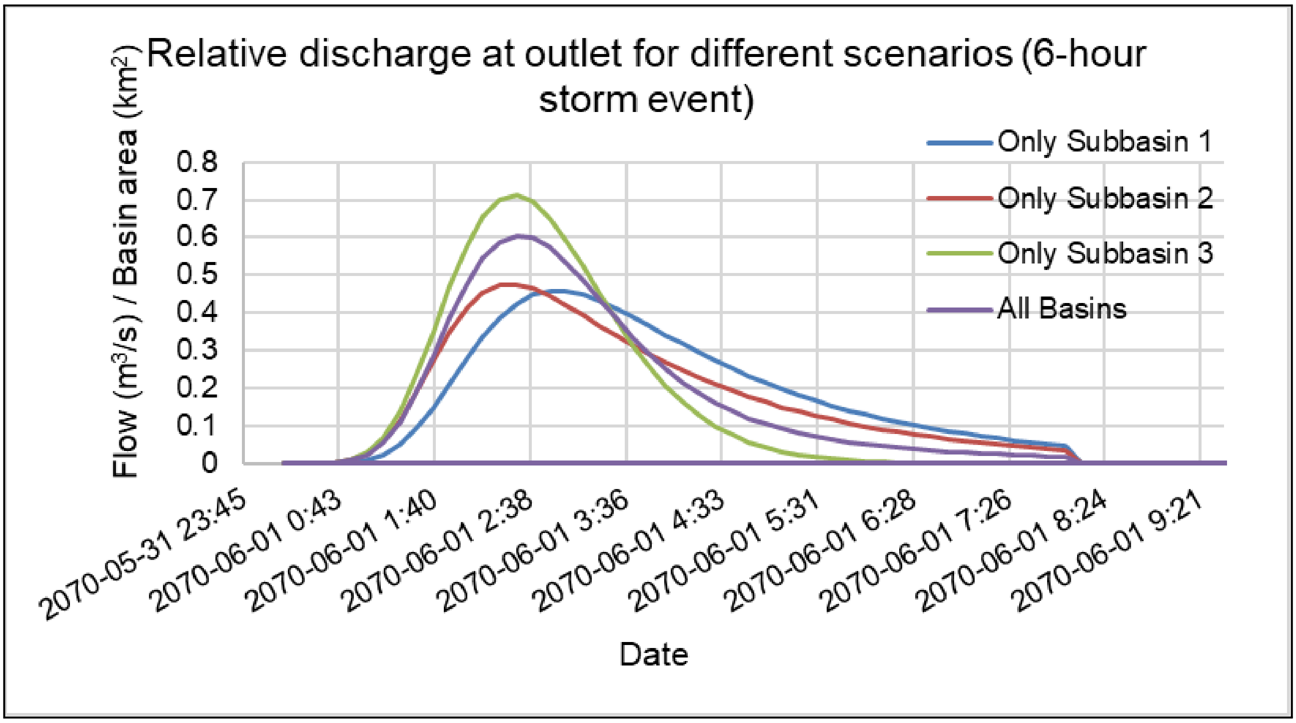

Figure 15. Relative discharge at outlet for different scecnarios (6 hour storm event)

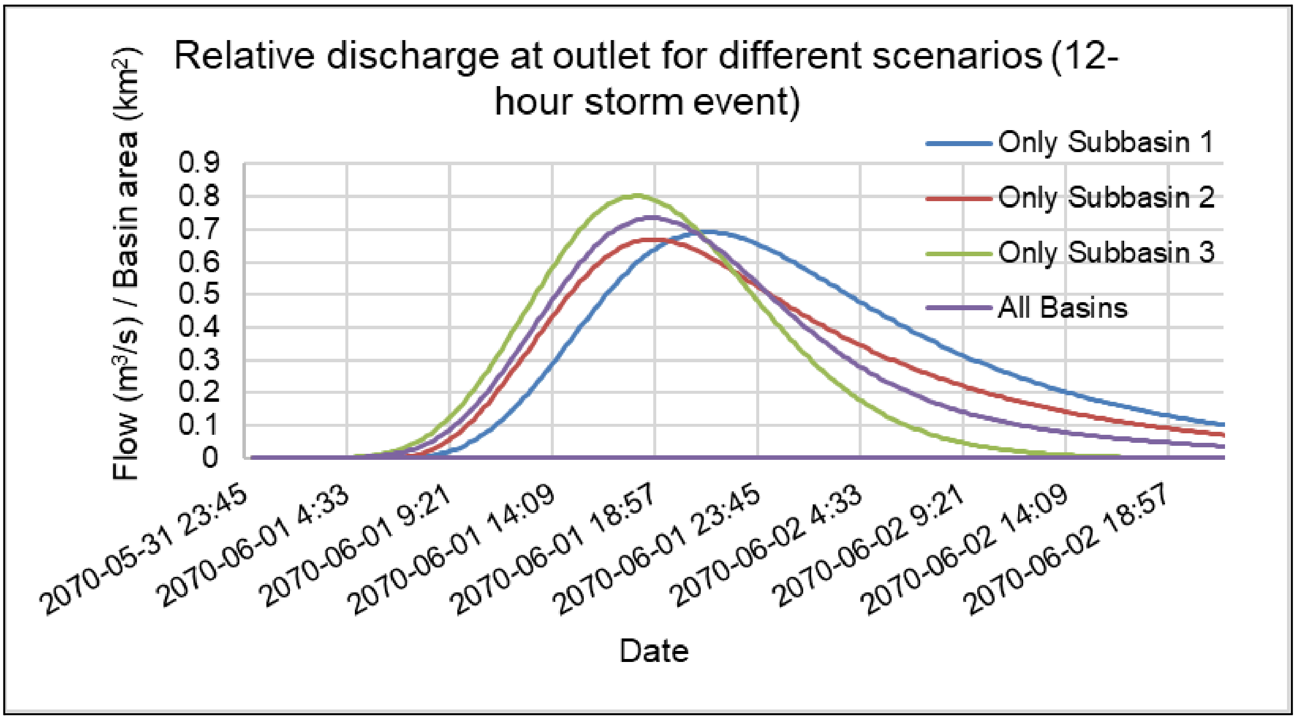

Figure 16. Relative discharge at outlet for different scecnarios (6 hour storm event)

From the figures above, it is clear that sub-basin 3 has the highest peak flow per unit area amongst all the basins and the combinations of basins for both the 6-hour and 12-hour storm events. This signifies that the sub-basin has the highest impact when it comes to storm events in the Ahr catchment. Furthermore, the coupling of basins, for example subbasin 1 & 2, 1 & 3 and 2 & 3, was done to get a better understanding of the sub-basin response. Similar to the single sub-basin approach, the sub-basins which considered coupling with sub-basin 3 had a greater impact on the peak flow than the ones which did not consider sub-basin 3.

For the shorter duration storm events, the difference in the peak flow per unit area between the sub-basins is more noticeable than for the sub-basins with longer storm duration events. This might be due to the fact that there is initial loss of rainfall and the effective rainfall period is shorter in the shorter duration storm events.

2.4 Flood stop lines

Flood stop line maps have been published by the RheinlandPfalz- Structure and Approval Directoriate North based on the 2021 flood events. The flood line maps are particularly useful to get the information about how the future flood levels behave when it passes through the Bad Bodendorf and Altenahr.

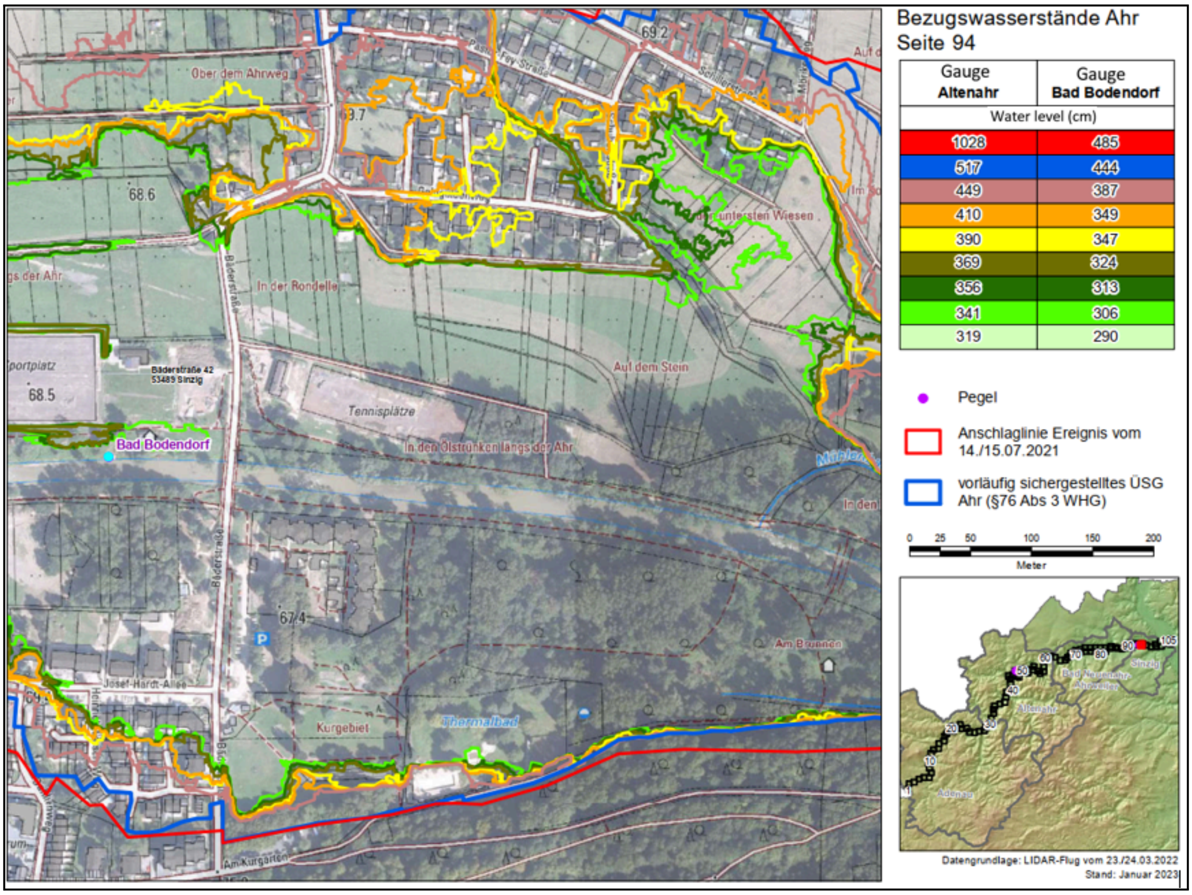

Figure 17. Flood lines at the Bad Bodendorf (Flood Stop Lines. Structure and Approval Directorate North, 2023)

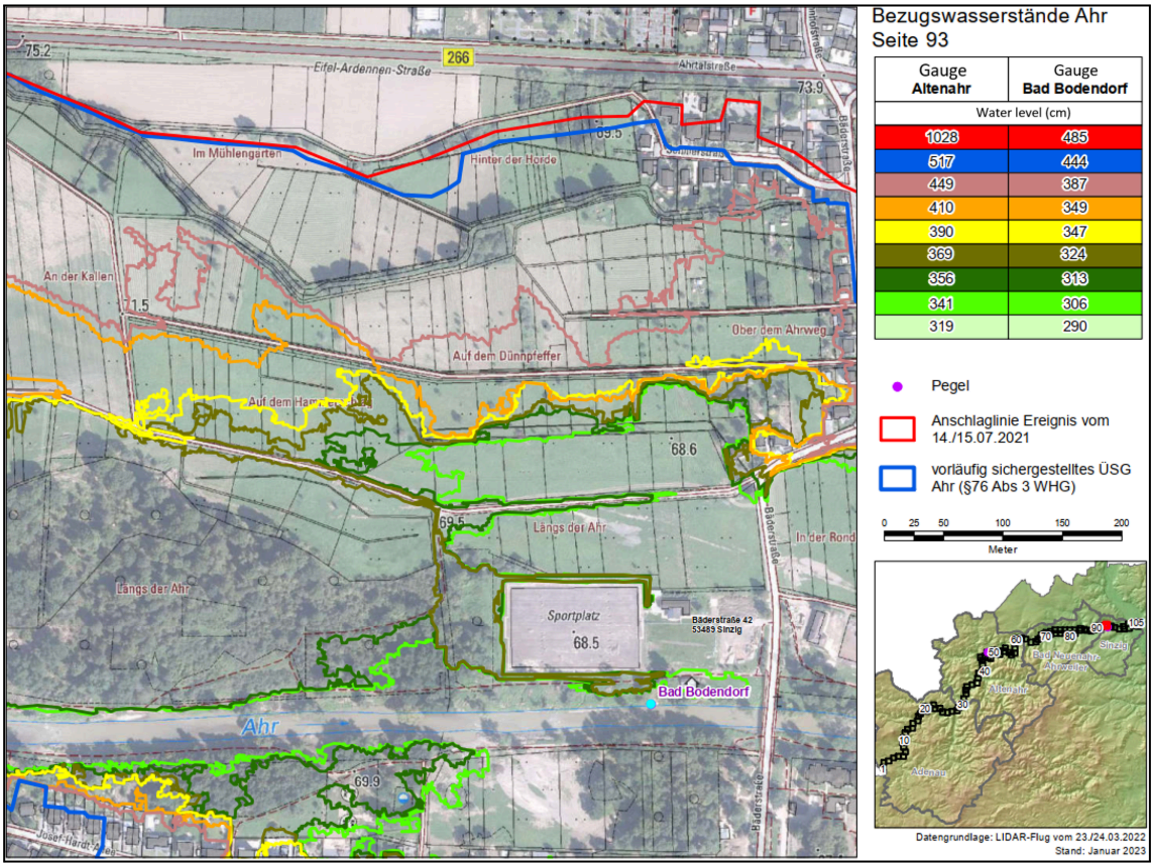

Figure 18. Flood lines at the Bad Bodendorf (Flood Stop Lines. Structure and Approval Directorate North, 2023)

The gauge level at Bad Bodendorf is 65.932m and the flood line map levels are drawn in reference to the gauge station. After the extreme storm analysis, the highest flow is converted to stage height (m) based on the rating curve at Bad Bodendorf.

The highest flows for 6-hour and 12-hour duration storm events are higher than 6 meters. Thus, in the event of 50-year return period floods, exasperated by climate change factors, it is expected that the Ahr river will submerge large areas of the valley similar to the 2021 July flood even

3 Flood protection measures

3.1 Using the 2021 flash floods as a case study

During the 2021 floods, a series of factors within the catchment accentuated the flooding, particularly in Bad Bodendorf. While the rainfall event was extremely rare and would have caused flooding regardless, addressing these weak spots in the catchments infrastructure could at the least minimise loss of human life or prevent flooding in more frequent return periods.

Since the magnitude of flooding cannot be directly mitigated within the confines of the Ahr catchment, the vulnerability of the population can be reduced.

The main four factors that made the flooding more severe were:

- **Clogging of debris and sediment**: The transportation of debris and sediment down stream caused clogging and acted as a dam at certain drainage paths, causing the water level to rise more than what the rainfall alone could produce.
- **Saturated soil**: Prior to the flash flood, consistent rainfall caused soil to reach the point of saturation. Therefore during the event, infiltration was not occurring, causing rapid runoff.
- **Infrastructure built on flood plains**: Much of the infrastructure of the Bad Bodendorf was built on flood plains, increasing the vulnerability.
- **Steep Topography:** The steep slope of the catchment, particularly upstream, results in less infiltration and rapid runoff

3.2 Flood Defence Strategies

A series of strategies were proposed to address these vulnerabilities. The focus was to use green infrastructure so as to not compromise the natural environment, which is an asset to the communities of the Ahr catchment. It was also decided to focus on subcatchment 3; firstly being that this is the most densely populated urban area with the Ahr catchment and suffered significant impact during the 2021 flash flooding; and secondly, flow at the outlet is most influenced by rainfall in subasin 3.

These strategies are:

- Sustainable Drainages Systems e.g. Swales, Permeable surfaces, Rain gardens, Retention ponds etc.
- River bank and slope stability e.g. Gabion cages along banks and adjacent slopes Riparian vegetation, Sediment traps.
- Reduce runoff upstream e.g. Long Green Dykes and Hill terracing for rural farms
- Policy change: Limit new infrastructure on flood plains/set new minimum standards for infrastructure flood proofing.
- Flash Flood Emergency Response: Temporary flood barriers/defence, Education/Community Knowledge and evacuation measures.

Figure 18 shows a map of key infrastructures within the town of Bad Bodendorf. It is the recommendation of this project to utilise SUDs within the critical infrastructure. Also green spaces are highlighted, these could be utilised to incorporate SUDs to enhance drainage and infiltration.

Map of Critical Infrastructure

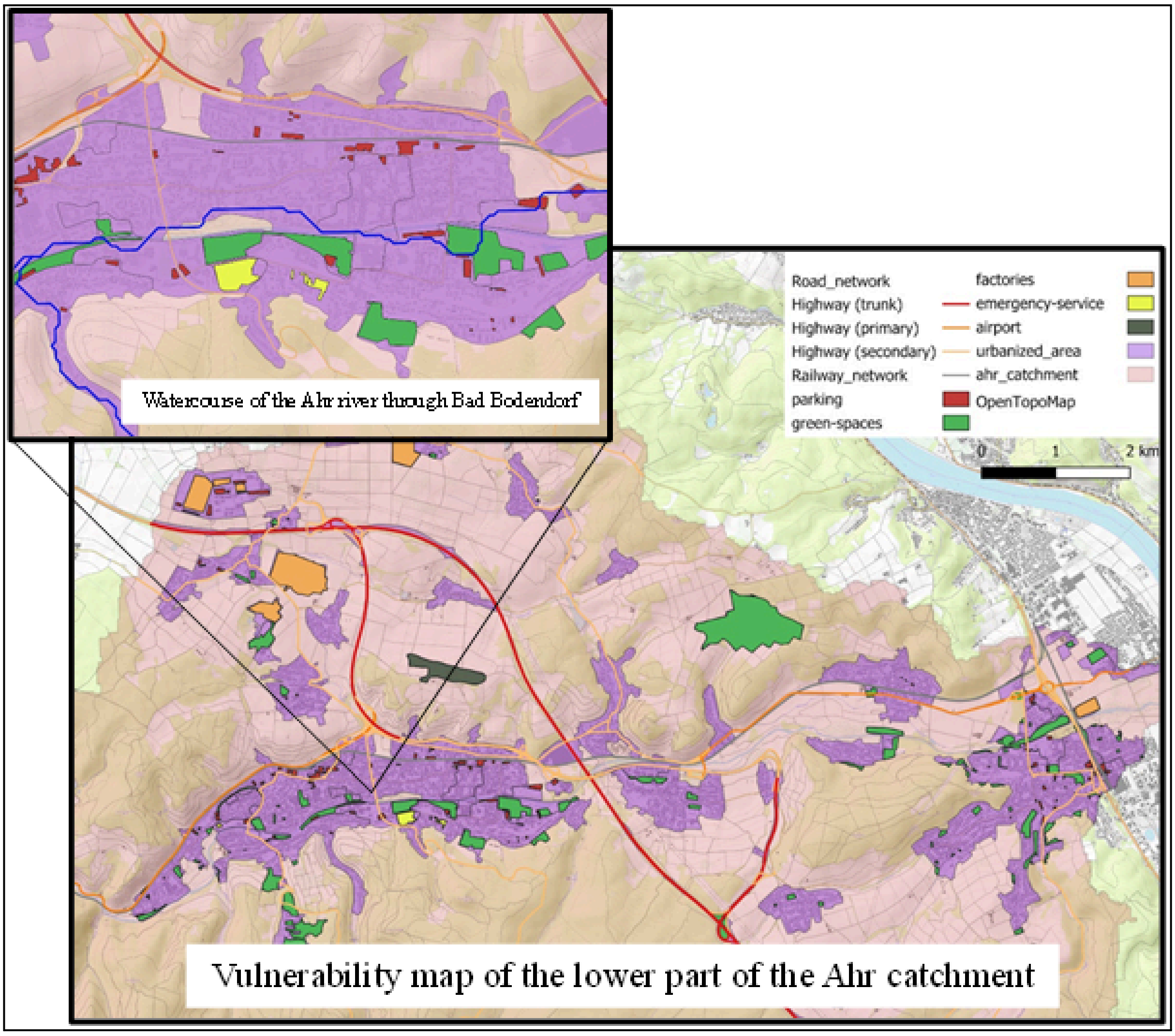

Figure 19. Map of Bad Bodendorf with highlighted critical infrastructure.

3.3 Uncertainty with Climate Change

Flood depths associated with the 400 year event in the 2021 flash floods were 4.8m. This caused catastrophic impacts for the population of Bad Bodendorf. The modelling in this project which used a climate change factor for the end of the century projected flood depths 6.5m . In the case of flash floods comparable to either event, the engineering solutions will not be significant enough to prevent flooding all together.

Therefore the most effective solution to prevent loss of life is an evacuation protocol and a more advanced forecasting ability. In addition, for monitoring of ground saturation, citizen science could be enacted to make estimates on infiltration rates prior to rainfall events.

4. Conclusion

Overall, across the course of the project, the effects of flash flooding on the Ahr catchment have been examined in considerable depth, along with possible flood prevention interventions discussed and considered. Through the initial phase of the project, the 2021 River Ahr flood was modelled on 1D software to initially understand the flood inundation. Building on this work, Cordex European Climate Projections for 6h and 12h duration storms were analyzed to provide a climate change factor for the RCP 8.5 emissions scenario. With this factor being used to modify DWD online available data for 50-year return period storms, the resulting climate data has been modeled using the HEC-HMS 1D model, to understand how the climate projections alter the flood hydrograph.

Observations from the projected precipitation data show that a 100-year return period storm in 2020, will be representative of a 50-year return period storm in the year 2070, meaning in the future more intense storms are likely to occur twice as frequently. Further observations from modelling 6h and 12h duration storms for the baseline along with climate projections, show that the duration of rainfall is inversely related to the difference of peak flow per unit area among the sub-basins.

The Telemac2D hydrodynamic model enabled us to set up a distributed model which was then compared with observations and results obtained with HEC-HMS. However, setting up this model, which takes into account precipitation (including spatialization) and infiltration, was time-consuming and we were unable to carry out a more detailed analysis. More time was required to calibrate and validate the model. In order to improve our model, we need to assess the impact of the spatial distribution of precipitation and implement radar precipitation data. We would also need to vary other parameters such as the initial abstraction factor or the antecedent moisture condition.

The precision of our DEM is not good for the precise estimation of water depths in our catchment and not as precise as it could be. Better DEM should be used because the current one (25m resolution) cannot accurately model the river as the width of the river is approximately 10m. We can further understand how good the model is by using the observation data e.g. Twitter videos showing water depth.

The strategies to reduce the vulnerability of sub catchment 3, particularly the town of Bad Bodendorf, involved improving drainage with the use of SUDs; increasing slope stability upstream with the use of gabion cages and riparian vegetation; hill terraces and dikes to control runoff and flow upstream, and policy changes to mitigate vulnerable in flood plains. However, while these strategies may be effective in reducing vulnerability during more frequent return periods, the best strategy to develop for the magnitude of flooding that happened in the 2021 flash floods, and also the return periods used in the simulations carried out in this project, is the development of rigorous emergency response, particularly a comprehensive evacuation protocol. In the future, site-specific evaluation and modeling should be carried out in order to estimate the most effective spaces for intervention construction.

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