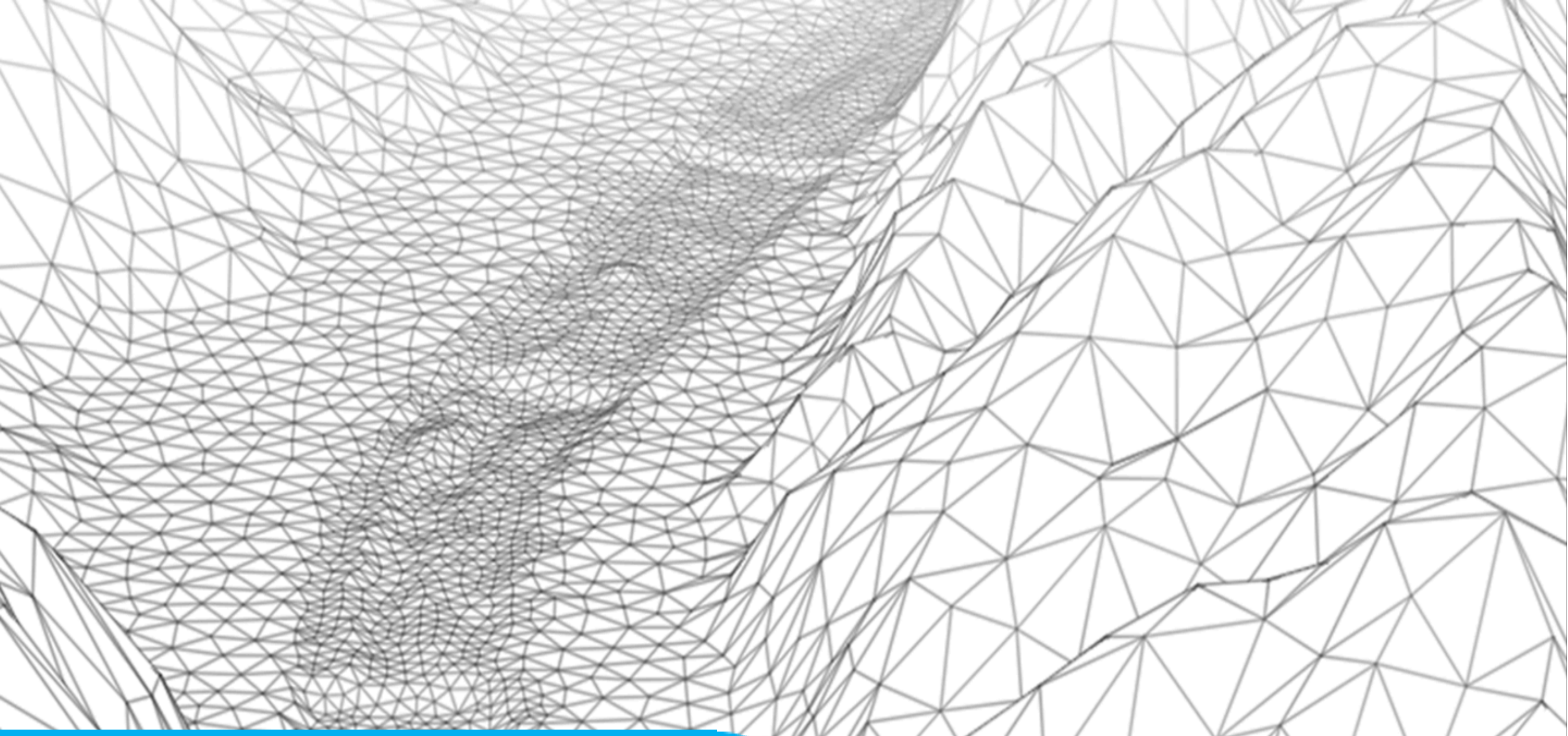

Team 05: Report Week 2

HYDROEUROPE

Erasmus+ Programme Cooperation Partnerships
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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 5 - Report Week 2:
Climate Change Impacts on Flash Floods

Team 05
Version 2.1 - 12 Jan 2023

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1. Objectives

The principal objectives of this academic project are as follows:

- Evaluate the impact of climate change on flash floods in the Ahr catchment.
- Assess the problematics associated with flash floods and its impacts on the most affected municipalities of the Ahr catchment.
- Provide a list of adaptation measures to mitigate the impacts of flash floods in the case study area.

2. Climate Change Scenarios

In order to assess the impact of climate change on the flash floods, different scenarios were considered. The scenarios shown in Table 1 were elaborated based on the KOSTRA-DWD report for the State of Rhineland-Palatinate. From the report it can be inferred that climate change may lead to an increase of roughly 20% in precipitation intensity for the region, to evaluate this, the intensity for the 10 and 20 years return period design storms were increased as presented in Table 1. Also, aiming to understand the impact of the precipitation duration on the floods, different durations were simulated.

Table 1*: Climate change scenarios considered to evaluate their impact on flash floods.*

Intensity	Duration	Return Period
2%	6h	10y
5%	12h	20y
15%	24h	-
20%	-	-

3. Hydrologic Modelling

This section presents the results of the HEC-HMS hydrologic lumped model of the Ahr catchment for the different scenarios considered to assess the impact of climate change. They correspond to modelled discharge hydrographs in the Altenahr river gauge station and allow to evaluate the effect of changes in precipitation patterns (e.g. larger rainfall intensities or durations) in the discharge profiles in this point of the Ahr catchment.

The reason for selecting this specific point in the catchment corresponds to the following criteria:

- It is located in the downstream part of the watershed. Hence, it is adequate to account for the majority of the runoff generated.
- It is the closest upstream river gauge station to the most densely populated area of the Ahr catchment and its main towns.
- Its rating curve allows it to transform flow to water level up to higher values compared to the curves existing for other stations.

The results of the hydrological model are presented below. Figure 1 shows the discharge hydrograph for the diferents precipitations intensities. As expected the increase in precipitation intensity leads to an increase in the peak discharge.

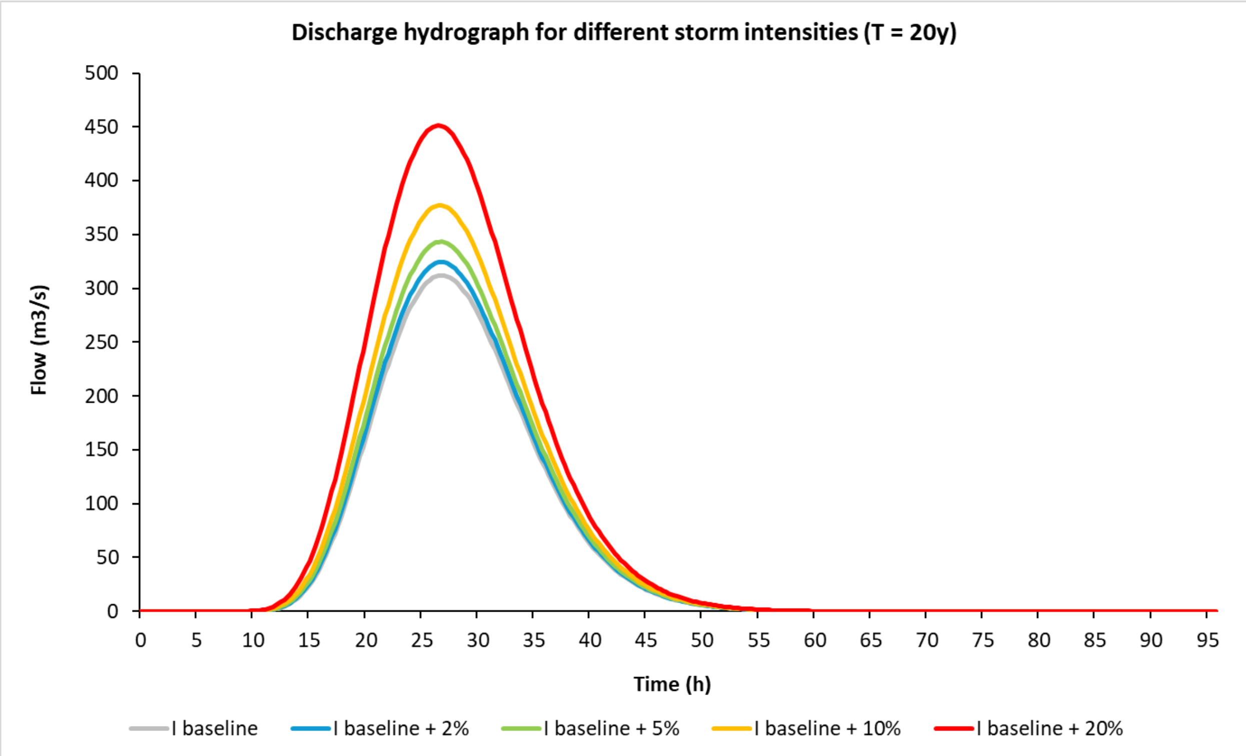


Figure 1: *Discharge hydrograph for different storm intensities.*

Table 2 shows how the total dicahrge volume and discharge peak reacts to an increase in the precipitation intensity. It is possible to observe that both the total volume and the peak discharge exhibit an increase at a rate twice that of the increased intensity. For instance, an increase onf 5% in the precipitation intensity results of an increase of around 10% in the total volume discharged and the peak discharge.

***Table 2**: Comparison of the total discharge volume and the discharge peak between and baseline intensity and different scenarios considering growing rainfall intensity*

Scenario	Total discharge volume		Discharge peak	
	V total (m^3)	Increment (%)	Q max (m^3/s)	Increment (%)
I baseline	1,81E+07	-	312,1	-
I baseline + 2%	1,89E+07	4,0	324,2	3,9
I baseline + 5%	2,00E+07	10,3	343,2	10,0
I baseline + 10%	2,20E+07	21,5	376,8	20,7
I baseline + 20%	2,66E+07	46,3	451,3	44,6

In Figure 2 it can be noted the impact of shorter storms durations in the peak discharge. It can be seen that for shorter durations the peak discharge is increased considerably. Also, the peak time becomes shorter as we decrease the precipitation duration and this cabe seen in Table 3.

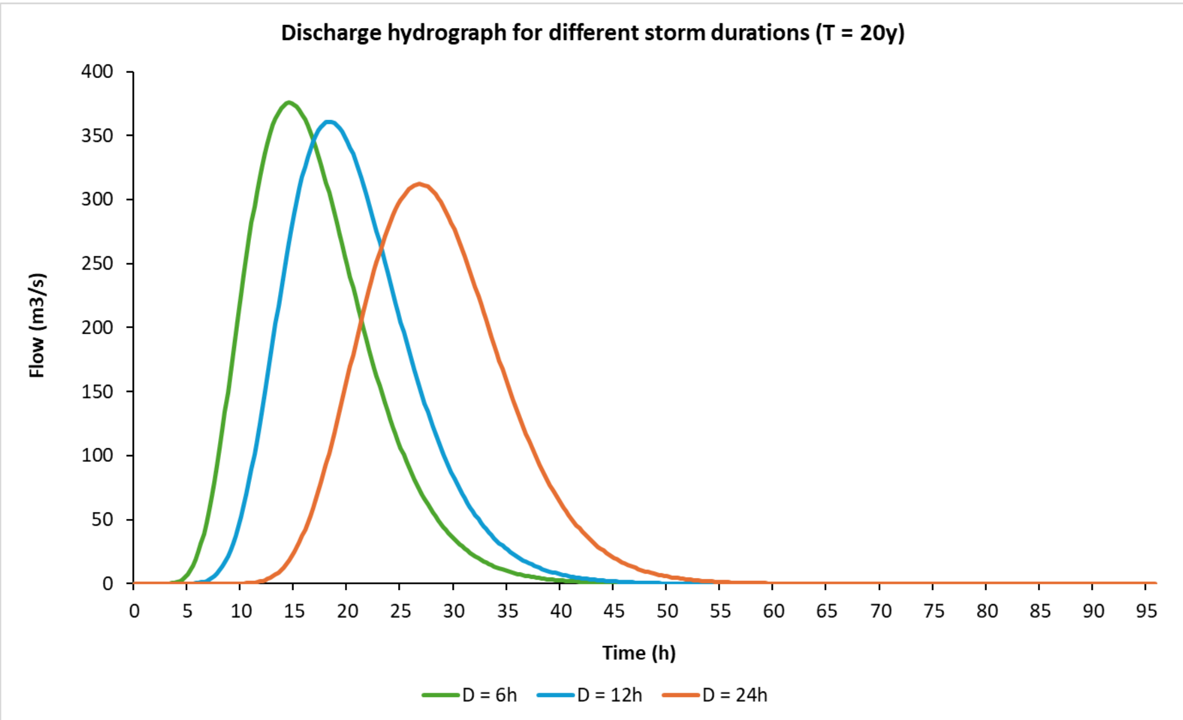


***Figure 2:** Dicharge hydrograph for different storm durations.*

***Table 3**: Peak time for different storm durations.*

Scenario	Peak time (h)
D = 6h	15:00
D = 12h	18:15
D = 24h	26:00

The graph in Figure 3 present a comparison of the baseline scenarios for 10-year return period with a scenario where shorter duration and more intensity precipitation is combined. It can be seen that the combined scenario yields a much higher peak discharge as well as shorter peak time.

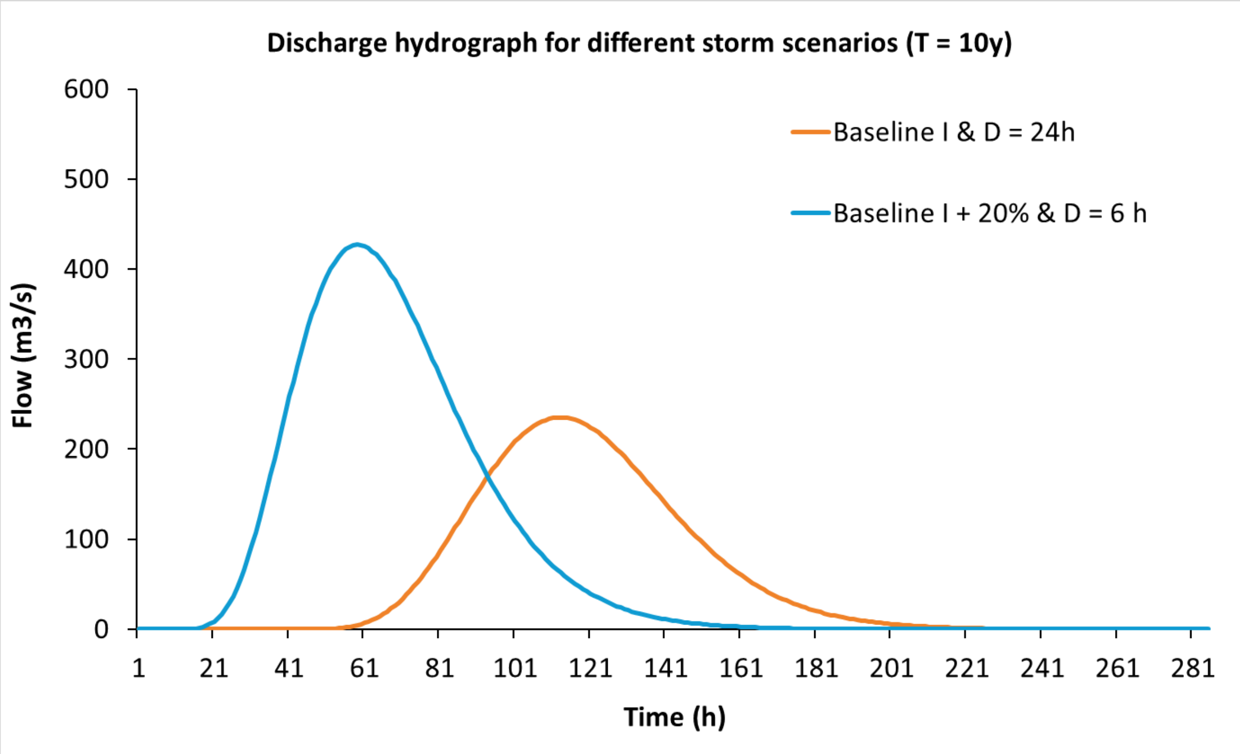


Figure 3: *Discharge hydrograph for different storm scenarios for 10-year return period.*

After modelling different scenario the resulting discharge time series were used as inflow input for the 2D hydraulic model. Figure 4 shows that wich area of the catchment was used for the hydrological model and each one was used as domain for the hydraulic model.

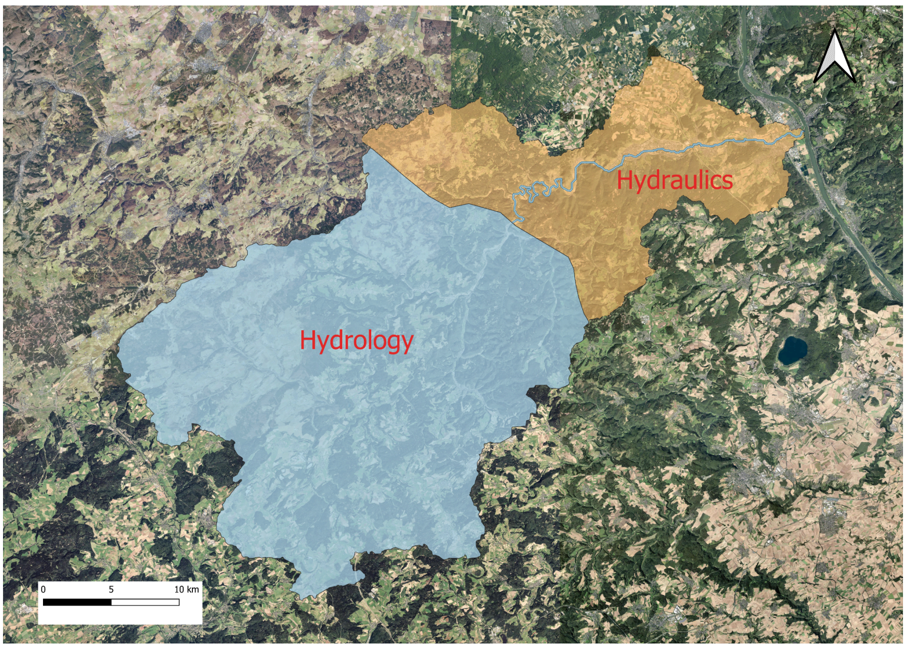


Figure 4: *Catchment division for hydrological and hydraulic modelling.*

4. 2D Hydraulic Modelling

This section is devoted to an in-depth analysis of the impact of the flash floods that occurred during the intensive rainfall of 13 to 15 July 2021 in the Ahr basin. The aim of this analysis is to gain a better understanding of the hydraulic phenomena that occurred during this flood, in order to anticipate possible phenomena linked to climate change. We used Telemac 2D software for this purpose. This section will detail the entire process, from the creation of the model to the results obtained.

4.1. Creating the Digital Terrain Model and Defining the Model Footprint

Modelling on Telemac 2D requires a certain amount of upstream data to be processed. We have extracted digital terrain models only around the study area and not over the entire watershed as shown in Figure 5.

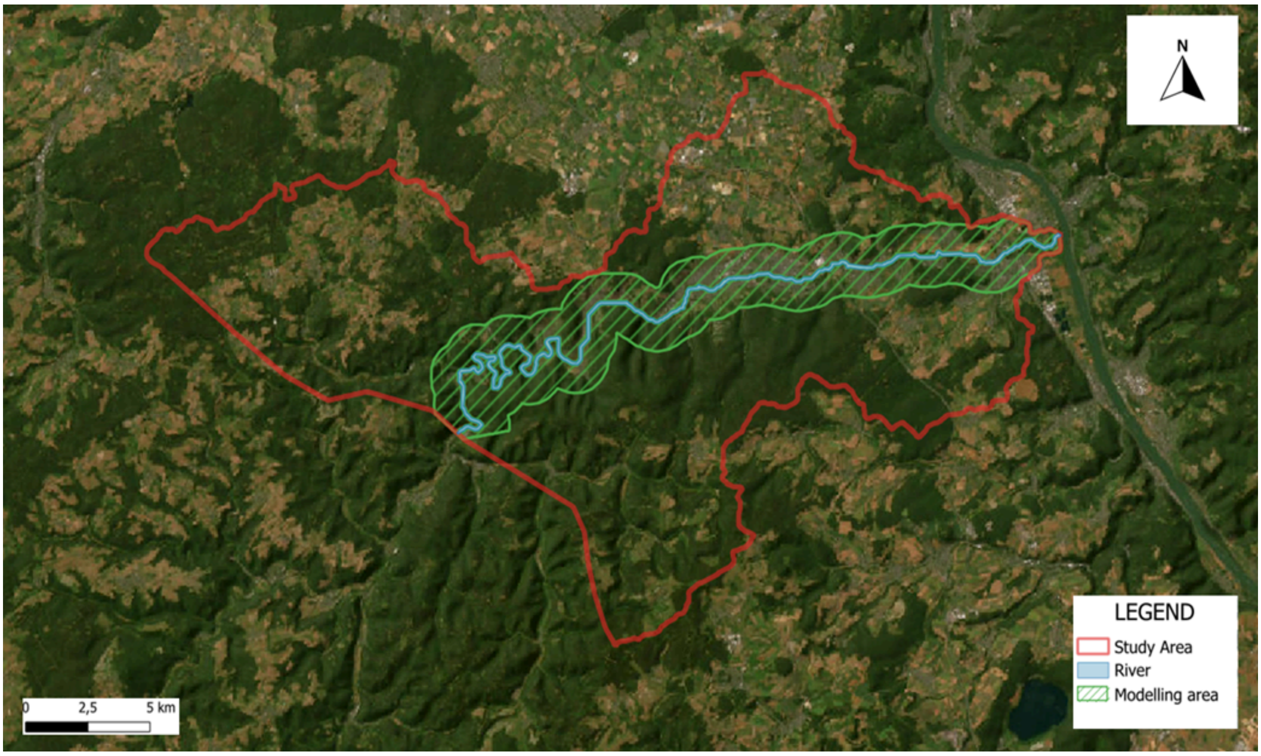


Figure 5: *Study area.*

4.2. Processing and Creation of Model Input Files on Bluekenue

After processing the Digital Terrain Model (DTM), the following steps were carried out using QGIS software. We delimited the area to be modelled, identifying the river's minor bed, the floodplain and the extent of the study area. These contours were exported as a point cloud, then converted to ".i2s" format on Bluekenue (Telemac's graphic interface).

The digital terrain model has been processed to convert it into a set of points represented in three dimensions (x, y, z), using the data contained in the pixels of the digital terrain model

(DTM) map. The output file is in ".xyz" format, after pre-processing. This data will be used to generate a mesh in the "Bluekenue" tool.

The Bluekenue software is specifically designed for the preparation, analysis and visualisation of hydraulic modelling data. The data integrated in Bluekenue is georeferenced, which means that it is associated with the spatial information of the model. The implementation of a 2D model on Bluekenue follows a two-step process: mash creation and boundary condition creation.

4.3. Mesh Creation

In this step, a detailed representation of the terrain's relief is created, integrating its features via a discrete mesh. This mesh is composed of a series of connected elements, each with an associated elevation, enabling the study area to be subdivided into distinct portions of the terrain. Each mesh element represents a specific area of terrain, facilitating the simulation of water flows by solving the hydraulic equations locally as shown in Figure 6.

The characteristics of the mesh are the following: 25 m for the minor bed; 50 m for the floodplain and 150 m for the rest of the study area.

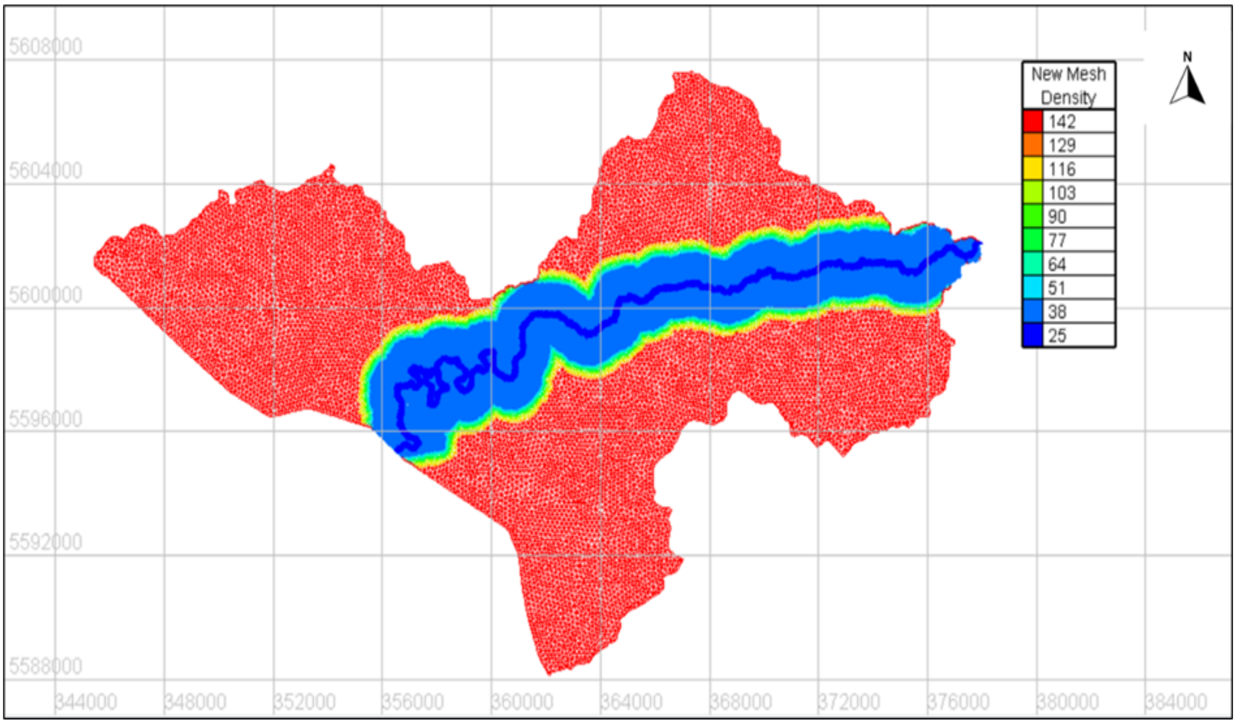


Figure 6: *Mesh configuration*.

Bathymetry, exhibited in Figure 7, is interpolated on the mesh configuration to create a model containing topographic terrain data.

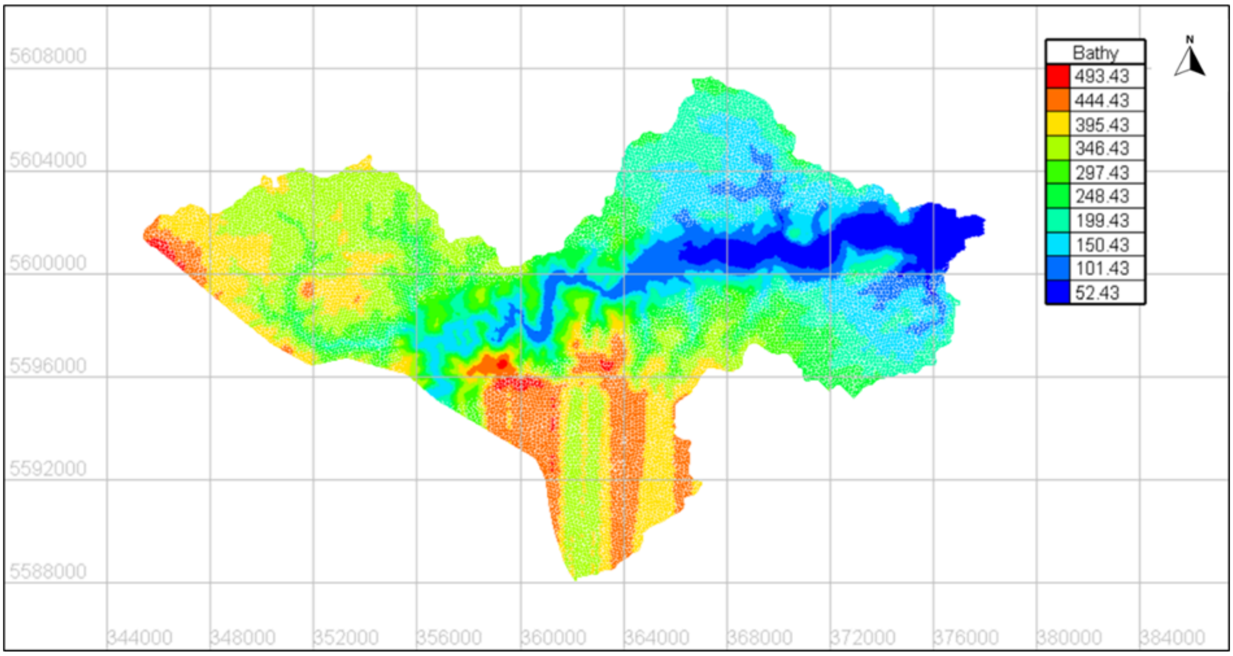


Figure 7: *Bathymetry.*

4.4. Creation of the Boundary Conditions File

The boundary condition file is required for simulation in Telemac. It defines the edges of the domain on which upstream and downstream conditions will be imposed. We have specified an upstream open boundary to impose a flow rate at the stream inlet, and a downstream boundary to set a water level. In our case, we have set a constant upstream flow rate of 8 m³/s (average flow rate of the Ahr). For the downstream section, we set a constant water level of 1 m (see Figure 8), thus ensuring the model's stability under steady-state conditions.

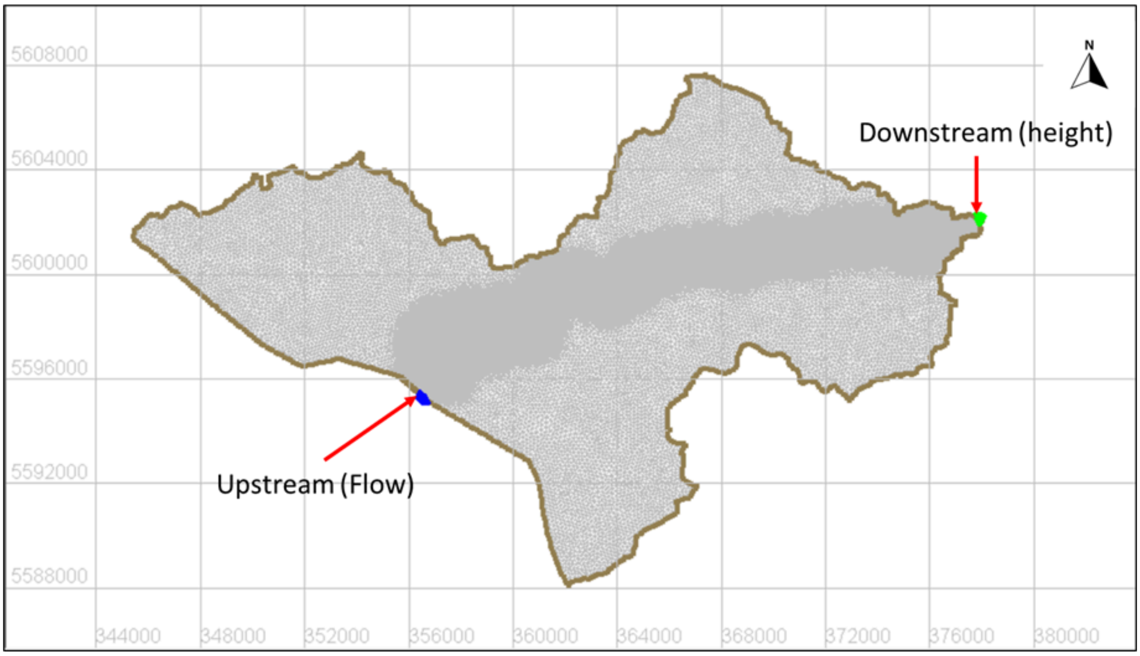


Figure 10: *Boundary conditions*

4.5. Initial conditions

TELEMAC simulation requires the reading of a ".cas" file, which defines the initial conditions and the model's physical and numerical parameters. This file is initially used to fill the model with water. The initial conditions are intended to establish the state of the model at the start of the simulation. Here are the initial specifications for our model:

- The initial height H of the domain is set at 0.1 m to initiate model filling.
- A maximum velocity of 1.5 m/s.
- The Courant-Friedrichs-Lewy (CFL) number must be less than 1 to maintain the numerical stability of the hydraulic flow simulation. For this reason, we set the CFL at 0.5.

Using this information, the time step dt is calculated using the formula below:

$$dt = \frac{0{,}5 * 25}{1{,}5 + \sqrt{9{,}81 * 0{,}1}} = 5$$

- dx is the length of the finest mesh, i.e. dx = 20 m.

The law of friction we used is Strickler's law. We decided to take a coefficient of friction equal to 40.

4.6. Model simulation

The model was tested under steady-state conditions, revealing an overestimate of flooding on the plain with an average river flow of 8 m3/s. This anomaly is attributed to the limited resolution of our DTM (see Figure 9), set at 25 metres. This resolution does not allow for an accurate representation of the riverbed, which has an average width of 10 metres and is often located in a narrow valley.

In our mesh scheme, each cell represents the average elevation of an area measuring 25 metres by 25 metres. This means that local variations in the terrain, such as the riverbed, may not be correctly represented. In a narrow valley, the two adjacent cell points may have significant differences in elevation relative to the riverbed, especially where the width of the river is less than the 25 metre resolution. This can result in an overestimation of the mean elevation, leading to an incorrect representation of the terrain, including a section of the river that appears as a straight line.

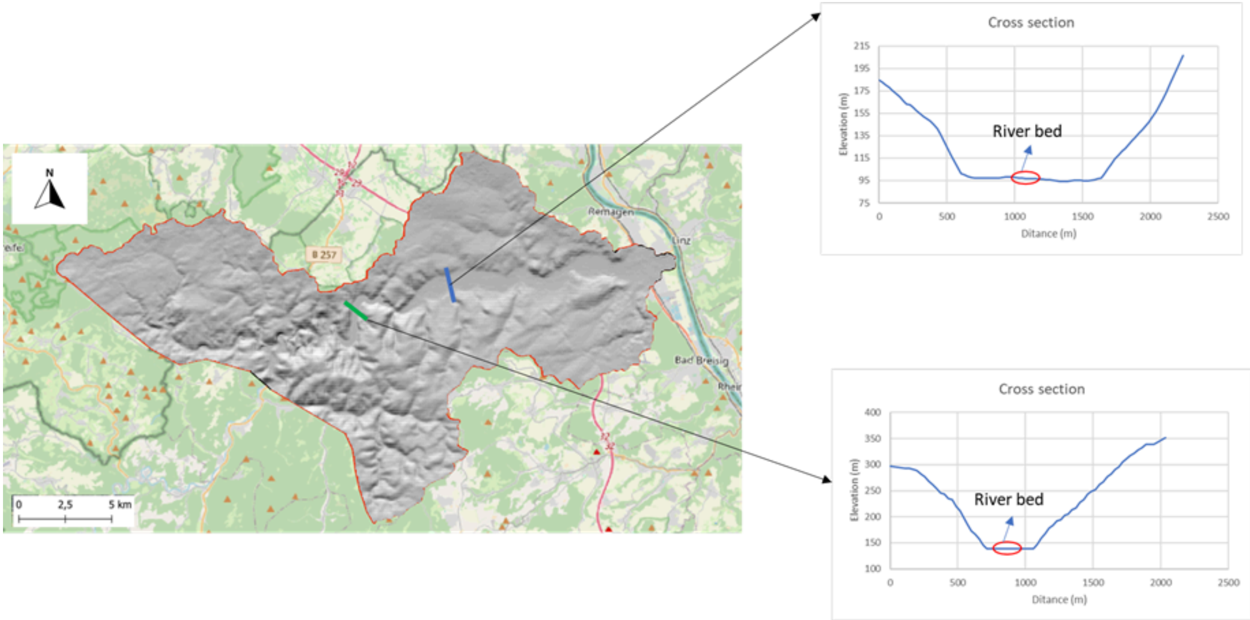


Figure 9: *Cross section.*

In the case of steep slopes, a cell with a significant difference in elevation could lead to an inaccurate mean estimate. This can lead to errors in the simulation, where areas susceptible to flooding are not correctly identified due to the limited resolution of the DTM (Figure 11).

The longitudinal profile of the watercourse in Figure 10 illustrates these challenges, particularly through the red marks indicating natural or artificial obstacles that disrupt the flow, resulting from the insufficient quality of the DTM. These variations in elevation affect the hydraulic dynamics of the watercourse (changes in velocity, induction of turbulence, and alteration of hydraulic characteristics), with notable impacts on water levels, which can reach up to 6 meters in some areas.

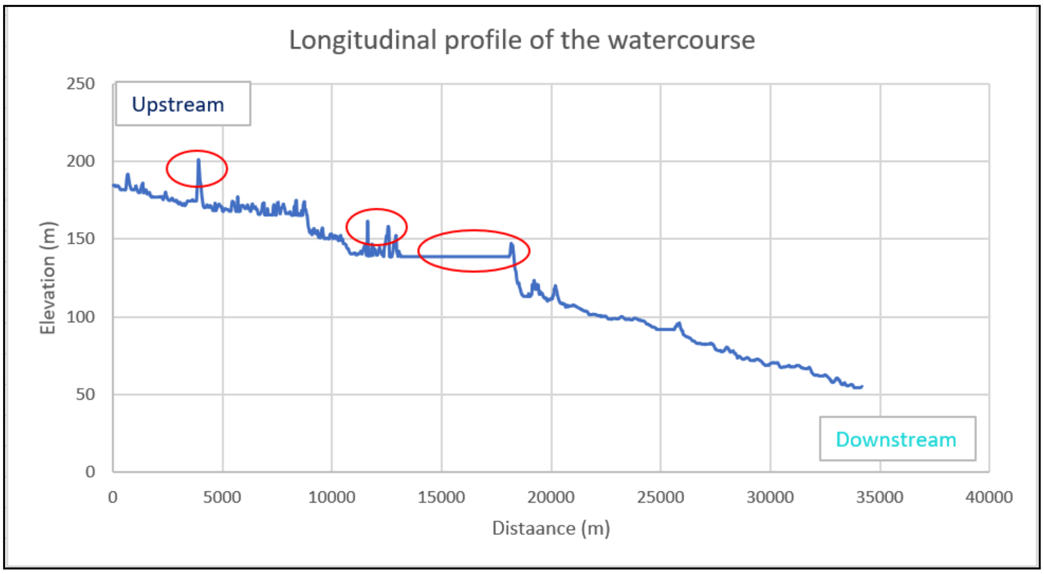


Figure 10*: Longitudinal profile of the watercourse.*

It is imperative to recognise these shortcomings in the current model. However, it is noted that exploring alternative solutions, such as increasing the resolution of the DTM, may become a considerable challenge due to the confidentiality of German government data.

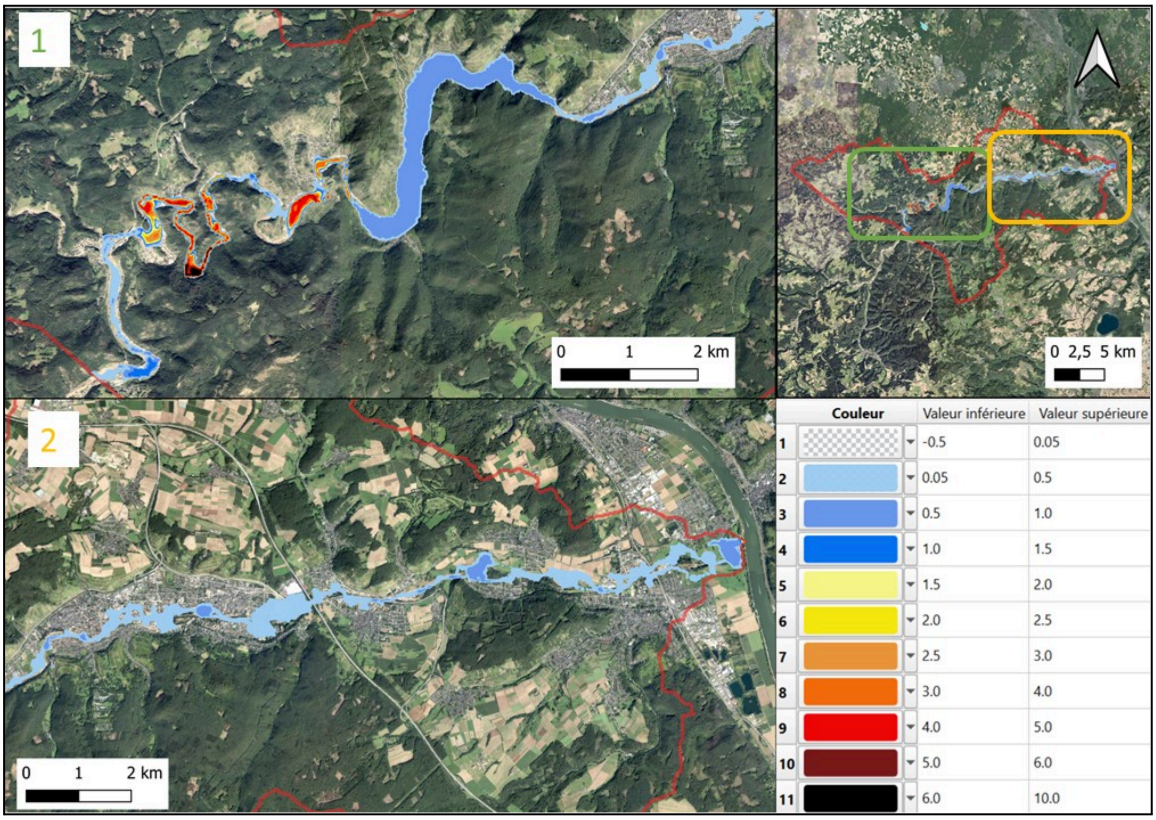


Figure 11: *Results of the telemac model in the permissive regime.*

4.7. Model Results

Considering the data limitations encountered in this project, it has not been possible to develop reliable flooding maps that can be used for decision making and the development of early warning systems.

Nevertheless, after the 2021 flash flood, the Wasserwirtschaftsverwaltung Rheinland-Pfalz (Water Management Administration of Rhineland-Palatinate) developed a report mapping the areas of the Ahr valley that were affected during the event. The report is named Bezugswasserstände der Ahr (Reference water levels of the Ahr). The mapping (see Figure 12) is based on observations of the water level and the flooded area measured during and after the event.

The coloured lines represent the limit of the flooded area corresponding to the water level measurements in the Altenahr and the Bad Bodendorf river gauge stations. The higher these values, the larger the flooded area. The table within the figure indicates which water level measurement corresponds to each colour.

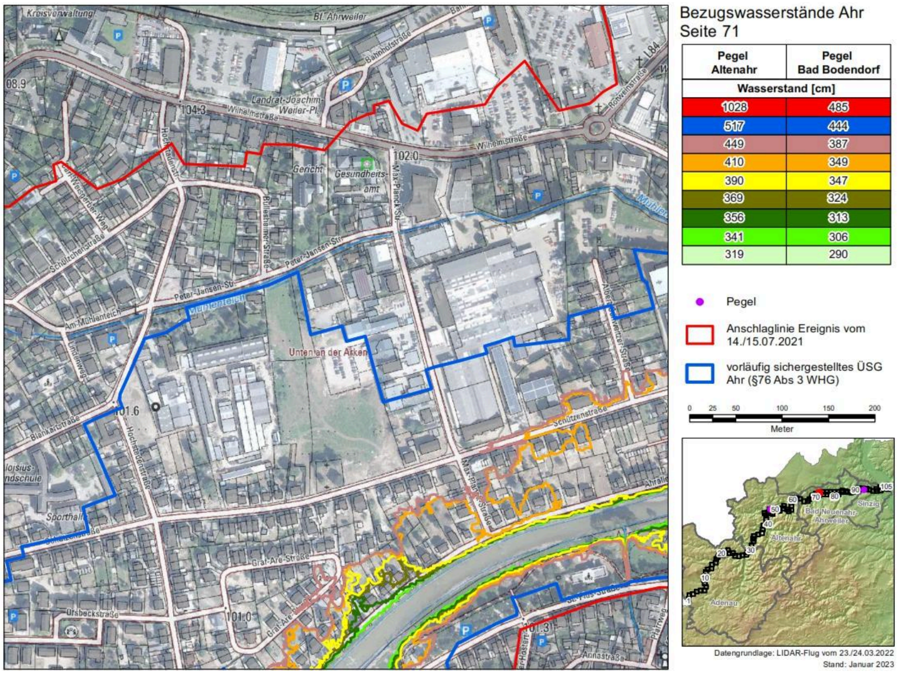


Figure 12: *Water level Map at station 71 in the study report 2021.*

It can be observed that with water depth measurements of 341 and 306 cm in the Altenahr and Bad Bodendorf stations, the river level begins to exceed the river channel height, and consequently, initiates flooding.

As an alternative method to get the results in the form of water level maps, the maps prepared by the water management administration of Rhineland-Palatinate (2023) for Ahr catchment were used along with the rating curve (Figure 13) at Altenahr gauging station to represent the results from the hydrological model developed in this study.

The upper threshold for discharge obtained from the rating curve at Altenahr gauging station was up to 400 m^3/s and corresponding water depth and water level at the gauging station were 6 metre and 166.522 masl as presented in Figure 13.

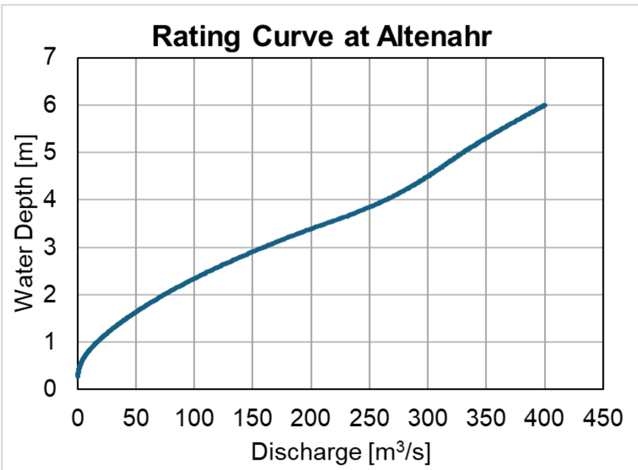


Figure 13*: Rating curve at Altenahr gauging station.*

Based on the upper threshold of the rating curve at Altenahr gauge station, four different scenarios were compared with a base case to assess the climate change impact in the form of water level maps as mentioned in Table 4.

***Table 4**: Different scenarios for climate change assessment.*

Scenarios	Altenahr		
	Q [m^3/s]	Water Depth, [cm]	Water Level [masl]
Base_Case_10Y_RP_D24H	235	370	164.222
Base_Case_20Y_RP_D24H	312	470	165.222
Scenario1_10Y_RP_D6H_Original_RI	281	422	164.742
Scenario2_10Y_RP_D24H_+10%_RI	292	437	164.892
Scenario3_10Y_RP_D24H_+20%_RI	353	535	165.872
Scenario4_10Y_RP_D6H_+10%_RI	350	531	165.832

The rating curve at Altenahr gauge station was used to determine the water depth and water level corresponding to the peak discharge from the hydrological model for each climate change scenario as presented in the Table 3 above.

After this, at the same station (Altenahr gauge) the discharge and corresponding water level were determined from the same rating curve for the given water depths in Figure 12.

***Table 5**: Scenario approximation with the 2021 study report (Water Management Administration of Rhineland-Palatinate).*

Scenario Approximation	Altenahr		
	Q [m^3/s]	Water Depth [cm]	Water Level [masl]
Base_Case_10Y_RP_D24H	234	369	164.212
Scenario1_10Y_RP_D6H_Original_RI	272	410	164.622
Base_Case_20Y_RP_D24H Scenario2_10Y_RP_D24H_+10%_RI	299	449	165.012
Scenario3_10Y_RP_D24H_+20%_RI, Scenario4_10Y_RP_D6H_+10%_RI	341	517	165.692

While observing the water depths and corresponding discharge in Table 4 and Table 5, it was found that the climate change scenario considered in this study can be approximated with results in Figure 12 as can be seen in the table above. The water depths lines (reference water level lines) in the map (Figure 12) were then digitised in GIS that matched the scenarios of this study and the maps corresponding to each scenario were then prepared and compared with base case scenarios.

A sample area was then selected to show the water level map Figure 14 and each scenario were then compared with the base case which is a 10 year return period rainfall with rainfall intensity of 62.4 mm (Original RI) that existed for 24 hours (10Y_RP_D24H) and a 20 year return period rainfall with intensity 71.87 mm that also existed for 24 hours (20Y_RP_D24H). As can be seen in the above Table 3, the base case '20Y_RP_D24H' is assumed to be the same as scenario2 which is again a 10 year return period rainfall with 10% increased rainfall intensity compared to 'Original RI' that also existed for 24 hours (10Y_RP_D24H_+10%_RI).

Also, it is important to note that for 'Base_case_20Y_RP_D24H', the peak flows were exceeding the upper threshold of the rating curve at Altenahr gauging station and hence water depths cannot be determined. So for this reason, climate change scenarios were not compared with the 20 year return period rainfall event base scenario and all the comparisons were done with the 10 year return period rainfall event.

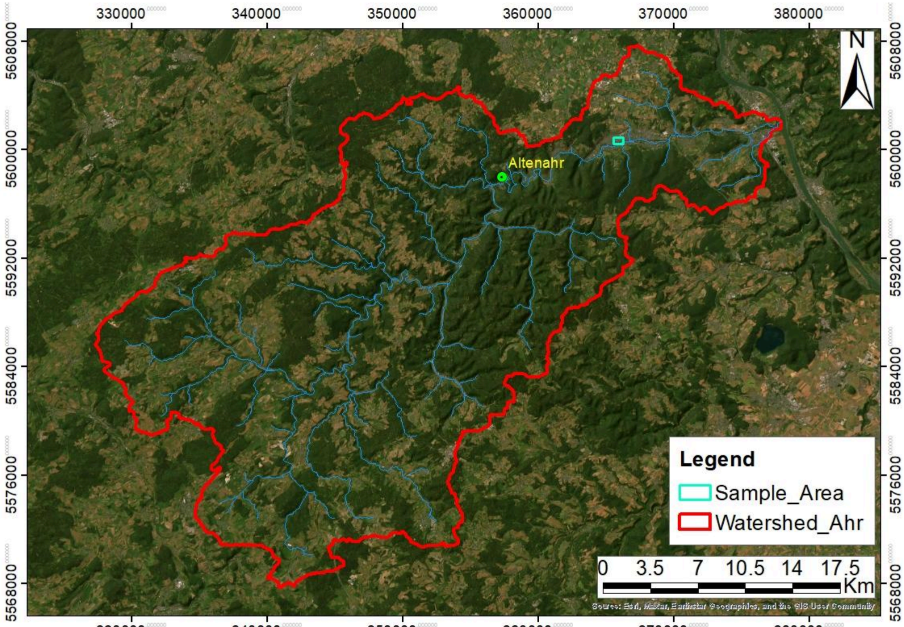


Figure 14*: Sample area within the Ahr catchment for water level map.*

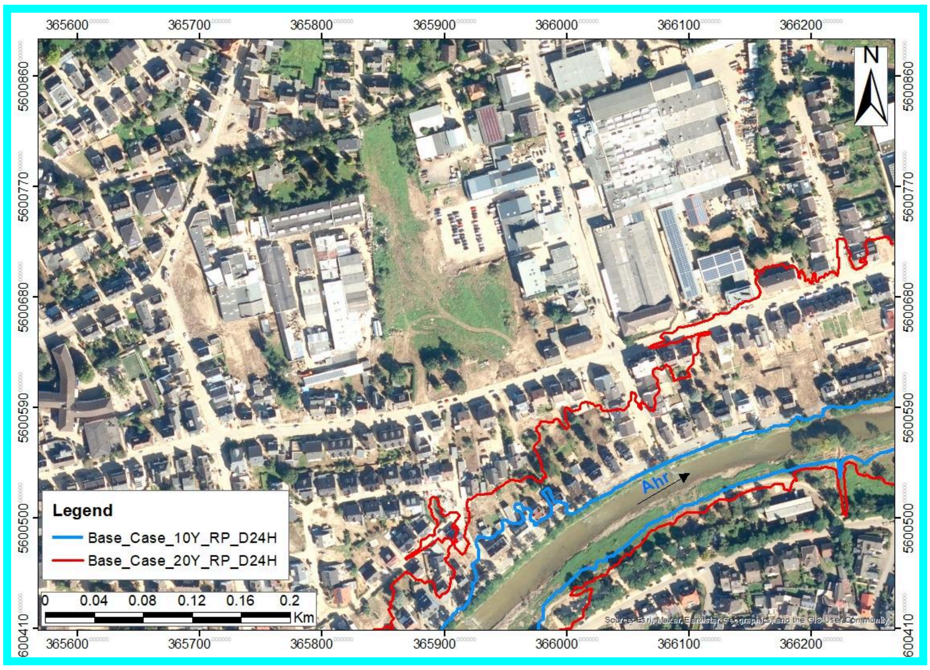


Figure 15*: Water level map showing the base cases for different rainfall event.*

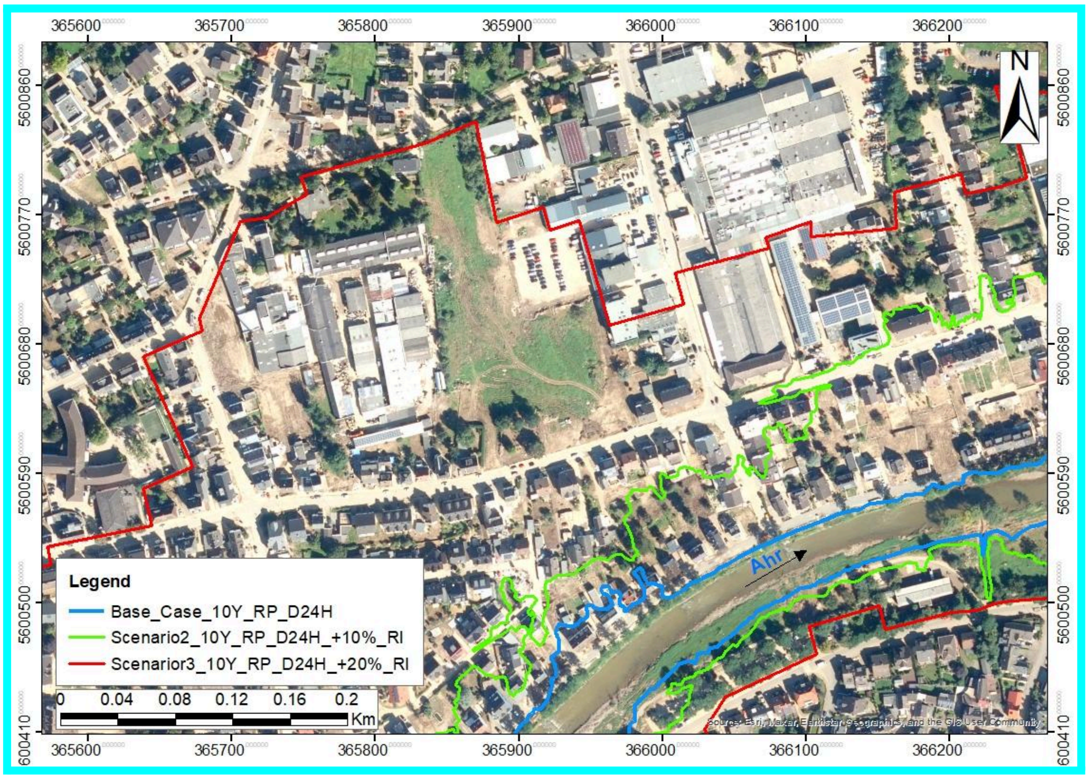


Figure 16*: Water level map showing comparison between base case versus scenario 2 and 3.*

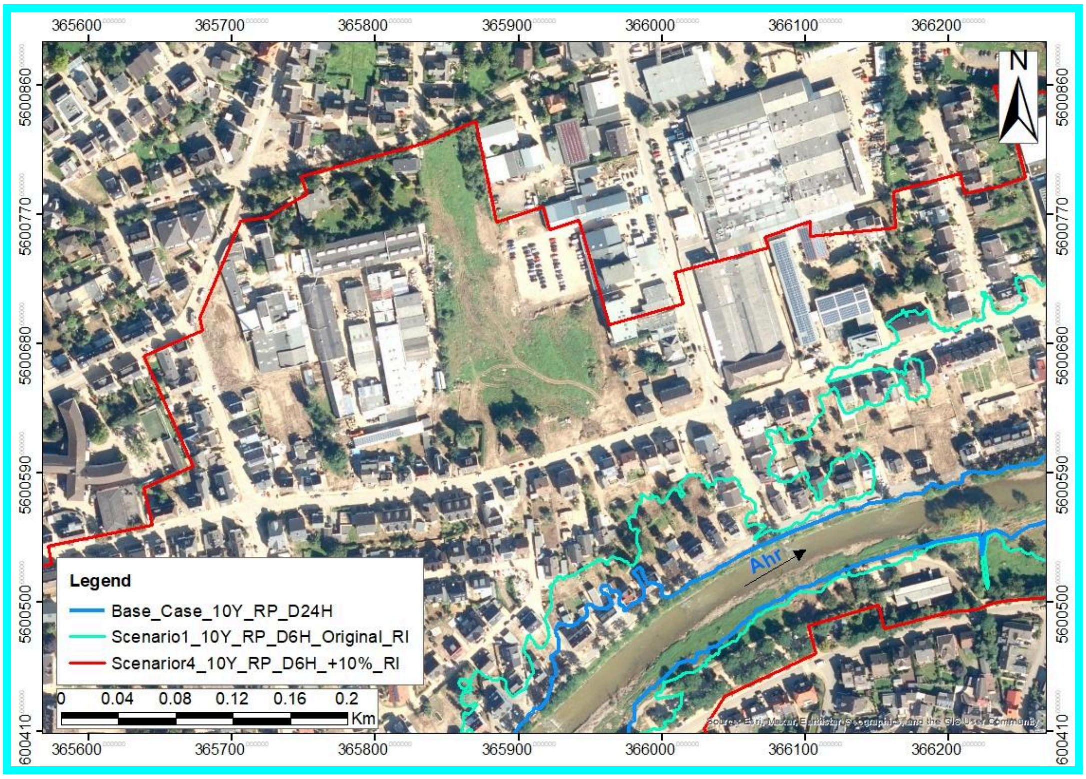


Figure 17*: Water level map showing comparison between base case versus scenario 1 and 4.*

As can be seen in the maps, intense rainfall events or rainfall events with shorter duration have larger extent of impact and it is clear that Ahr valley is prone to flash flood like climate change impacts.

Based on the results above, an initial rough definition of the threshold values to activate emergency and evacuation protocols in the Ahr catchment could be done.

5. Activities and Actions for Flash Flood Prevention

5.1. Risk: Log Jam (Bridge)

In case of flash flood, tree trunks or other debris can float in the river. These can also accumulate and create a log jam (snagged on rocks, trees, bridges). There are 29 bridges in the city Bad Neuenahr-Ahrweiler, marked in Figure 18. Therefore, there is a high risk of log jam in the city. Depending on the geometry of the bridge, some bridges have a higher risk of log jam. We can determine bridges with a higher risk of log jam based on photos and how the bridges are built.

Risk in the Ahr catchment : log jam.

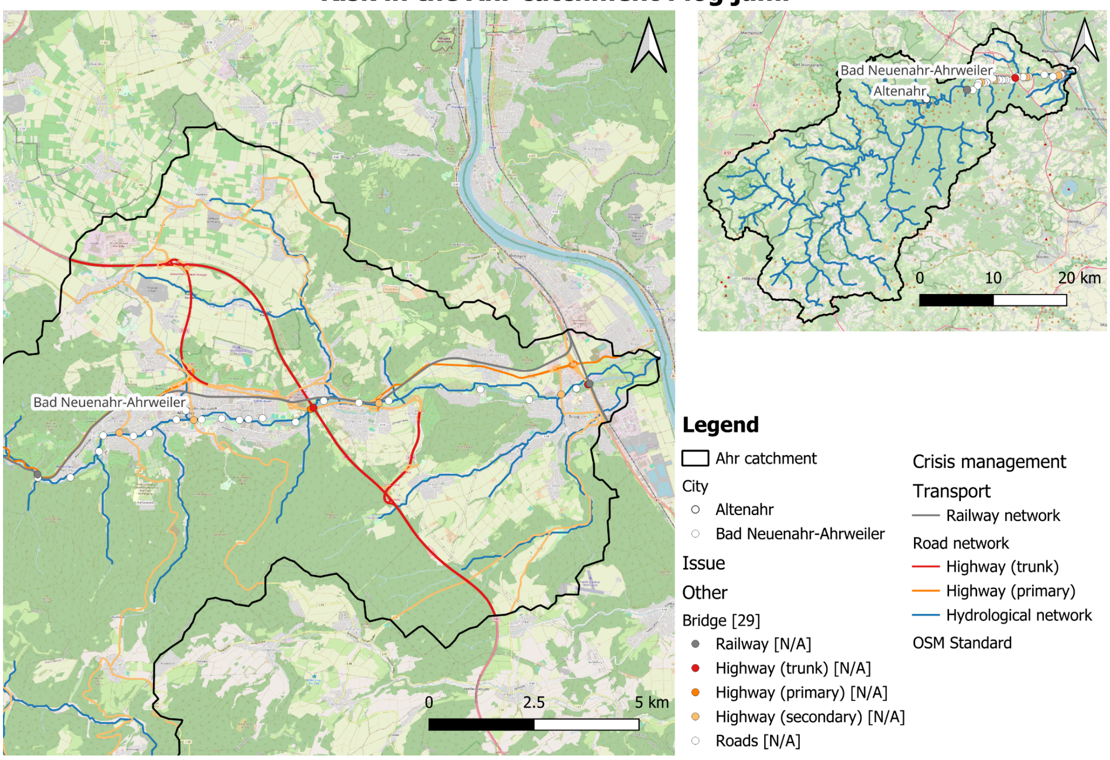


Figure 18: *Log jam map.*

After conducting an in-depth analysis of bridges using Google Earth, we have identified six structures that would mostly be affected by log jam and they are presented in Figure 19 and in the log jam map in the Appendices.

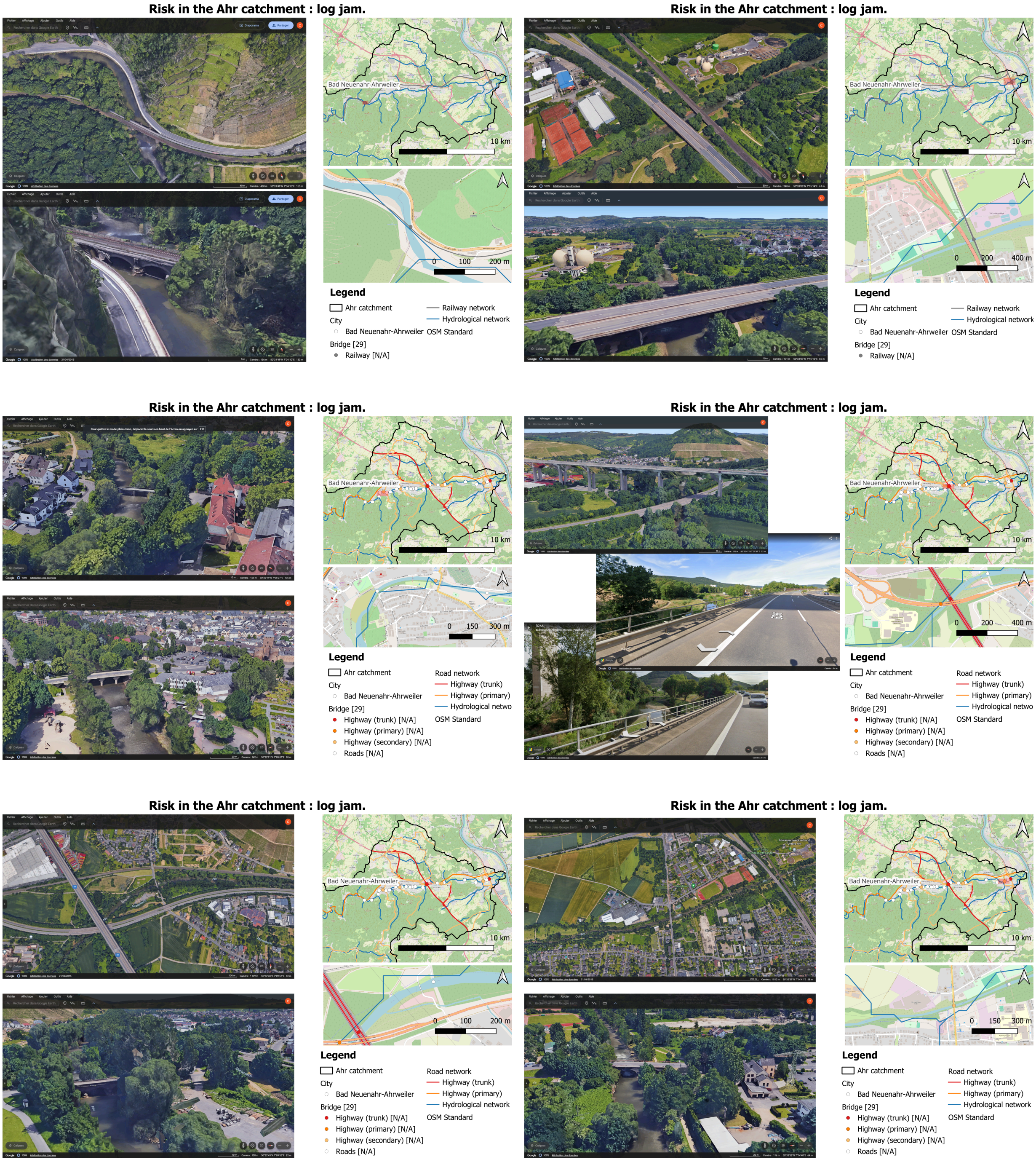


Figure 19: *Bridges that would be jammed.*

5.2. Overall Risk

The map shows places with a risk in the zone of interest of the Ahr catchment. The points are in the floodplain area as shown in Figure 20.

Risks in the Ahr catchment (zone of interest).

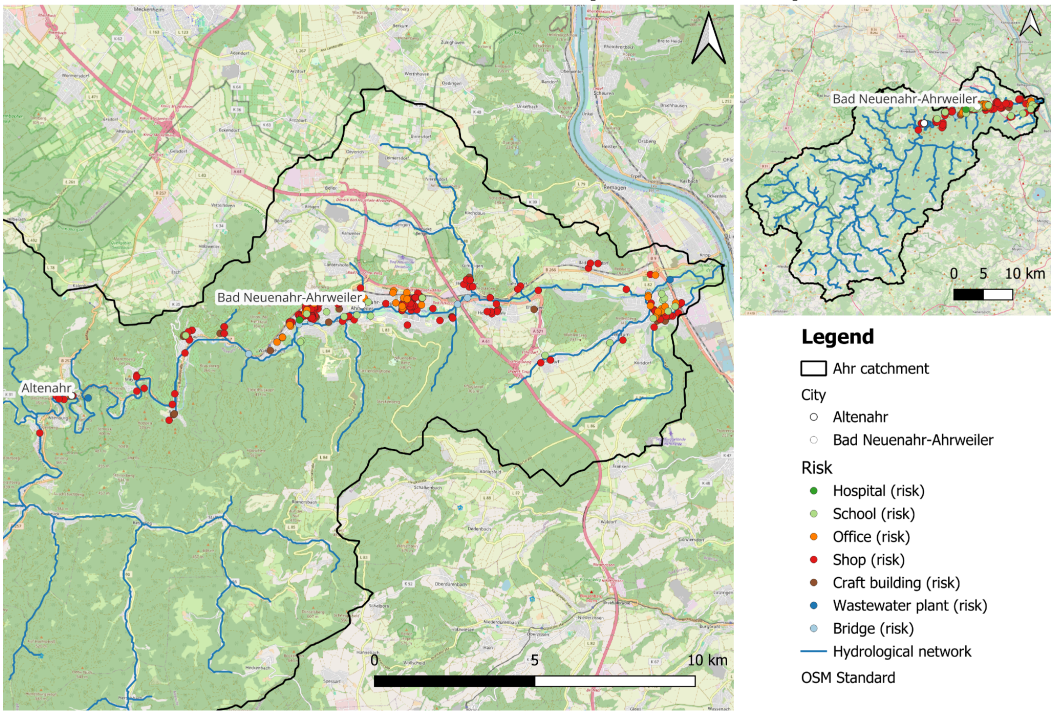


Figure 20: *Vulnerable assets.*

5.3. Agricultural Area Risk

The Ahr catchment is covered by 332.5 km² of agricultural areas and it represents 37.0% of the total catchment area (Figure 21). There is also a risk of soil leaching.

Agricultural land cover in the Ahr catchment (zone of interest).

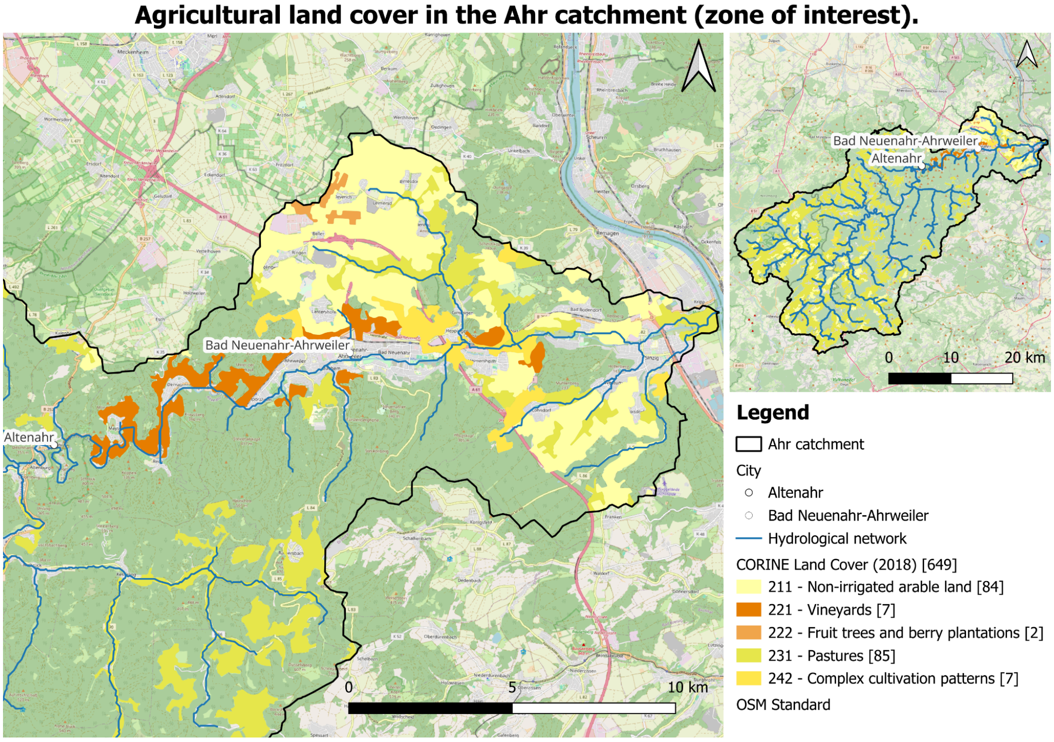


Figure 21: *Agricultural land cover.*

6. Adaptation Measures

The Ahr catchment, and specially its downstream area, are flood prone areas. As it occurred in 2021, flash foods can impact this watershed causing major human losses and structural damages.

Improving preparedness to mitigate the impacts of these events is a complex challenge that would require a more thorough hydrologic and hydraulic assessment of the Ahr catchment than the scope of this course. Such study could, for instance, lead to an engineering project to channel some parts of the river to prevent its overflow of extreme rainfall events up to a certain return period. Nevertheless, this kind of measures would still fall short to prevent damages for events with larger return periods than their design criteria.

Considering the limitations and capabilities of the work developed, one proposed solution to mitigate the effect of flash floods in the Ahr catchment is an Early Warning System (EWS). This system should enable authorities to alert inhabitants about upcoming flash floods and organise evacuation plans or other measures.

6.1 Prevention Measures at Different Levels

The 2021 event showed that people were not prepared to face such an extreme flash flood. Indeed, the number of human casualties was very high and illustrated a deficient system. That is why it is vital to think about how to best manage the crisis at all levels of society.

- **Local people:**
    - Before an event:
        - Being aware of flood zones. Indeed, a lot of infrastructures and habitations have been built on flood zones. Furthermore, many people in Ahr valley were not informed they were potentially in a risk zone. This is why being aware of this information can help to act rapidly and prepare for any events.
        - Ask the local council if there is a plan or information for special events so that you know where to go to be safe.
    - During an event:
        - Escape far away from the river, at a higher level.
        - In case of trapped people, they should go upstairs. Taking a car or moving outside could be very dangerous during flash floods. It is important to stay inside a building, but upstairs.
- **Municipal level:** Introducing a crisis management plan to reduce the impacts for the next events. In the Ahr area, there is no plan which describes and gives answers to

manage flood risk at municipal level. Count every element available to help facing a crisis such as equipment and human means, public or private places.

Ensure security for the population:

- Creation of shelters (at least 2 for small villages) such as gymnasium, lodge, retirement homes or hotels requisition which are located in safe zones (non-flood zone) to host people in critical situation.
- Launch the alarm system as soon as we know a dangerous event will occur (heavy rains).
- Communicate with social media or send messages on mobile phones to warn the population.

- **District level:**
  - Higher investments are needed to find solutions and deal with flood risks.
  - Re-evaluate our standards for hydraulic infrastructures. There are several problems :
    - Structure's size is not built for extreme events such as in July 2021. It should be important to review our design to avoid water overtopping the dam for example.
    - Creating or resizing retention basins to store rainwater in strategic areas. Using retention basins near housing estates or individual homes can be a way of managing heavy rainfall and preventing the risk of flooding. However, the volumes to be stored for a significant reduction in flood magnitude are too high for the solutions to be effective. The cost, compared with the effectiveness of the solution, is considered too high.
    - Building some flood control basins. This is a dam built across the river pierced by an orifice at its base (sluice) which naturally lets the water flow. When the flow exceeds the capacity of the sluice, the reservoir fills up so as not to let pass downstream as the desired flow rate, then empties gradually during the decline.
  - Riverbank and watercourse maintenance plans: this would help to limit solid flow, which can cause serious damage, and also prevent major logjams during flood periods.
  - Working on a plan to rehouse people affected by the 2021 floods. Indeed, rebuilding housing in the same location as the flood zones would be counterproductive.

- To reduce flash floods impacts, renaturation of watercourses could be a solution because it contributes to the restoration of wetlands, floodplains, remeandering.. In Ahr catchment, it could be interesting to look for areas which can be renaturate, for example next to cities or villages that have been impacted, or even in upstream areas to manage Ahr's flow.
- Finally, reconsidering agricultural practices can also be helpful. Indeed, there are many agricultural lands which cover the downstream area of our catchment. Increased water runoff is not just a consequence of urbanisation. They have often become impermeable through overexploitation of the soil.

Reception and assembly center in the Ahr catchment (zone of interest).

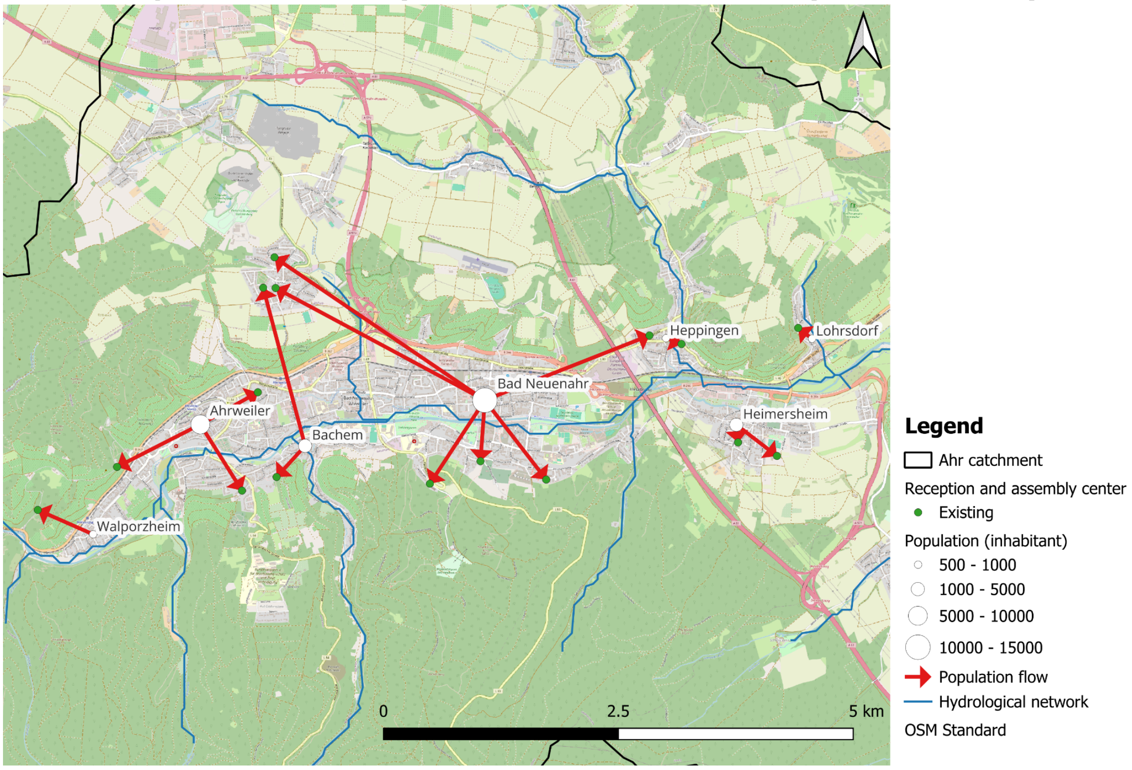


Figure 22: *Reception and assembly for an eventual flood event.*

7. Conclusions

In conclusion, the substantial impacts of climate change on flash floods demand serious consideration. The undeniable link between the changing climate and the increased frequency and intensity of flash floods necessitates a proactive approach in understanding and addressing these challenges. The simplicity of the hydrological model, while serving as a valuable tool, introduces uncertainties that must be acknowledged. It is imperative to recognize the limitations imposed by the model's simplicity and the evolving nature of climate-related events.

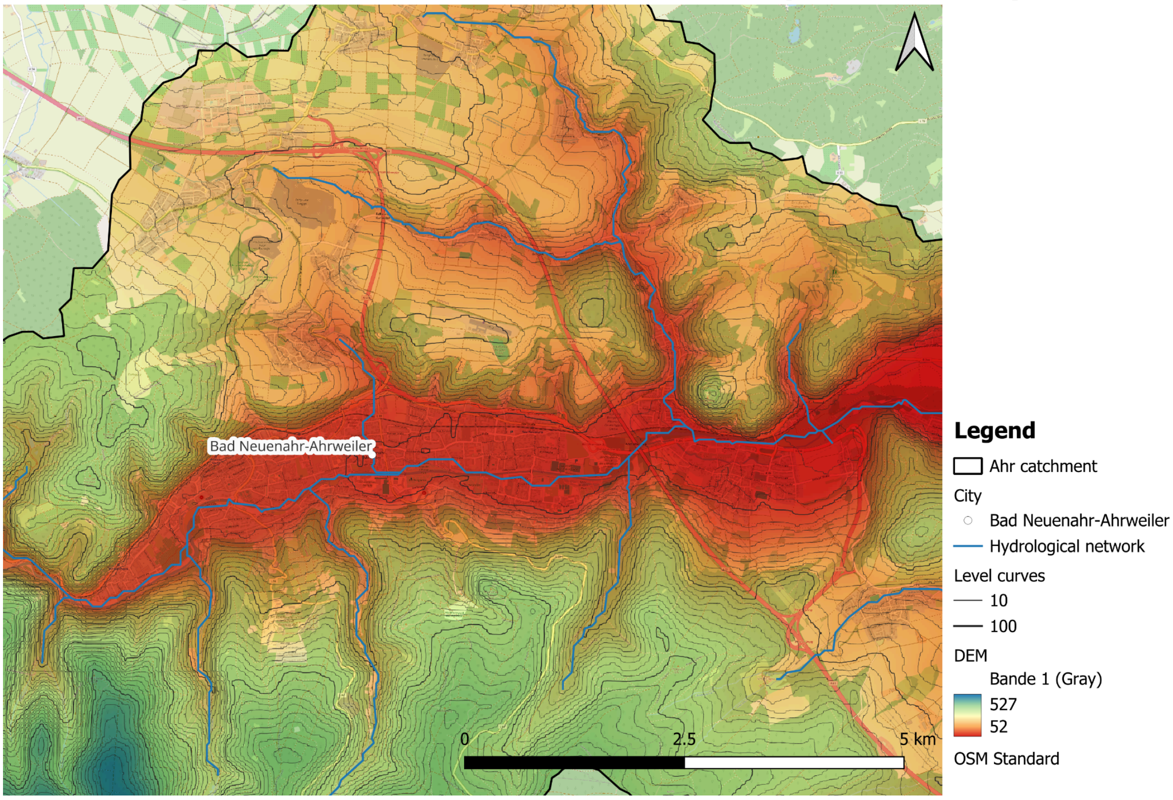
Moreover, the effectiveness of the hydrological model is directly tied to data availability. The limitations in data collection and availability present challenges in achieving a comprehensive and accurate representation of flash flood dynamics. These data constraints underscore the need for robust data collection systems and improved accessibility. Overcoming these limitations is pivotal for refining the model's accuracy and ensuring its applicability in addressing the real-world complexities associated with flash floods.

While the hydrological model serves as a starting point for preliminary analyses, it is crucial to emphasize that its utility is contingent on continuous refinement. To accurately evaluate the full impact of flash floods and devise effective solutions, further research and development are indispensable. Collaborative efforts among researchers, policymakers, and environmental agencies are necessary to enhance the model's sophistication, broaden data availability, and, ultimately, contribute to more informed decision-making in managing the consequences of climate change-induced flash floods.

Appendices

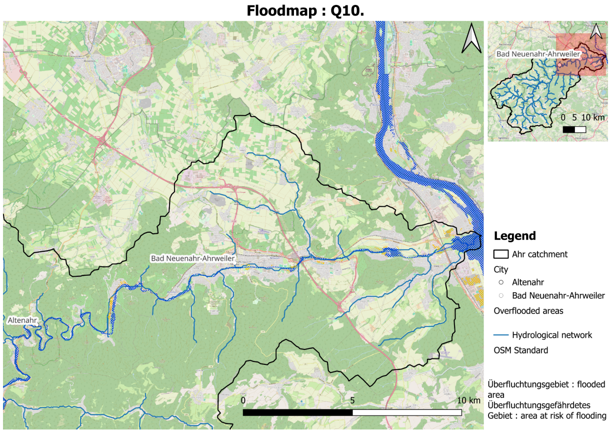
The digital elevation model allows us to determine high and low points. The map shows very clearly the valley.

Digital elevation model in the Ahr catchment (zone of interest).

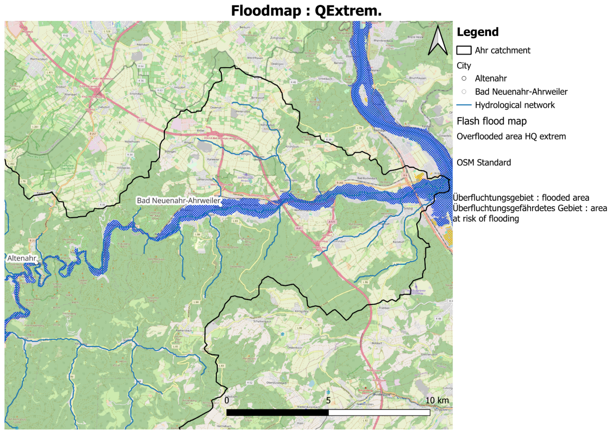


These flood maps were taken on the governmental website. Because we do not have a 2D-simulation, it allows us to identify flood hazards.

Floodmap : Q10.

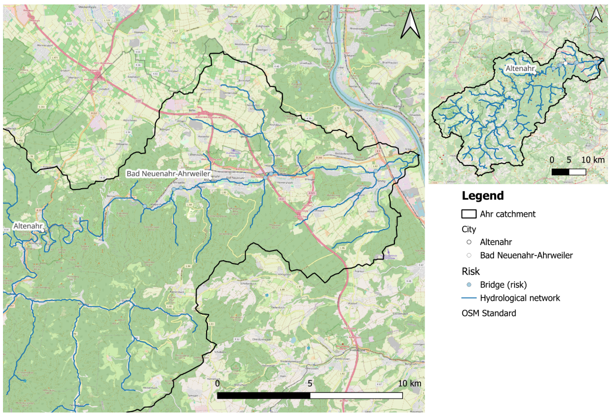


Floodmap : QExtrem.

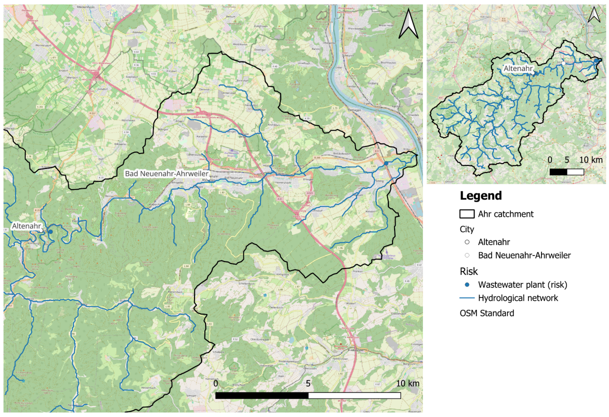


Several risks are detailed below.

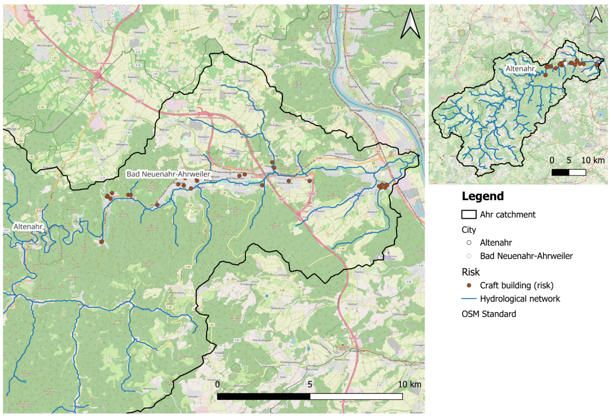
Risks in the Ahr catchment.



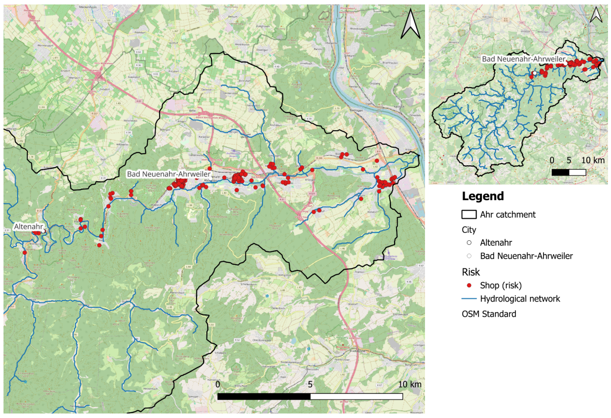
Risks in the Ahr catchment.



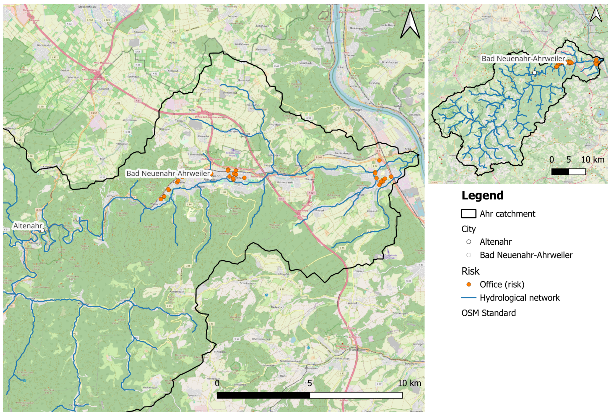
Risks in the Ahr catchment.



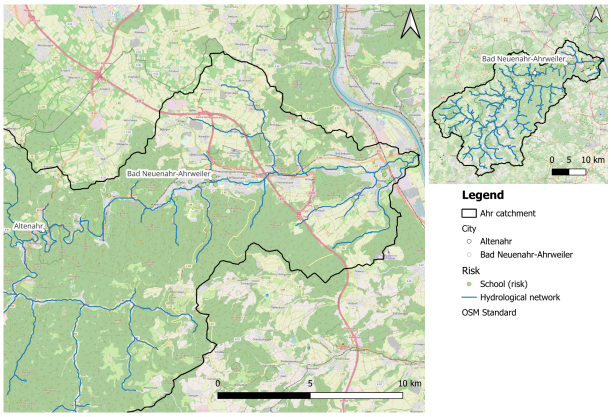
Risks in the Ahr catchment.



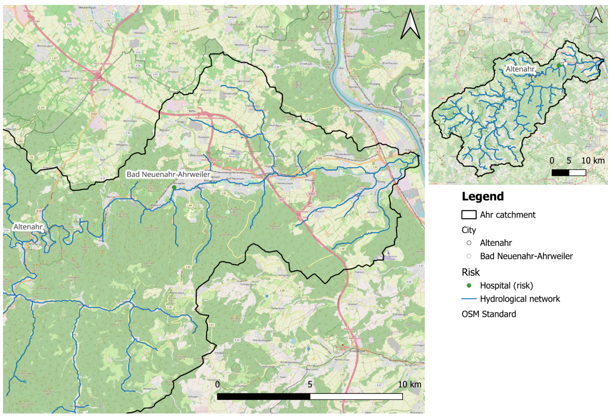
Risks in the Ahr catchment.



Risks in the Ahr catchment.



Risks in the Ahr catchment.



The geological map gives us an idea of the historical river bed thanks in particular to the age of the deposit.