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Post-flood field survey of the Ahr Valley (Germany)
Building damages and hydraulic aspects

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P. Korswagen, S. Harish, J. Oetjen & D. Wüthrich

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TU Delft

IWW Institute of Hydraulic Engineering and Water Resources Management

RWTH AACHEN UNIVERSITY

Post-flood field survey of the Ahr Valley (Germany)

Building damages and hydraulic aspects

By

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REPORT

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Document checking

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Chapter 1. Introduction

1.1. Background

In July 2021, several regions in Germany were affected by intense and long-lasting rainfalls, resulting in destructive flash floods. These floods caused at least 170 fatalities and 820 injuries (CEDIM, 2021) and the recovery from damages to both buildings and infrastructure is expected to last multiple years.

The flood was a consequence of the combination of high-pressure zones over the Atlantic and Eastern Europe, which was accompanied by the intense low-pressure zone “Bernd” over Central Europe (CEDIM, 2021). As a result, the atmosphere moisture held a large amount of precipitable water, which was released due to the pressure induced by the high-pressure zones on the low-pressure zone. This resulted in heavy rainfall up to 150-200 l/m^3 within 48 h, leading to extreme floods, further amplified by the nearly fully saturated soil from the long-lasting rainfalls in the previous months (CEDIM, 2021). To date, no exact measurements or values of flood discharge and flow depth are available, because of the failure of many measurement stations during the flood events. However, Table 1.1 shows the precipitation height on 13.07.2021 and 14.07.2021 for selected gauge stations in North Rhine-Westphalia and Rhineland-Palatinate, which did not fail. During this period the precipitation height reached twice the average precipitation over one month. As an example, at the measurement gauges of Cologne-Stammheim and Schneifelforsthaus such high precipitation values were never measured in over 70 years of operation and partly exceeded the values of a one-in-hundred-year event. Further detailed information on the meteorological development of the event can be found in CEDIM (2021).

An area that was highly affected by the flood is the “Ahr Valley”, at the border between North Rhine-Westphalia and Rhineland-Palatinate (Figure 1.1), which is the focus of this report. According to first estimates, the historical maximum discharge of the River Ahr at Altenahr was 236 m^3/s with a water level of 3.71 m, which was exceeded by 170 m^3/s to 470 m^3/s (400 m^3/s to 700 m^3/s), respectively 3.3 m to 4.3 m (7-8 m) during the 2021 event (CEDIM, 2021). The peak discharge in the River Ahr is believed to have occurred in the late evening of July 14th and early 15th, even if it is not exactly known due to the lack of measurements (CEDIM, 2021). For the same reason it is difficult to determine the end of the flood event, but on July 17th the flood decreased significantly.

The Ahr Valley has an area of 86 km^2 (total catchment area of the Ahr River is 897.5 km^2) and resembles a notched valley of varying flank steepness, which fans out in eastern direction before flowing into the Rhine river near Sinzig. The flanks of the valley are often forested and consists of several protected reserves, including the bird protection area “Ahrgebirge” and the special area of conservation “Ahrtal” (BFN, 2012). The River Ahr has a mean discharge of 6.95 m^3/s at Altenahr with a flow depth of 0.75 m.

The Ahr Valley was affected by significant floods in the past, including major events in 1804, 1888, 1910, 1918 and 1920, evaluated and quantified by Roggenkamp and Herget (2014). This investigation focused on these five floods based on historic flood level markings in Dernau, Walporzheim and Ahrweiler as well as on photographs taken in Neuenahr in 1910. Among these, most information is available for the 1910 event, which is known to have endangered residents and damaged structures near the River Ahr, becoming a threat for bridges along the stream (Roggenkamp and Herget, 2014; Ulrich, 1938). The flood event in 2021 is assumed to have been less intense than the 1804 event, but comparable to that in 1910 (CEDIM, 2021). However, the 1910 event is not considered in the current official risk assessments for the Ahr Valley since the time series applied for deriving the statistical reoccurrence intervals were based on measurements beginning in 1947. Subsequently, the estimate for a flood event of the HQ100 did not consider the events in 1910 and 1804 and was determined to be only 241 m^3/s (CEDIM, 2021). Table 1.2 shows the highest measured discharge for the 2021 event in comparison with the estimated HQ100 for the River Ahr. It can be seen that the former maximum discharge and one-hundred-year estimate is exceeded in both stations. Furthermore, the measurement gauge failed in Altenahr during the flood and the actual value is assumed to be beyond the last measurement (CEDIM, 2021).

Roggenkamp and Herget (2014) already assumed that future heavy rain events might result in extreme flooding (i.e., higher than in 1804) throughout the Ahr valley due to reduced retention areas in the upstream catchment area.

Table 1.1. Daily precipitation sums at selected measurement gauges from the 13.07.2021 and 15.07.2021. (Table partly taken from CEDIM, 2021; data base: DWD).

Region	Coordinates	Coordinates	Precipitation [mm]	Precipitation [mm]	Accumulated Precipitation [mm]
.	Latitude	Longitude	13 July 2021	14 July 2021	.
Cologne-Stammheim	50.989	6.978	11.6	153.5	165.1
Wipperfürth-Gardeweg	51.164	7.423	53.1	111.8	164.9
Kall-Sistig	50.501	6.526	16.5	144.8	161.3
Wuppertal-Buchenhofen	51.226	7.105	64	90.8	154.8
Aachen-Orsbach	50.798	6.024	55	98.7	153.7
Hückeswagen (Bevertalsperre)	51.143	7.366	50.5	101.1	151.6
Gevelsberg-Oberbröking	51.333	7.341	71.1	78.9	150
Lüdenscheid	51.245	7.642	31.6	114.4	146
Simmerath (Kalltalsperre)	50.647	6.312	49.9	93.5	143.4
Schleiden-Morsbach	50.564	6.448	36.5	102.7	139.2
Schneifelforsthaus	50.297	6.419	13.5	124.1	137.6

Table 1.2. Exemplary discharge comparison between the former maximum measurements, hundred-year estimate and the 2021 event (CEDIM, 2021; reworked).

Gauge	Former measured discharge [m³/s]	HQ100 [m³/s]	2021 event [m³/s]
Müsch	132 (02.06.2016)	152	320 (14.07.2021; 19:00 h)
Altenahr	236 (02.06.2016)	241	332 (14.07.2021; 19:15 h; gauge failed)

1.2. Report Overview

In the present report we evaluate the damages induced by the flood in (sorted from North to South) Dernau, Mayschoß, Rech, Altenahr, Altenburg, Kreuzberg, Brück, Schuld and Insul (Figure 1.1). The basis for the evaluation is an exhaustive field survey conducted between the 17th and 19th of August 2021 in the Ahr Valley which was documented by photographs, measurements of high-water marks and personal communications with inhabitants. The present report focuses on metadata descriptions of damages and does not try to evaluate the exact flow conditions (i.e., flow velocity; depth). This report is intended as a metadata description of the GPS logged photographs of which coordinates, and elevation data is available. Nevertheless, the GPS measurements of elevation need to be treated carefully due to their insufficient accuracy. Along with the evaluation of over 130 photographs, short assessments of the flood height, main flow-direction (where possible) and resulting damages are given. For some particular cases and where possible and meaningful, descriptions of building materials and the failure characteristics are additionally included. Furthermore, witness statements from engaging locals were collected when they voluntarily approached the survey team.

Estimations of mean or maximum discharges are not part of the present report for two main reasons:
1) Evaluating such parameters could only be done reasonably if a broad basis of video recordings (or exact measurements) would be available, which was not the case during the preparation of this report.

Furthermore, even if such video records were available, it would be difficult to derive general flow parameters since these records encompass only short time-ranges. 2) The field survey was conducted four weeks after the flood and the actual on-site situation was already altered significantly. Subsequently, it was not possible to evaluate certain parameters, e.g., the debris distribution directly after the flood and at some points no information were available if certain damages occurred during the flood or if they occurred during cleaning or reconstruction.

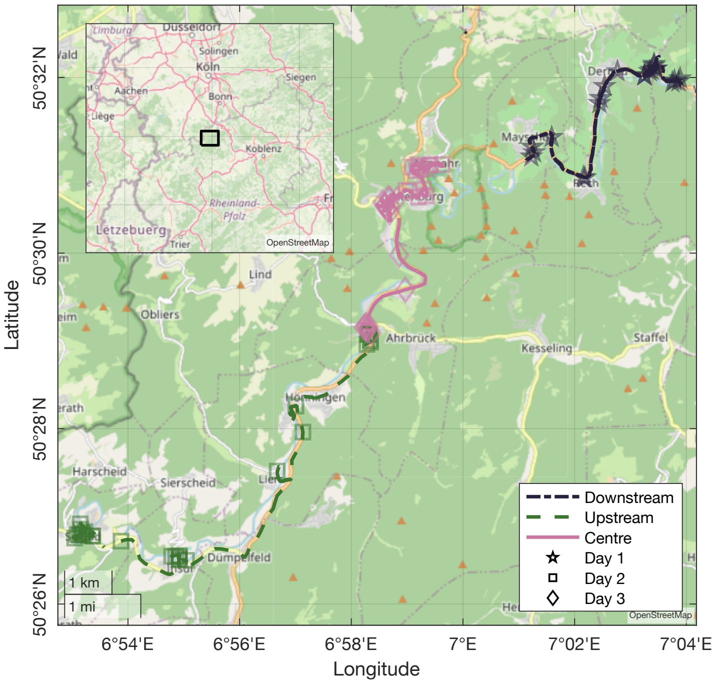

Figure 1.1. Area and path of the visit based on the GPS log.

The visit can be organised into three sections: the upstream part of the valley, centre, and downstream. The topography illustrated in figure 1.2 depicts the narrow valley which, probably contributed to a high flood wave. The GPS trace shows the locations visited and, the more points are gathered on a certain spot, the more time was spent at that location.

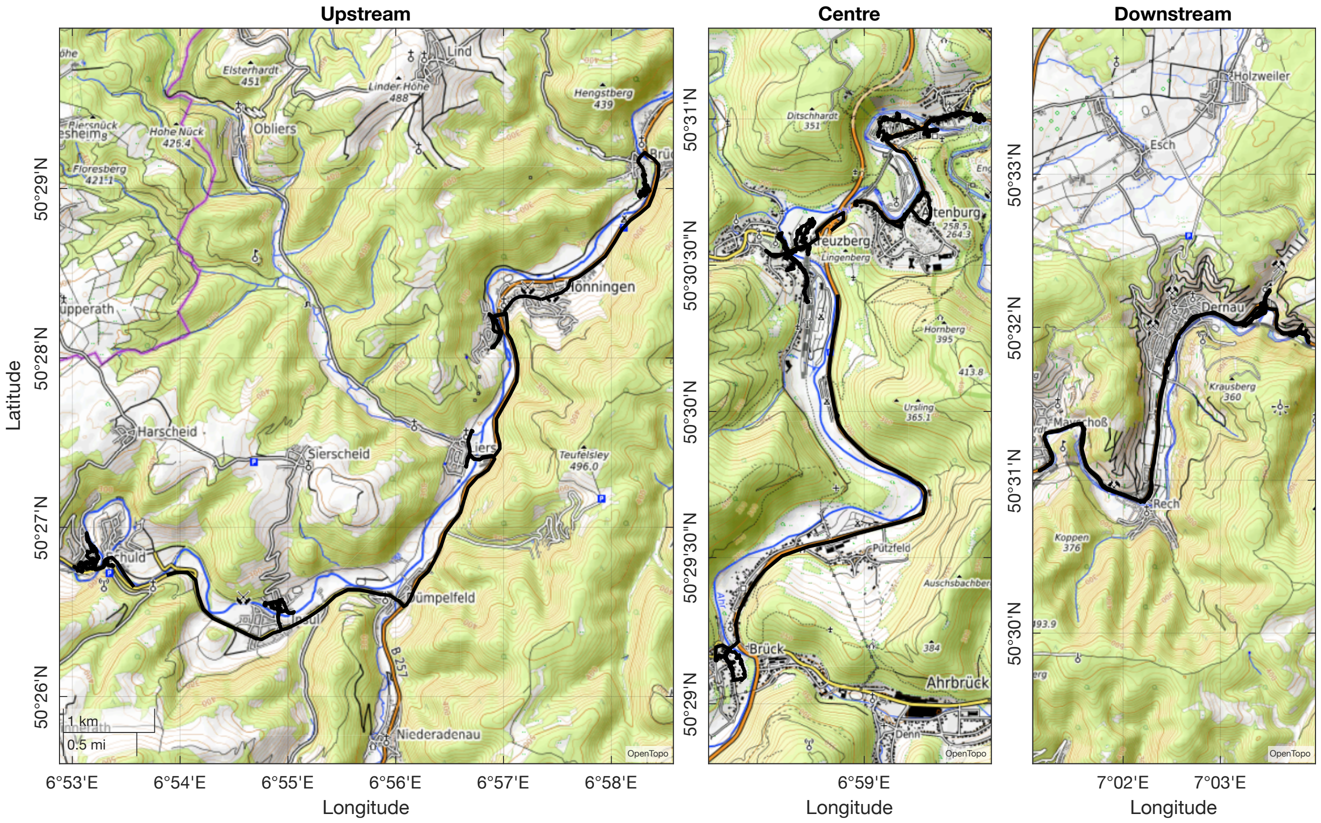

Figure 1.2. Topographic map of GPS trace.

1.3. Metadata

Photos have been separated into the town or city in which they were made. Nine locations have been selected: Dernau, Rech, Mayschoß, Altenahr, Kreuzberg, Altenburg, Brück, Insul, Schuld. These are shown in the following maps in figure 1.3. Files are named starting with the first letter of each group, such as 'D' for Dernau.

Moreover, photos have been broadly categorised into three groups: photos showing a watermark in a façade (W), photos identifying building damage (H), and other miscellaneous images (M). In addition, a few photos which portray scour at the building corners and at the building front are denoted with (S). These characters are placed second in the file names.

Next, photos are numbered continuously for every location (01 to 99); this means that sequential photos were also taken close to each other in space. For every location, case studies of building damage (H photos) are further grouped together with an identifying character behind an underscore space (_).

An example of a resulting files name is DH01_A for a photo taken in the Dernau location (D), showing building damage (H) and belonging to case study D_A.

The following link provides access to all photos and spreadsheet files (DOI: 10.4121/19222656):

https://doi.org/10.4121/19222656

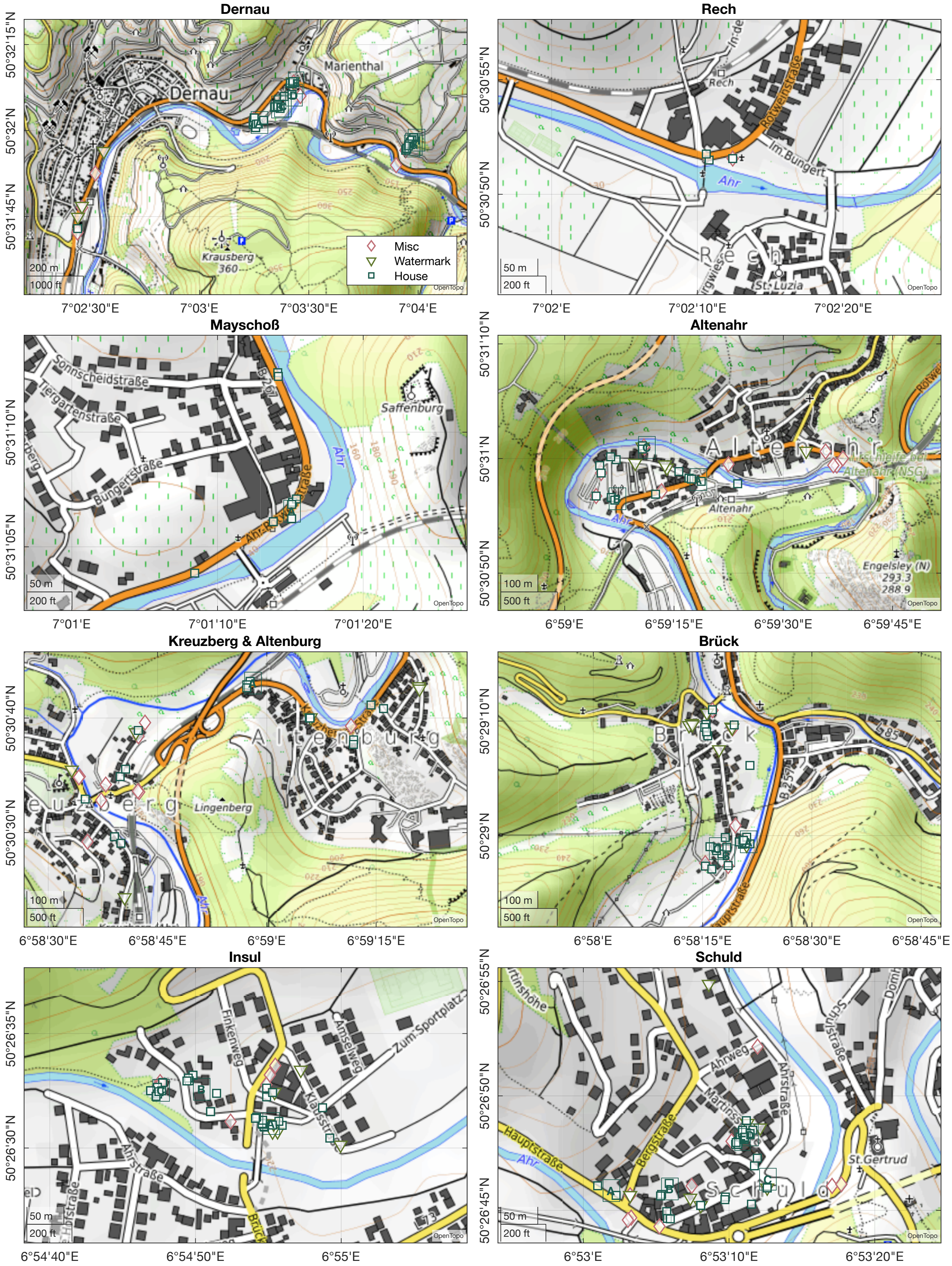

Figure 1.3. All eight locations where photos were taken.

Chapter 2. Locations

Figures 2.1 and 2.2 present the magnified view of the eight locations with the precise GPS locations where each photo was taken.

The following eight chapters deal with each selected area, beginning at the most downstream location of the Ahr River (i.e. Dernau) and continuing upstream of the valley, until Schuld. Each chapter presents general information about the location, an overview of the hydraulic aspects and then detailed selected case studies focusing on structural performances and a deduction of the flood actions that could have caused the observed failures. Each case study is identified with up to four pictures, but additional photos can be found in the data archive. Similarly, up to six photos with watermarks are included per chapter; these watermarks complement those observed in the case studies. Key findings and selected case studies at each location are reported in this document, while more detailed data can be found in the (data) repositories.

Hydraulic aspects will focus on:

1. The flow depths measured from water marks at various locations. The flow depths were measured from the traces left on the facade of the building.

- 1-3 meters: low water depths

- 3-5 meters: medium water depths

- 5-7 meters: high water depths

2. Scour depths measured at selected building locations.

The objective of this report is to categorise the damage to the structures, linking it to the potential cause of the damage, based on observations and local people statements.

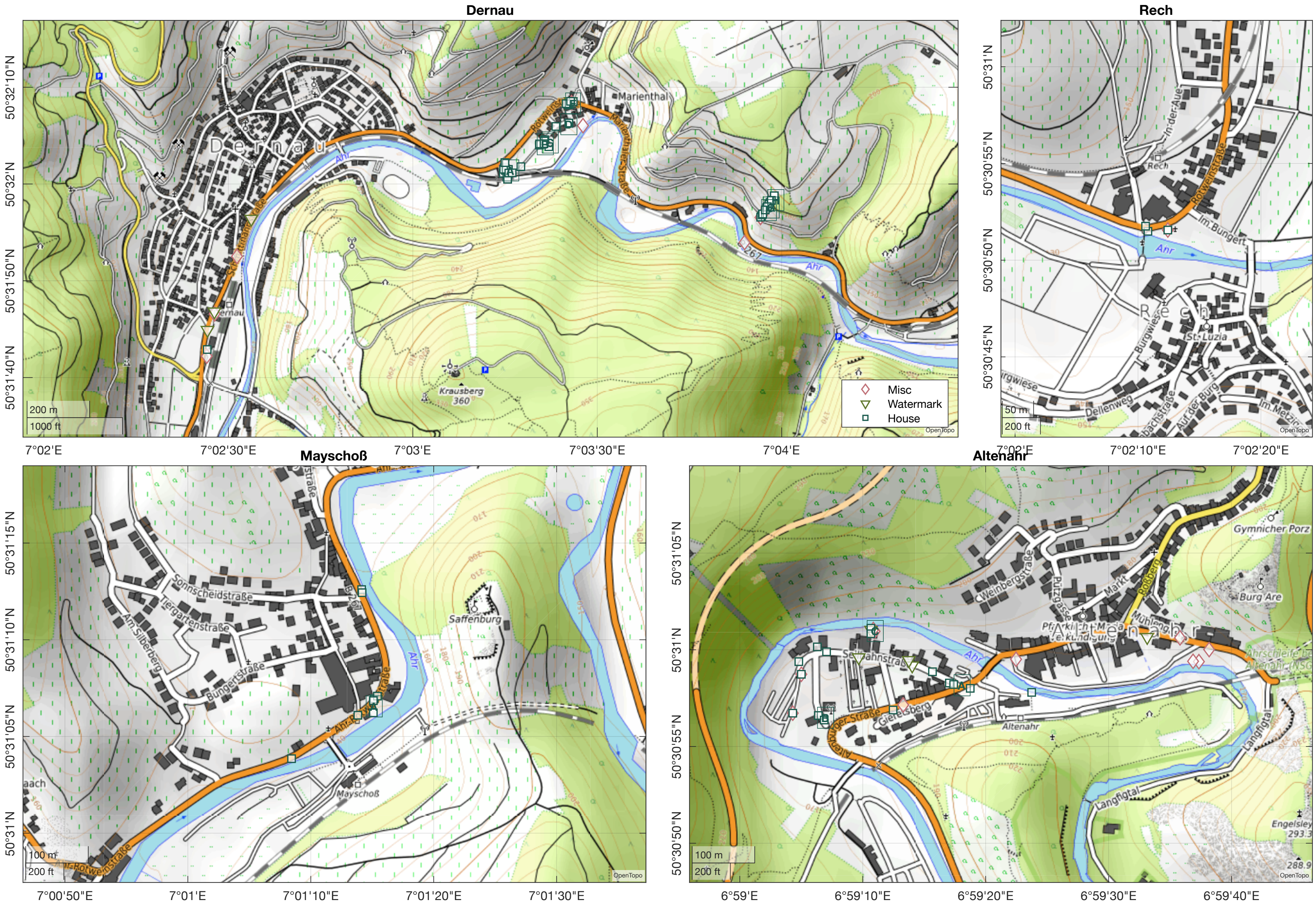

Figure 2.1. a. Magnified regions.

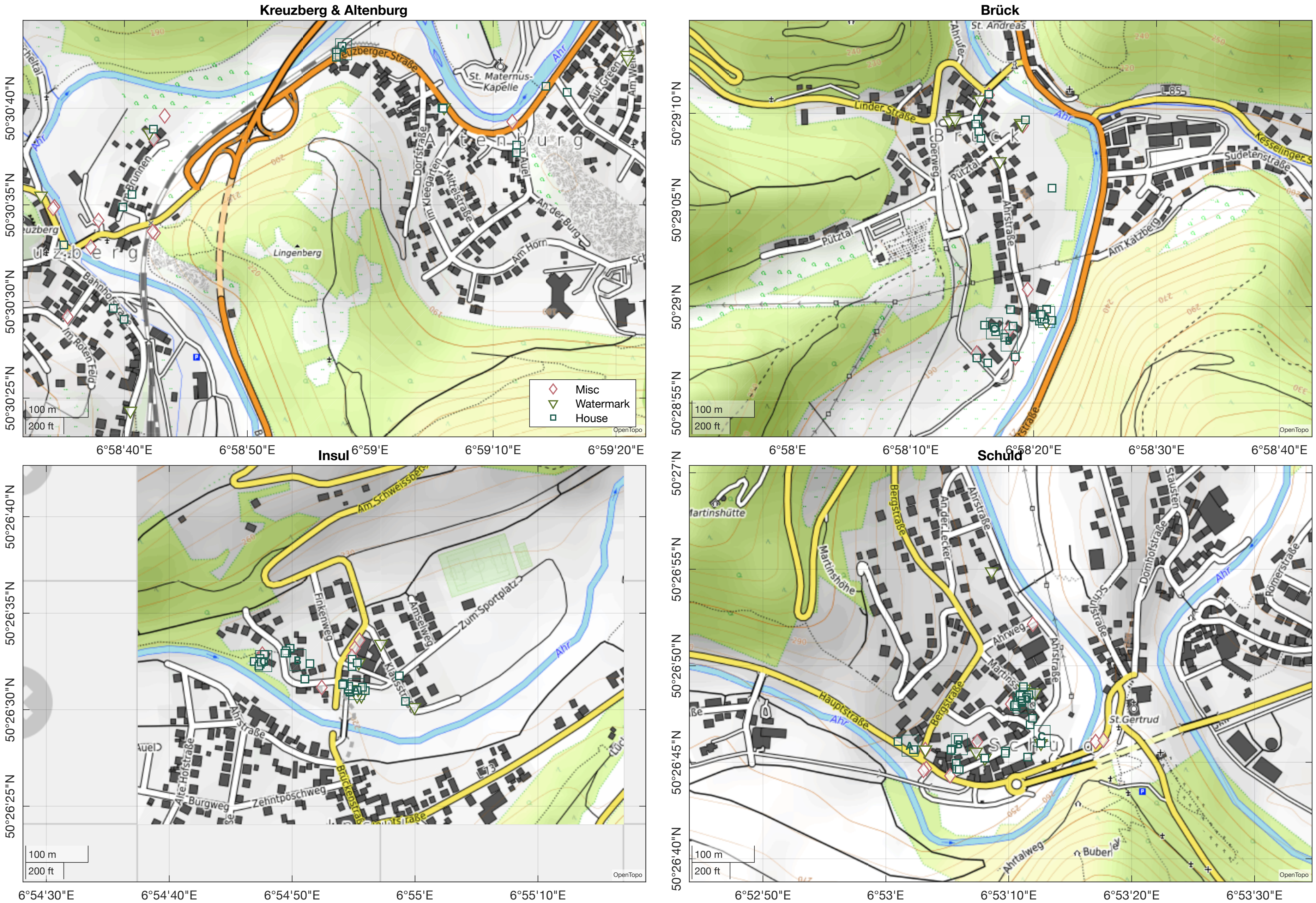

Figure 2.2. b. Magnified regions.

Chapter 3. Dernau

3.1. General - Dernau

Dernau is located in the lower part of the Ahr valley, including the Marienthal Straße and the village of Marienthal. The areas investigated during the survey are shown in this section's map.

It is important to point out, that being located downstream of the valley, this location received most of the floating debris gathered by the flood wave through its descent. Debris and driftwood tended to accumulate, damming against houses and inducing higher pressures and therefore more important, sustained loads. In addition, debris, impacting on buildings corners and walls, caused additional local forces, often responsible for severe damage.

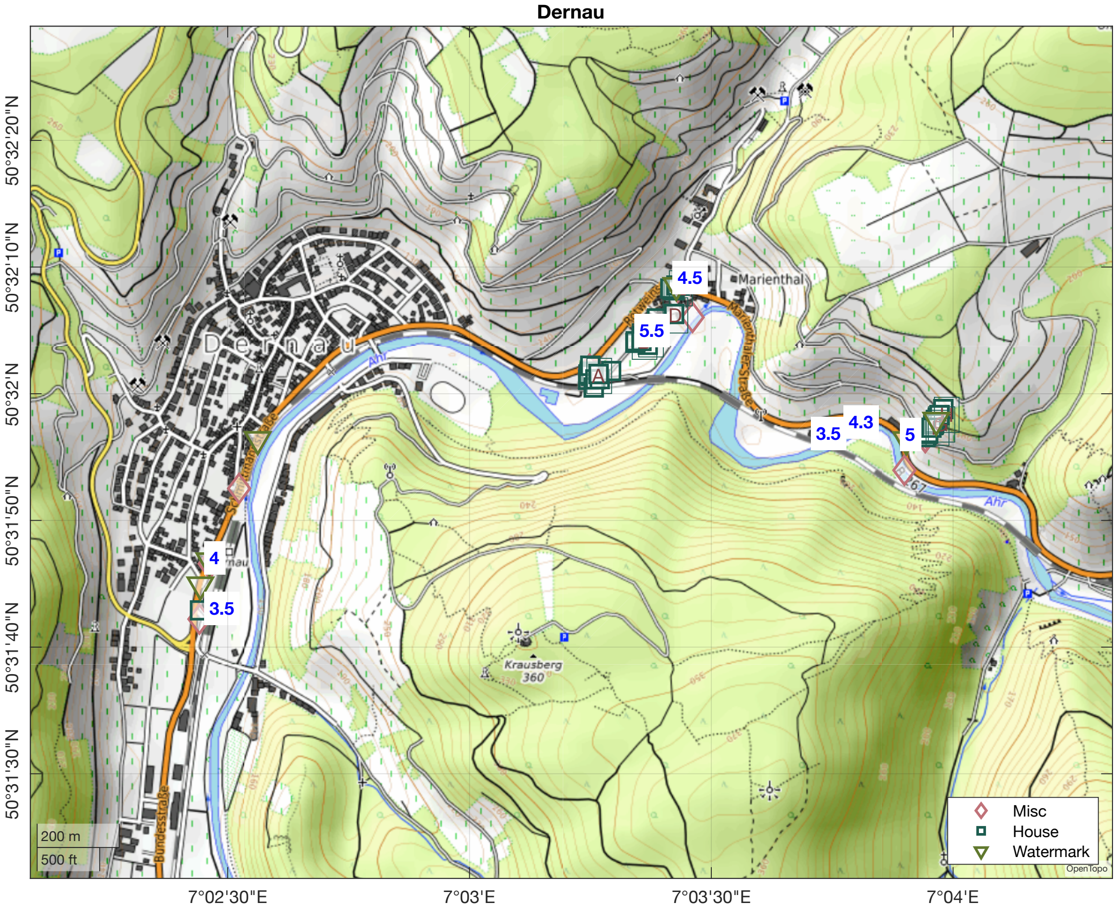

Figure 3.1. Dernau

3.2. Hydraulic Aspects - Dernau

The water marks measured on the facade of the buildings showed mostly medium water levels, with higher levels at certain locations. In particular, at the Am Saenger Hotel in the lower part of Marienthal Stra§e (Figure DW5), water levels of approximately 5 m were recorded, while 100 m upstream (Figure DW6) a mark indicated water depths of 4.3 m to 3.5 m. This difference in water levels can be attributed to the geomorphology of the valley, with the extrados of the river bending being associated with higher water levels. Nevertheless, these levels showed that during the flood, the water reached the top of the first floor, just below the roof.

Further upstream, in the village of Marienthal, slightly higher water levels were measured, with local values of 4.5 m to 5.5 m, responsible for damages to buildings further described in Section 3.3. According to an eyewitness report, the water level in the Ahr river rose to 8 m during the flood event compared to the normal water level.

Slightly lower levels were recorded in the village of Dernau, ranging between 3 m to 4 m. This was likely associated with the larger width of the valley compared to Marienthal. This also explains the relatively lower damages observed in Dernau compared to other locations in the Ahr Valley.

The Dernau region was also highly affected by scour, i.e. local soil erosion associated with fast moving water. In particular, it was noted that buildings located adjacent to the banks were the most affected in terms of water depths, scour and damages. An example of a deep scour hole is presented in Figure DS01 at the rear side of the building hosting the Restaurant Klenoid, facing the Ahr River. The scour hole had a depth of 1.5m and a length of 1.25m, however it did not reach the foundation and, thus, did not affect the stability of the building.

Bridge piers were also highly affected by the scour due to the flood. An example of scour around the pier of a railway bridge is presented in Figure DM08, where the fast-moving waters removed sediments, creating an extensive scour hole on the upstream side that affected the shallow foundation and, therefore, the piers vertical stability. The degree of leaning shows the intensity of the scour hole and, therefore, of the flood.

The building in Figure DS02_D showed limited scour depths, despite being located next to the Ahr River. This could be attributed to the block pavement that surrounded the building, thus showing the importance of these protection measures to guarantee stability in case of flood. The building in Figure DS03_B, despite being shielded by the building upstream (Figure DH02), revealed scour depth around 0.5 m-0.75 m at the backside corner, potentially attributed to local flow accelerations at the rear side due to the presence of surrounding buildings, therefore confirming the spatial variability of the flow conditions during extreme events. Nevertheless, the scour holes in Figure DS03 did not reach the foundation and the stability remained guaranteed.

Large amounts of debris were observed throughout the Ahr valley. An example of the amount of debris deposited after the flood is presented in Figure DH56. It is the first building on the upstream side of Marienthal Stra§e and, therefore, the first to face the flow behind the river bend. At this location, debris mostly consisted of trees, branches and local vegetation. According to eyewitnesses, most debris hit the building and accumulated on its upstream side during the flood (Figure DH56). Some of these wooden debris also penetrated through the windows (Figure DH58) with a high degree of interlocking, responsible for the formation of a debris-dam on the upstream side of the building.

In addition, the remains of cars were also observed, as shown in Figure DM04. Eyewitnesses during the flood event observed a parade of floating cars, reporting that most vehicles travelled with a lighter rear (trunk) and a heavier front (motor). This confirmed the ability of the flow to lift and drag cars along its path. Although their origins remain unknown, the extensive damages to cars in Figure DM20 are a clear representation of the intensity of the flood.

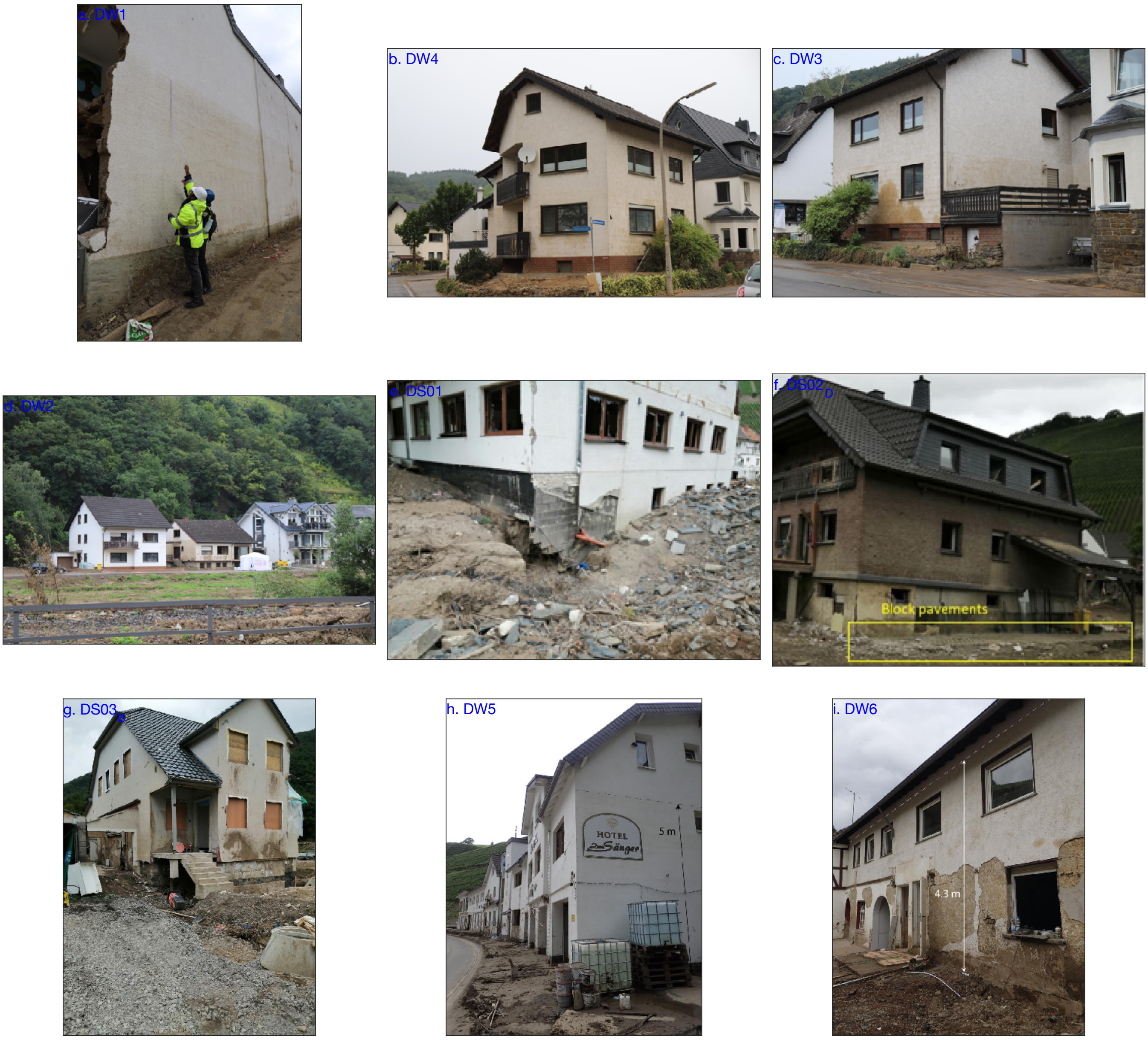

Figure 3.2. Watermarks Dernau

3.3. Case Studies - Dernau

Case D_A

This structure, located upstream of a settlement east of Dernau and next to a bend in the river's path (see A in this section's map), was attacked by driftwood, which accumulated in its interior. The impact damaged and partially collapsed the timber roof structure of the building and the brick veneer of its façade. The structural masonry leaf, consisting of concrete blocks and confined by a concrete upper floor poured in-situ, seems to be unaffected.

Moreover, the flow of water caused scour around the foundation of the building at the front but did not reach a high depth.

Figure 3.3. Case Study D_A

Case D_B

This three-storey building experienced high water levels that reached and damaged the windows on the top floor. The damage was likely caused by floating debris, as evidenced by the impacts left on three of the corners of the building oriented towards the flowing water.

Figure 3.4. Case Study D_B

Case D_C

A two-storey water level affected this house sporting a cavity wall of inner concrete blocks and outer clay brick masonry. The corner of the building was damaged by high flow velocities or impacts of floating debris. The outer leaf collapsed in the corner, while the structural, hollow, concrete blocks were locally damaged.

Figure 3.5. Case Study D_C

Case D_D

Similarly, this house also experienced damage to the outer leaf of the cavity walls and to the lower ends of the timber-structure roof. The outer leaf, which is only supported with (steel) ties to the inner, structural leaf, was pressed inwards by the water and potential debris at the corners of the structure.

Figure 3.6. Case Study D_D

Case D_E

This house, with relatively old, hollow concrete blocks and timber floors, experienced the collapse of its front façade. Structurally, the house was poorly laid out since the timber joists, spanning only in one direction, were supported on the front façade which had many openings for windows. This is uncommon since it is structurally more favourable to support the floors (when they are one-way spanning) on the main transverse walls which sport fewer openings. The unusual configuration meant that when the weak front façade, with narrow piers, was affected by the pressure of water, possibly with a few of the piers being knocked out by impact of debris, the entire façade collapsed and with it, also the floors. Had the house being laid out 'correctly', the failed piers would probably not have failed altogether, and even if they had, the upper section of the façade would not have collapsed and neither would have the floors.

Newer structures are required to be designed with resiliency in mind, such that the aforementioned failure mechanism is not likely.

Figure 3.7. Case Study D_E

Case D_F

This house was located upstream after a bend in the river, similarly to case study D_A. As such, it received the main impact of the flood wave and sheltered the structures behind it.

The structure consisted of an L shaped floor plan of which the tip of the L was completely destroyed by the flood. According to the owner, that part of the building and its basement was removed by the water.

Considering the depth of the water and the damming of debris at the surface of the flow, which would place the point of application of the main turnover force much higher, this failure mechanism is not entirely inconceivable. In combination with a large buoyancy force, resulting from a rapid rise rate of the water, this part of the building could have been bent, sheared off, and ultimately turned-over by the water.

The larger part of the L, being parallel to the flow of the water, was much better prepared to withstand the flood actions.

Figure 3.8. Case Study D_F

Case D_G

This structure looks to be impacted by debris. Its outer insulation appears damaged. In a few locations at the side of the building facing the flood wave, where large window openings were present and piers were consequently narrow, some piers were knocked out by the flood. Their locations match where the structure is propped up by steel pipes. Interestingly, only piers on the second level where affected. This may be due to two reasons: firstly, the higher location may have coincided with the depth of floating debris at the surface of the water (as supported by the watermarks); and secondly, the upper piers carried a lower vertical load which has a stabilising effect against lateral load and thus were more vulnerable than the piers on the first level which carry the entire first floor and upper storey of the building.

By the time this survey took place, the hotel had removed all the windows and renovation work had begun. It is suspected that many windows were affected by the flood.

Figure 3.9. Case Study D_G

Case D_H

This long structure was relatively unaffected but displayed horizontal and diagonal cracks on the piers between windows. It is difficult to say whether the cracks where directly related to the flood actions or indirectly related through foundation effects. The direction of the cracks, if they are due to in-plane effects, is not entirely consistent with the orientation of the house in respect to the flood wave, nor is it consistent with the out-of-plane effect of water pushing inwards on the walls.

Figure 3.10. Case Study D_H

Chapter 4. Rech

4.1. General - Rech

The village of Rech is located upstream of Dernau, on the intrados of the Ahr River. Building damages were limited compared to Dernau and the village was mostly affected by scour and bank erosion. The survey mostly focused on the area around the bridge that collapsed, as shown in this section's map.

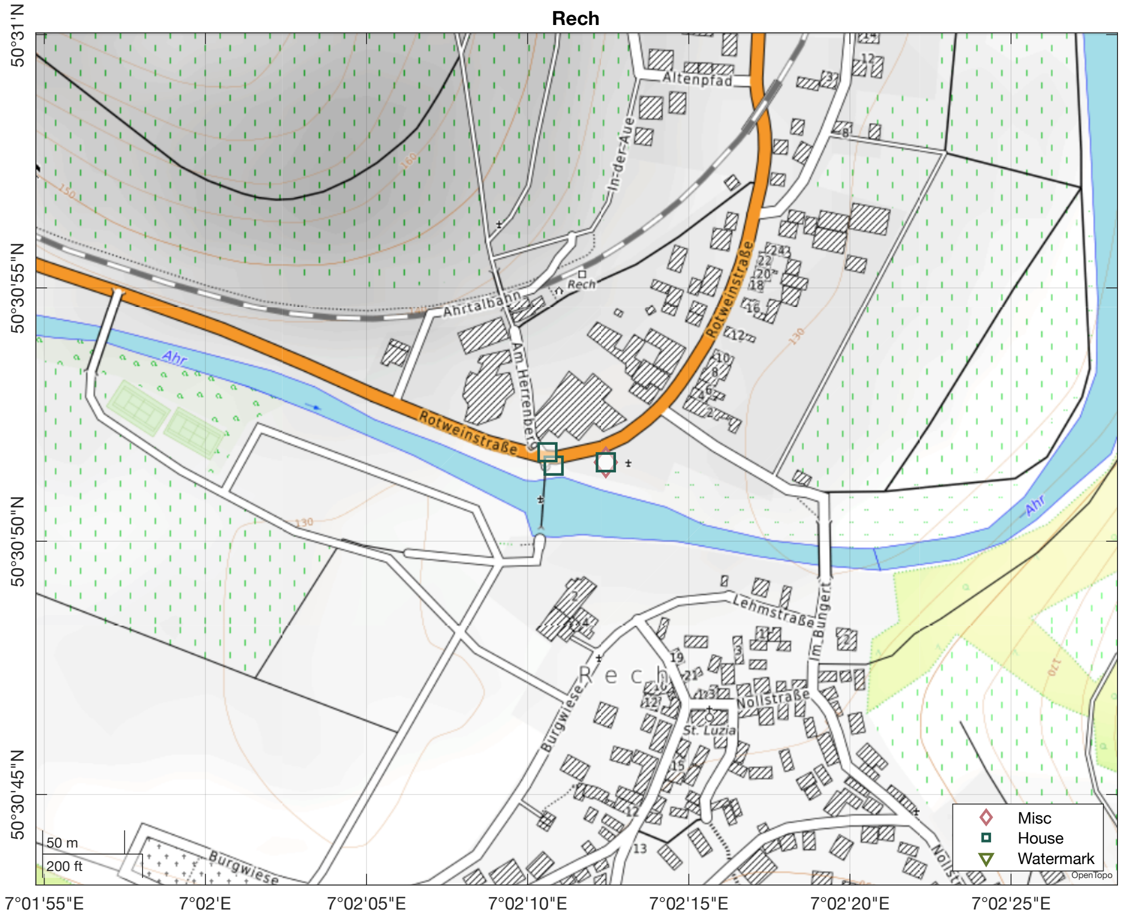

Figure 4.1. Rech

4.2. Hydraulic Aspects - Rech

Water levels at approximately 2/3 of the first floor, which was slightly higher compared to those measured in Dernau.

The flood was responsible for intense scour in the village of Rech. In particular, the buildings located adjacent to the Ahr River were highly affected by scouring and bank erosion in the extrados of the river bend (Figure RH2). The latter exposed the foundations of the buildings, thus preventing any load transfer to the soil, which resulted in structural instabilities. The masonry bridge was also highly affected by the flood, resulting in the collapse of the fourth pier in Figure RM1_modified. While the reasons for its collapse are unknown, the scour observed below the third pier might suggest a failure mechanism associated with the pier's foundation. Note that in Figure RM1, the fourth pier was in the process of being reconstructed.

Chapter 5. Mayschoß

5.1. General - Mayschoß

The village of Mayschoss is located upstream of Rech, also on the intrados of the Ahr River. Mayschoss presented more building damages compared to Rech, however most were concentrated in the area downstream of the bridge.

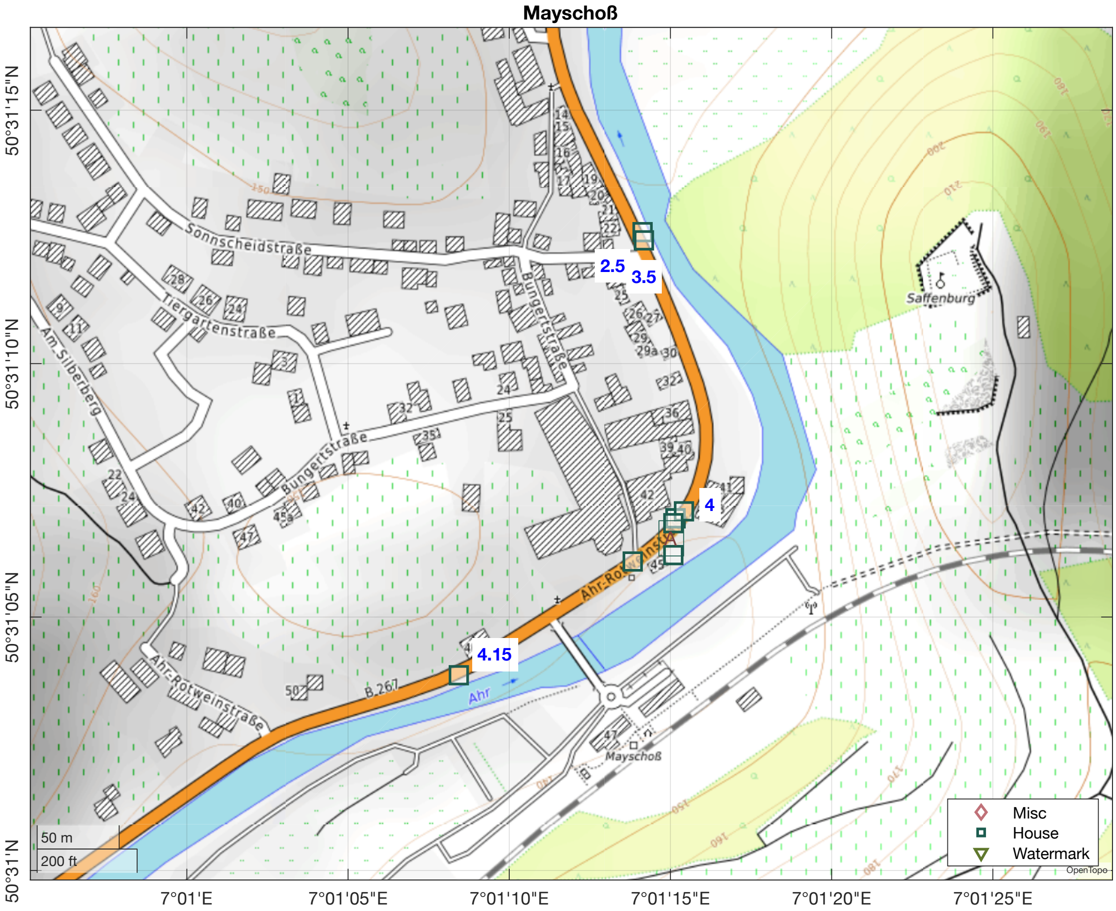

Figure 5.1. Mayschoß

5.2. Hydraulic Aspects - Mayschoß

Watermarks in Mayschoß revealed low to medium water levels of approximately 4.1 m at the upstream side, where the water reached half of the 1st floor, as shown on the map and throughout pictures in Figure MW1.

The building in Figure MS01 was located at the intrados of the river bend in Mayschoß, thus directly exposed to the flow. The eroded depth was around 1.5m, and the shallow foundation of the buildings became visible after the floods. However, the footing remained not visible, which ensured the stability of the structure. This kind of failure was more prone in the area where bank erosion protection structures were absent.

Figure 5.2. Watermarks Mayschoß

5.3. Case Studies - Mayschoß

Case M_A

In Mayschoß, this structure displayed a peculiar failure mechanism in the first storey where the spandrel below a party of three windows was pushed inwards by the flood. This failure is similar to that of the stone masonry fence which encircled the terrain of the property and which was almost completely levelled by the flood actions. The spandrel was only supported at the sides since the small columns between the windows were not strong/stiff enough. Moreover, through the opening, one can observe the railing of a flight of stairs. This means that this spandrel was not supported at the level of the floors and was actually much taller. Such a tall wall was then toppled over by the hydrostatic or hydrodynamic actions of the flood, probably without the additional impacts of debris.


a. MH2
b. MH3
c. MH4
d. MH5

Figure 5.3. Case Study M_A

Chapter 6. Altenahr

6.1. General - Altenahr

The village of Altenahr is one of largest in the valley. It is located upstream of Mayschoß and it is divided in two parts by the Ahr River, as shown in Figure 6.1. The survey investigated both sides of the village, with the upstream one revealing higher water levels and more damages compared to the downstream one.

Note that the connection between Altenahr and Mayschoß was interrupted because of the damaged main road.

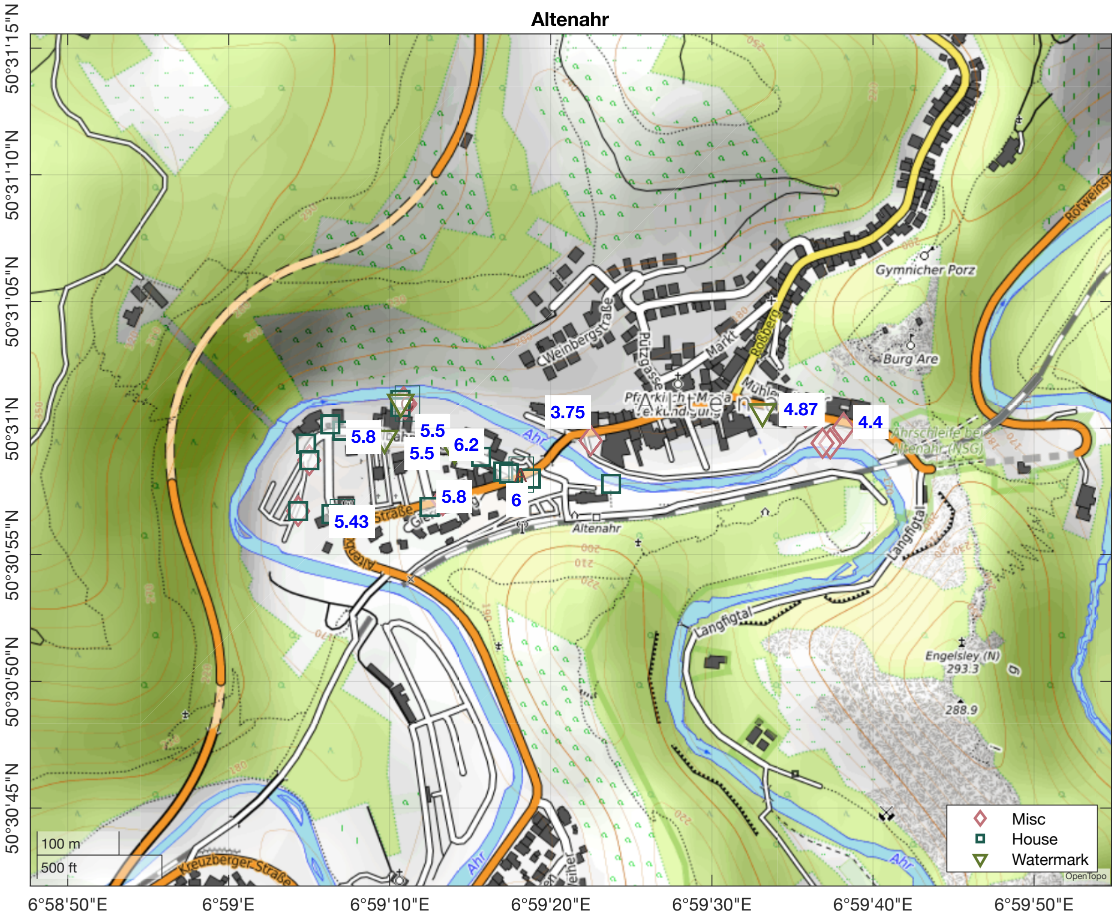

Figure 6.1. Altenahr

6.2. Hydraulic Aspects - Altenahr

The survey of the village of Altenahr revealed high water levels, with values between 4.4 m and 7.2 m (along the river side), as shown in the map.

In multiple locations, the water marks were easily detectable, as shown in Figure AW2. A noticeable difference was observed between the inundation depths on the Seilbahnstraße and those on the riverside due to topographical differences (Figure AW2). In the downstream part of the village, i.e. on the left bank of the Ahr River, slightly lower water depths were observed.

In particular, the building Hotel Lang (case study A_A) at Altenburger Strasse 1 showed marks from the previous flood level, approximately 0.85 m above ground level. However, in the 2021 flood, at that location the maximum water level recorded was 6m, which damaged all the non-structural components of Hotel Lang. While in this location many small structures were destroyed, large structures seem to have mostly suffered from non-structural damages.

Local scours were also observed in Altenahr, with depths of 1.3m at the building corners, as reported in Figure AH07.

Figure 6.2. Watermarks Altenahr

6.3. Case Studies - Altenahr

Case A_A

This structure used to have a roof covering its front terrace. The anchor points of the roof's joists can be observed on its façade. This roof was completely removed by the flood.

Figure 6.3. Case Study A_A

Case A_B

This building displays a large amount of scour together with the failure of the outer leaf of its cavity wall. The structural system appears to be confined masonry, with a double-wythe clay-brick masonry wall (all headers bond pattern) framed by reinforced concrete tie columns and tie beam. This is an unusually strong masonry system, often employed only in high-seismic areas which suggests that this structure had a special function either for industry or services.

The confined masonry seems unaffected by flood actions, while the outer leaf, from either calcium-silicate or light concrete bricks, only supported by cavity ties, was ripped out by the flood. It is also possible that part of the outer veneer was removed after the flood to prevent it from hazardously collapsing.

Figure 6.4. Case Study A_B

Case A_C

This structure was built next to the river (see map); subsequently, it experienced a high water level on its river-facing-façade. This level reached approximately the middle of the upper storey, which corresponds to a water level about 7 m. From the outside, the building appears structurally fine yet its façade is riddled with cracks (see magnified photo). Since the building was only observed from a distance, it is not clear whether the cracks appear only on the plaster of the outer insulation or if they also compromise the inner structural elements.

The cracks are very consistent with out-of-plane failure from loads acting inwards on the façade and further reveal the structural supports behind the façade.

Figure 6.5. Case Study A_C

Hotel Lang

Additional photos for case study A (Hotel Lang) were also made in a special visit to the interior of the building.

The flow depth measured at the location was 6m, and a water depth of 1.8 m was identified at the first-floor slab level. The hotel was a framed structure, with columns (either RCC or composite) and beams (I section or composite section) spreading in the longitudinal direction. In the transverse direction, the timber joists spanned to support the wooden slabs (could be a one-way slab). The timber joists were positioned over the horizontal beams for support. Structurally, the hotel survived the flood. However, the internal components of the buildings were severely damaged; see figure. The façade of the building was utterly distorted during the flood. However, the supporting steel frames were unaffected.

Interestingly, although the flow depth did not reach the second-floor level, the timber flooring on the second floor was equally affected (Figure 6.6). A portion of the concrete spalled out in the transverse beam (It should be a composite section), and the crack was developed even at the second-floor level beams. The hydrostatic pressure was capable of dislodging the wall masonry wall from its position, even at the second-floor level. Overall, although the load-bearing columns and the beams were unaffected, the walls and the timber slabs were more affected. This kind of buildings required detailed structural member inspections followed by major retrofitting works for the non-structural member. Similar kinds of failures were observed in the nearby locations (see this section's map).

Figure 6.6. Case Study hotel Lang

Chapter 7. Altenburg

7.1. General - Altenburg

The village of Altenburg is located upstream of Alternahr, in a floodplain next to an extrados of the Ahr River (Figure 7.1). Because of the high water levels that characterised this relatively flat area, the survey investigated both the buildings along the river, as well as those inland. Visual observations revealed fewer debris at this location, while inundation depths seemed to be more intense compared to other villages.

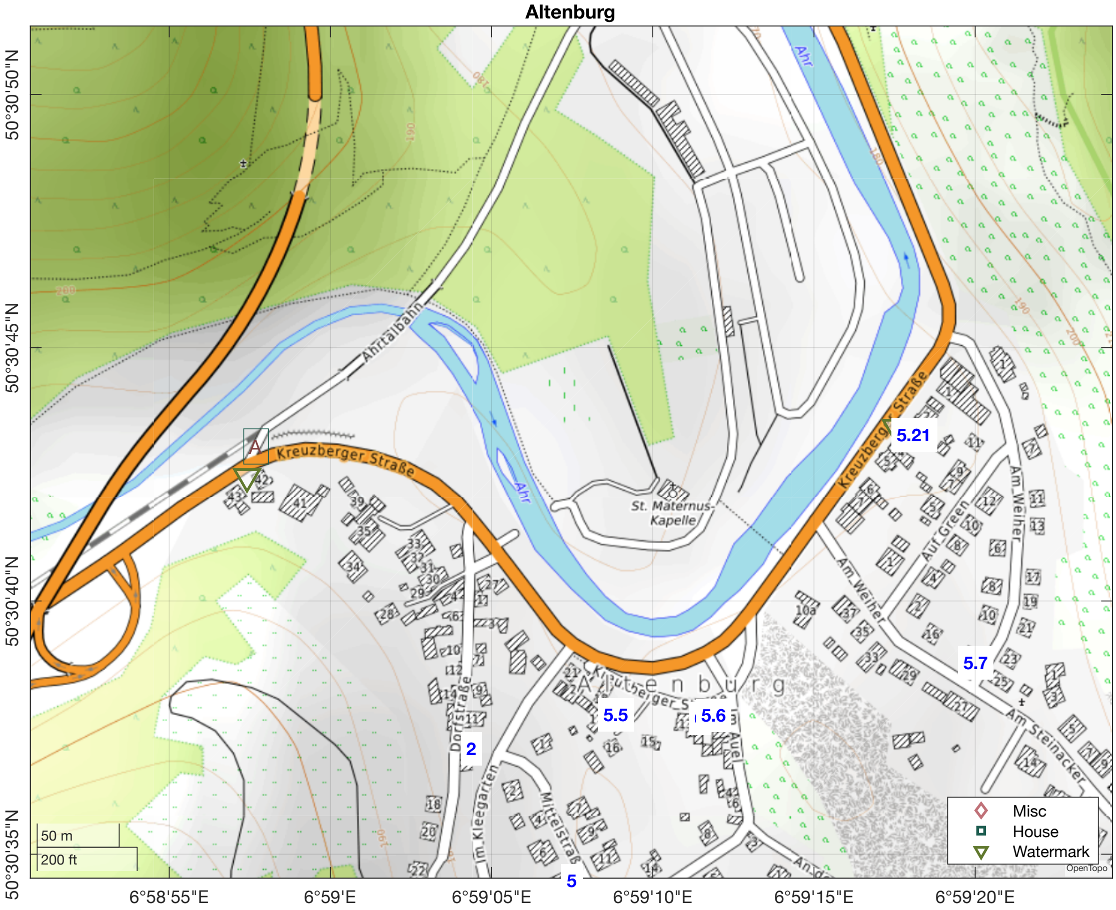

Figure 7.1. Altenburg

7.2. Hydraulic Aspects - Altenburg

Measurements at different locations revealed high, but relatively constant, water levels throughout the village, with values ranging from 5 m to 6 m.

Water marks can clearly be seen in Figure KW7, indicating that the water reached the top of the first floor. Compared to other sights, a lesser amount of debris was found in Altenburg which exhibited also surprisingly low damages, despite the high water levels. No scour was reported during the survey, thus suggesting slightly lower velocities in this area.

From a hydraulic perspective, the Haus Irmgard was of particular interest, which is located on the upstream side of the village. This building reported water marks of approximately 4.9 m on the downstream side (Figure KW9), while the corner of the upstream side revealed marks up to 5.7 m. This corresponds to a ratio of 1.16, which is in line with previous laboratory observations for steady flows around buildings with various geometries (Wüthrich et al., 2020). In addition, local damages attributed to the impact of debris were observed only below 4.9 m, with no visible damages in the remaining 1.8 m. These data confirmed the temporal and spatial variability of the flow conditions during floods, as well as the non-uniform distribution of loads exerted on buildings.

Figure 7.2. Watermarks Altenburg

7.3. Case Studies - Altenburg

Case L_A

This older house, built from what appears to be old concrete bricks in a double-wythe configuration, seems to only have been affected at the corner which was facing the flood wave. This corner was possibly impacted by debris, yet the failure was only local and the rest of the structure appears to not have been affected.

Figure 7.3. Case Study L_A

Chapter 8. Kreuzberg

8.1. General - Kreuzberg

The village of Kreuzberg is located upstream of Altenburg, on a river bend of the Ahr river, with one side of town on the right-bank intrados and the other side on the left-bank extrados. During the field survey both areas were investigated, as shown in this section's map, with a particular focus on right-side, where most structural damages were observed.

Note that the flood plain on the intrados of the river bend was used to accumulate the debris, providing a clear indication of the volumes transported by the river during the flood.

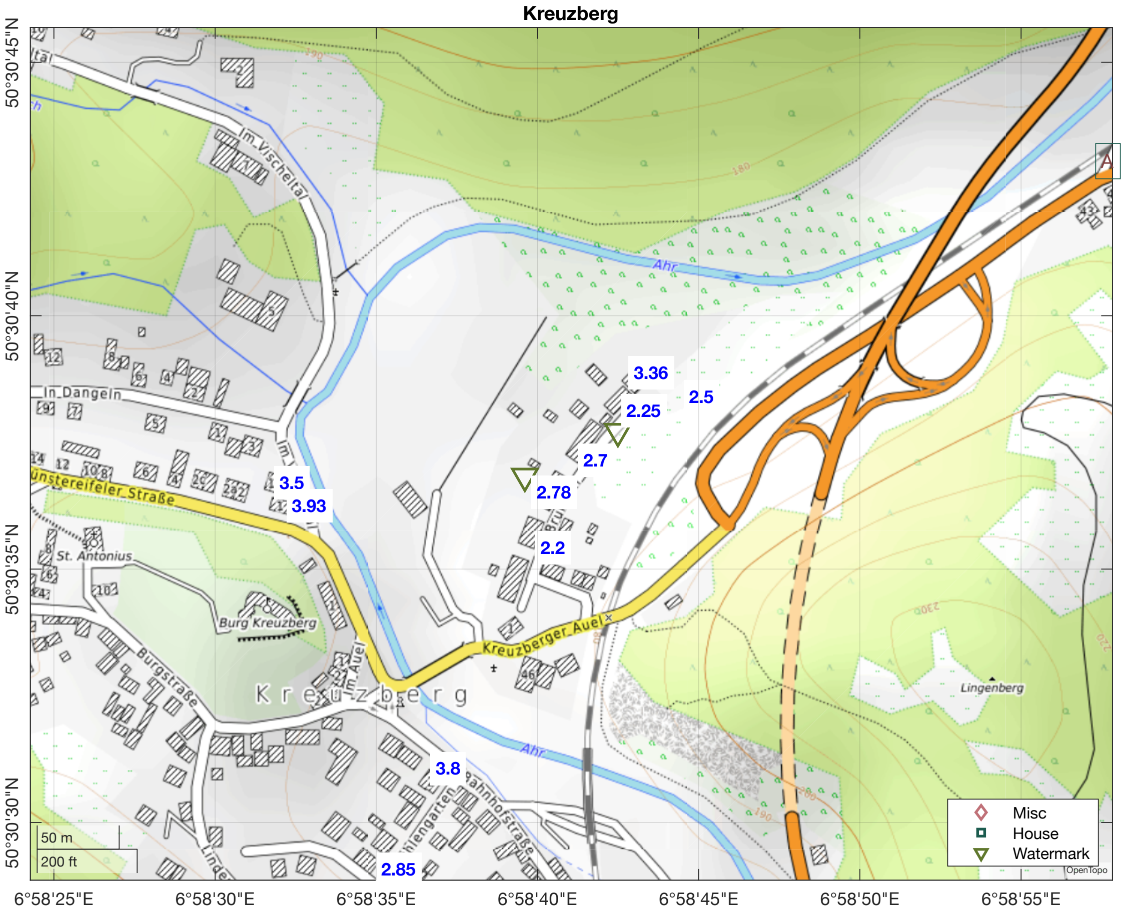

Figure 8.1. Kreuzberg

8.2. Hydraulic Aspects - Kreuzberg

Measurements of water marks revealed levels between 2.2 m and 3.9 m (low to medium water levels). As shown in the map, the highest values were located closer to the river, while the lower ones were associated with buildings at higher ground elevations. No major differences in terms of water depths were observed between the two sections of the village.

The building in Figure KS01 was the last in the Am-Brunnen Strasse and faced the flow directly. Scour depth of 0.75m and scour length of 2.5m was observed at the corner of the building.

Large amounts of debris were observed in the flood plains of Kreuzburg. Many oil tanks and cans stored in the basement for heating became sources of oil spread in the building and debris in that area (Figure KH02). These accumulation piles in Figure KM03 are likely the result of reconstruction and recovery plans; however, they show the nature of the debris that were transported during the flood, including both wooden (Figure KM03) and man-made metallic debris (Figure KM02).

Figure 8.2. Watermarks Kreuzberg

Chapter 9. Brück

9.1. General - Brück

The village of Brück is located upstream of Kreuzberg, on the left bank of the Ahr River. The survey focused on two main areas, including the upstream section of the village, as well as the left-bank upstream of the bridge.

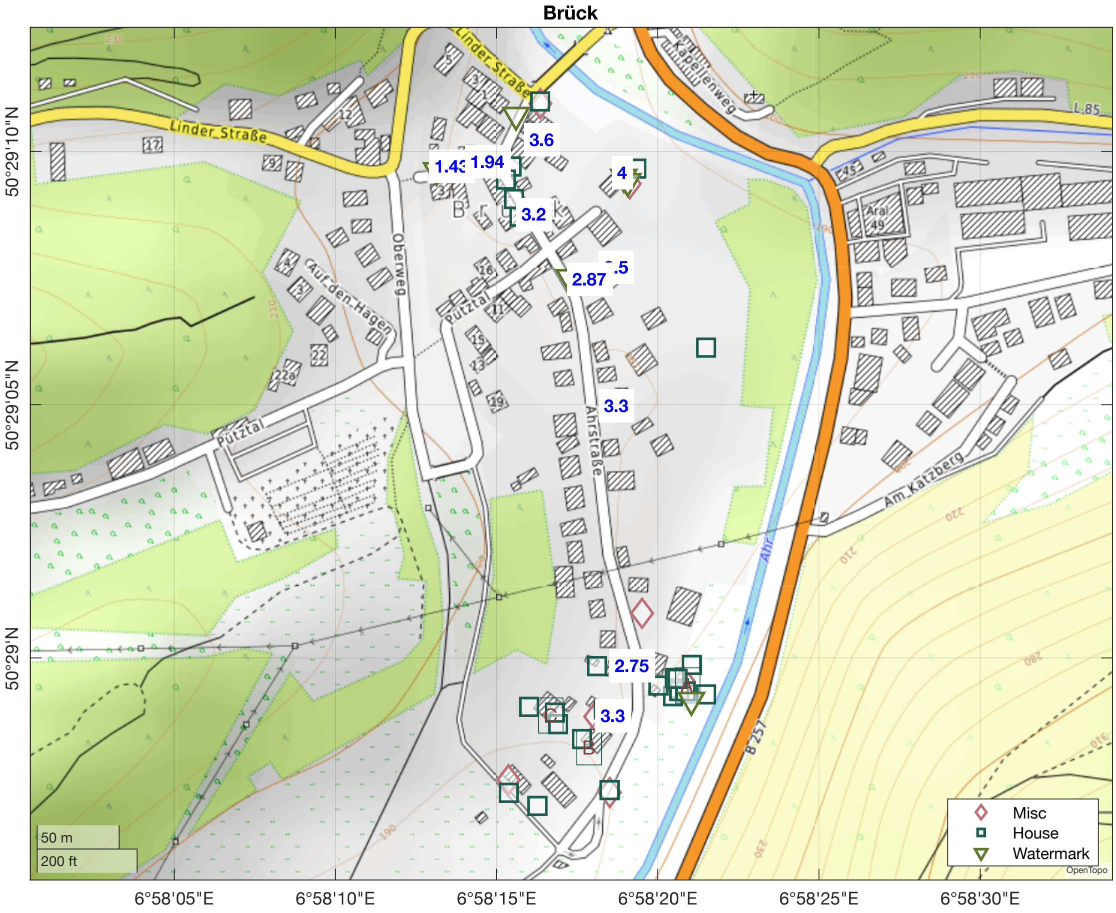

Figure 9.1. Brück

9.2. Hydraulic Aspects - Brück

Measurements of marks on buildings revealed water levels ranging from 1.2 m in the higher grounds to 4 m near the river side (low to medium water depths).

Examples of water marks are provided in Figure BW2, with one building on Pütztal 2 (BW4 and BW3) showing a water mark from the flood in 1910, during which more than 200 people died. The present water mark from the 2021 flood was 2.7 m above the previous mark, thus confirming the catastrophic nature of the recent event.

Severe scours were also observed in Brück, as detailed in the cases studies A (BH14) and C (BH24).

Figure 9.2. Watermarks Brück

9.3. Case Studies - Brück

Case B_A

The building closest to the river and most upstream in the town of Brück was seriously affected by the flood. This building consisted of a concrete-block masonry ground floor and a timber-frame storey and roof. This building was one of the few that had not been cleaned at the time of the survey and showed the sheer amount of drift wood that tangled together and probably increased the hydrodynamic loading of the flood on the structure. One must note that only the debris which got stuck on the building remains to be observed and the rest continued to be carried by the flood.

From the outside, the masonry ground storey appears structurally unaffected. The side garage, which appears to be founded on a thin reinforced concrete slab under which severe erosion left large scour holes, also seems to be in relatively good condition. The upper timber-frame storey however, seems to have been ripped out by the flood actions. The upper beam appears split longitudinally, what suggests an outwards, out-of-plane failure mechanism of the timber façade. Yet, the rest of the timber structure seems to be supporting the roof and the structure should be able to be repaired.

Figure 9.3. Case Study B_A

Case B_B

This masonry structure, with an outer clay brick veneer was almost fully submerged by the flood. The corners of the outer wall and of the roof seem to have been affected by debris.

Figure 9.4. Case Study B_B

Case B_C

A large scour hole, about 1.5 m deep, formed next to this masonry structure. The basement of the structure prevented the scour from affecting its stability. The insulation material of both the basement and the upper structure was apparently damaged by debris collision. The tiling of the roof was also affected.

Figure 9.5. Case Study B_C

Chapter 10. Insul

10.1. General - Insul

The village of Insul is located upstream of Brück, with buildings on both sides of the River. Visual assessment showed that the part most affected by the flood was on the left side of the Ahr River, which was the focus of the field survey.

Note that the bridge connecting the left-bank to the main road had collapsed and that a temporary army bridge had been installed to allow communications.

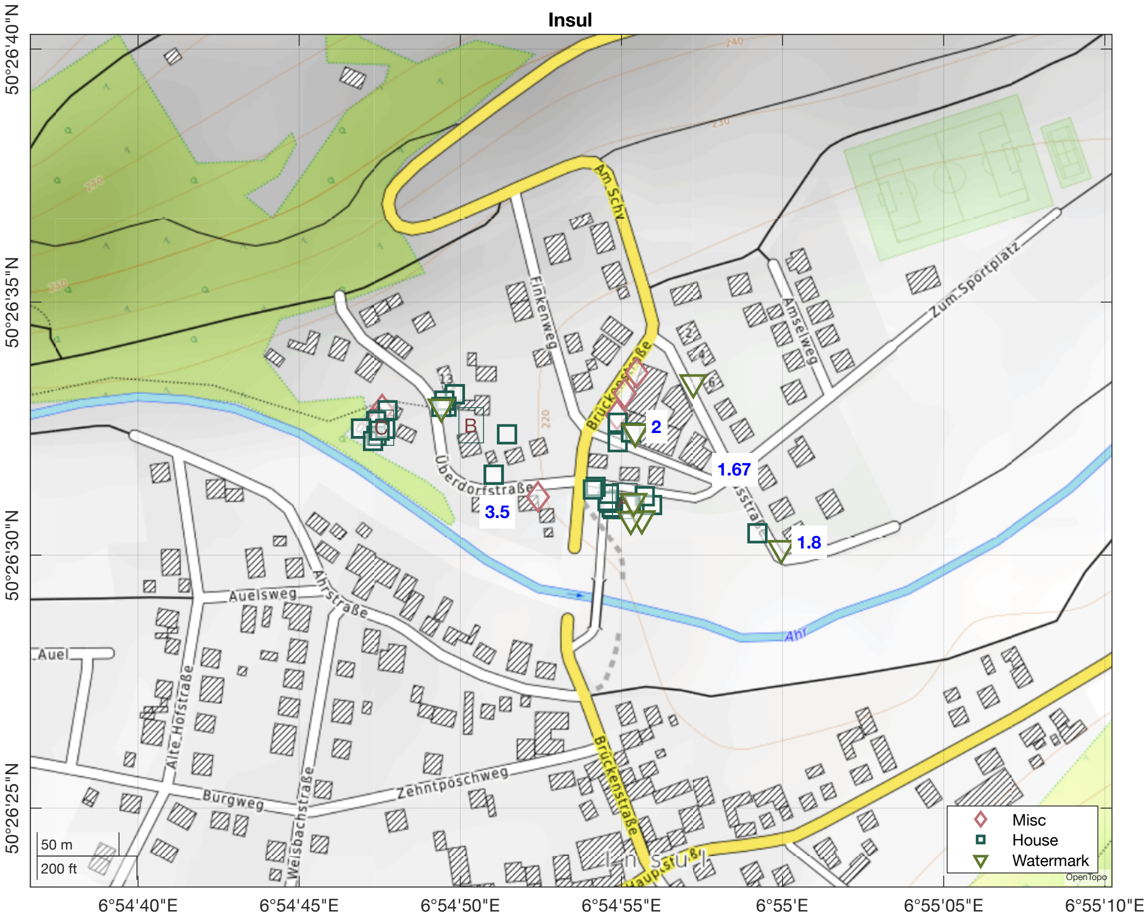

Figure 10.1. Insul

10.2. Hydraulic Aspects - Insul

In Insul water levels were between 1.7 and 3.5 meters (between low and medium water depths).

Some buildings presented water marks at different elevations depending on their exposition to the flow. An example is the one presented in FIGURE IW7, where assuming a brick height of 71mm (typical in Germany) and a mortar height of 10mm, allows to estimate the flow depths to 2.1, 2.9 and 2.3m, respectively. Closer to the river, higher water levels of 3.5 m were recorded (IH28_C), responsible for severe building damage and bank erosion.

A specific case study was investigated in IW8, where a concrete block was lifted by the flow. The survey showed that the building had a length of 4.2 m, a depth of 2.58 m and a height of 2.73 m with a corresponding overturning angle estimated at 10-15 degrees. Water marks on the side showed flow depths of approximately 2m, sufficient to generate a failure of the foundation and overturning of the structure with an uplift on the upstream side of approximately 0.47 m.

Smaller floating debris generated during the flood event accumulated inside the buildings through openings (Figure IH27). This pointed out a potential negative effect linked to the presence of openings, increasing the loads on the structure.

Figure 10.2. Watermarks Insul

10.3. Case Studies - Insul

Case I_A

This older masonry structure, which appears to be a combination of clay-brick and concrete-brick masonry was severely affected by the flood. The double-wythe wall of the basement at the front façade, including the corner of the building, collapsed. The ground floor, a structure consisting of steel I beams supported on the basement walls, also collapsed at this corner. An inner structural wall, in the centre of the building and perpendicular to the collapsed basement wall, remained standing and probably prevented the rest of the structure from collapsing. The first floor, also of steel beams but spanning in the direction parallel to the collapsed basement wall and supported by the inner structural wall, did not collapse and possibly supported the upper part of the collapsed wall to remain in place. In fact, it looks surprising that this upper portion of the wall, apparently unsupported, did not fall. The façade shows cracks consistent with a cantilever behaviour which widens towards the top. This deformation suggests that a different supporting mechanism was present. It is possible that the wall remains confined by the timber roof structure which typically has horizontal members in tension (in this case this would be the second floor).

The failure of the basement-ground-floor wall is likely to have begun at the corner where debris may impacted the structure. The steel-beam floor is only stiff in one direction and thus could not provide lateral support for the wall at the corner. Once the corner was affected, the rest of the façade was, likely, pushed outwards by the flow of the water.

The building also sported an extension on the side as a separate, light structure constructed from timber members. This structure seems to have been undermined by erosion at its foundation. It is difficult to say whether the scour appeared before or after the collapse of the basement wall.

Figure 10.3. Case Study I_A

Case I_B

This structure, constructed with concrete-block masonry with a cavity wall of clay-brick veneer, was extensively damaged by the flood. It seems that fast flowing water perpendicular building side affected both corners of the structure. The building appears to have a shallow foundation on good gravel/rocky soil with no basement. This foundation may have been eroded from underneath the building at the corners where the water velocity is the highest. Consequently, both load-bearing masonry piers at these two corners failed when their support was undermined and were further pushed off their positions by the flood. The pier at the front of the building (with the main entrance) rotated out of plane, while the pier at the back of the structure collapsed completely. Fortunately, two aspects helped the structure survive. Firstly, the load-bearing components at the centre of the side of the building perpendicular to the flow were not affected as seriously and continued to support the rest of the structure. Secondly, the failed pier at the back appeared to be carrying only a terrace with the façade of the building being recessed and supported by inner piers, not directly affected by the flood. Nonetheless, these inner piers, subjected to an increased overburden after the failure of the other structural components mentioned before, have also failed but continue to support the building.

In sum, scour underneath the two corners of the building facing the flood seems to have led to the local failure of the shallow foundation and the masonry components supported directly on it.

Figure 10.4. Case Study I_B

Case I_C

This building offers unique insight into its structural behaviour because all structural elements are clearly visible. Moreover, the flood actions leading to the partial collapse of the building are relatively clear, too. The concrete-strip foundation of the building, with a stiffening concrete beam of about 1.2m height, which formed half the wall of the basement, was completely undermined by erosion by the water flow. The soil at the location, a sandy gravel layer (presumably where the building is founded), is topped by about two meters of clayey sand, as seen from the photos. These two layers were eroded away by the flood, which seems to have moved the river bed several metres towards the building. Under such large undermining, it's not surprising that the foundation and basement of the structure collapsed.

The structural typology is remarkably similar to case study I_A with: concrete strip foundation and basement, on top of which a concrete-block masonry is built. The floors have I-profile steel beams, and besides the load-bearing walls on the perimeter of the building, a strong masonry wall is placed in the middle of the structure. This wall was fortunately oriented parallel to the collapsed wall and thus ended up supporting the rest of the structure. In fact, the mechanism observed in case study I_A is repeated herein. The upper two storeys, surrounded by the gable roof, cantilever over this middle wall. Again, it seems that the roof provides confinement for the cantilevering upper portions of the masonry walls, which exhibit cracks widening towards the top. The ground and first floor supported on the collapsed corner of the house also collapsed.

In sum, the flood, acting as an erosion-driving force, undermined the foundation of the building, even below the basement, which led to the subsequent collapse of a corner of the house. Had the stiffening concrete foundation beam been reinforced with steel rebar (what would have been a strange practice, especially for this older structure), it is likely that the house would have remained in one piece but instead tilted as a rigid body towards the undermined side.

Figure 10.5. Case Study I_C

Chapter 11. Schuld

11.1. General - Schuld

Schuld was the most upstream village of the Ahr valley that was investigated during this field survey. It is also one of the villages most affected by the flood, with severe damage to buildings and critical infrastructure. The majority of the buildings were located on the intrados of a narrow bend of the river, where water marks revealed water depths that ranged between 1 m and 3.7 m (low to medium water depths). Buildings located on the extrados were located at a higher elevation and, therefore, less affected by the flood.

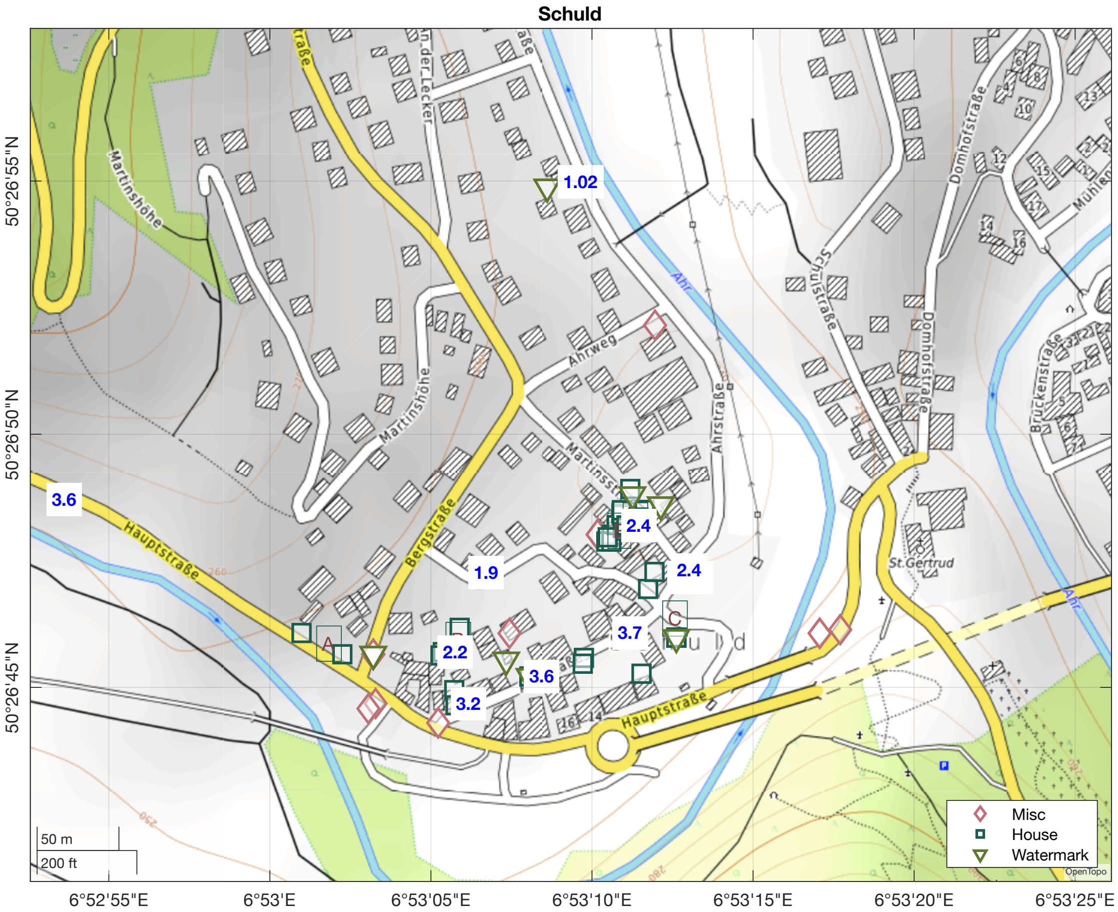

Figure 11.1. Schuld

11.2. Hydraulic Aspects - Schuld

Selected examples of watermarks observed in Schuld are presented in SW5, where the highest water levels reached the windows of the first floor. An interesting pattern was observed at a building in the centre of the village (SW9 and SW2), where the side that was frontally exposed to the flow showed water marks of 3.0 m, while the sides had marks at 2.1 m. This showed a ratio between front and side of 1.4, which was higher compared to previous locations, thus suggesting a slightly faster flow at this specific location. Nevertheless, this confirmed the variability of flow characteristics within the village and, therefore, the non-uniform distribution of the forces acting on the building during floods.

In terms of scouring and bank erosion, the village of Schuld seemed to be less affected compared to other locations. SS01 provides an example of scour around a building corner and some bank erosion on the downstream side of the bridge (SS02), but their entity remains limited.

Figure 11.2. Watermarks Schuld

11.3. Case Studies - Schuld

Case S_A

This old building with an exposed timber frame filled with plaster suffered some damage from the flood. In this case, it seems that the structural timber frame was unaffected, and only the plaster panels were damaged by the flood.

Figure 11.3. Case Study S_A

Case S_B

This structure seems to be built from large stone elements combined with stone bricks in the ground floor, and the upper storey seems to be of more recent clay-brick and stone-brick masonry. In this sense, the assorted construction technique did not seem significantly affected by the flood. The damage caused to the structure appears to have been limited to the removal of plaster from the masonry, small marks of collision from debris at the corners, and the damage to a veranda that may have been located at the front.

Figure 11.4. Case Study S_B

Case S_C

This traditional, filled-timber-frame building was affected by the flood with water levels covering to about the ceiling of the ground floor. The load-bearing side walls appear undamaged, but the end wall has collapsed. It is not clear if the structure had any additions on this end and if they were removed by the flood too.

Figure 11.5. Case Study S_C

Case S_D

This building has a ground floor extension with large window openings between piers. The piers are calcium-silicate blocks and the structure is covered with an insulation layer with plaster on the outside. The extension had four stand alone piers; two of these were severely compromised by the flood and the other two were damaged. The two (semi) collapsed piers have been replaced with timber props while the building is further repaired. The two remaining piers display horizontal cracks at the top and bottom supports and at the middle of the span. This cracking layout is characteristic of out-of-plane bending along the vertical direction. However, the pier on the longer façade shows signs of being bent outwards while the pier next to the remaining window with glass has cracking associated with bending inwards.

Witnesses stated that the extension was full of debris which flowed in through the entrance of the building. This is consistent with the cracking layout left on the piers. The water flow pushed the debris against the entrance opening and caused the corner pier to fail while also bending the neighbouring pier inwards; then, the flow continued through the building and exited through the long façade where it bent the other pier outwards and caused the remaining pier to fail.

It is very likely that the damming effect of driftwood, focused the hydrodynamic pressure of the water flow onto the single piers which resulted in extremely large forces on these elements.

Figure 11.6. Case Study S_D

Case S_E

This building had two thick walls from natural stone brick (almost rubble stone masonry). The front façade seems to be a combination of concrete-block masonry and filled timber frame, where the filling is actually brick masonry (the material is unclear but could be earthen bricks). The first floor appears to be composed of I-shape steel beams with (pre-fabricated) concrete plates between them. The roof is a timber construction. In this sense, the building is a mix of building materials and techniques, referring perhaps to various retrofits over the decades.

The corner of the building facing the presumed floor direction and made out between the two natural stone walls appears entirely collapsed. It is likely that the water flow carrying floating debris dislodged the stones from the wall until failure occurred.

Figure 11.7. Case Study S_E

Chapter 12. Conclusions

The field visit to the valley of the river Ahr in Germany was successful in providing a good overview of the (structural) flood damage sustained by typical buildings in the region, consisting mostly of masonry houses of two to three storeys in height, due to the flash flood of the 13th and 14th of July of 2021 that resulted in considerable loss of life. Yet, this report did not focus on the specifics of the loss of life but contemplated instead the structural failure of buildings. The total or partial collapse of several masonry structures led to inadequate vertical evacuation possibilities and resulted in the direct or indirect loss of life. Understanding of the flood actions that caused structural failure during the Ahr flood will help develop better adaptation and mitigation strategies to combat future floods and their consequences.

Very few cases of structural failure due to hydrostatic flood pressure alone were observed among the nine locations visited of: Dernau, Rech, Mayschoß, Altenahr, Kreuzberg, Altenburg, Brück, Insul, and Schuld. Most severe structural damage was caused by erosion and damming of debris. High flow velocities around buildings located in the periphery of towns due to the constriction and/or redirection of the water flow caused deep scour holes that undermined shallow foundations. In some cases, the erosion was such that it displaced the river path. Moreover, the flood carried a large amount of debris, such as driftwood, which had the unfavourable characteristic of interlocking and tangling itself together, creating dams and resting on the facades or roofs of houses. These dams possessed several destructive features: firstly, they provided a large area upon which the hydrodynamic pressure of the flood could act; secondly, they led to local increases of water levels which resulted in increased hydrostatic pressures and elevated the point of application of the flood forces. This led to extremely high forces for which the buildings, usually located on the upstream side of towns, had insufficient strength. Lastly, the floating masses of debris impacted against buildings, often at corners, and left evident collision marks around the water level, and in many cases, led to the collapse of the outer masonry veneer of the cavity walls of buildings. Visual surveys of watermarks also pointed out different water levels on the front and sidewalls, thus suggesting an unequal distribution of the loads around the buildings.

The field visit was also successful in providing a dataset of watermarks across all villages surveyed in the Ahr Valley. This data gives an indication of the maximum water levels in respect to the survey buildings as reached by the flood and it is expected to be most useful in the validation of future numerical simulations.

In conclusion, the hydrostatic water pressure on buildings, often neutralised by the water inside flooded buildings, was overshadowed by the catastrophic effect of damming and impact of debris and by the scour generated by the water flow of the flood. Potential strategies should focus on the placement of 'strong buildings' around towns that can withstand and divert high flow velocities and capture debris preventing it from affecting more vulnerable buildings.

Chapter 13. Acknowledgements

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Last but not least, the authors would like to thanks the local citizens for welcoming them in their towns and showing them around, often sharing valuable information in support of this fact-finding report.

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