Geotechnical Reconnaissance of the 2021 Western European Floods

Flood Event: July 14-15, 2021
Flood locations: Germany, Netherlands, Belgium, and Luxembourg
Reconnaissance Visit: August 9-18, 2021

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Outreach Video on the Western European Floods (Dutch/English):
https://youtu.be/vtluiFhaHeA

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Abstract

Record rainfall triggered devastating and deadly flooding in Western Europe between July 14-16th, 2021. The extreme weather event killed more than 230 people in Germany and Belgium and cost billions of dollars in damage. Reconnaissance studies within some of the most affected areas of all three countries, provided insight into geotechnical and geo-structural performance of critical infrastructure elements, such as bridges and road networks. This report presents reconnaissance observations collected between August 9th - August 16th, 2021. The reconnaissance team used terrestrial LIDAR technology, multispectral imaging, visual observations, and cellular photography, as well as UAV (unmanned aerial vehicle) imaging and structure for motion modeling to discern critical damage patterns of infrastructure networks and buildings, and to document important erosion and soil relocation patterns along the river courses.

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Outreach Video (High-School level)

As part of this reconnaissance effort, an outreach video has been produced to educate high school students about flood events and their impacts on engineered structures. This video has been recorded and produced by team member Kees van Ginkel (Deltares) and is available in Dutch language with English subtitles at: https://youtu.be/vtluiFhaHeA

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1. Introduction

A major storm system (low pressure system "Bernd") stalled over Western Europe on July 14-15, leading to record-setting rain over Belgium, Germany, Luxembourg, Switzerland, France and the Netherlands. The areas most affected by the storm were Germany, Belgium, Luxembourg, and the Netherlands. The flooding resulted in at least 191 fatalities in Germany and 38 in Belgium, with several more people missing to date and estimated insured losses over $3 billion (reuters.com). Belgium reported an estimated insured loss of EUR 2.164 billion (RTBF, 2021) suggesting that overall losses of at least two to four times that amount have to be expected there. Adding the loss figures from all other affected countries the overall amount from the July floods yields EUR 46 billion (Munich Re, 2022).

Considerable damage to infrastructure included houses, motorways and railway lines, bridges, and utility lines. Road destruction and closures left some places inaccessible for days, cutting off some villages from evacuation routes and emergency response. Due to local access restrictions and military mobilization in many of the affected areas, access to the public was not permitted until July 30th, 2021. In addition, towns most affected by the flood experienced large amount of disaster tourism (e.g., tourist busses arrived to inspect the flood consequences) as well as heavy air traffic due to personal drone flights by observers and curious onlookers, hindering German military units (Bundeswehr) and emergency response units (Technisches Hilfswerk) to quickly access and conduct rescue operations.

The severe flooding was caused by extreme rainfall over a period of 1-2 days (July 14-15th), pre-event soil saturation from previous rain, and local hydrological factors. Areas near small rivers or river tributaries without flood defenses became quickly overwhelmed by the volume of rain and represented the most affected/damaged areas. Some of the hydrological monitoring systems were destroyed during the flood and data of sufficiently high quality and quantity is not available from all hydrological stations (WDR.de, 2021). The amount of damaged/destroyed monitoring stations accumulates to more than 30.

The observed rainfall amounts in the Ahr/Erft and the Belgian part of the Meuse catchment broke historical records by large margins. According to preliminary data, the flood was initially categorized as a 500-year return event or rarer, more recent estimates anticipate the event to be closer to a 1000 year or higher return event. On 16 July, the German Ministry of Defense declared a state of emergency in the parts of the country that were most affected (Muenchner Merkur, Jul 16, 2021).

The 2021 flood was amongst the deadliest floods in Western Europe and worldwide. According to floodlist.com, an international data collection site for flood events, July 2021 represents the worst month on record with over 920 casualties in floods, landslides, and other rain-related incidents worldwide (Floodlist.com, 2021). While areas in Germany (e.g., Valley of the river Ahr, "Ahrtal") have historically experienced a multitude of flood events (see Section 1.4), this event surpasses any of the previously recorded death tolls in Europe due to flooding. Local authorities are investigated for inadequate preparations, as forecasters issued warnings similar to the 100-year flood event in 2016 when water levels rose from 0.9 m to 3.75 m along the river Ahr, but in some cases failed to take appropriate action. Water levels during the 2021 floods in the Ahrtal exceeded 11.00 m (10 times rise in water elevation) at selected locations, representing a significantly larger flood event than 2016. Many survivors told the reconnaissance team that, while warnings were issued, the severity of the flood event and the predicted volume of rainfall, which was estimated by forecasters to be significantly higher than the 100-year return event, was not communicated clearly to residents through local authorities. As a result, some of the victims underestimated the danger and did not evacuate, nor turn off electricity, according to the Chairman of the German center for disaster management (BBK), Armin Schuster (EDNHnews.de, 2021). A recent EU evaluation estimated around 56,000 people living along the river Ahr prior to the flood events. The Supervisory and Service Directorate (ADD, Aufsichts- und Dienstleistungsdirektion) assumes that 42,000 people are affected. At least 17,000 of them have lost their entire belongings or are facing considerable damage.

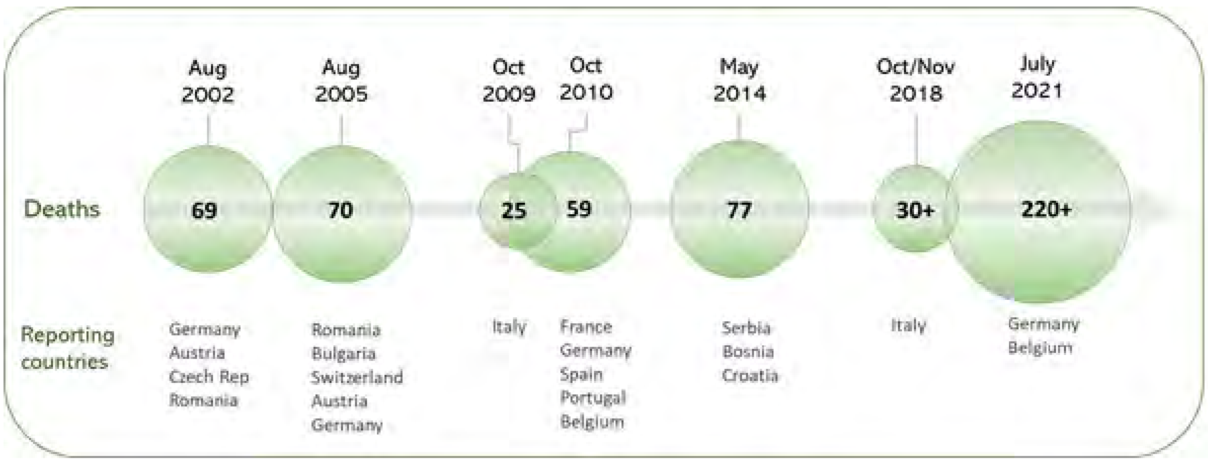


Figure 1.1. European flood events in the last two decades, current flood shows preliminary data for July 2021 (adapted and updated from https://ednh.news/why-have-the-floods-in-europe-been-so-deadly/)

1.1. Location of flood events and focus of reconnaissance efforts

As documented by the BBK, the German center for disaster management (Bundesamt für Bevölkerungsschutz und Katastrophenhilfe), the two German states most affected by the floods were Rheinland-Pfalz (Rhineland-Palatinate) and Nordrhein-Westfalen (North Rhine-Westphalia). In Rheinland-Pfalz, the most damaged areas included the Ahrtal, several regions in the National Park “Eifel”, as well as the city of Trier. In Nordrhein-Westfalen, the floods created most damage to the districts of Hagen and Wuppertal, the county of Euskirchen, as well as the Rhein-Sieg area. Figure 1.2 shows a map with the most impacted areas in Germany.

Figure 1.2. Areas in Germany affected by the 2021 Western European Floods, Source: Bundesamt für Bevölkerungsschutz und Katastrophenhilfe (BBK)

Flooding in Belgium concentrated mainly in the valley of the river Vesdre (districts of Pepinster, Ensival, and Verviers), the valley of the river Meuse (Maaseik, Liege), the valley of the river Gete (Herk-De-Stad and Halen), and the Southeast of Brussels (Wavre). Figure 1.3 shows a map that includes the affected areas in Belgium and the Netherlands. The Netherlands were the least affected country amongst its neighbors, experiencing strong flooding but no casualties. Major damage concentrated in the district of Limburg in the South of the Netherlands.

Figure 1.3. Map of heavily flooded areas in Belgium, Netherlands and Germany

1.2. Areas visited by the reconnaissance team, overview of schedule and locations

The reconnaissance team visited the most heavily affected flood areas from Aug 8, 2021 - Aug 18, 2021. Table 1 presents a day-by-day schedule of the locations studied within the scope of the on-site efforts. Some of the key locations are highlighted in Figure 1.4. Information leading to the choice of locations were obtained from different local and federal authorities as shown in Figure 1.5. The international constellation of the reconnaissance team allowed for separating members into smaller groups with specific expertise, foci, and language skills to maximize data collection, measurements, and on-site communication with survivors and authorities in the field.

Table 1.1 Reconnaissance site visit itinerary

Sunday, Aug 8th	Arrival, Germany, Team Meeting @ Nuerburgring
Monday, Aug 9th	Visit to downtown Bad Muenstereifel & surrounding areas, visit Euskirchen downtown and suburb areas
Tuesday, Aug 10th	Visit Gmünd, Erftstadt-Blessem, Blessem gravel mine, Erftstadt freeway connector (Autobahn A1), Bliesheim, Steinbachtalsperre
Wednesday, Aug 11th	Visit Ahrtal Part 1: Muesch, Antweiler, Schuld, Ahrbrueck
Thursday, Aug 12th	Visit Ahrtal P3 Bad Neuenahr-Ahrweiler, Sinzig, Rhein river areas
Friday, Aug 13th	Visit Ahrtal P2: Altenahr, Dernau, Bad Neuenahr)
Sat Aug 14th	Schleiden, Ruhrbachtalsperre
Sun Aug 15th	Travel to Liege, Belgium
Monday, Aug 16th	Belgium, Valley of the river Vesdre, from Liege via Pepinster to Verviers
Tuesday, Aug 17th	Belgium, Valley of the river Meuse
Wednesday, Aug 18th	NL (Maastricht area), Meeting with the Limburg Waterboard, Site visit

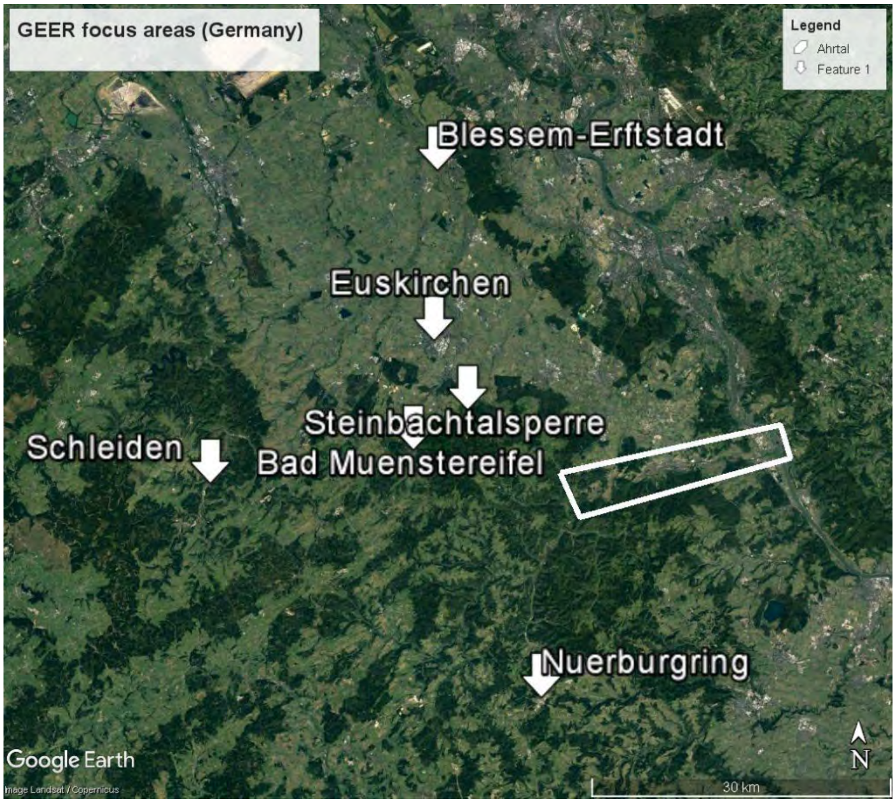


Figure 1.4. Map of some of the visited key areas with the Ahrtal highlighted by the white box.

Figure 1.5. Aerial imagery example of damaged locations as available from public resources. Here: Erftstadt-Blessem obtained from https://activations.zki.dlr.de/images/products/ACT152/P30/2021_DLR-ZKI_004_P30_V01_Germany_Flood_beforeafter_3_timestamps_Blessem_300

1.3. Meteorological conditions prior and at the time of the event

1.3.1. Germany

The weather situation in Germany on the days from July 12 to July 15, 2021 was characterized mainly by low air pressure over Central Europe. In conjunction with a low-pressure system slowly approaching from France, the troposphere was increasingly unstably stratified. Warm and very humid air masses reached Germany from the Mediterranean region in a rotating motion around the low-pressure system "Bernd". Forced uplift (orographically and dynamically) and slight damming effects in the western low mountain ranges (Sauerland, Westerwald, and Eifel) resulted in recurring or persistent heavy rain, first regionally and later over large areas. In the following days, high pressure system "Dana" pushed low pressure system "Bernd" away toward southeastern Europe which led to persistent heavy precipitation in the Eastern Erzgebirge and Lusatia, as well as in the Berchtesgadener Land (Junghaenel *et al*., 2021).

According to the German Meteorological Services, Baden Württemberg, Hessen, Rheinland-Pfalz, Saarland, and Nordrhein-Westfalen were the first areas to be affected by the rainfall event starting July 12, 2021.

On July 13, precipitation occurred primarily in the center of Germany (Figure 1.6). For example, according to radar measurements, up to 87 liter/m² fell in 2 hours in the Erzgebirge Mountains (Marienberg region) (Table 1.2). In the Hofer Land (Upper Franconia), 43 liter/m² fell in only 30 minutes according to radar measurements in Selbitz. In Querfurt (Saalekreis), 66 l/m² were recorded in only 2 hours at the Mühle-Lodersleben station. But also the northern parts of Hessen (Waldeck-Frankenberg district) and especially the Ruhr area and South Westphalia were strongly affected. The cities of Solingen and Hagen, as well as Wuppertal, were severely affected by major flooding. In Hagen, more than 241 liter/m² of precipitation were measured in only 22 hours at a station of the State Office for Nature, Environment and Consumer Protection (LANUV, 2021).

Beginning on 14 July and until the morning hours of 15 July, heavy continuous rainfall with localized extreme rainfalls were reported. The focus of the precipitation activity extended from Dortmund over Cologne, Euskirchen, Gerolstein, Bitburg to Trier (Figure 1.6). Here, more than 100 liter/m² of precipitation were recorded over a wide area in 72 hours. Regionally, more than 150 l/m² of precipitation fell within 24 hours (Figure 1.6 and Table 1.2).

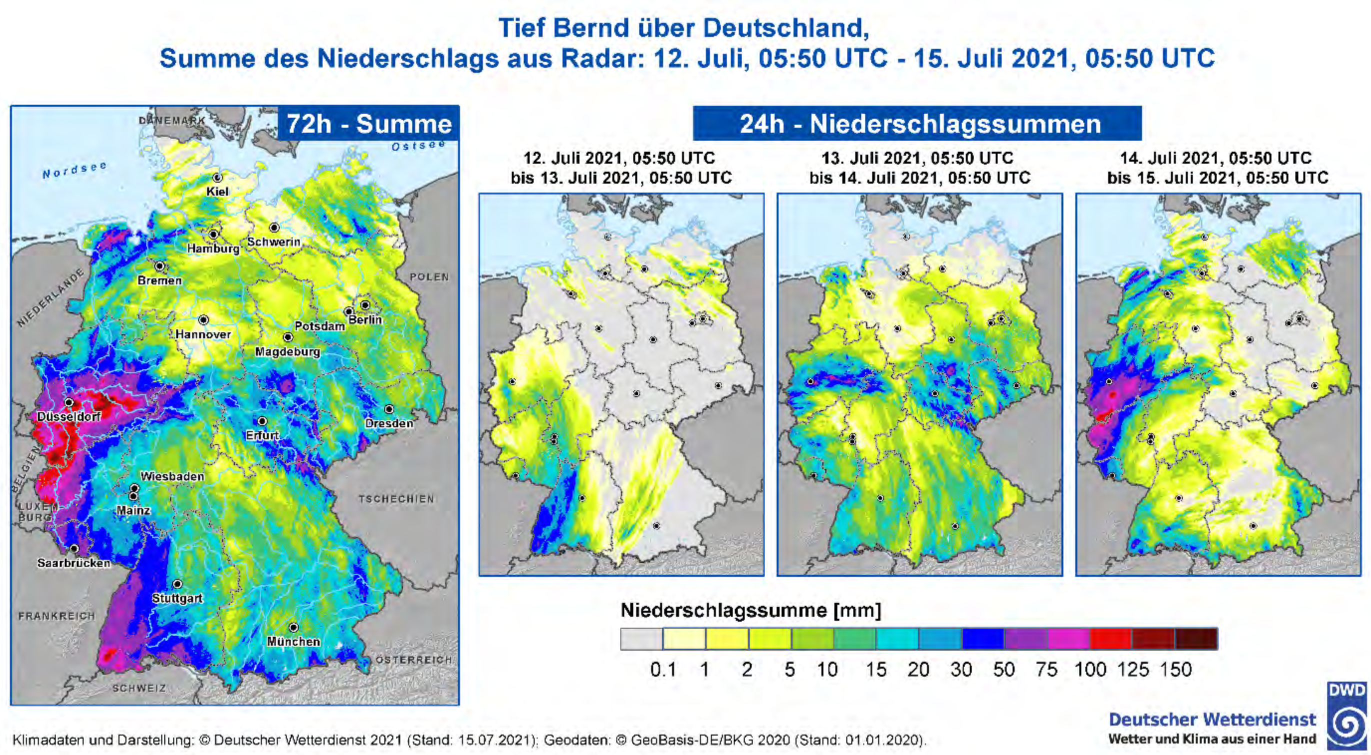


Figure 1.6 RADOLAN precipitation analysis showing rainfall over 72hrs (left) and 24hrs (right) prior to the 15 July major flood. Source: DWD, Hydrometerologie, obtained from Junghaenel et al., 2021

Table 1.2 presents average and maximum daily precipitation data over the three days prior to the main flood. For comparison the reference rainfall data for years 1991-2020 in the month of July is included.

Table 1.2. Average and maximum precipitation per day or over 3 days per river basin in l/m², as well as the mean total for July (reference period 1991-2020). Source: DWD Hydrometerologie, obtained from Junghaenel et al. 2021

Einzugs-gebiet	12.07.21		13.07.21		14.07.21		3-Tage-Summe	Referenz (1991-2020)
	Mittel	Max	Mittel	Max	Mittel	Max	Mittel	Monat Juli
Agger	9,2	18,7	14,7	39,9	82,5	124,4	106,4	100,6
Ahr	8,7	13,0	12,1	23,5	94,5	147,5	115,3	69,4
Emscher	1,1	3,3	20,9	31,2	45,6	83,8	67,6	82,5
Erft	11,9	26,3	23,8	56,8	93,8	169,1	129,5	67,9
Kyll	4,0	15,8	17,8	33,8	103,7	145,7	125,5	73,1
Lippe	0,7	4,0	15,0	50,1	29,1	88,8	44,8	84,1
Mosel	5,2	17,7	18,8	52,3	50,9	145,7	74,9	71,6
Prüm	2,6	12,4	25,5	35,0	97,5	124,3	125,6	74,5
Ruhr	3,7	18,7	34,5	76,1	62,2	121,4	100,4	96,4
Rur	3,2	13,4	36,0	66,8	82,8	154,1	122,0	74,4
Sieg	10,9	24,0	8,2	39,9	47,3	124,4	66,4	93,7
Wupper	2,9	9,6	35,4	66,9	105,4	151,4	143,7	100,7

1.3.2. Belgium

On 14 and 15 July 2022, the catastrophic flood over Belgium was caused by a stationary low-pressure area with a core over Germany that hardly moved because it was 'trapped' between 2 high pressure areas, one high pressure area with a core in the Near Atlantic Ocean west of the British Islands and a second anticyclone over Central and Eastern Europe. An occlusion attached to the depression and situated over western Germany and the south and east of Belgium produced intense excessive rainfall.

Such a phenomenon is better known as a "blockade". In this case, it was a low-pressure blockade with persistent precipitation over the same regions for many hours or even longer than a day, leading to extreme precipitation totals. The rain zone stretched in a north-easterly direction over Belgium, causing the same regions to be affected for a long time by intense precipitation. The relief of the Ardennes and the High Fens also formed a reinforcing factor. The following precipitation amounts were measured in Belgium over a period of 48 hours (see also Figure 1.7):

- At Jalhay : 271.5 mm
- At Spa : 217.1 mm
- At Neu-Hattlich : 189.0 mm
- At Mont Rigi : 192.4 mm

At such extreme amounts of precipitation, people referred to it as “water bomb”. For comparison, the average expected amount of precipitation in July in central Belgium is 76.9 mm.

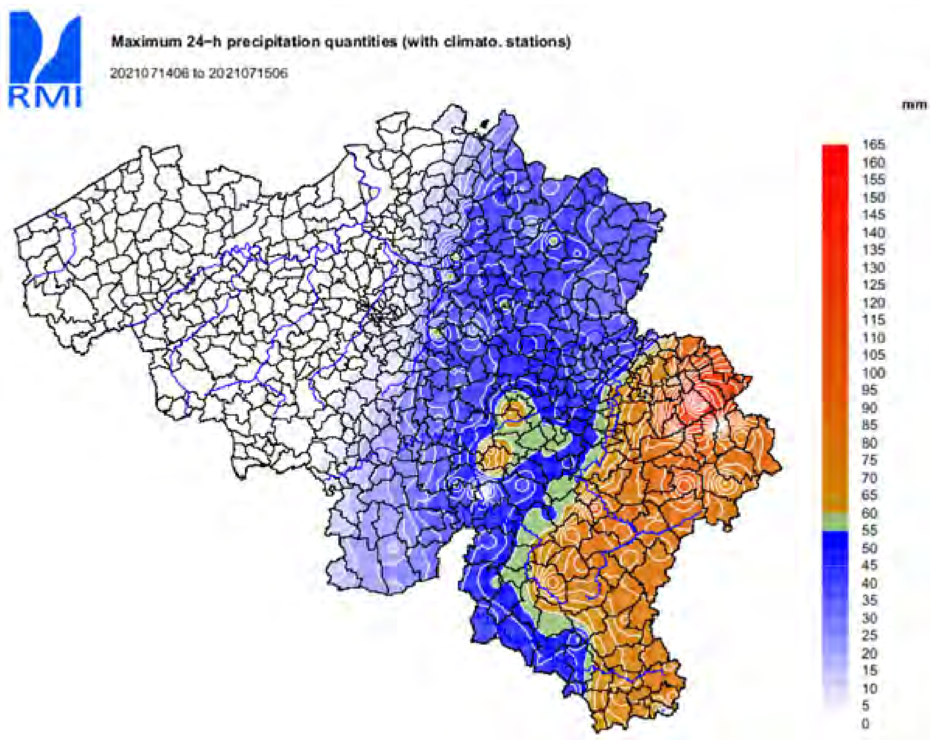


Figure 1.7. Map of rainfall amounts over 48 hours in Belgium on 14-15 July 2022 (source: RMI)

Comparison of these rainfall amounts with local observations and extreme value statistics shows that in the current climate such a precipitation event can be expected once every 400 years. Due to climate change, both the intensity and the frequency of this type of events are expected to increase.

The extreme amounts of precipitation have led to unprecedented high discharges in several rivers in the Walloon Meuse basin, including Vesdre Amblève, Ourthe, and Hoëgne. Also, the thin stony soils in the Ardennes, which can absorb little water, and the previous precipitation in June and early July, which already partly saturated the soil with water, were partly responsible for the rapid drainage of water. Small streams like the Hoëgne, a tributary of the Vesdre, have quickly become raging mountain streams. For example, the Hoëgne has a discharge of less than 1 m³/s in a normal summer period. On the night of 14 to 15 July 2021, however, a discharge of 87 m³/s were measured, and a water height of 2 m was recorded.

More than 38,000 homes in Wallonia were damaged by the floods, 5,000 of which were severely damaged, and 642 homes completely destroyed. The human toll is also extraordinarily heavy: many people were surprised in their house, in their cellar or in their car by the suddenly rising water level. In addition to dozens of missing persons, there were 41 fatalities.

1.3.3. Netherlands

On Tuesday and Wednesday, July 13 and 14, 2021, exceptionally heavy precipitation in the Belgian, German, and Dutch parts of the Meuse and Rhine basins, led to flooding of the (side) rivers in many places. The 1- and 2-day precipitation amounts (160 - 180 mm in two days) and discharges of the rivers are very rare, particularly in the summer season. For both precipitation and peak discharges, the probability is much smaller than can be directly deduced from the measurement series and is estimated to less than 1:100 to 1:1000 per year. Several days in advance large amounts of precipitation were predicted; discharge forecasts were adjusted upward until shortly before the flood event.

The peak discharge on the Meuse near Eijsden and several tributaries is the highest ever recorded. Water levels on the Meuse are lower downstream of Roermond than during previous floods and also lower than expected on the basis of earlier model calculations. The probabilities of occurrence of the measured water levels is approximately 1:200 per year on the Meuse at Borgharen and decreases, due to top flattening, to a probability of occurrence of 1:15 per year at Gennep. Also in the tributaries the exceeding frequency of the measured water levels varies strongly. At many places along the Geul, the Geleenbeek and the Roer the probability of occurrence is estimated at 1:100 to 1:1000 per year.

At the time of the high water the hydrological measuring network of the Limburg Water Board functioned reasonably well (except for a few failed measuring points due to failed gauges), giving a good overview of events. However, the information on actual precipitation was of insufficient quality. The number of precipitation meters in the area is limited, and the real-time KNMI radar product underestimated the precipitation volumes by approximately a factor of three to four.

It is estimated that more than 2,500 homes, 5,000 residents and some 600 businesses in the directly flooded area. With the standard method for damage assessment (SSM2017), experiences, and based on international sources, the total damage is currently estimated in the range of € 350 - 600 million. Household and building damage to homes and businesses, business interruption, damage to infrastructure and agriculture are the biggest damage items.

1.4. Geological and geophysical conditions in the flood regions of Germany

The main flooded areas in Germany are the Eifel region and the Ahr valley. Both regions have unique geological and natural features.

Surface geology in the Eifel area is mostly characterized by Devonian rock and red sandstone from the Triassic period. Soil of the Eifel are reflective of the different surface rocks with brown topsoil covering often Devonian rock and podzolic soils often covering red sandstone. Erosion has led to mineral and organics depleted top soils on many of the slopes (https://www.nationalpark-eifel.de/en/nature-landscapes/geology-soils-and-climate/).

The river Ahr cut the Ahrtal into sandstone, siltstone, and clay slate. Steep to vertical walls frame the Ahr in sections, while significant meanders resulted from limited inclination (Meyer, 1993). Wineries have taken advantage of many of the steep slopes with 53% of all grape fields being located on slopes > 60 degree. The river Ahr has a length of about 90 km with an elevation change of approximately 400 m. Soils along the Ahrtal are dominated by slate with some loess and sandy clays from Altenahr to Rech and sandy to gravelly clays and loess from Rech to Ahrweiler. Sandstone, loess and basaltic rock can be observed in many locations along the Ahrtal (https://www.lgb-rlp.de/fileadmin/service/lgb_downloads/boden/steinundwein/ahr_07032017.pdf).

Narrow river valleys are common within the Eifel National Park and are characteristic for the Ahrtal. This amplified the flood severity through significant rainwater catchment and runoff, small to negligible flood plains, and accelerated flow velocities. Figure 1.7 shows an example of the terrain surrounding Bad Münstereifel. The cross-sections were generated with the open source GIS tool of Rhineland Palatine (available at: https://www.wms.nrw.de/geobasis/wms_nw_dop and https://www.geoportal.nrw/). The river Erft, located at the lowest point in the valley (Figure 1.7) has limited flood plain areas and is fringed by often steep slopes. Local geologists highlighted specifically the role of steep rocky slopes along the Ahrtal as a key contribution to the severe and rapid flooding (https://www.ardmediathek.de/video/swr-aktuell-rheinland-pfalz/experte-geologie-im-ahrtal-beguenstigte-flutkatastrophe/swr-rp/Y3JpZDovL3N3ci5kZS9hZXgvbzE1ODUxMjI/).

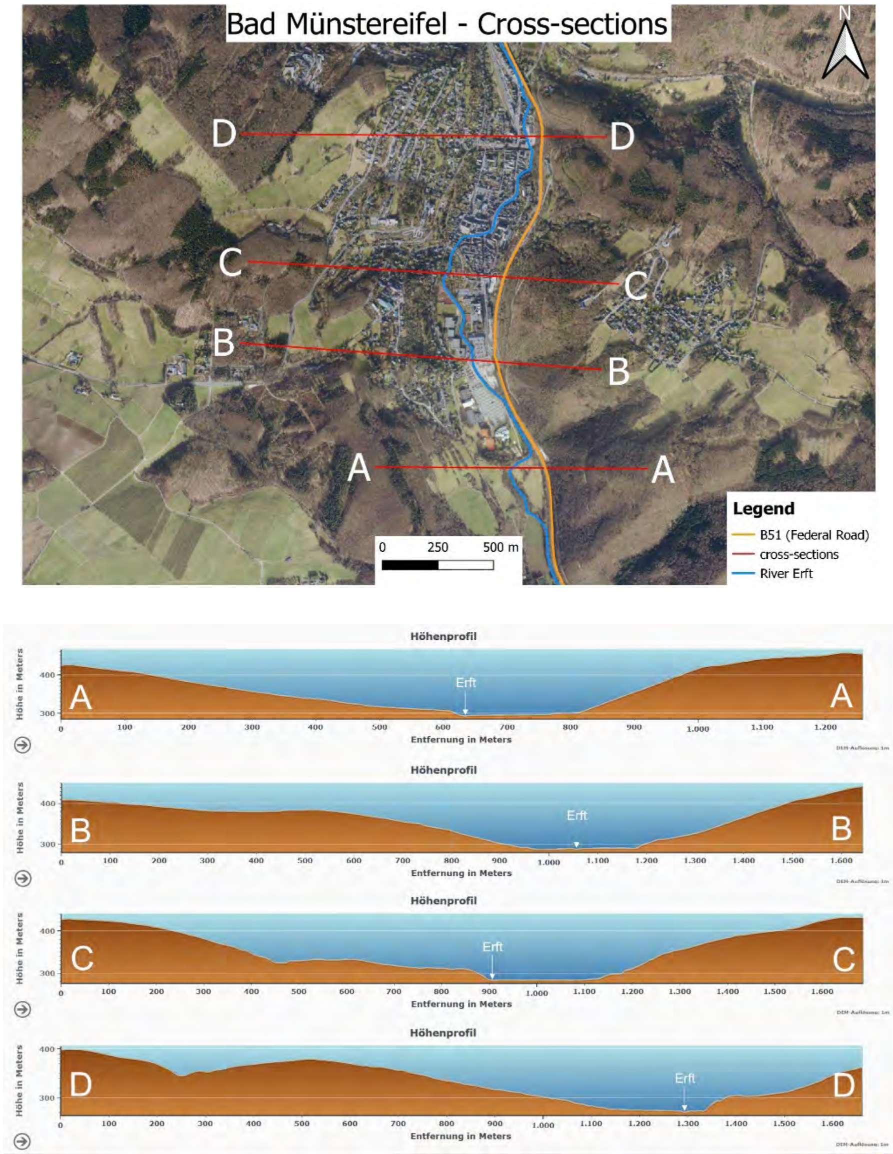


Figure 1.8. Top) Aerial image of the Erft River in Bad Muenstereifel with highlighted cross-sections (https://www.wms.nrw.de/geobasis/wms_nw_dop). Bottom) Elevation profiles for cross-sections A-D based on https://www.geoportal.nrw/.

Soil conditions including state of saturation play an important role in the development of flood events. While soil can store and retain precipitation, soil behavior can change with changes in saturation, and the amount of water that can be absorbed is restricted by the type of soil and the initial water content. According to the German Meteorological Services (Deutscher Wetterdienst, DWD). The three weeks prior to the flood event were characterized by recurring precipitation throughout Germany resulting in increased soil saturation and limited water absorption capabilities prior to storm event “Bernd” (Fig. 1.9). The soils in Rhineland-Palatinate and in South Westphalia were reported to have hardly any capacity for water absorption (in some cases less than 10 mm free soil water storage), the soils in the southwest of North Rhine-Westphalia were still capable of absorbing water to a limited extent (just over 75 mm free soil water storage).

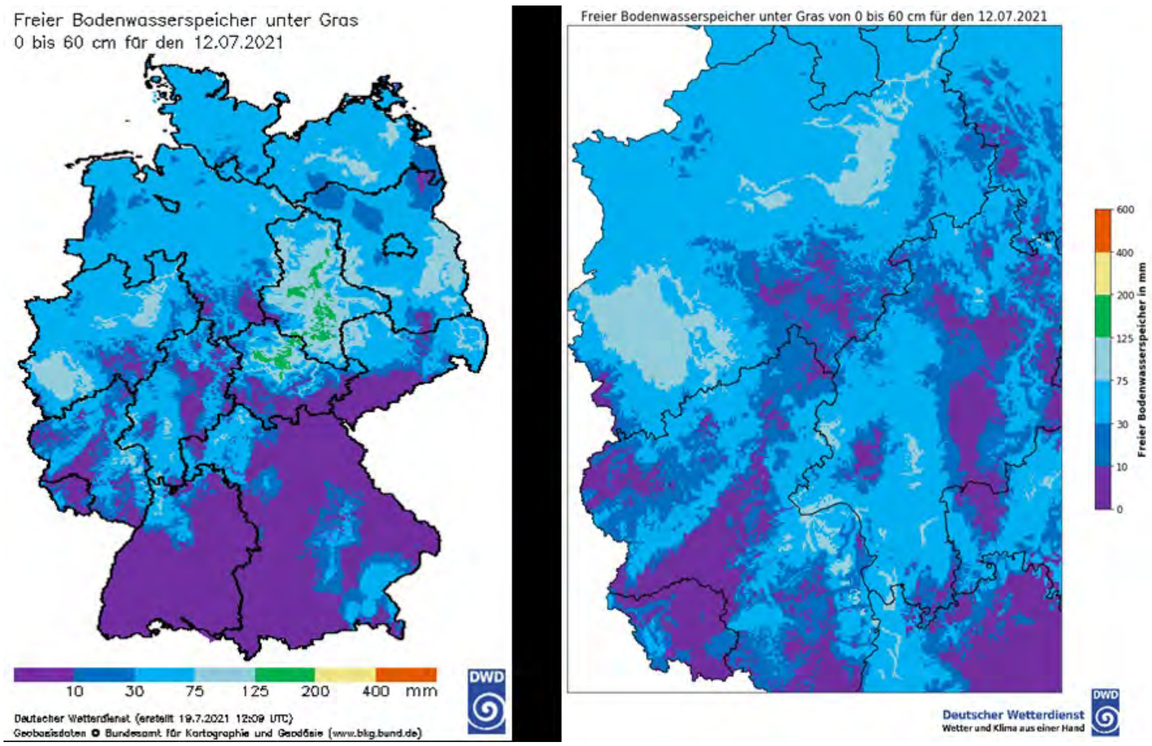


Figure 1.9. Remaining water absorption capabilities of soil covered with grass within the top 60 cm of the soil layer on July 12, 2021, estimated by the German Meteorological Service (DWD).

1.5. Historical context of flood events in the regions

The regions visited during the August 2021 reconnaissance are historically known flood regions in Germany in which repeated strong rainfall events have led to substantial flood related incidents and damage. Hereafter, we review the flood history of three of the four main rivers involved in the most recent flood events, the rivers Erft, Urft, Ahr, and Wupper. Areas around the river Wupper were not visited by the team.

Erft: The Erft rises on the northwestern edge of the Ahr Mountains, part of the Eifel region, in the village of Holzmülheim, district of Euskirchen, and flows into the Rhine after 106.6 km near Neuss-Grimlinghausen. The elevation change from the spring (527 m a.s.l., mainstem headwaters) and the mouth (31 m a.s.l.) is 469 m, corresponding to a bottom gradient of 4.7 ‰. The Swist, the largest tributary, flows into the Erft north of Weilerswist. Extreme runoff situations are typical for the Erft, with extreme floods mainly resulting from local heavy precipitation in the Erft catchment in the summer. A list of flood events of the river Erft can be found at https://de.wikipedia.org/wiki/Liste_der_Hochwasserereignisse_an_der_Erft

Ahr: The Ahr rises in Blankenheim in the district of Euskirchen, flows through the Ahr valley, and into the Rhine River near the town of Sinzig in the district of Ahrweiler. Its total length is 85.1 km. The elevation change from its spring (474 m above sea level) to the mouth (53 m above sea level) is 421 m, corresponding to a bottom slope of 4.9 ‰. The characteristic feature of the summer floods of the Ahr is the rapid rise in water level combined with high flow velocity and a rapid decline. Winter floods, on the other hand, swell slowly, usually have a preliminary high-water stage and a longer duration with gradually fall back to average water levels. In a historic compilation of flood events of the Ahr by Seel (1983), 31 of 64 recorded floods occurred between May and October and 33 in November to April. Extreme flood events had a similar occurrence regarding summer versus winter with 5 in summer (1601, 1804, 1818, 1848, 1910) and 4 in winter (1687, 1739, 1795, 1880). Based on documented damage, the most severe floods are those of 1601, 1804, and 1910, all summer floods triggered by thunderstorms. A complete list of flood events along the river Ahr can be found here: https://de.wikipedia.org/wiki/Liste_der_Hochwasserereignisse_an_der_Ahr.

To date, according to the EU evaluation, around 56,000 people live along the Ahr River in the district of Ahrweiler. The Emergency & Response Directorate (ADD) assumes that 42,000 people were affected by the 2021 flood. Of these at least 17,000 have directly lost belongings and/or are facing considerable damage, based on satellite assessments. The Ahr flooded an area of about 200 hectares and damaged about 3000 of a total of 4200 buildings (70%). 62 bridges were destroyed. The region is traditionally characterized by wine production and tourism, representing the economic basis of the Ahr valley. While vineyards are located on the slopes, residential areas and tourist infrastructure are mostly located at low elevations close to the river.

Urft: The Urft is a 46.4-kilometre-long (28.8 mi) right-hand tributary of the river Ruhr in the county of Euskirchen in North Rhine-Westphalia. It flows through the village of Urft in the municipality of Kall. The Urft rises in the North Eifel region. The Urft river caused substantial damage in the town of Gmuend, and its tributary, the river Olef, caused severe damage in the city of Schleiden. The Urft Dam is the oldest dam in the Eifel and is in the middle of the Eifel National Park. It was constructed for the purpose of flood protection and energy generation, as well as for drinking water supply in the region. With a length of 12 km, a width of 1 km, and a maximum depth of 52 m, the Urftsee reservoir has a capacity of 45.5 million cubic meters. The dam did not experience any damage during the flood event; however, water was released during the rainfall event contributing to increased downstream water volume in nearby towns.

Wupper: The Wupper is a 116-km long tributary of the Rhine in North Rhine-Westphalia. Rising near Marienheide in the western Sauerland region, it runs through the mountainous region Bergisches Land in Berg County and enters the Rhine near Leverkusen, south of Düsseldorf. Fifteen dams and two large river impoundments are located in the Wupper catchment area. They have significantly mitigated flood peaks since the end of the 1980s (Ministerium für Umwelt, Landwirtschaft, Natur-und Verbraucherschutz, NRW).

1.6 Existing flood protection mechanisms and preparation for flood events in affected countries

Flood events are recognized as a local natural hazard in all the affected regions, and a variety of flood protection mechanisms have been put in place. For example, the "Landesamt fuer Natur, Umwelt und

Verbraucherschutz NRW" (LANUV; State agency for nature, the environment, and consumer protection) lists the following mechanisms to manage flood risk: flood watches and warnings including the publication of water level stages at different gages along the rivers, updated watches and warnings, and an information website; flood risk maps and flood risk management plans; identification and mapping of spatial flood extend; bathymetric and flow velocity river maps; flood protection infrastructure such as levees and dams; wetland development that can serve as flood plains; public information regarding flood protection in construction, flood response planning, and insurance (https://www.lanuv.nrw.de/umwelt/wasser/hochwasserschutz). Similarly, Rhineland-Palatine (RP) offers a flood portal (https://www.hochwasser-rlp.de/) with flood watches and warnings, water level recordings, flood maps and flood risk maps (https://hochwassermanagement.rlp-umwelt.de/servlet/is/200042/). RP is also developing increased wetlands and natural flood plain zones and has invested in flood water retainment mechanisms such as levees (https://hochwassermanagement.rlp-umwelt.de/servlet/is/201062/).

The river Meuse that was center of many of the damages and loss of life in Belgium and the Netherlands has been center of a significant river restoration program over the last 30 years (https://www.rivierparkmaasvallei.eu/sites/default/files/2101005_maasinbeeld.pdf) including the development of natural flood plains, the extraction of gravel, and strengthening of dikes. Indeed, the sections of the river that were subject to this significant river restoration project encountered less damages through the increased flood capacity of the river. In Belgium, flood warnings were issued by the Royal Meteorological Institute and also through the European Flood Awareness System (EFAS; https://www.efas.eu/en).

In the Netherlands, river flood protection particularly along the rivers Rhine, Meuse, and Scheldt has been an important topic of civil and environmental engineering since the Romans. Flood protection mechanisms reach from hard and earthen flood protection mechanisms such as dikes, levees, pumping stations, and canal design to natural approaches including reclamation of wetlands and flood plains. A detailed overview is provided by a report from the Dutch Center for Water Management (Rijkswaterstaat) available at: https://web.archive.org/web/20140221225045/http://www.rijkswaterstaat.nl/en/images/Water%20Management%20in%20the%20Netherlands_tcm224-303503.pdf. Water management in the Netherlands is distributed between the Rijkswaterstratt and district water boards. Flood warning, mapping, and risk assessment is provided by Deltares (https://www.deltares.nl/en/areas-of-expertise/flood-risk/) including through the forecasting model FWS Rivieren (https://www.imprex.eu/system/files/generated/files/resource/flood-early-warning-and-forecasting-across-europe-netherlands.pdf).

In summary, the affected neighboring countries have invested a significant amount of effort in flood prediction and warning, as well as flood mitigation and response mechanisms on local, regional, state, country, as well as European Union level. Nevertheless, the flood 2021 was referred to as a "monumental failure of the system" regarding warning and response (e.g., https://www.theguardian.com/world/2021/jul/19/german-villages-could-be-left-with-no-drinking-water-after-floods). Such media publications are in line with statements by local stakeholders and residents received by the GEER team. In the media, local decision making (or lack thereof) in response to the warnings was often pointed at as the most impactful issue. Local residents who talked to the GEER team stated that they were aware of warnings but felt that the information they received did not clearly communicate the severity of the event and risk.

1.7 Early remote data collection and before and after imagery

Significant amounts of imagery and information became available early through residents and local stakeholders actively posting imagery and videos on social media platforms. Those images and videos were rapidly further disseminated by the media. Additionally, aerial imagery was collected by regional, state, and federal authorities, and partially published to inform the public and provide timely updates on flood maps. A variety of these information outlets also provide before-during-after flood imagery of affected areas. Here, a small selection is provided with respective sources.

The German Remote Sensing Data Center (ZKI) and the German Aerospace Center (DLR) offer many before-after aerial images with detailed supplementary information. Those can be accessed at www.dlr.de. The following are some excerpts of examples (Fig. 1.10-1.12). The ZKI also communicated with the GEER team prior to GEER mobilization and provided imagery that assisted with reconnaissance planning.

Figure 1.10. Before (left) and after (right) imagery obtained from along the Ramersbacher Strasse and the Ahr river in Bad Neuenahr-Ahrweiler, Germany. (Source: ZKI/DLR, accessed through dlr.de).

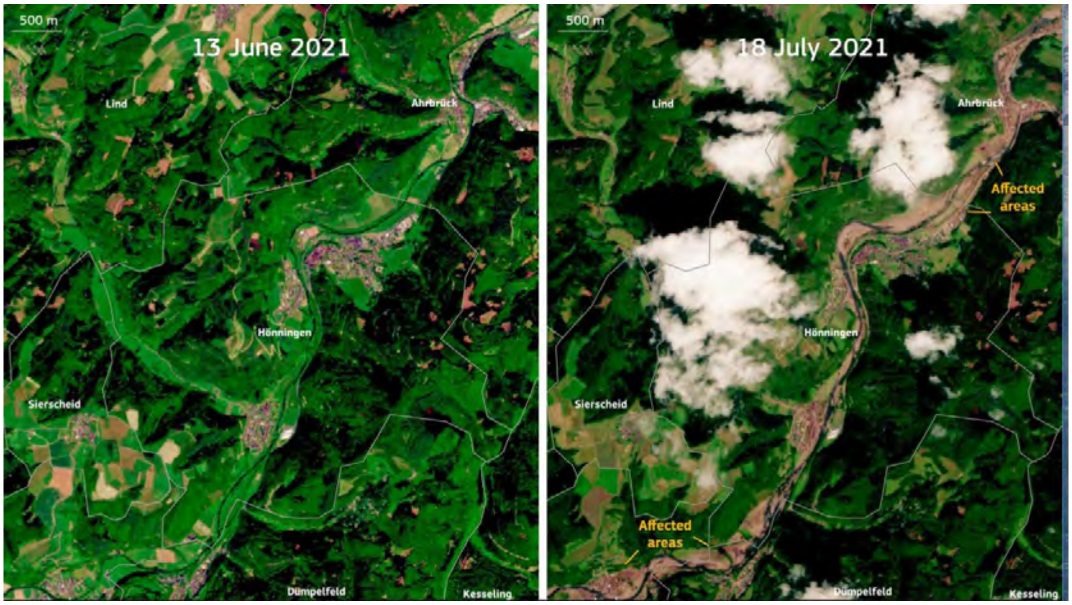


Figure 1.11. Copernicus-Sentinel 2 imagery from June 13, 2021 (left) and July 18, 2021 of the Ahrweiler region. Source: EU Copernicus Sentinel 2, accessed via dlr.de.

Figure 1.12. Aerial imagery obtained from Erftstadt-Blessem from June 30, July 16, and July 18, 2021. Source: ZKI/DLR, accessed through https://activations.zki.dlr.de/.

The following examples represent publications through different media channels.

Figure 1.13. Before and after imagery of Altenburg (district Altenahr) published by the ARD Tagesschau and accessed through https://www.facebook.com/tagesschau.

Residents, visitors, as well as media outlets also published numerous videos and contributions during and after the flood events through YouTube. The amount of public data assisted significantly with the planning and decision making for the GEER reconnaissance mission. However, many privately published information were often unclear regarding specific timing and locations. Therefore, special thanks goes particularly to federal and state agencies who provided well georeferenced information, as well as to the many representatives of different local authorities who assisted with identifying key locations of interest as well as safe access for the team.

2. Data Collection

2.1. Overview of information collected & technology used

Reconnaissance data were collected through unmanned aerial vehicle (UAV) and terrestrial photography, terrestrial light detection and ranging (LiDAR) scans, multispectral photography, UAV-derived structure-from-motion models, satellite imagery, on-site measurements (manual), material sample collection (shovel & bags), and on-site interviews. The documentation included geotechnical and structural damage, water levels (taken at visible watermarks) on buildings, general information on flood progression and water level rise, infrastructure damage, riverbed erosion and sediment redeposition, scour, utility network performance, and first response information.

LiDAR scans were performed at five sites in Germany and two sites in Belgium. LiDAR is an optical remote-sensing technique that uses laser light to densely sample the surface of the earth, producing highly accurate 3D measurements. LiDAR produces dense mass point cloud datasets that capture the three-dimensional condition of the location being scanned. These point clouds can be managed, visualized, analyzed, and shared using the open-source software package Cloud Compare as well as proprietary packages such as ArcGIS. LiDAR scans were collected using a ground-based Leica RTC 360 medium-range laser scanner and processed using Cyclone 360 (proprietary software for Leica scanners). Additional LiDAR scans were obtained using a hand-held iPad Pro 2020 with built-in LiDAR sensor which was accessed using the 3D Scanner App for data collection and processing.

Multispectral imaging was performed at one site. This was a test application where images were taken from the ground to determine if this type of deployment is useful in rapid, post disaster reconnaissance. The multispectral sensor collects simultaneous images at five high resolution narrow bands (blue, green, red, red edge, and near infrared) as well as a thermal image. With the resulting images, it is possible to identify features in the images that reflect light in a similar fashion, potentially identifying erosive or depositional patterns in soil or degree of saturation in different materials. Multispectral images were collected using a MicaSense Altum multispectral and thermal camera and manually processed in Python using MicaSense multispectral image processing libraries.

UAV imagery was collected both through double-gridded autopilot missions and manual image collection to document flood damage. Double-gridded nadir image collection provides multiple overlapping images taken from different sides of objects such that high resolution; three-dimensional models of a site can be created using structure-from-motion (SfM) techniques. UAV image collection is quicker and provides more coverage compared to LiDAR, though at lower accuracy. For the automated gridded missions, image overlap ranged from 70-90%—this maximized the amount of data that could be collected while still providing reasonable resolution in the generated 3-D models. Drone images were collected using DJI Mavic2 drones and three-dimensional SfM models were created using Pix4D.

Table 2.1 Overview of Lidar Scans during the reconnaissance visit (obtained with Leica RTC 360)

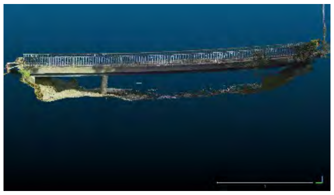
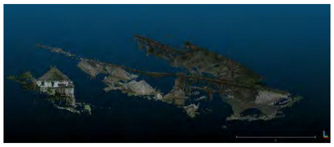
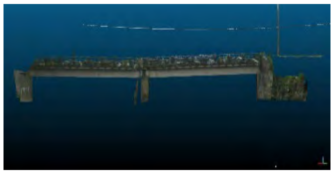
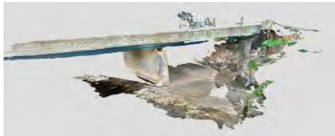
Type of Structure	Location (City/Country)	GPS coordinates	Photo
Road Bridge across Erft river	Euskirchen, Germany	50°40'01.2"N 6°47'56.5"E	
Rail Bridge + Pedestrian Bridge	Mayschoss, Germany	50°31'05.2"N 7°01'36.4"E	
Tunnel Exit/Road	Altenahr, Germany	50°30'59.0"N 6°59'48.6"E	
Double Bridge near Tunnel Exit	Altenahr, Germany	50°31'01.0"N 6°59'48.2"E	
Road Bridge	Liers, Germany	50°27'25.2"N 6°56'43.2"E	
Road Bridge	Trooz, Belgium	50°34'16.3"N 5°41'22.9"E	
Road Bridge	Pepinster, Belgium	50°34'0.552" N 5°46'57.648" E	

Table 2.2. Overview of Lidar Scans during the reconnaissance visit (obtained with iPad Pro 2020)

Type of Structure	Location (City/Country)	GPS coordinates	Photo
'Outlet' from City Wall	Bad Münstereifel, Germany	50°39'59.99" N 6°47'57.03" E	
Footbridge	Bad Münstereifel, Germany	50°33'19.18" N 6°45'53.64" E	
Bridge Pier - Erft River	Euskirchen, Germany	50°39'38.71" N 6°48'17.13" E	
Bank Scour - Erft River	Euskirchen, Germany	50°39'42.44" N 6°48'16.02" E	
Floodplain Scour/Deposition - Erft River	Euskirchen, Germany	50°39'46.46" N 6°48'11.91" E	
Bridge Abutment - Erft River	Euskirchen, Germany	50°39'59.99" N 6°47'57.03" E	
Bridge Deck/Pier - Erft River	Euskirchen, Germany	50°39'59.99" N 6°47'57.03" E	

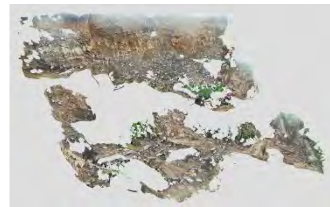
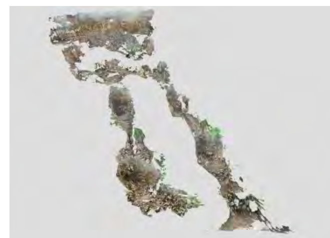
Road (Head-cut from Gravel Pit)	Blessem, Germany	50°48'48.76" N 6°47'42.04" E	
Dam - Steinbach Talsperre (Scour near crest)	Near Kirchheim, Germany	50°35'25.7249" N 6°50'5.5184" E	
Dam - Steinbach Talsperre (Rills downstream face)	Near Kirchheim, Germany	50°35'25.7249" N 6°50'5.5184" E	
Bank Scour - Ahr River	Putzfeld, Germany	50°29'39.25" N 6°58'57.13" E	
Bridge Pier / Abutment Scour - Ahr River	Putzfeld, Germany	50°29'39.62" N 6°58'54.34" E	
House Foundation Scour	Bad Neuenahr - Ahrweiler, Germany	50°32'29.45" N 7°6'35.79" E	
Bridge Pier Scour	Sinzig, Germany	50°32'58.81" N 7°14'40.65" E	

Table 2.3. Overview of SfM models recorded during the reconnaissance visit

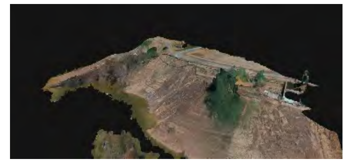
Type of Structure	Location (City/Country)	GPS coordinates	Photo
Gravel Mine	Blessem, Germany	50.81865° N 6.79390° E	
Flooding Damage near Radmacherstrasse	Blessem, Germany	50.81360° N 6.79483° E	
Dam (Talsperre)	Steinbach, Germany	50.59326° N 6.83894° E	
Bank Scour, Floodplain Scour/Deposition - Erft River	Euskirchen, Germany	50.66126° N 6.80463° E	
Bridge Abutment Scour	Bad Münstereifel, Germany	50.55739° N 6.76583° E	

Table 2.4. Overview of Multispectral Camera Imaging conducted during the reconnaissance visit

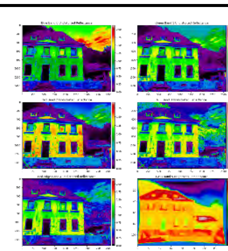
Type of Structure	Location (City/Country)	GPS coordinates	Photo
High water mark on hotel	Bergischer Hof Bridge, Germany	50°31'04.80" N 7°01'37.16" E	

Table 2.5. Overview of Soil Sample locations collected

Type of Sample	Location (City/Country)	GPS coordinates	Photo
Soil sample, riverbed, Erft	Bad Münstereifel, Germany	50.55628179196182, 6.765454452058204	
Sediment deposit in flooded car	Bad Münstereifel, Germany	50.551309740679955, 6.762934764639411	
Soil Sample	Campground Gut Puetzfeld	50.49439166912573, 6.982455823015818	
Soil Sample, Gravel mine	Blessem, Germany	50.81948591139152, 6.79356877369972	
Rock sample, Tunnel Exit	Altenahr, Germany	50.516294189855685, 6.99653790006852	

2.2. Data curation and publication

Data collected by the GEER team during the reconnaissance mission from August 9 - 18, 2021 in Germany, Belgium, and the Netherlands are published and available through the DesignSafe-CI Data Depot under DOI: 10.17603/ds2-0ddt-ss87. The data repository is organized by country and data collection dates (Germany, August 9-13, 2021; Belgium, August 16, 2021; Netherlands, August 18, 2021), and contains general information about the instruments (i.e., data collection tools) used. Within the different country folders, data are organized by location (i.e., town, region, or specific sites such as the two dams visited). Within the different location folders, data are organized by data collection method (i.e., photos, drone aerial imagery, structure from motion, lidar). Readme files are provided for all location folders describing the types of data collected at this location and listing the GEER members who collected the data including contact information.

2.3. Sample Data

A set of sample data, including LiDAR, UAV imagery, UAV based SfM models, multispectral imaging, and photographs of collected information are depicted below. Figures 2.1 and 2.2 show sample LiDAR data obtained from (a) the Leica RTC360 laser scanner and (b) iPad Pro 2020 using the 3D Scanner App.

Figure 2.1 shows a bridge in Trooz Belgium, which suffered damage to the middle pier and the bride abutments. Scour likely caused settlement of the middle pier, inducing rotation and damage to the bridge deck. The bridge was passable for pedestrian traffic; however, restricted for motorized vehicles. The team took extensive photography and obtained LiDAR scans of the bridge from 2 locations.

Figure 2.1. Photograph (top) and Lidar model (bottom) of road bridge crossing the river Vesdre in Trooz, Belgium.

Figure 2.2 shows scour on the downstream side of a railroad bridge pier crossing the Erft River near Kölner Straße in Euskirchen, Germany. The armoring, which consisted of a hardened concrete-rock cap, was eroded and undermined exposing the pile walls surrounding the bridge pier. The exact failure mode could not be deduced, however hard armoring such as this is brittle and subject to cracking. Cracks can allow hydraulic jacking of sections of the concrete-rock cap (the same process that can occur in concrete spillway chutes, like the Oroville Flood Control Outlet Spillway in California, USA during the 2017 flood events).

Figure 2.2. Photograph (left) and LiDAR model (taken with the iPad Pro 2020) (right) of scour damage at foundation level of railroad bridge crossing river Erft, parallel to Kölner Straße

Figure 2.3 shows an example of post-processed imagery from the multispectral camera. In this image, the maximum water level reached during flooding can be clearly seen just below the 2nd story windows. The color variation indicates the undistorted, calibrated reflectance for a particular narrow band–the blue band in this case, which differentiated the high-water mark most clearly. Since multispectral imagery was manually collected on-foot, it was not possible to automatically post-process collected images using software such as Pix4D as might be normally done with drone-borne image collection. Image processing was performed in Python using the MicaSense image processing library provided through GitHub (https://micasense.github.io/imageprocessing/). With this library, the radiance to reflectance conversion factor for each of the narrow bands is extracted so that raw radiance images can be converted to reflectance, as shown in Figure 2.3. This workflow in Python is ideal for manually processing and visualizing relatively small datasets, as was the case with this test deployment.

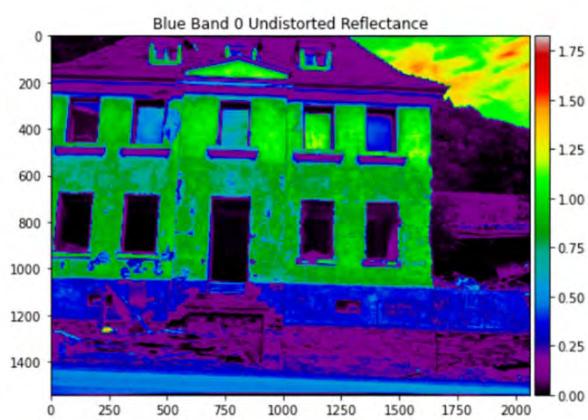


Figure 2.3. Multispectral imaging of residential building near Mayschoss.

Figure 2.4. shows a structure from motion (SfM) model generated from UAV-collected images. The SfM model is of the Steinbachtalsperre, located between Euskirchen and Bad Muenstereifel. The SfM models created of this dam had ~2cm resolution with measurement error of approximately 8 cm in plan and 13 cm in vertical. Images were collected using a DJI Mavic2 drone with both manual image collection and autopilot missions planned using Pix4Dcapture. For the images collected to create this model, approximate flight time was 40 minutes. The SfM model shown in Figure 2.4 was created in Pix4D using 288 images.

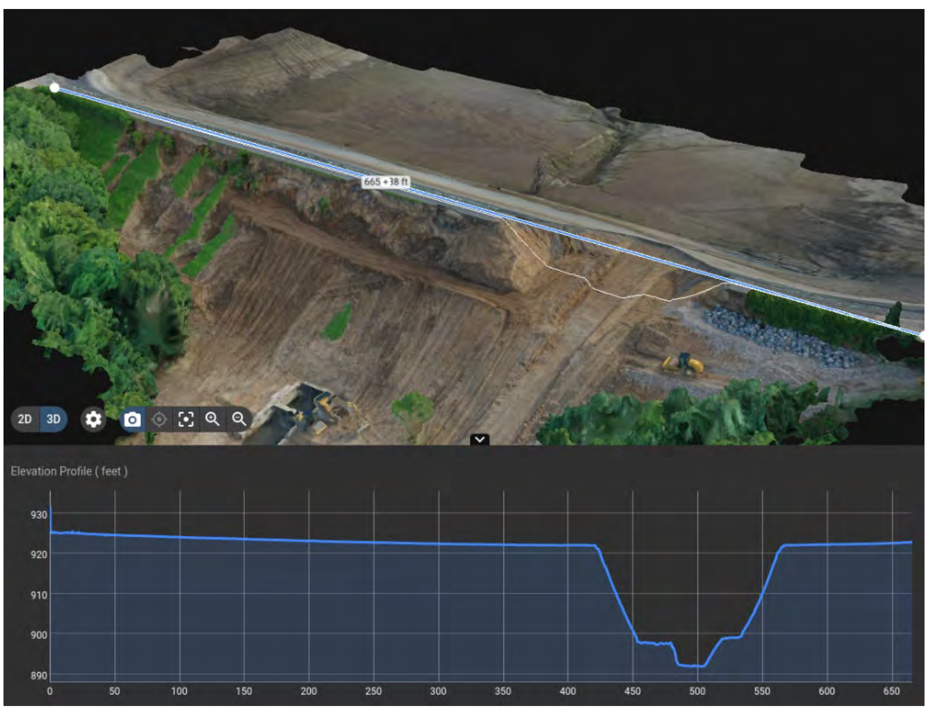


Figure 2.4. Structure for Motion model of Steinbachtalsperre

Standard UAV imagery was collected using two DJI Mavic2 drones, operated by the team on the ground. Still image and video footage was captured to provide an aerial view of damage. Figure 2.5 (left) shows an aerial photograph of a riverbed near Euskirchen, which documents the extent of riverbank erosion and exposure of critical infrastructure; Figure 2.5 (right) shows an aerial photograph in Blessem near the gravel mine, where access was entirely restricted due to ongoing rescue and cleanup activities.

Figure 2.5. Sample UAV photos taken, Left: Erft river in Euskirchen, Crossroad Kölner Straße; Right: landslide damage triggered through inflow into the Blessem gravel mine

3. Field observations (documented in chronological order)

3.1. Day 1: Bad Münstereifel & Euskirchen

3.1.1. Introduction and Locations

Figure 3.1 & 3.2 show maps of areas visited during the first day of the reconnaissance. Bad Münstereifel is a historic town in the district of Euskirchen, Germany, with about 17,000 inhabitants, situated in the southwest of North Rhine-Westphalia. The town represents a popular vacation destination. Bad Münstereifel and its surroundings has an area of approximately 151 km^2 (58 sq mi) and is located at elevations of 200 m to 586 m (656 to 1,923 ft) above sea level. The river Erft flows through the town. Over the centuries, floods of the upper Erft river caused numerous severe events, repeatedly resulting in loss of life and severe damage to houses, roads, bridges, and fields. Table 1 presents specific places visited by the team and their GPS coordinates.

Figure 3.1. Location of Bad Münstereifel in Germany

Figure 3.2. Bad Münstereifel, shaded area representing the area explored by the team, blue line represents the river Erft

Table 3.1. Places visited, Data collected, and GPS-coordinates

Town	Visited Places	Applied methods	GPS-coordinates
Bad-Münstereifel	historic city-centre	images soil samples measurement of water levels	50.552137; 6.763145
	Werkbrücke	drone images	50.553238; 6.761479
	Werther Tor & Bridge near Werther Tor	drone images	50.557341; 6.765897
Euskirchen	Downtown	images measurement of water levels	50.660776; 6.788895
	Kölner Straße (Bridge Scour & Riverbed erosion)	images drone images, shear strength lidar	50.661224; 6.804757
	Brücke Erftstraße	Images, drone images, lidar	50.666848; 6.798949

3.1.2. Observations

3.1.2.1. Bad Münstereifel: Historic City Center

The team started its investigations near the Orchheimer Tor and walked the city center to document damage. Figure 3.3 shows a before and after photograph of the historic downtown area. Substantial damage was observed to houses (basements and ground level stories), embankments, historical bridges, roads, and utility services.

Figure 3.3. Before (left) and after (right) photograph of the city center Bad Münstereifel, Source: https://www.dw.com/en/flooding-in-germany-before-and-after-images-from-the-ahr-and-eifel-regions/a-58299008

At the time of the team's visit most of the city center area has been filled with soil (and compacted) to enable residents and rescue services to access the city center. Local residents reported an outage of all utility services immediately after the flood. Five days after the flood event, drinking water was re-established and about 50% of the city center was re-connected to the fresh-water network, however, water had to be boiled before consumption. About one month later (August 18th), the water boiling mandate was relieved and only selected parts of the city were required to continue with precautions (https://www.bad-muenstereifel.de/rathaus-service/hochwasserkatastrophe/). Twelve days following the flood, electricity was re-established. Mobile service points from Germany's primary telecommunication providers (e.g., Telekom) were established to help residents with wireless services and charging options. To date (November 2021), the landline communication network has not yet been re-established in the city center.

Residents reported an overwhelming support system immediately after the event, including food sharing and distribution, first aid and response to elderly residents, emotional and medical support, clean up and disinfection (especially for houses with wastewater issues), and immediate financial help. Local restaurants cooked their food reserves on outside gas stoves, supplying hundreds of affected inhabitants, until external supplies arrived.

Approximately one month after the event (August 16th), train replacement services were established using bus and taxi networks. The German association of Engineers without Borders visited the town on a monthly basis to provide structural assessment services free of charge to local residents. Above all, old half-timbered structures were particularly affected by the consequences of the flood. In order to preserve the historic building fabric, the Rhineland Regional Council (LVR) has actively published useful information on its homepage about drying, exposing and preserving half-timbered structures, as Bad Münstereifel strives to re-establish its historic charm. Figure 3.4 shows photographs immediately following the flood obtained from online sources. The photos show screenshots of video footage taken 1-2 days after the flood. The photographs in the top row depict damages directly adjacent to the Erft river, and the photographs on the bottom show damage to a pedestrian zone not located near the Erft. However, flood waters ripped out the entire street and its subsurface construction, uncovered utility infrastructure, and held water residues in many parts of the city center area. As visible in Figure 3.4 (top left), the water level in the Erft was still high, reaching elevations just below the arch of the bridge. Road construction seemed to have been performed with cobblestone placed on asphalt and underlain by compacted fill.

For reference, Bad Münstereifel is located in "frost zone 1" (Frosteinwirkungszone 1), a mapping system in Germany that indicates frost penetration depths across the county. Zone 1 represents the lowest (i.e., shallowest) frost depth with a maximum estimated penetration of 1.2m (BASt, 2012). Zone 1 requires the upper 40-55cm below surface to represent structural bearing layers for road construction. In this zone, utility infrastructure such as wastewater and electricity are typically placed 60cm below ground surface. The minimum embedment depth of drinking water pipelines is 80cm below ground surface, most construction however, places drinking water pipes at approximately 100cm -120cm below ground surface. Drinking water pipelines also must be placed at least 100cm away from wastewater pipes. Figure 3.4 top left indicates the two sets of utility supply lines (the shallower lines on the right (wastewater, and electricity/telecommunications) and the lower left line to be drinking water. The exposed pipes suggest damage depths in extent of at least 1.0m below ground surface.

Figure 3. 4. Screenshots of damage immediately following the flood, Source: (Wochenspiegel.de, 2021: https://www.youtube.com/watch?v=Oxhy68LQ96E)

Figure 3.5 shows photographs of damaged structures in Bad Münstereifel taken during the team's visit. All walkways and temporary dirt roads were filled after the flood.

Figure 3.5. Damage to embankments, bridges, utility lines along the Erft in the historic center of Bad Münstereifel (all photos by the GEER team)

3.1.2.2. Bad Münstereifel Werkbrücke

The Werkbrücke is located right in front of the Bad Münstereifel Stadtmauer (the wall that encompasses the city center), built in the 13th century and the first half of the 14th century. It is 1.6 km long and has several passages for the Erft river. Figure 3.6 shows a set of photos before and after the flood event which depict the Werkbrücke and Stadtmauer prior to the flood (top, and center left) during the flood event (Source: Twitter, Bad Münstereifel), and at the time of the team visit (Fig. 3.6 bottom row).

Figure 3.6. Picture of the Werkbruecke: Top row: Before flood (Source: google earth); Center: during flood (center) Source: Patrick Hamm one day after flood (July 16th), Source: https://www.youtube.com/watch?v=7mZDH_P_1q4 , Bottom photos: at time of teams visit, August 9th, 2021

3.1.2.3. Bad Münstereifel Werther Tor

As the youngest of the four city gates, the Werther Gate was rebuilt in 1416. Its predecessor was washed out by the flood of July 1416 and collapsed. The gate did not experience any substantial damage during the 2021 flood and remained structurally intact. However, water masses rushing through the gate removed and destroyed an entire house just northeast of the gate. Adjacent to the Werther Tor was another, smaller gate (unnamed), through which water exited with high velocities. Substantial road damage was documented just outside the gate, exposing utility networks.

Figure 3.7. Left: Werther Tor, immediately after the flood (Source: @AshfordTwinning, https://twitter.com/AshfordTwinning/status/1415990484925919236); Right: small gate to the left of Werther Tor, with substantial surface damage (50.557167, 6.765114)

Damage areas around the outskirts of the city wall are highlighted in Figures 3.7 and 3.8. The reconnaissance team investigated the bridge near the Werther Tor and adjacent surface damage as shown in Figure 3.7.

Figure 3. 8. Bridge and surface damage outside the Bad Muenstereifel Stadtmauer, near Werther Tor

As shown in Figure 3.8, the bridge itself was passable and structurally intact at the time of the teams visit, however, all on-ramp and off-ramp infrastructure was washed out. Much of the soil surface adjacent to the bridge (right side in the photograph below) is post-flood fill material. The surface of the parking lot on the left-hand side (Fig 3.9) was eroded as well. Figure 3.10 shows a wide-angle view of the destroyed area, including the washed-out bridge support.

Figure 3.9. Bridge near Werther Tor, at time of reconnaissance visit (left) and google earth picture showing pre-flood condition (50.557369, 6.76584576)

Figure 3.10. Aerial photo showing extent of damage to adjacent parking lot and erosion of soil material within bridge abutment area (50.557486, 6.765991).

Figures 3.11 and 3.12 show close-up photographs of the damage around the bridge, including the depth of the scoured material. Utilities are exposed, the depth of the manhole is estimated to be 50cm. Damage to the river embankment is visible in Figure 3.11. Further embankment damage was documented in the downstream direction (Fig. 3.12).

Figure 3.11. Damage around the bride, riverbank damage (top row), bridge on-ramp and off ramp damage with severely scoured surface material and exposed manholes (50.557325, 6.7658949)

Figure 3.12. Embankment damage just below the bridge structure (50.55748613, 6.7659919).

3.1.3. Water level documentation in Bad Münstereifel

Water level measurements were taken at several locations throughout Bad Münstereifel. These included primarily visible water line marks at houses. Figures 3.1 displays several photographs of team members recording water marks at houses based on dirt lines in windows or wet marks along a brick façade. Figure 3.14 shows the water level rise in downtown Bad Münstereifel, indicating an estimate rise of up to 4.0m at the location shown in the photograph.

Figure 3.13. Examples of watermark recordings along Wertherstrasse in Bad Münstereifel

Figure 3.14. Example of water level rise of the Erft in the city center of Bad Münstereifel (50.5536697, 6.7626261)

3.1.2.5. Euskirchen Downtown

Severe flooding destroyed large parts of downtown Euskirchen causing damage to business and residential buildings in the city center. Figure 3.15 shows a photograph of Euskirchen taken during the flood event.

Figure 3. 15. Captures from online footage showing water rushing through the city center of Euskirchen, Source: https://www.youtube.com/watch?v=VA_BOmNI1jI, Source of photo on the right: Spiegel.de, by Gabriel Rinaldi, 17.07.2021.

At the time of the team visit, most parts of the city center were in the progress of being cleaned up, with most of the larger debris removed. Stores along the city center's pedestrian zone were almost fully flooded, construction and repair work was underway. Water levels in the downtown region were visually estimated and watermarks suggested water levels of nearly 2.0m above the ground surface.

Figure 3.16. City center (pedestrian zone along Neustrasse) of Euskirchen at the time of the team's visit (50.6602526, 6.7899711)

A large contributor to the flooding of Euskirchen's city center appeared to be the underground routing of the river Erft through tunnels and with many structural flow obstructions, as shown in Figure 3.17 and 3.18 below. Immediately next to (or rather behind) the bridge shown in Figure 3.18 was a Gabion wall, which was tilted and damaged at the time of the team's visit, likely due to the pressure of the water overflowing the channel.

Figure 3.17. Channel system of the Erft tributary "Mitbach" in the center of Euskirchen (50.657640, 6.7861305)

Figure 3.18. Bridge over small Erft tributary (Veybach) which obstructed the river flow (left), damaged gabion wall immediately behind the bridge (right), (50.6579006, 6.78616520)

3.1.2.6. Euskirchen: river Erft near Kölner Straße

The team visited a stretch of the Erft river near Kölner Straße, Euskirchen. Figure 3.19 shows three specific locations assessed. Foundation damage was investigated near the railroad bridge shown on the right of Figure 3.19. Foundation scour was also observed at the foundation level of the road bridge; however, damage was relatively limited, allowing for continued bridge traffic. Substantial riverbed erosion was documented along the remaining stretch of the Erft.

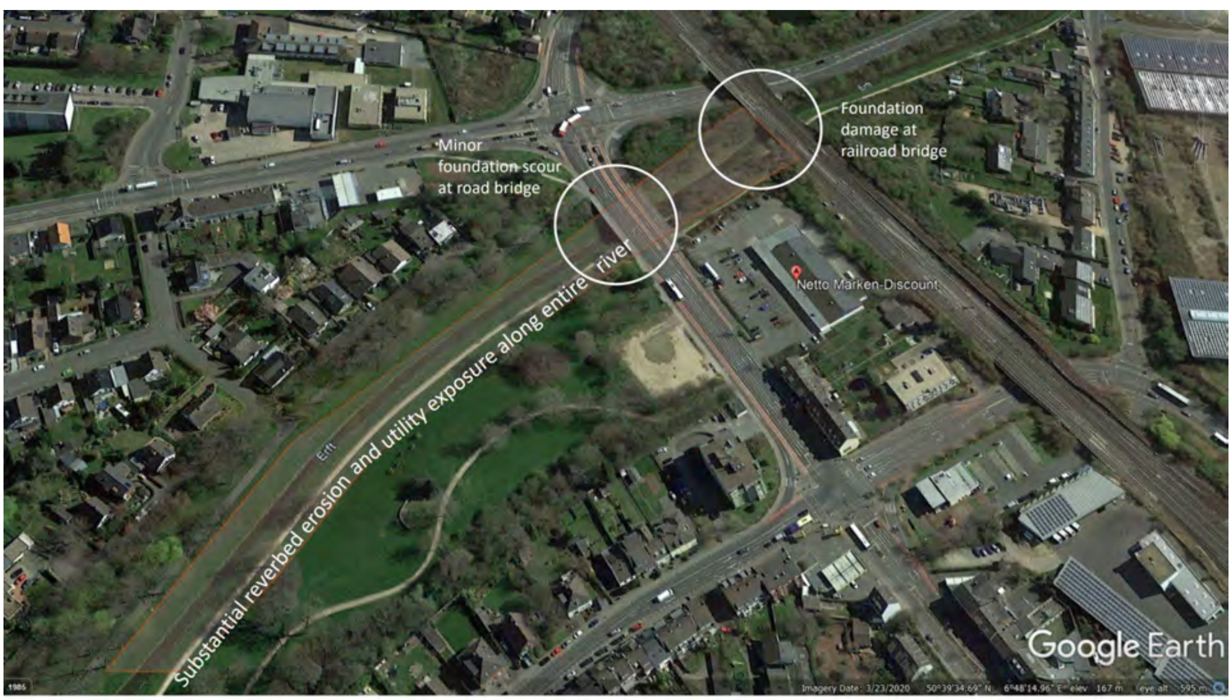


Figure 3.19. Erft river in Euskirchen with three areas of damage documented by the reconnaissance team.

Figure 3.20 shows the foundation damage at the railway bridge. The middle pier appeared to be supported by a cofferdam foundation, which experienced severe scouring and erosion. The riverbanks were also eroded and partially refilled by contractors on site.

Figure 3.20. Foundation damage at middle pier of railway bridge (50.660347, 6.805227)

Figure 3.21 shows the road bridge from an upstream location. Exposed utility lines are shown to the left, severe river erosion is visible on the right. The connection between the bridge foundation area and the existing river soil (i.e., the rip-rap region) was substantially damaged, several parts of the rip-rap were relocated downstream.

Figure 3.21. Scour damage at the foundation level of the Road bridge across the Erft @ Kölner Strasse (50.660347, 6.805227).

Further downstream and along a small park, the Erft riverbanks showed significant erosion with clear erosion scarps, as well as exposed utilities (Fig. 3.22). The erosion scarps revealed vegetation grown on about 10-30 cm of topsoil over an approximately one meter thick, rocky soil layer (possibly historic fill) over finer grained and muddy river bed sediments (Fig. 3.23). Flood waters reached well into the river-fringing park. Mostly organic debris accumulated around tree bases, and more interestingly coarse sediment accumulations stretched meters towards the downstream direction of the trees, sometimes topped with fine river sands (Fig. 3.23 (right) and Fig. 3.24). The deposits showed similarities to the dune accumulation from lee-wake vortices and scour in unidirectional flow conditions.

Figure 3.22. Riverbank erosion along the Erft river near Kölner Str in Euskirchen (50.661315, 6.8048277)

Figure 3.23. Left: Close-up of eroded Erft riverbank scarp. Right: Organic debris and gravel deposits around trees (50.6628713, 6.8038167).

Figure 3.24. Fine sediment on coarse sediment deposition stretched meters in the downstream direction from trees, particularly when organic debris was wrapped around the tree base (50.6628713, 6.80381670).

3.1.2.7. Euskirchen: Bridge across the river Erft @ Erftstraße

The bridge on Erftstrasse crossing the Erft was blocked for any car sized vehicle traffic at the time of the team visit. The bridge was missing one of its supporting elements which appeared to be an abutment wall; the remaining pier experienced substantial tilt (50 cm of horizontal movement below the bridge girder), only poorly supporting the bridge on an edge. The bridge had consequently sagged, but not failed. Before-After imagery obtained from Google maps is shown in Figure 3.25.

Figure 3.25. Bridge Crossing before flood per Google maps (left), Bridge after flood at time of teams visit (right). (50.6668240, 6.7988197)

Residents reported that people had still driven personal car size vehicles over the sagged bridge before it was blocked. Scour development was visible at the river center side of the still standing pile and of the missing pile. Interestingly, deposits seemed more prominent on the riverbank side of the piles, instead of a traditionally expected upstream/downstream focused differentiation of scour evolution. Erosion at the abutments suggests that the river may have risen to or beyond the bridge deck height, raising the question if flotation of the bridge deck may have contributed to the structural response, and specifically the loss of the bridge abutment structure and shift of the other. Erosion on the riverbank side of the lost abutment wall appeared more severe than on the other side where soil cracks suggested that a larger riverbank failure would have occurred soon, but eventually did not happen, likely also being related to the loss of the bridge abutment structure on the heavily eroded side versus the shifted bridge pile on the lesser eroded bank side.

Figure 3. 26. Erft river bridge on Erftstrasse. Top left) Overview of damaged bridge highlighting severe erosion on the left riverbank side and the total loss of a bridge pile on the same side. Top right) Larger context of the shifted bridge pier showing distinct scour at the river center side and deposition on the riverbank side. Bottom left) Shifted and tilted bridge pile with gravel deposits on its river bank side, minor erosion at the foundation of the abutment and river bank erosion aligning well with the bridge abutment. Bottom right) Aerial image of the scene revealing river bank near gravel deposits. (50.666831, 6.798996)

Figure 3.27. Shifted and tilted bridge pier with team member J. Stamm for reference (left). Horizontal movement of pier at deck interface (center), tilted support pier (right). (50.6668317, 6.7989968)

3.1.4. Samples collected

Soil samples were collected in Bad Münstereifel (BM) from within a parked car (Table 2.3), thus, representing sediment loads carried within the flood waters (BM1), from an eroded riverbank location near the Werkbrücke (BM2), and from within the Erft river in Bad Münstereifel downtown (BM3; Table 2.3). Sieve analysis and Atterberg tests were conducted for BM1. Limited soil material allowed Atterberg tests only for BM2, and sieving was only performed on BM3. For BM1, sieve analysis suggested 63.31% fines, 35.5% sand, and 1.2% gravel. Atterberg testing suggested a liquid limit of 35, a plastic limit of 28, and a plasticity index of 7. BM2 yielded a liquid limit of 54, a plastic limit of 35, and plasticity index of 19. BM 3 featured a median grain size of 3.76 mm with 0.11% fines, 93.7% sand, and 6.3% gravel, and with a coefficient of uniformity of 8.3 and a coefficient of curvature of 0.93. Water content measurements were taken with a Dynamax moisture gauge yielding w = 41% directly by the water, 30% at a distance of 50 cm away from the river, and approximately 1% near the road.

In Euskirchen, samples were collected from the Erft river bank at the Kölner Strasse (E1), from a tree in the park along the Erft (E2), from another tree in the park along the Erft (E3), and from the Erftstrasse bridge (E4). For E1, sieve analysis suggested 25% fines, 74% sand, and 1% gravel with a median grain size of 0.132 mm. For E2, sieve analysis yielded 39% fines, 60% sand, and 1% gravel with a median grain size of 0.090. Atterberg testing showed a liquid limit of 29, a plastic limit of 24, and a plasticity index of 5. E3 was characterized by sieve analysis by 1% fines, 95% sand, and 4% gravel with a median grain size of 0.98 mm, a coefficient of uniformity of 5.13, and a coefficient of curvature of 1.01. A replicate sample confirmed these measurements. Sieve analysis of E4 yielded 25% fines, 74% sand, and 1% gravel with a median grain size of 0.125 mm.

Figure 3.28. Team member N. Stark during sample collection in the Erft river in Bad Münstereifel's city center (50.556031, 6.7651736)

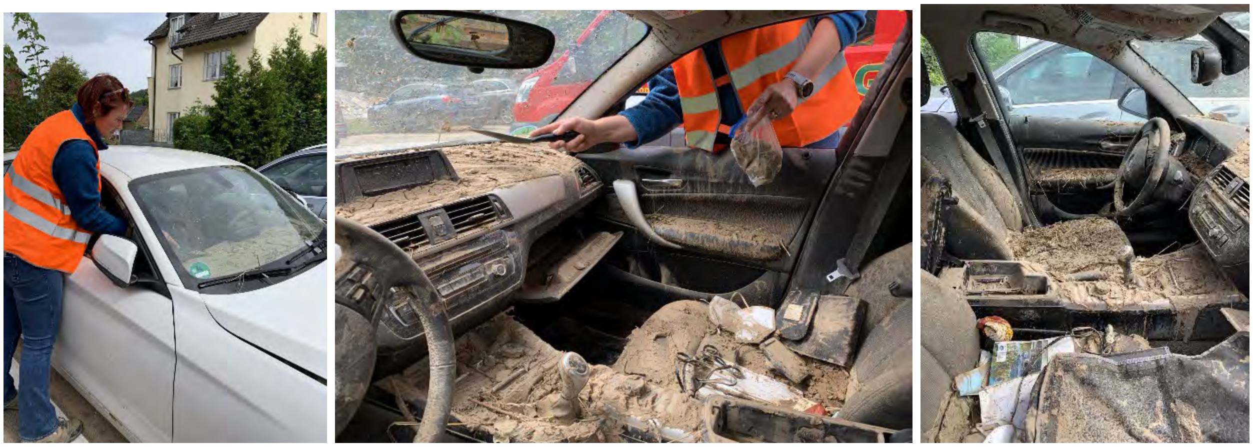


Figure 3.29. Team member N. Stark during sample collection from within a parked damaged car in Bad Münstereifel (50.5513042, 6.76283450)

3.2. Day 2: Erfstadt-Blessem & Surroundings, Steinbachtalsperre

Table 3.2 shows an overview of places visited during the second reconnaissance day. The team visited Blessem, a town which is under the official jurisdiction of Erftstadt. The village of Blessem lies immediately to the right of the dyked Erft across its floodplain. The federal highway (Bundesstrasse) B265 runs along the eastern edge of the village, the autobahn A1 along the western edge. Between July 14 and 16, 2021, heavy precipitation and resulting flooding inundated the village of Erftstadt-Blessem and an open-pit gravel mine located to the north of it. Among other things, this led to severe soil erosion between the Blessem open pit mine, the Blessem district and the Erft River, with considerable damage to buildings on the outskirts of Blessem and the Autobahn intersection A1/A61. The A1 and the A 61 meet near the village at the Erfttal interchange. The freeway intersection was closed at the time of the team's visit and remains closed for construction and repair work until summer 2022. Figure 3.30 shows the location of Erfstadt-Blessem and highlights the heavily flooded and destroyed area around the Blessem gravel mine, and adjacent to the Autobahn A1.

Table 3.2. Visited places with applied methods and GPS-coordinates

Town	**Visited Places**	**Applied methods**	**GPS-coordinates**
Blessem (Erftstadt)	Radmacherstraße	- Drone images - SfM models	50.813556; 6.794965
	Gravel mine	- Drone images	50.818171; 6.794562
	Autobahn A1/A61 intersection	- Drone images	50.813551; 6.788993
Bliesheim	Bridge	- cellular photography	50.782199; 6.822505
Euskirchen	Steinbachtalsperre	- Drone images - Lidar	50.594124; 6.838211

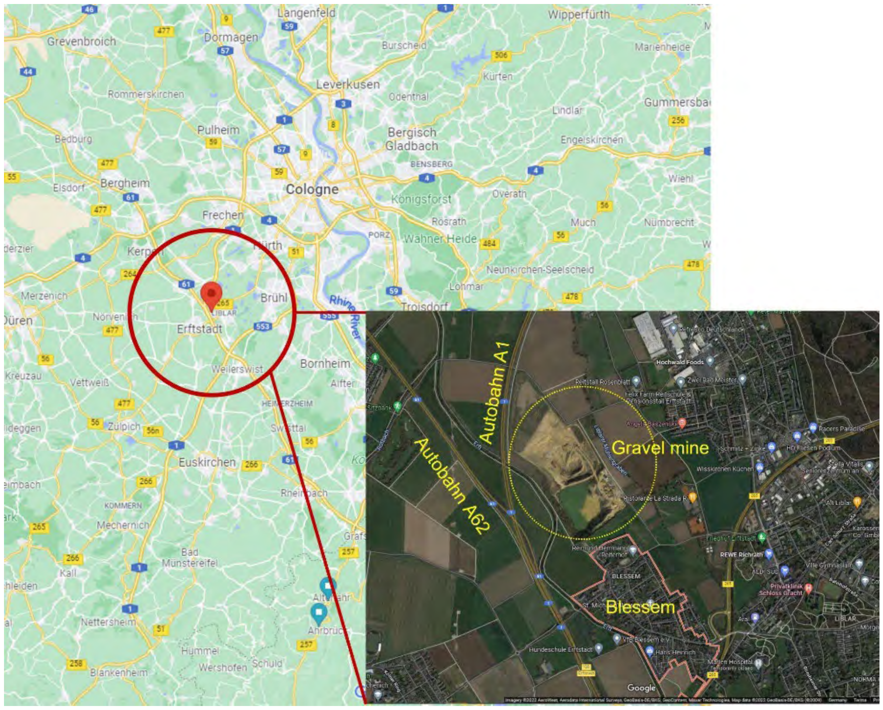


Figure 3.30. Location of Erftstadt Blessem (left) and enlarged view of geographic placement within the vicinity of the Autobahn A1/A62 and the Blessem gravel mine

3.2.1. Blessem - Radmacher Strasse

The Rademacher Strasse (Rademacher street) and the Frauenthaler Strasse (Frauenthaler street) were immediately adjacent to the floodplain and formed the edge of the “landslide crater” formed from the gravel mine. The gravel pit is located in the center of a floodplain, a landscape conservation area, is tangential to a drinking water protection area, and ends not far from residential buildings. The gravel pit filled with water in the night from July 15th to July 16th, destabilizing surrounding soil and triggering “landslide” scale erosion towards the gravel pit. The surrounding, highly permeable soils slipped towards the gravel pit, forming a canyon-like landscape following the water withdrawal. Figure 3.31 shows the aerial extent of the gravel pit and the extent of the flooded and destroyed area which experienced landslide-scale erosion. Figure 3.32 shows a flood map of the region obtained from Copernicus, depicting the extent of all flooded areas around Blessem.

According to government officials (Bezirksregierung Arnsberg), immediately after the flooding, the first safety measures were taken to avert further dangers. The city of Erftstadt secured the embankments on the outskirts of Blessem. To prevent further water from entering the erosion area and the open pit mine, the Erftverband restored the actual course of the Erft River. For the open pit, the mining authority immediately convened an ad-hoc working group to initiate appropriate safety measures together with the gravel pit operator and experts. The Erftverband developed a secondary floodplain concept to rehabilitate and redesign the erosion area, to create a retention area and to improve flood protection.

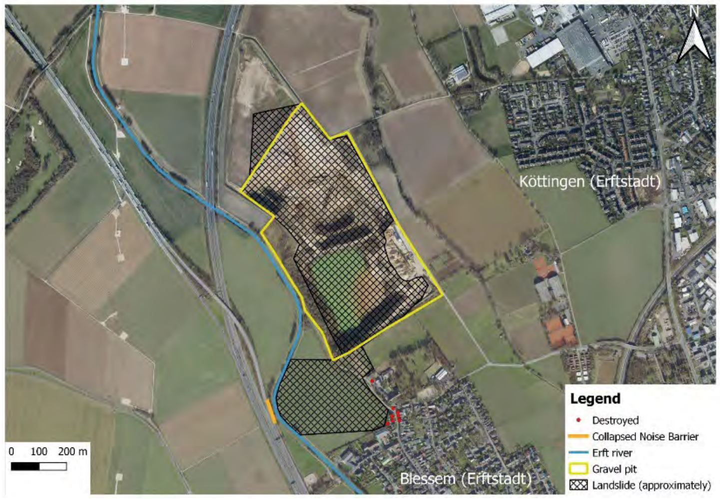


Figure 3.31. Overview Map of flood and landslide damage in Blessem (Erftstadt)

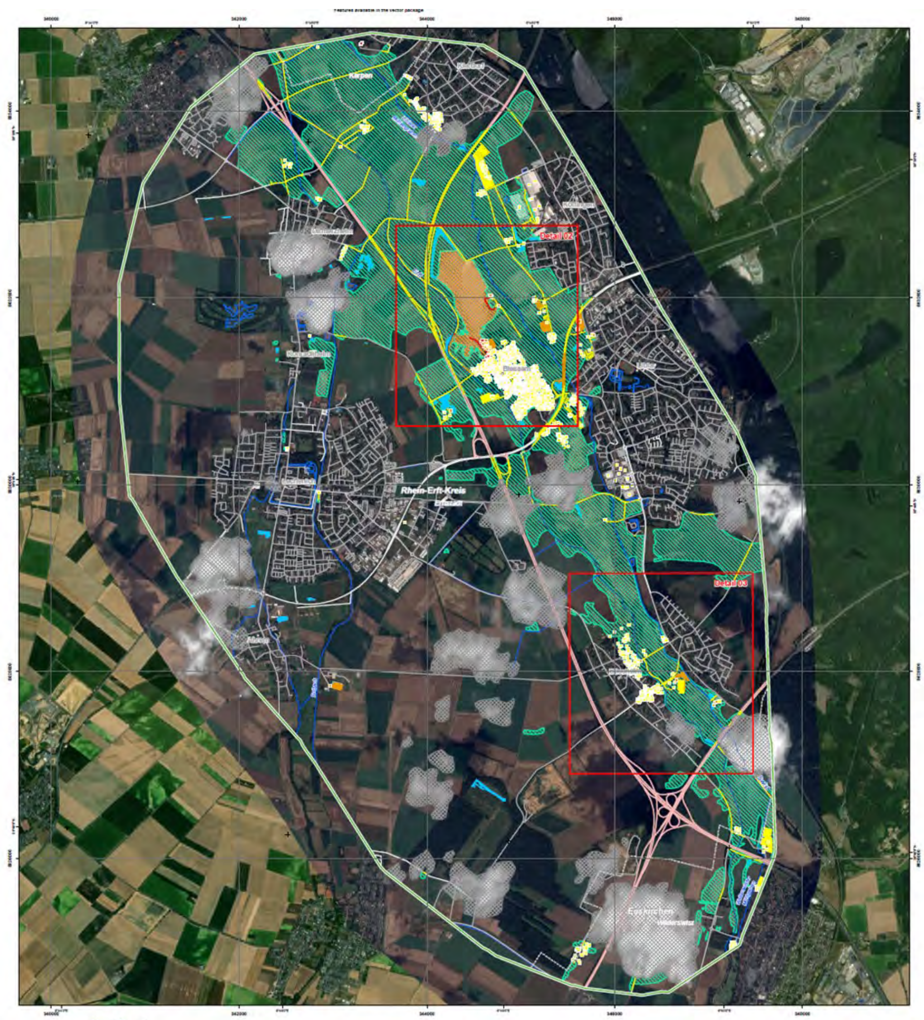


Figure 3.32. Flood map Source: Copernicus, green shaded region indicates flooded areas

Figure 3.33 depicts photographs of the location “Radmacherstrasse”, which approximately represents the boundary of erosion. Figure 3.33 left shows the water flowing towards the gravel mine, Figure 3.33 bottom shows the damage to residential buildings upon water retrieval. Aside from severe residential damage and destruction, all utility networks were eradicated.

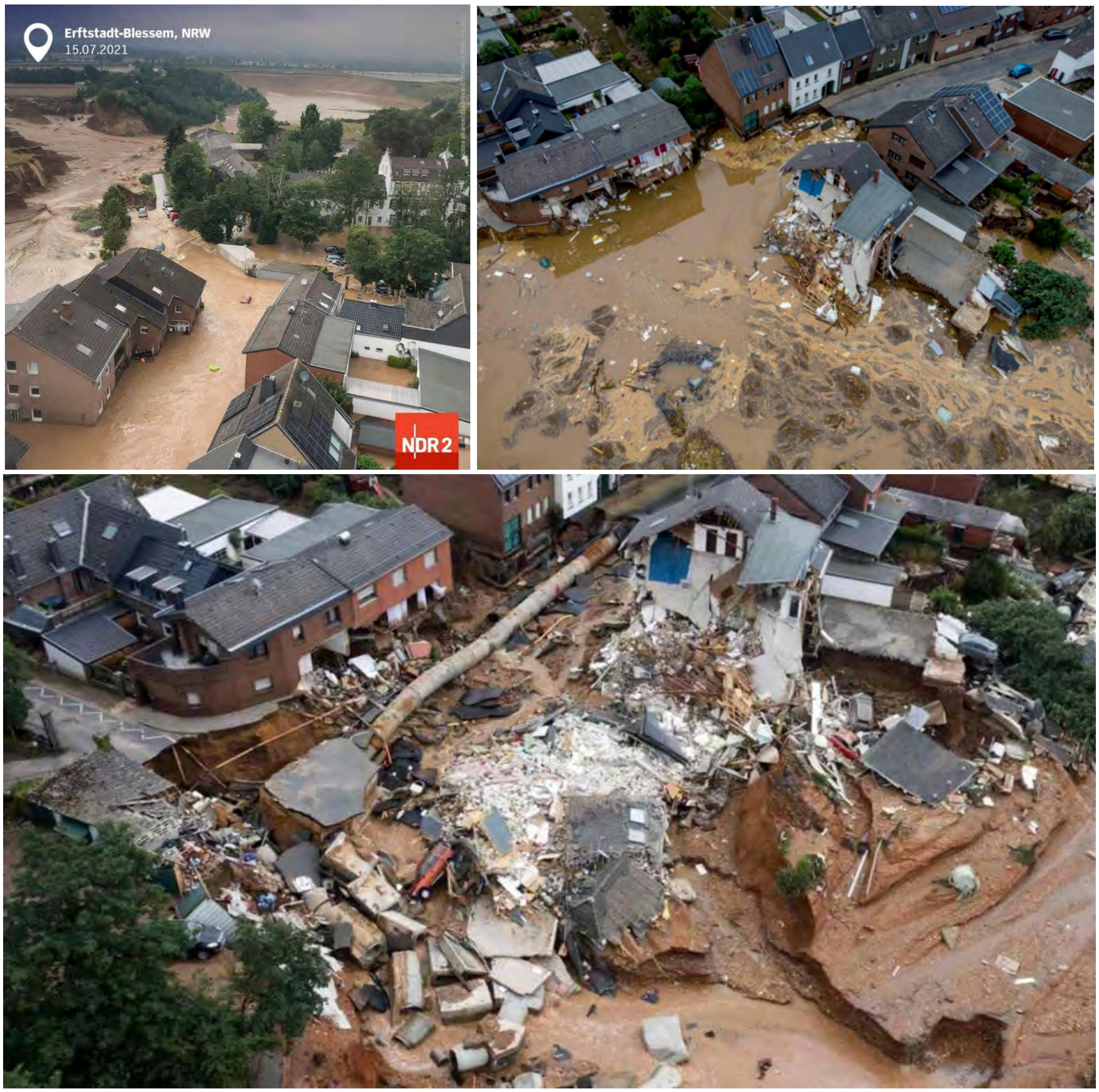


Figure 3.33. Flood extent (top left) and damage to the area surrounding Radmacherstrasse in Blessem. Source: https://www.facebook.com/NDR2/photos/pcb.10158168188895222/10158168178100222/?type=3&theater, Top Right: https://www.dw.com/en/german-floods-climate-change/a-58959677; Bottom: https://www.krone.at/2590810#fb-10555-df2b71f6-1

The flooded and eroded area surrounding the gravel pit is shown in Figure 3.34. Figure 3.35 shows before and after aerial photographs depicting the landscape near the residential area.

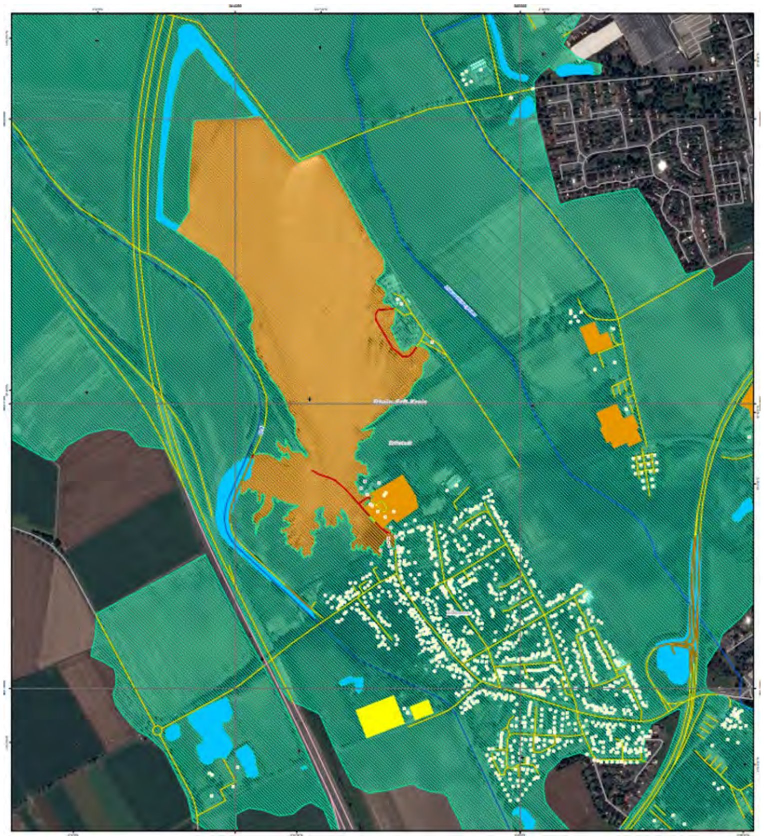


Figure 3.34. Flooded and eroded area around gravel pit. Eroded areas in brown shade and flooded areas in green. Source: Copernicus

Figure 3.35. Before and after photos (source: https://reportage.wdr.de/hochwasser-nrw-vorher-nachher-fotos#chapter-140)

Figure 3.36 shows the corner Radmacherstrasse in Blessem on August 10th, the day of the teams visit. A large amount of debris was being removed by onsite construction equipment. The UAV photograph shows the corner house (still visible in Figure 3.33) in the process of being demolished. The UAV image in Figure

3.37 also shows the large, exposed wastewater and storm drain networks, and significant soil erosion depths.

Figure 3.36. On-site situation on August 10th, 2021 (50.813582, 6.7950140)

Figure 3.37. UAV image of the reconnaissance team standing at the edge of the Radmacherstrasse, exposed utility networks underneath the street (50.813582, 6.7950140).

The Erftverband developed a secondary floodplain concept to rehabilitate and redesign the erosion area, to create a retention area, and to improve flood protection (Bundesregierungsanstalt, NRW, 2021). Figure 3.38 shows the rehabilitation plan. In the first section of the project (A), the area between the Federal Highway 1 and the Erft River is to be lowered by approximately one meter to serve as a retention area, i.e., as a safe flooding area in the event of possible floods. In the second section (B), the deep cut in the terrain created by the flood between the northern edge of Blessem, the Erft and the open pit is to be filled in again, and the southern slope of the gravel pit is to be restored. As a third section (C), the new "secondary floodplain" is to be extended around the current settling basin as an additional flooding area as part of the recultivation of the open pit. Extensive backfilling is required for this. (Bundesregierungsanstalt, NRW, 2021).

Figure 3.38. Rehabilitation plan with various sections for the remediation of the floodplain areas, source: Bundesregierungsanstalt, NRW, 2021

3.2.2. Blessem, Gravel mine

The reconnaissance team was able to visit the gravel mine and walk inside the open-pit facility. At the time of the visit, water had returned to regular water elevations. Substantial erosion was observed along the pit slopes (Figs. 3.39 – 3.41)

Figure 3.39. Inside the Blessem gravel mine, looking towards Blessem town and the inflow area (left) (50.818468, 6.794142)

Figure 3.40. Reconnaissance team atop slop failure in the gravel mine (50.818468, 6.794142).

Figure 3.41. Left: Damage to asphalt gravel roads; Center: Soil cracks possibly indicated deeper seated slip surfaces; Right: Water levels of the gravel pit at the time of the team visit (50.818468, 6.794142).

3.2.3. Blessem, Autobahn damage

From the Bliesheim interchange to the Bergheim Süd junction, the Erft approaches and flows close to the highway A1. Its flood waters have washed out the roadway and caused noise barriers to collapse along a stretch of almost 100 m. The entire asphalt, as well as part of the subgrade material, the shoulder lane and the right-most driving lane between the Erfttal interchange and the Bliesheim interchange suffered irreparable damage and need to be renewed (AUTOBAHN RHEINLAND, 2021). Figures 3.42 and 3.43 show aerial photographs obtained from google maps, documenting the flood extent, and damage to the Autobahn. The aerial photograph in Figure 3.44 also indicates the original course of the Erft river.

Figure 3.42. Aerial photograph of flooded fields and flooded gravel pit adjacent to the freeway A1/A62

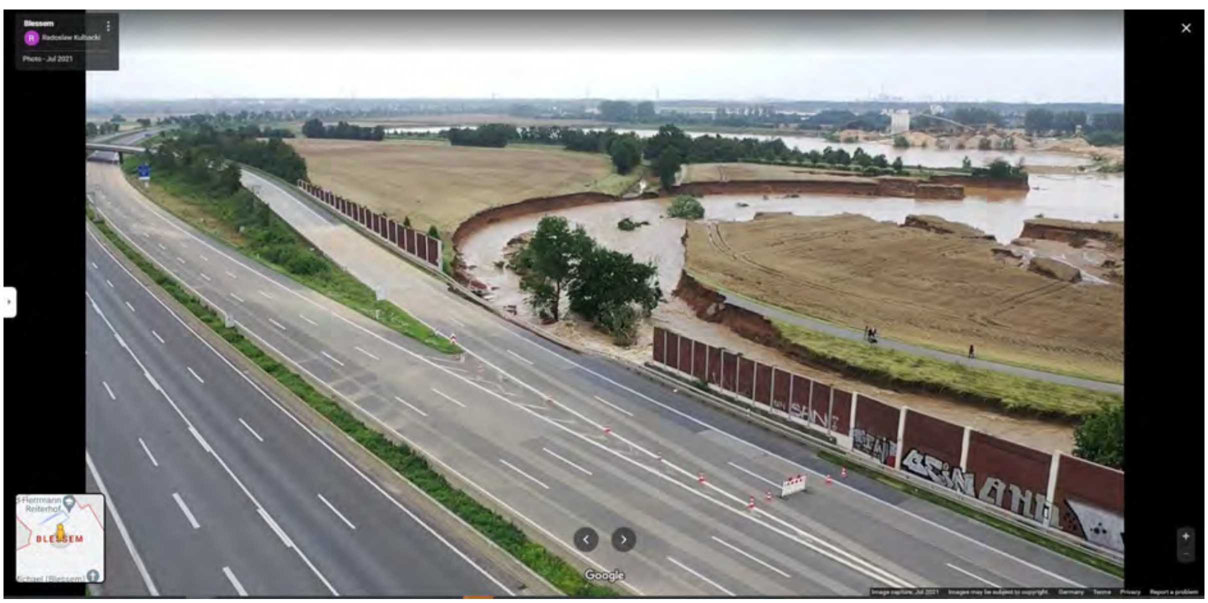


Figure 3.43. Aerial photograph showing damage to embankment and noise protection wall along freeway A1.

Figure 3.44 shows an aerial view before and after the flood event. The highway can be seen on the left edge of the image.

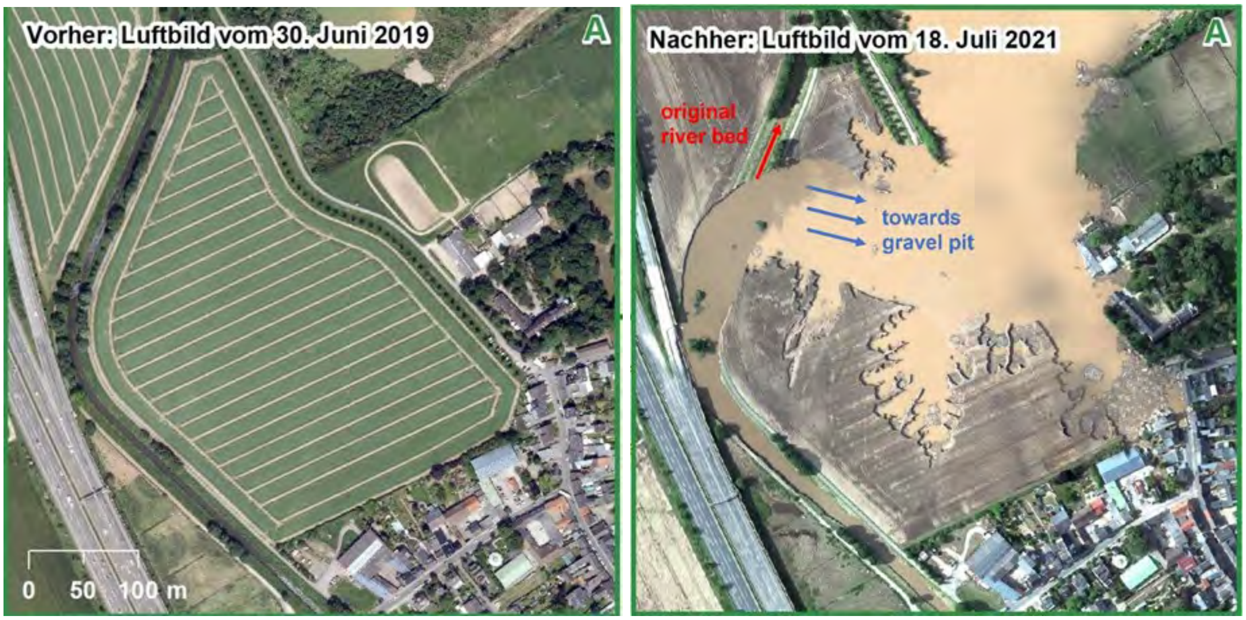


Figure 3.44. Pre-event aerial view (06/30/2019) (GEOBASIS- DE/BKG, 2021) [left] , Post-event aerial view (07/18/2021) (HS KOBLENZ, 2021) [right]

Screen Footage capturing the failure of a noise barrier wall along the A1 Autobahn on July 16th, 2021 is shown in Figure 3.45. Figure 3.45 also depicts the scouring and erosion underneath the freeway shoulder and lane.

Figure 3.45. Failure of noise barrier wall, captured on video, Source: https://www.welt.de/vermischtes/article232546283/Hochwasser-in-Erftstadt- Standstreifen-der-A1-bricht-ab-und-stuerzt-in-die-Erft.html

Figure 3.46 includes an aerial view of the of the damage along the A1/Erft. The pedestrian walkway/bicycle path shown to the right was completely damaged.

Figure 3.46. UAV photo taken during team's visit on August 10th, 2021(50.8134771, 6.7890135)

As one of the first measures after the flood event, the German military (Bundeswehr) built a temporary dam made of big bags filled with gravel in the new riverbed of the Erft (Figure 3.47). This dam was significantly reinforced later. In the meantime, water from the newly created riverbed of the Erft has already started to be rerouted (see Figure 3.47) to its old riverbed (see red arrow Figure 3.47) (MRASEK, 2021). The goal of this measure is to stop the inflow to the gravel pit (see blue arrows Figure 3.44) and thus prevent further erosion, which should also prevent further damage to the highway (MRASEK, 2021). The highway was completely closed after the flood and the reconstruction of the roadway was started on October 12, 2021 (EPA, 2021).

Figure 3.47. Aerial view of temporary dam and river rerouting by the Blessem fire department (50.8134771, 6.7890135).

Figure 3.48. Aerial view of damage around gravel mine on August 10th, 2021 (50.8134771, 6.7890135).

3.2.4. Bliesheim, Bridge

The team visited the bridge Merowingerstrasse, Bliesheim-Erftstadt crossing the Erft River (Fig. 3.49). At the time of the visit, the bridge was still closed to vehicle traffic, but accessible by foot. Cleaning up and repair work had already started here addressing erosion that led to damage to the pedestrian path on the bridge and cobble stone-based soil stabilization on the riverbank slope between the abutment and the bridge pier (Figs. 3.49 and 3.50). From the damage and erosion, it appears that significant water flow occurred from the bridge deck onto the riverbanks and into the Erft, eroding materials in its path.

Figure 3.49. Photos of the Merowingerstrasse bridge across the Erft river in Bliesheim-Erfstadt. Left) Flowpaths and erosion was visible parallel to the bridge down the riverbank slopes. Right) Soil erosion on the riverbanks near the bridge abutments and piles and possibly removal of cobble slope reinforcement between the abutment and the pile are visible (50.782199; 6.822505)

Figure 3.50. Erosion suggested flow from the road down the riverbank's slopes created damage to the pedestrian path of the bridge section connecting with the riverbanks (50.782199; 6.822505).

3.2.4. Steinbachtalsperre, Euskirchen

The Steinbachtal dam ("Steinbachtalsperre") (Fig. 3.51) is located in Euskirchen, NRW, with a height of 23 m, a length of 240 m, and a crest width of about 5 m. The dam volume is estimated at 100,000 m^3 and the total capacity of the reservoir is 1.2 million m^3. The original dam construction started in 1934 with completion in 1936. The original dam purpose was to meet the local water needs that recently increased from the local textile industry. The dam was updated at the end of the 1980s with recommissioning in 1990.

The reservoir and spillway capacity was insufficient to accommodate the July 2021 flood event, leading to overtopping of the dam for a duration of about three hours. Additional blockage of the spillway made the situation more dire. Severe erosion occurred on the downstream side of the dam from the overtopping (Fig. 3.51). This represented an increased risk for dam failure under the continuing load from the flood, leading to the immediate evacuation of multiple communities downstream of the dam. First responders were able to remove the blockage, increasing controlled outflow again, and pumped water out of the reservoir. The dam did not fail, and the evacuation was lifted after five days. The presence of the hardened asphalt road across the length of the dam crest prevented down-cutting and likely prevented total failure of the dam. Additionally, the crest of the dam was relatively flat, as shown in a section through the SfM model in Fig. 2. 4, and further evidenced in the relatively evenly distributed eroded gullies across the downstream face, as shown in Fig. 3.51. This likely prevented significant concentration of flow. The eroded gullies on the downstream face of the dam exhibited a step-pool geometry caused by hydraulic jets plunging from step to step. This is a typical erosive pattern in more cohesive material.

Figure 3.51. Steinbachtalsperre; Top: before the flood event (top: https://honnef-heute.de/steinbachtalsperre-unkritischer-wasserstand-erreicht-evakuierungsmassnahmen-aufgehoben/), immediately after the event (top right, Source: https://www.24rhein.de/rheinland-nrw/hochwasser-euskirchen-rhein-sieg-kreis-steinbachtalsperre-trinkwasser-keime-katastrophenfall-90865213.html), and after water release (bottom, photo by David Young/dpa, Source: https://www.tag24.de/thema/hochwasser/steinbachtalsperre-drohte-beim-hochwasser-zu-brechen-jetzt-laufen-hier-krisen-besucher-durch-2075576).

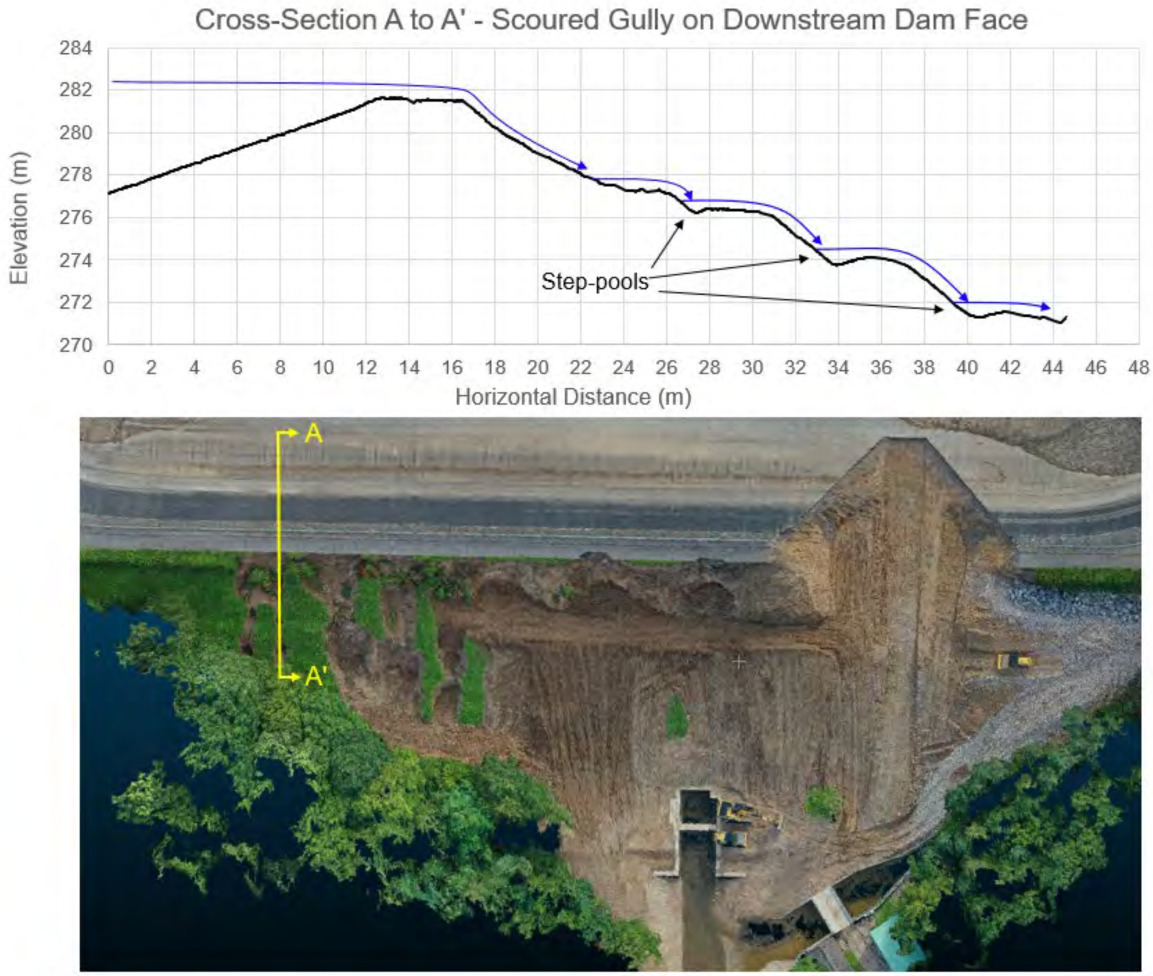


Figure 3.52.Cross-section of scoured gully on the downstream face of the Steinbachtalsperre showing step-pool geometry. Cross-section developed from the SfM model.

At the time of the team visit, active repair of the dam was ongoing with a completely emptied reservoir. Particularly, the spillway section of the dam was removed and under reconstruction (Figures 3.53 – 3.54). Deep erosion channels were identified by the GEER team members downstream of the dam.

Figure 3.53. Left: Open cross-section of the Steinbachtalsperre during the team visit when repair was ongoing. Right: Reservoir-side view of the removed center part of the dam (50.594124; 6.838211).

Figure 3.54. Photograph of empty dam at time of the team's visit (50.594124; 6.838211).

3.3. Days 3-5: Ahrtal Part A: Wednesday – from Müsch to Altenahr (tunnel entrance)

3.3.1. Preface

The Ahrtal was still difficult to access due to first responder work and crucial repair work of lifelines from the communities of Mayschoss to Bad Neuenahr-Ahrweiler. Frank Heuser, a representative of the local authorities located in Bad Neuenahr-Ahrweiler and actively involved in response with focus on the local wastewater systems, met with the team and took a subgroup of 4 members to selected sites in the Ahrtal of which he provided additional background information. Observations from this initial visit on Tuesday, August 10th are not presented separately, but are included in the following sections about the Ahrtal, which were collected by all team members during Wednesday, August 11th - Friday, August 13th, 2021.

The reconnaissance team would like to acknowledge Frank Heuser specifically for his time and effort in support of the team's data collection. He assisted immensely with the identification and data collection of special sites of interest in the Ahrtal.

Figure 3.55 shows a map of towns along the Ahr river. The team began their visit in Müsch and worked through Schuld and all Ahr-neighboring towns towards Altenahr. Table 3.3 lists the specific damage and observations documented in this chapter.

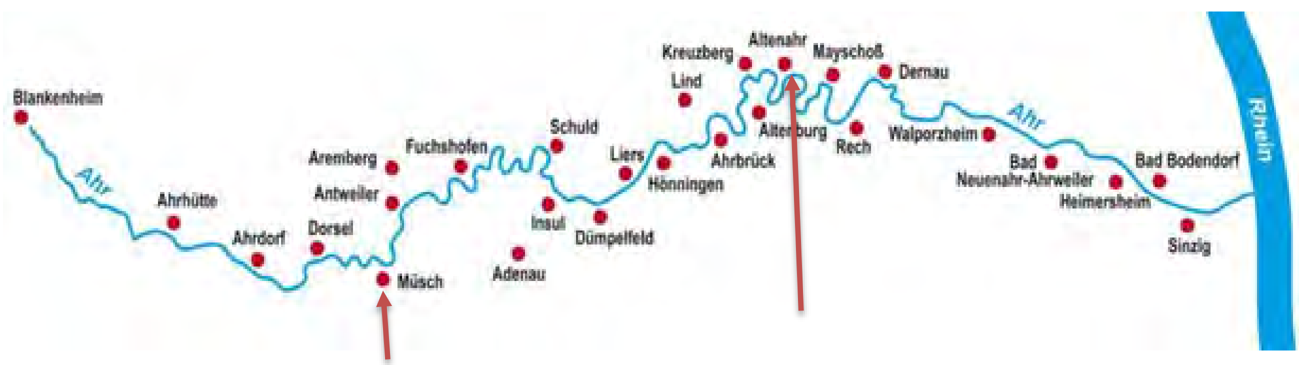


Figure 3.55. Towns along the river Ahr visited on Day 3 (Müsch to Altenahr)

Table 3.3. Locations and coordinates of documented damage and other observations from: Müsch to Altenahr Tunnel Entrance

Town	Places visited/documented	Data collected with:	GPS coordinates
Muesch	Bridge at Town Entrance	Photos	50.387694, 6.827253
Fuchshofen	Embankment damage & Repair	Drone & on-site photography, interview with on-site construction crew	50.4299573412811, 6.85018737167022
Wershofen L73/L74 intersection	Bridge at inflow of Laufenbach into Ahr river	Photos	50.43284065777638, 6.858008878155796
Schuld	Schuld: town entrance area, bridge and road damage	Photos	50.447020389365676, 6.875312978897658
Schuld	Town Center	Photos	50.44592437838917, 6.887536079823383
Hoennigen/Brueck	Bridge near Campingplatz Leuer, between Hoennigen and Brueck	Photos	50.48074785416399, 6.970032437760903
Liers	Bridge at Joseph Emmerich Strasse, Residential Damage and destroyed floodplains	Photos Lidar	50.456871011298446, 6.9458676236669765
Brück (Ahrbrück)	Road Bridge across the Ahr,	Photos	50.48672669963366, 6.971406624343253
Pützfeld (Ahrbrück)	Campingplatz Gut Puetzfeld, Bridge at Campground	Photos	50.494205, 6.983025
Altenahr	Rail Bridge near town entrance along B267	Photos	50.512523, 6.983989
Altenahr/ OT Altenburg	Bridge near St. Maternus Kapelle	Photos	50.511551, 6.985069
Altenahr	Rail Bridge at Campground Altenahr	Photos	50.51501148556613, 6.986271382745565
Altenahr	Town Center, Damaged buildings	Photos	50.516555, 6.989286
Altenahr	Camping Altenahr	Photos	50.5136747988638, 6.986920955192656
Altenahr	Bridges and area around tunnel entrance	Photos	50.51634074353249, 6.995542077602541

3.3.1. Müsch

Müsch is located near the entrance to the Ahr valley, at the intersection of Bundestrasse B258 and the Ahrstrasse (L73), the primary road leading into the Ahr valley. Muesch has nearly 200 inhabitants; most of them were mildly affected by the flood according to local information available at the town's homepage. Figure 3.56 shows the road bridge at the intersection of B258 and L73. This bridge experienced no damage and appeared structurally and visually intact.

Figure 3.56. Road Bridge across the Ahr at the intersection of B258 and L73; Top: before flood event (picture credit Heinz Grates, via https://www.aw-wiki.de/w/index.php?curid=67214); Bottom: Post flood on August 9th, 2021(50.385609, 6.827283)

Figure 3.57 shows road damage along the Ahrstrasse, immediately following the B258/L73 intersection, which included damage to the shoulder and curb, as well as substantial erosion of the river embankment. Figure 3.57 (top right (before) and bottom (after)) shows a severely damaged road bridge across the Ahr. The abutment structure on the downstream side has been completely removed by the flood, leading to collapse of the bridge deck.

Figure 3.57. Road and Bridge damage in Müsch. Top left: Road damage along the L73, Top right: Bridge prior to flood, Bottom left: damaged bridge in August 2021, Bottom right: close up of missing abutment and collapse of bridge deck (50.385952, 6.8288141)

3.3.2. Embankment Damage in Fuchshofen

The local embankment failure shown in Figure 3.58 (top) was unique in that many of the damaged embankments observed in other regions were of historical design and did not include soil nailing. Failure likely occurred as a result of increased active earth pressure due to backfill saturation and insufficiently long soil nails (2-2.5m depth). Repair work was underway at the time of the team's visit and carried out by using 10m long soil nails, where the top row of pins will be driven into bedrock (personal communication with onsite contractors).

Figure 3.58. Localized Embankment failure in Fuchshofen and ongoing repair work (50.429957, 6.850187)

3.3.3. Wershofen: Bridge damage Laufenbach Creek Mündung-Ahr

The bridge in Wershofen was a critical crossing over the Ahr as the L73 road represents the only access road to Schuld from the upstream direction of the Ahr (Figure 3.59). The team was able to speak with local residents who worked alongside construction workers to reestablish access across the bridge. The last arch of the bridge as well as the bridge abutment was completely destroyed, as captured by the local resident and shared with the team.

Figure 3.59. Bridge at the intersection of the L73/L74 in the district of Wershofen before the flood event (Source: https://www.aw-wiki.de/w/index.php?curid=41580)

Figure 3.60 shows photographs taken on July 15th, after the first day and night of the extreme rainfall. Figure 3.61 shows several photographs of the adjacent floodplains in the vicinity of the bridge and along the river Ahr. Deep cuts are visible in the surrounding fields. Figure 3.62 shows an estimated water level rise just upstream of the bridge, estimates are based on debris and clothing visible in the trees following the flood as well as slope failures along the river.

Figure 3.60. Bridge damage in Wershofen (photo credit top and bottom left: local resident, anonymous; 50.432840, 6.858008)

Figure 3.61. Floodplains and deep surface cuts after water receding (50.433086, 6.857974)

Figure 3.62. Team members walking upstream of the bridge inspecting damage and debris deposits along the riverbanks (50.43275924, 6.85851324)

At the time of the team's visit the damaged area had been temporarily filled and compacted with soil by local contractors to allow for river crossing. Figure 3.63 shows photographs of the Wershofen bridge and its upstream and downstream areas. The upstream photographs shows the creek "Lauterbach" merging into the Ahr (Figure 3.63 top left), the downstream side shows the washed-out areas around the bridge and the flood plain (Figure 3.63 top right). The bridge was passable for vehicle and pedestrians, a missing bridge arch had been filled with soil.

Figure 3.63. Upstream (top) and downstream (bottom) side of the bridge showing fill soil in lieu of bridge arch (50.432840, 6.858008))

3.3.4. Bridge, embankment failure and intersection damage at the town entrance to Schuld ("Bikertreff Haus Waldfrieden")

The team visited the destroyed intersection at the entrance to the town of Schuld (Figure 3.64). This location was popular as motorcycle meetup. At the time of the team's visit, the intersection was stabilized with fill material after substantial erosion destroyed the road. Specifically, damage was caused by the creek "Armuthsbach", which is indicated in the bottom of Figure 3.65. The creek flows into the river Ahr through a small bridge with 2 narrow arches, as shown in Figure 3.66 left. As flood waters became too large for the discharge cross-section, the water flooded the surface road, eroding most infrastructure around the inlet.

Figure 3.64. Location of damaged area immediately outside Schuld

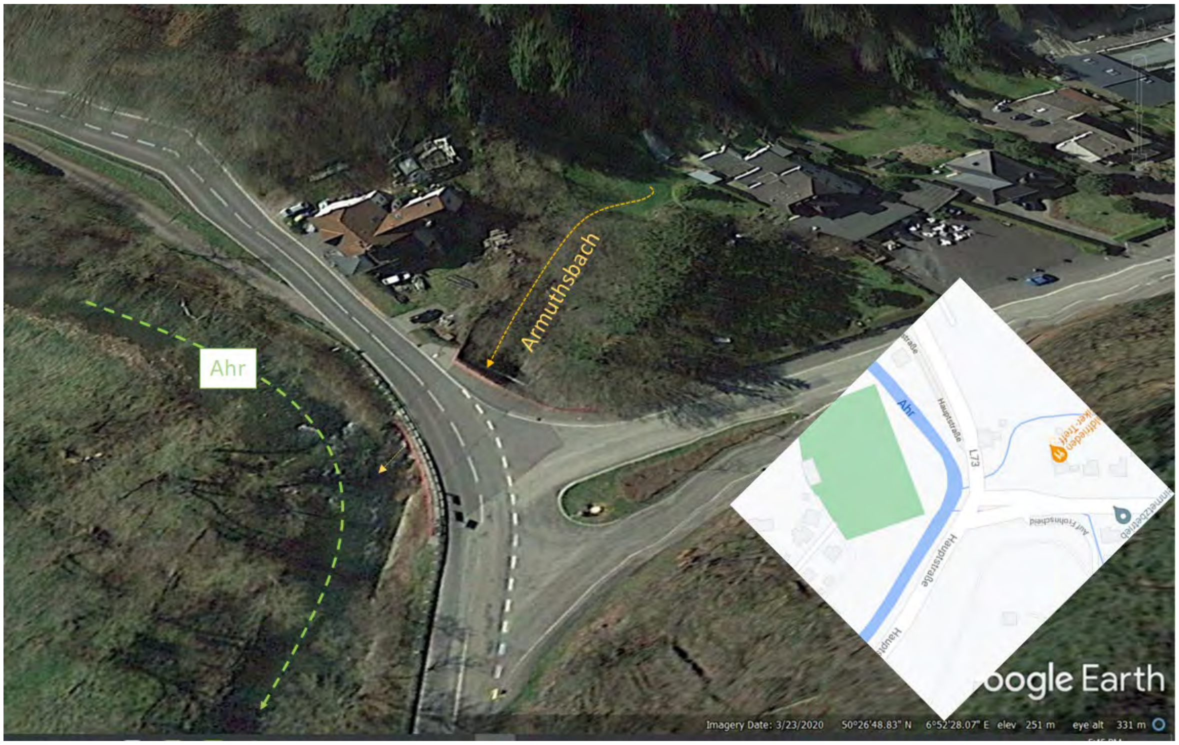


Figure 3.65. Location of merging point between Armuthbach creek and Ahr river

Figure 3.66. Bridge structure with 2 inlet arches (left), and destruction of surrounding areas; Dirt fill to re-establish road across bridge where waters have eroded the road and slope into the Ahr (right) (50.4470071, 6.8753387)

3.3.5. Schuld

Schuld is a village along the river Ahr with 660 inhabitants. Schuld experienced severe damage to infrastructure (roadways, bridges), residential housing, commercial business including business infrastructure, and utility/supply networks. Until October, residents needed to boil drinking water prior to consumption (SWR.de, 2021). Even though more than 70 people were missing immediately following the flood, no fatalities were reported in Schuld. Figure 3.67 shows a map of Schuld, including the walking path of the GEER team around Schuld on August 11th, 2021. Figure 3.68 shows before and after photos of the area highlighted in the map of Figure 3.67. The single residential house and the adjacent electricity building (white tower structure), serve as comparison points. Figure 3.69 documents the damage immediately following the flood.

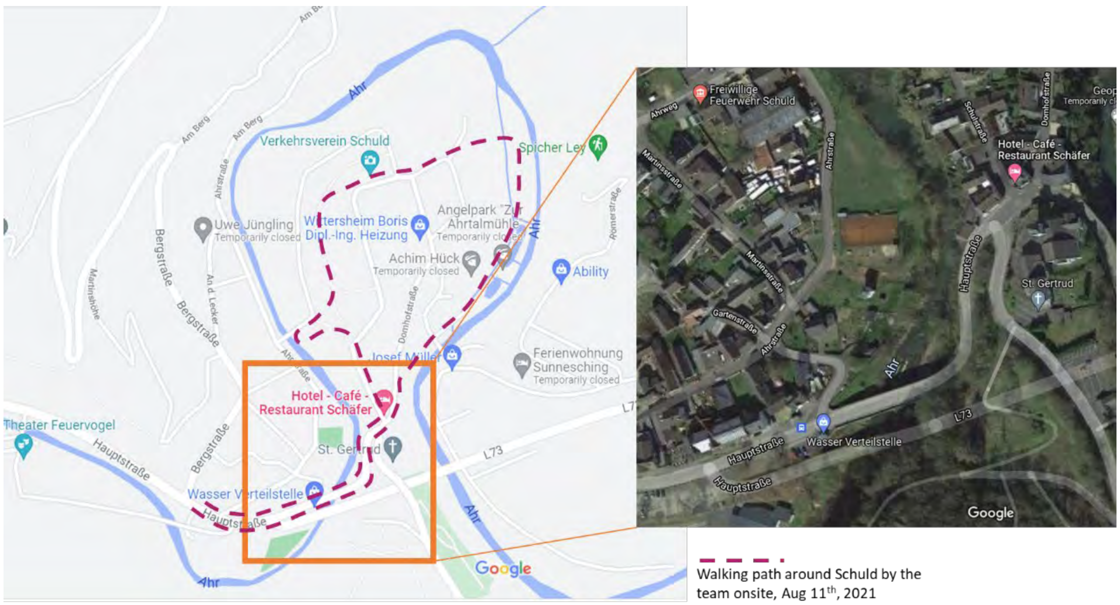


Figure 3.67. Map of Schuld with walking path, and excerpt of flooded area with available before and after photography (shown in Figure S2)

Figure 3.68. Aerial view, Schuld, showing town condition in September 2014 (left, Source google maps) and August 2021 (right, Credit: Roessler/dpa/Archivbild, accessed through: https://www.wn.de/nrw/merkel-kommt-in-hochwassergebiete-nach-rheinland-pfalz-2004374)

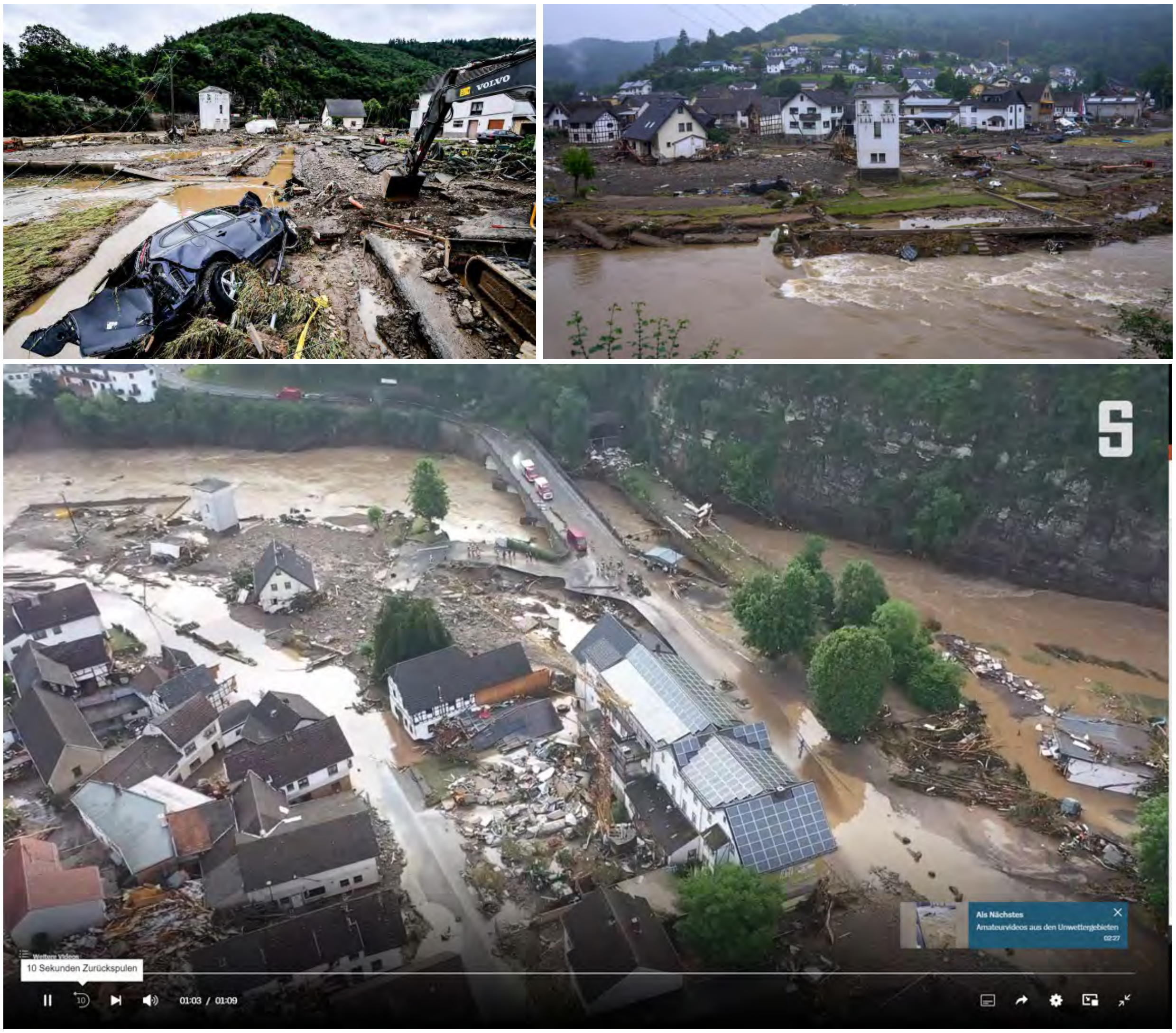


Figure 3.69. Photographs showing damage in Schuld immediately after the flood. Top left: photo by Spiegel.de (https://www.spiegel.de/panorama/wiederaufbau-nach-der-flut-im-ahrtal-wir-muessen-klar-sagen-dass-es-gefaehrlich-ist-a-dadc7d55-ff25-4d61-886f-cb994f4f6c96); Top right: photo by picture alliance/Getty Images (https://www.cnbc.com/2021/07/16/floods-in-germany-claim-81-victims-more-than-1000-missing.html), Bottom: Aerial view obtained from drone flight (SPIEGEL.de)

Figures 3.70 – 3.71 show several images along the walking path (marked in Fig. 3.67) of the GEER team. The photos depict the extent of soil erosion, exposure of utility infrastructure and much of the backfill placed for temporary stabilization, temporary dirt roads, and re-construction of the original riverbed.

Figure 3.70. Photographs of Schuld taken by the GEER team (50.44635960, 6.8871441)

The town of Schuld has a total of four bridges. Two bridges (both historic bridges) remained intact. At the time of the team's visit, diving inspections were underway to investigate potential damage to the bridge foundations. The road bridge across the Ahr (Hauptstrasse) remained open for vehicular traffic (Figure 3.71), the adjacent railroad bridge was closed in 2020, but remained in use for pedestrians only. The bottom right photograph of Figure 3.71 shows the road bride while standing on the former rail bridge into the tunnel prior to the flood event.

Figure 3.71. Top (left, right) and bottom left: historic road bridge along Hauptstrasse in Schuld, opened post flooding for regular traffic. Bottom right: view of road bridge prior to flood (source:google street view); (50.4459658, 6.8877725)

A smaller bridge, used as bicycle and pedestrian bridge along the Ahrstrasse was entirely washed away. This bride is called Stefansbruecke and is located along the Ahrbend (Ahrschleife) in Schuld. The team spotted remains of one of the abutment structures. Figure 3.72 shows the bridge prior to the flood for reference:

Figure 3.72. Stefansbruecke in Schuld, Photos by Heinz Grates, Source: https://www.aw-wiki.de/w/index.php?curid=67210

A fourth, historic bridge along Domhofstrasse (Figure 3.73) suffered severe damage but remained structurally intact. The bridge was reopened for pedestrian traffic at the time of the team's visit. Temporary scaffolding erected in lieu of the bridge deck allowed for bridge crossing. Figure 3.73a shows the bridge at Domhofstrasse prior to the flood. Figure 3.73 center shows the bridge one day after the flood, and Figure 3.73 bottom shows the bridge at the time of the team’s visit.

Figure 3.73. Top: Bridge along Domhofstrasse prior to the flood. (Fotos by Heinz Grates, source:https://www.aw-wiki.de/w/index.php?curid=35184), Center: Bridge at Domhofstrasse immediately following the flood, source: CNN on Facebook, Bottom: Bridge at Domhofstrasse on August 11th,2021 at the time of the team visit.), (50.4481131, 6.8901355)

Figure 3.74 shows close-up photos of the structural integrity of the bridge (top), along with the riverbanks in downstream direction of the bridge. Any slope stabilization and earth retention structures have been washed away or largely damaged. Figure 3.75 shows the high water marks from the flood event. The house is adjacent along the Domhofstrasse, adjacent to the bridge with temporary scaffolding.

Figure 3.74. Top: damage around the bridge superstructure, bottom: massive amounts of riverbank erosion and the temporary fill (bottom left); (50.4481131, 6.8901355)

Figure 3.75. Water levels near Domhofstrasse (50.4480798, 6.8898841)

In the upstream direction (of the bridge at Domhofstrasse), substantial erosion down to bedrock was visible. (Figure 3.76)

Figure 3.76. Substantial soil and rock erosion along riverbank (50.4482905, 6.890290)

Following the walking path of the team, substantial erosion and redeposition was also visible along the entire stretch of the river, consisting of mixtures of soil, rock, tree debris, and remaining trash. The fish hatchery located along the Ahrbend, which included three large fishponds was completely destroyed. At some locations along the river the THW placed filter tanks to separate oil and other contaminants from the water (Figure 3.77).

Figure 3. 77. Top: destroyed residential houses and dirt landscape along the river; Center: former fishery business (destroyed) (50.449709854, 6.8919458); Bottom: THW clean up and filtration tanks (50.4467077, 6.890212)

3.3.6. Liers

Liers is part of the municipality Hönningen. Some area of flood plains fringes both sides of the Ahr river, however several residential houses and one major business experienced severe flood damage.

Figure 3 78. Location of Liers, adapted from Google Earth

Figure 3.79 shows a satellite image of Liers. The extent of flood damage can be seen by the widening of the Ahr river and the adjacent mud-covered areas. Figure 3.80 shows the flood areas in front of the residential housing. Most houses were flooded (at the basement level), some experienced flooding up to the ground level floors (Erdgeschoss). No casualties have been reported in Liers.

Figure 3.79. Aerial view of Liers after the flood, obtained from https://www.thesun.co.uk/news/15629211/pics-shows-germany-floods-chaos/

Figure 3.80. Extent of flood plains adjacent to the Ahr river, Source: Screenshot of video footage filmed by Alois Sheuer, source: https://www.youtube.com/watch?v=6EXwo6ZxrFs)

The Ahr bridge of Liers connects the town with highway 271. It is triple-arched and has rounded pier foreheads covered with semicone-shaped hoods made of basalt lava. The parapets are masonry. The bridge was built in 1881, replacing the then existing wooden bridge. During the flood of 1910 one of the arches was destroyed and subsequently repaired. The bridge also suffered damage during World War II, when it was hit by bombing in 1944. It took until 1954 until damages were repaired. In 1997/1998 the bridge underwent a general retrofit consisting of extensive maintenance and some strengthening work of the piers (Figure 3.81).

Figure 3.81. Ahr bridge in Liers @ Josef Emmerich Strasse before flood, source: https://www.aw-wiki.de/w/index.php?curid=15614, https://www.aw-wiki.de/w/index.php?curid=58526

The bridge experienced substantial damage during the 2021 flood, which again destroyed one of the arches and the abutment area of the bridge. Similar to other bridges affected by the flooding, the abutments of the bridge were damaged by overtopping. Looking in the downstream direction, soil was eroded from the right abutment with extensive scour on both the upstream and downstream sides. The left side of the bridge experienced the most damage where the entire abutment was destroyed (Figure 3.82). The left abutment appears to have displaced downstream and destroyed the immediately adjacent arch in the process. Based on closer inspection of the abutment materials and discussion with locals, it appears that previous repairs had been done to the left abutment–it is not clear whether these repairs were performed in 1954 or if they were part of the 1997/1998 retrofit. These repairs consisted of unreinforced concrete, as shown in Figure 3.82-3.84. Additionally, parapet walls on top of the bridge were entirely removed from overtopping during the flooding. Similar to other old bridges, the large bridge piers and low arches led to a constricted cross-section. This potentially could have exacerbated and accelerated flow velocities and overtopping of the bridge during the flood event.

Figure 3.82. Bridge damage at the time of the team's visit (Aug 11th, 2021), (50.4568710, 6.9458676).

Figure 3.83. Photographs by the GEER team documenting the damage on August 11th, 2021 (50.4568710, 6.9458676).

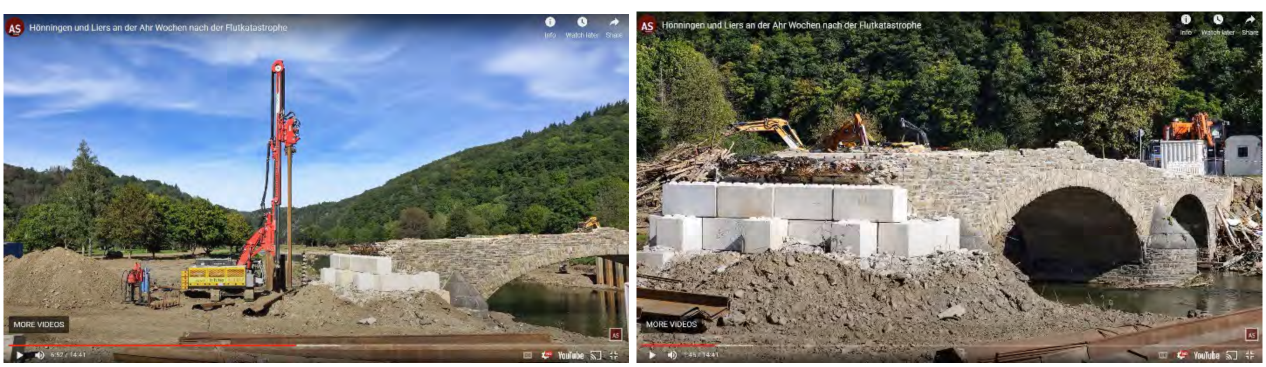


Figure 3.84. Online video footage documenting temporary repair efforts at the main bridge. Source: https://youtu.be/6EXwo6ZxrFs

Figure 3.85. Emergency Bridge across the Ahr river, Source: https://youtu.be/6EXwo6ZxrFs

3.3.7. Hönningen

The team passed through the town of Hönningen, which is located between Liers and Brück (Figure 3.86). Substantial erosion along the riverbanks was observed as shown in Figure 3.87. The major highway 273 was only one-sided, the lane closest to the river was closed due to major embankment damage (Figures 3.87 -3.89).

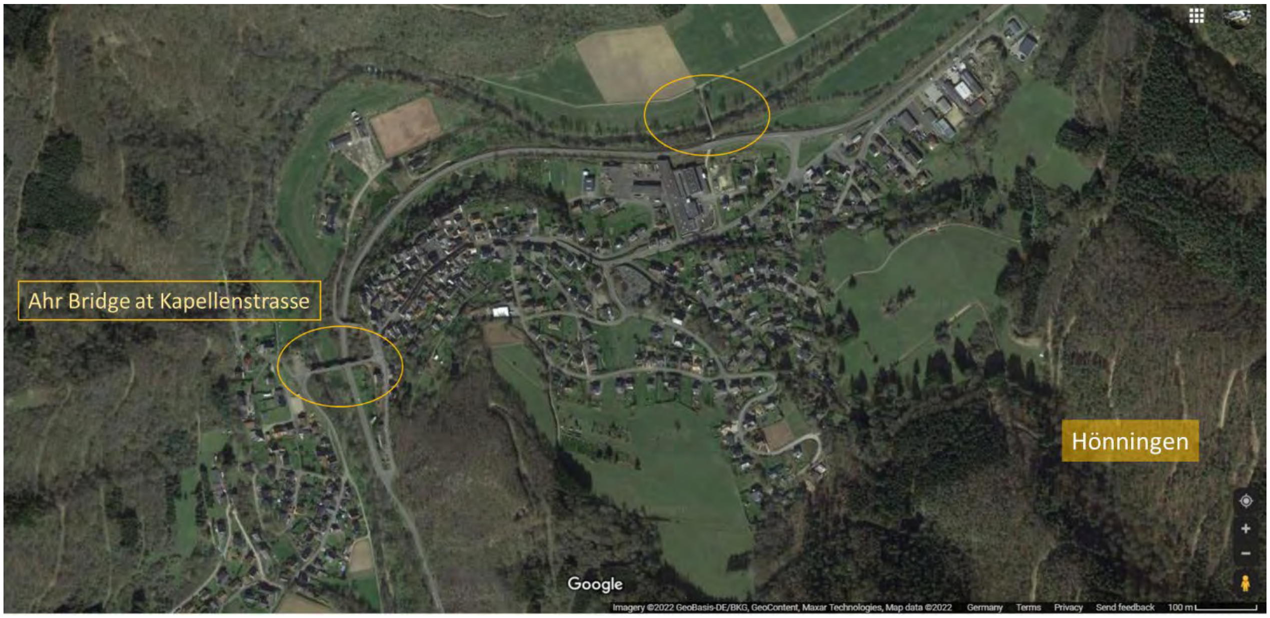


Figure 3.86. Aerial view of Hönningen with landmarks visited by the team

Figure 3.87. Substantial erosion along Ahr river in Hönningen (50.4714083, 6.9494501).

Figure 3.88. View of road 273 in Hönningen, October 2021, source: Screenshot of video footage filmed by Alois Sheuer, source: https://www.youtube.com/watch?v=6EXwo6ZxrFs

Figure 3.89. Embankment damage along road 273 in Hönningen, taken several weeks after the flood (source: Screenshot of video footage filmed by Alois Sheuer, source: https://www.youtube.com/watch?v=6EXwo6ZxrFs)

3.3.7.1. Bridge @ Kapellenstrasse, Hoenningen

The Ahr Bridge in Hönningen has a span of 104.70 meters and an overall height of 12 meters (Figure 3.90 and 3.91). It is the largest bridge crossing the Ahr. It has five piers and four round arches that span the Ahr and the bypass road (federal highway 257), the former railroad line, and the former mill stream. Due to its low, elongated structure, the building, which dates to 1912/13 and was extensively renovated in 1995, appears delicate and light. Instead of a parapet, the bridge has an iron railing interrupted by small stone pylons (WikiAW). The street leading over the bridge is called Kapellenstraße. Due to its elevation and large cross-sectional openings, the bridge did not experience any major damage. Road damage below the bridge is shown in Figure 3.92.

Figure 3.90. Ahr bridge at Kapellenstrasse, taken by the GEER team (50.4714083, 6.9494501)

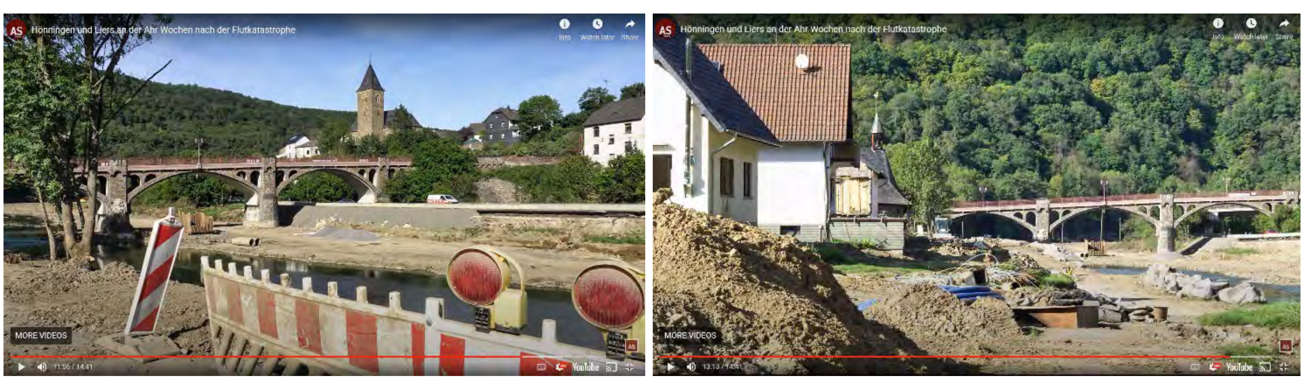


Figure 3.91. View of bridge at Kappellenstrasse from Hönningen town; source: screenshot of video footage filmed by Alois Sheuer, source: https://www.youtube.com/watch?v=6EXwo6ZxrFs

Figure 3.92. Road damage along the Ahr, underneath the bridge Kapellenstrasse (50.4709796, 6.9495415)

Figure 3.93 shows a residential building and a small chapel near the Ahr river. The house showed potential high-water marks based on the mud-colored line between the first and second story.

Figure 3.93. House in Hoenningen, with post-flood water mark visible on the outside stucco; Source: Screenshot of video footage filmed by Alois Sheuer, source: https://www.youtube.com/watch?v=6EXwo6ZxrFs

Hönningen's second bridge across the Ahr river was also a historic bridge (see Figure 3.94). No information was collected. Based on map updates in Google (2022), this bridge seems to be destroyed, and was removed from the maps.

Figure 3.94. Location of Ahrbrucke Hoenningen (left) and before flood bridge photograph (right), source: https://www.aw-wiki.de/w/index.php?curid=40856

3.3.7.2. Railroad Bridge Brueck, near Campground Leuer (Ahrbrueck), between Hoennigen and Brueck

The railroad bridge near campground Leuer, located between the towns of Hönnigen and Brück is a semi-historical bridge which has been retrofitted and reconstructed with a newly added reinforced concrete bridge. The newly added part of the bridge was constructed immediately adjacent to the existing bridge, and railroad tracks have been added to the reinforced concrete bridge. The historic part of the bridge was not used for train traffic, but was left in place (see Figure 3.95, bottom left).

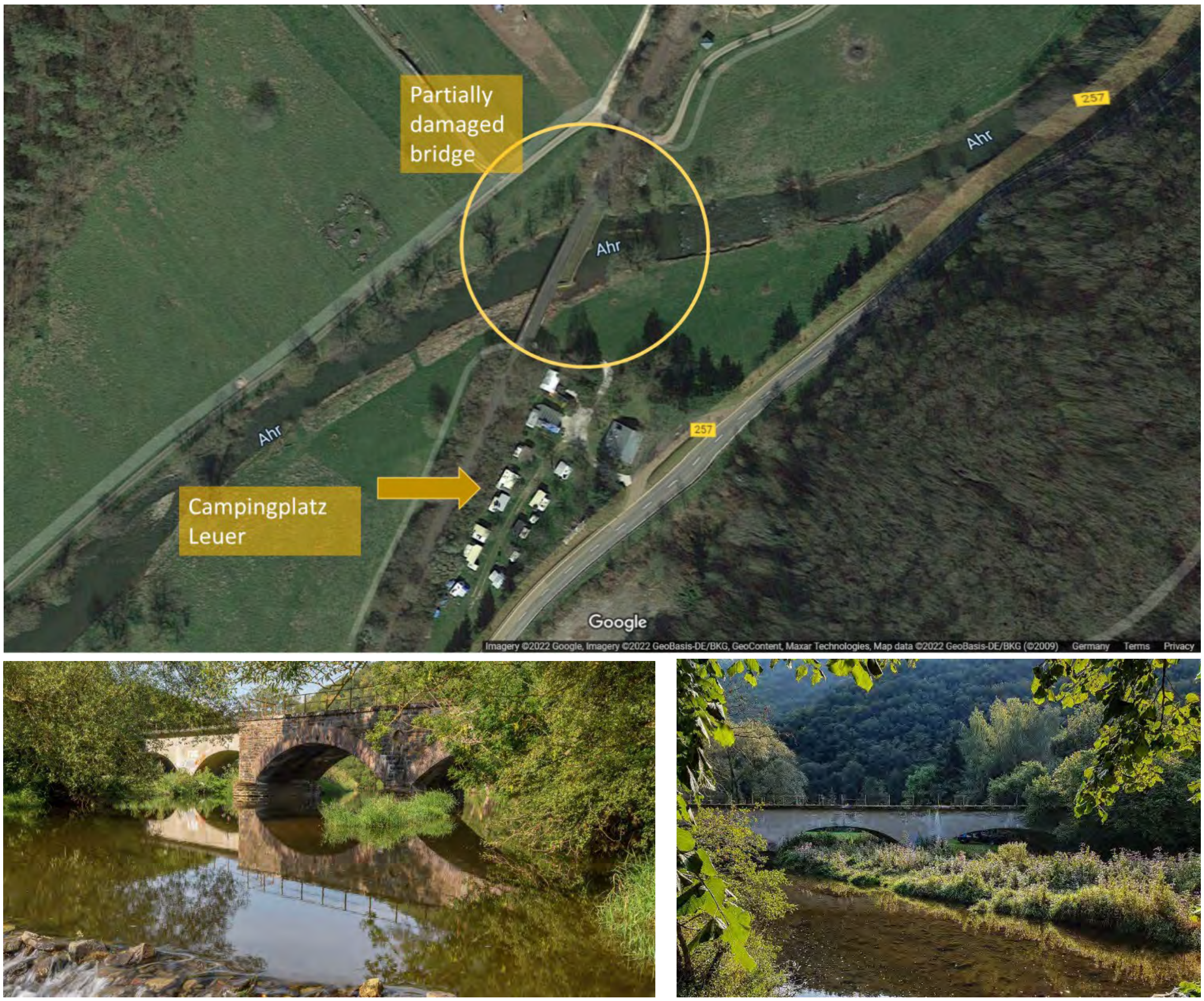


Figure 3.95. Location of destroyed railroad bridge (top), and before imagery of the bridge from downstream (bottom left) and upstream (bottom right) direction. Before photos credit: Heinz Grates, Source: https://www.aw-wiki.de/w/index.php?curid=67328

Even though the bridge appeared to be damaged at first, a closer inspection by the team on site and a comparison of before and after imagery following the reconnaissance visit suggested that the bridge sustained most of its integrity, and the abutment area adjacent to the bridge was washed out. This becomes furthermore apparent when comparing Figure 3.96 top and bottom. The bridge seemed to have directly connected into natural soil at the site, with no structurally built abutment wall. The segment between the end of the bridge and the tunnel on the right side consisted of natural soil (perhaps stabilized, but unknown), covered partially with vegetation. The dam-shaped segment supported the railroad tracks (see highlighted area in Figure 3.96(top)). The tunnel structure to the right is part of the famous Ahr Radweg, a bicycle path that runs along the river Ahr for more than 60 km.

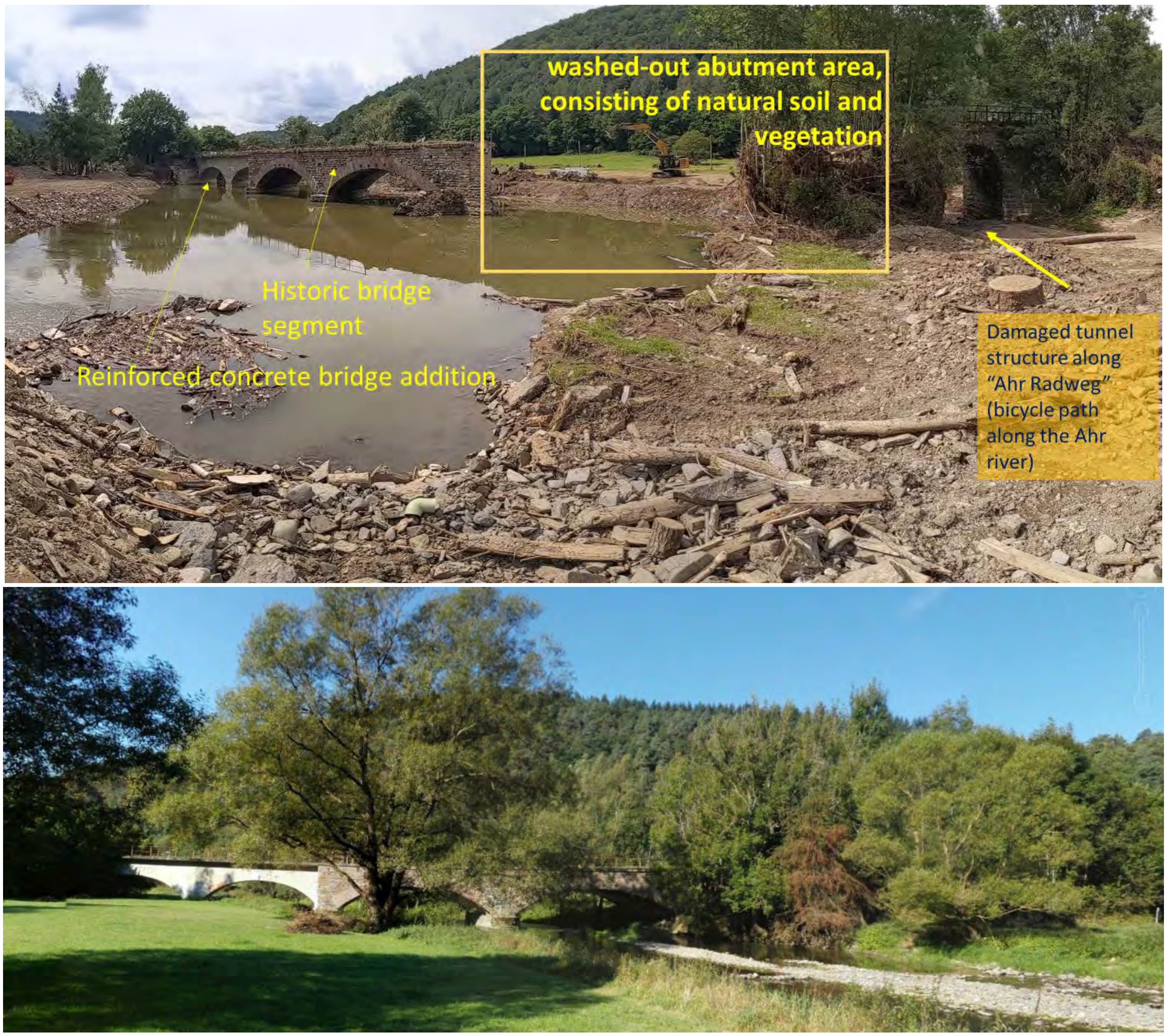


Figure 3.96. Comparison of post flood condition of the bridge and its surroundings (top, 50.480833, 6.968818) with pre-flood imagery obtained from google earth (bottom)

Figure 3.97 shows a set of photos taken by the team on August 11th, 2021.

Figure 3.97. Photographs of damaged bridge and surroundings on August 11th, 2021(50.480833, 6.968818).

Figure 3.98. Photo of damaged bicycle tunnel from upstream direction showing washed out soil (dam) segment in between the two structures and the temporary water rerouting (pipes) in the background (50.480833, 6.968818).

Figure 3.99. Concrete pipes and fill-based dam structure for temporary river crossing constructed by the Germany military; pipe inlet from upstream (left) and downstream (right) direction, (50.480833, 6.968818).

At the time of the team's visit, the German military finished the construction of a temporary river rerouting using an interim dam structure and concrete pipes (Figures 3.98 and 3.99). Simultaneously heavy equipment was used to re-establish the original river boundaries using fill material. Clean up of massive amounts of debris, soil deposits, trash and dead wood was also underway (Figure 3.100). While most historical bridges along the Ahr river did not sustain the combination of water pressure, debris impact, and scour, and consequently experienced a loss of structural stability (and failure), the location of this particular bridge within a wide flood plain consisting of open, undeveloped meadow areas might have potentially contributed to preservation of the bridge structure.

Figure 3.100. Destroyed landscape around bridge structure, showing debris, dead wood and temporary fills for dirt roads and emergency infrastructure. (50.48057075, 6.9684412)

3.3.8. Brueck

Ahrbrück with its districts Ahrbrück, Brück, and Pützfeld was largely destroyed by the flood. Several houses were washed away, and multiple deaths reported (SWR.DE, 2022). The district of Brück was hit particularly hard. The Ahr bridge, which connects the districts of Ahrbrück and Brück, was severely damaged by the flood and completely covered with debris, leaving the district of Brück, which lies on the left side of the Ahr, inaccessible for the first days following the flood. Medical support was scarce and the only medical office in town was completely destroyed. An emergency office was set up in Brück’s elementary school (RTL News, rtl.de). At the time of the team’s visit, the town had no drinking water, electricity, or telecommunication. On site rescue personnel delivered electric generators to residents and businesses. Drinking water and telecommunication networks were re-established in September of 2021(SWR.de). Figure 3.101 shows an excerpt of Brück obtained from google maps. The highlighted structures in Figure 3.101 were completely washed away by the flood. The flood plains surrounding the Ahr were covered with debris and mud (Figure 3.102 -3.103). The town of Brück had two bridges across the Ahr river: (1) the main road bridge (not highlighted) which was heavily damaged and left partsof Brück inaccessible for several days - this bridge was temporarily “repaired” by filling the destroyed arch with dirt to enable passage. The destroyed arch and abutment were located downstream direction right (see Figure 3.103, bottom). The riverbanks adjacent to the main road and close to the missing bridge arch (L273) were stabilized with gravel (Figure 3.102 and 3.103, bottom). The second bridge, a smaller bicycle bridge, was missing. Figure 3.105 shows two residential houses, completely lifted and washed away, according to eyewitness reports gathered onsite.

Figure 3.101. Location of Brück and highlighted structures along and across the Ahr which were completely missing (washed away)

Figure 3.102. Ahr bridge Brück (road bridge) with temporary fill placed on the right arch to enable bridge passage (50.4866352, 6.9717177)

Figure 3.103. Floodplains and riverbanks around the Ahr bride and bridge abutment in Brück (50.4866352, 6.9717177).

Figure 3.104. Bridge and temporary retrofit to missing arch and superstructure (50.4866352, 6.9717177).

Figure 3.105. Before view of houses near Ahr embankment (top) Source: Google maps(left) and https://www.aw-wiki.de/w/index.php?curid=42060; same site with destroyed (missing) houses (bottom) - only the foundation slab of one of the buildings remained (bottom, right, 50.486959, 6.9717834)

3.3.9. Campingplatz Gut Pützfeld, District Ahrbrück

The campground "Gut Pützfeld" is one of the four campground sites in Ahrbrück and has been a popular destination area for several decades. It is located approximately 4 kilometers upstream of Altenahr. The campground hosts long term camp-sites, often rented over several years, as well as vacation campsites for short term usage. Figure 3.106 shows a map of the campground obtained from google maps. The map also shows two bridges, which were still standing, but heavily damaged. The campground is encompassed by the highway 257, the railroad track of the "Ahrtalbahn" and the Ahr river. Figure 3.107 shows a historic image of the campground and Figures 3.108 and 3.109(left) show the campground prior to the flood event. The campground has experienced several flood events, none of which were as severe as the 2021 flood. The reconnaissance team spoke with the campground owner Mr. Hans-Gerd Leyedecker onsite. The campground was flooded in 2016, during the 100-year flood event, but recovered relatively quickly. No fatalities occurred in 2016. Some people were airlifted during the flood, but most people were evacuated. Figure 3.108(right) shows imagery of the campground during the 2016 flood.

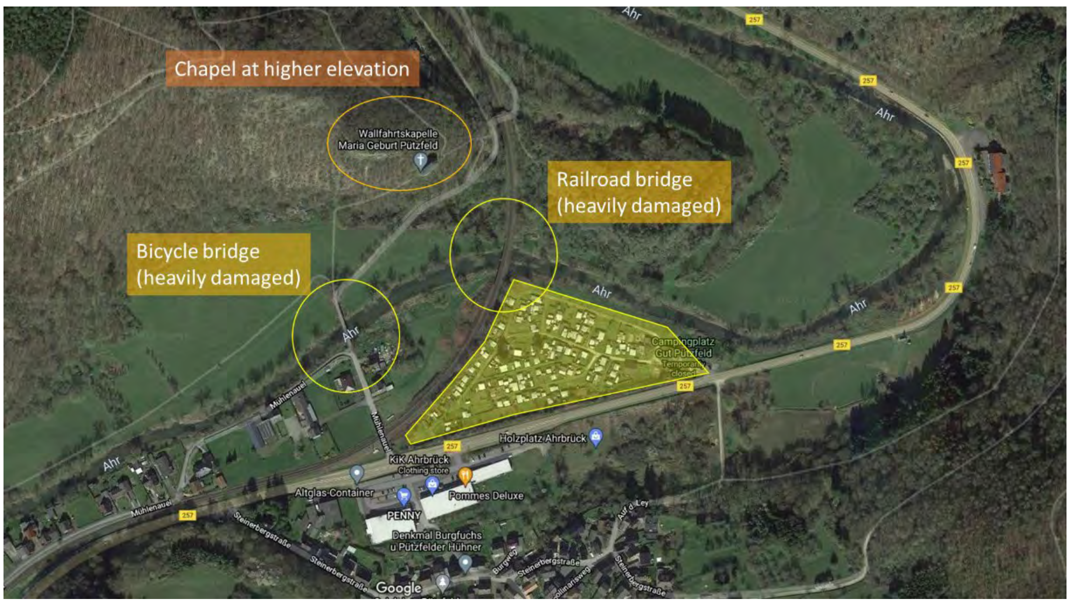


Figure 3.106. Location of campground Gut Pützfeld along highway 257.

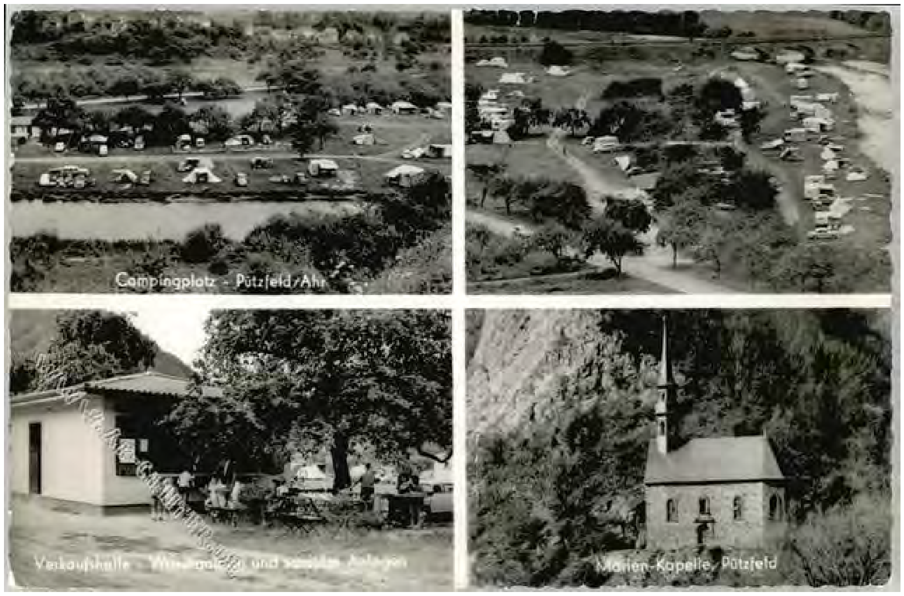


Figure 3.107. Historic Photograph of campground Gut Pützfeld, Source:

Figure 3.108. Campground before flood (source: aerial photo on left: https://de.nailizakon.com/a/12-rp/ahrbruck/campingplatz-gut-puetzfeld-luftaufnahme.html; campground entrance right: campstar.com

Figure 3.109. Left: aerial photo of campground before flood (source: https://www.aw-wiki.de/w/images/7/76/Drohne_7.jpg); right: Campground during the 2016 flood event (source; campstar.com)

The campground was heavily destroyed during the July 2021 flood event. The campground owner told the team that most mobile homes were evacuated in the evening of July 13th, and the morning of July 14th, 2021. He drove most mobile homes to higher elevations, and parked them along the road to the chapel Maria Geburt Pützfeld (see Figure 3.106). There was only one fatality associated with the campground, namely an elderly man who decided to walk to the Ahrbrück train station and was caught in a flood wave from upstream. Figures 3.110 and 3.111 show the campground immediately after the flood. At the time of the team's visit, some of the debris depicted in Figure 3.112, as well as most of the caravans were removed from the campsite. Figure 3.113 shows the campground during the team's visit. The campground owner was waiting for heaving construction equipment to remove the remaining debris and to level the site. He is planning on reopening the campground, even though it is clearly located in the floodplains of the Ahr and permission to do so is still pending.

Figure 3.110. Images of the campsite immediately after the flood, Source: EMS Media TV, accessed through: https://www.youtube.com/watch?v=MSrJRXl6dQA

Figure 3.111. Additional images of the campsite immediately after the flood, Source: EMS Media TV, accessed through: https://www.youtube.com/watch?v=MSrJRXl6dQA

Figures 3.112 and 3.113 show the campsite with debris and soil deposits at the time of the team's visit. Photographs at the center and bottom of Figure 3.112 depict the severe embankment erosion and soil redeposition. The bank erosion along the Ahr River near the Campingplatz Gut Pützfeld resulted in exposure of approximately 1.5 meters of historic sedimentary deposits (Figure 3.113). The cut in the right channel bank exhibited alternating layers of fine- and coarse-grained materials. Eight layers were exposed, with Layer 8 being the existing surface layer. Of particular interest are Layer 4 and Layer 6. Particles in these layers are larger in size (particularly in Layer 6) as well as less organized in depositional nature (e.g., compared to Layer 2 which shows greater imbrication). This suggests these layers were deposited quickly and in a more chaotic, high-energy, fluvial environment and most likely associated with prior extreme flood events on the Ahr River. These exposures, and others along the river reach, can be helpful in understanding characteristics of prior extreme flood events. A handheld LiDAR scan of the bank cut (Table 2.2.) was also taken from which grain sizes of the larger materials could be derived.

Figure 3.112. Pictures of the Campground Gut Pützfeld during the team's visit, along with riverbank erosion (50.4943691, 6.9822398)

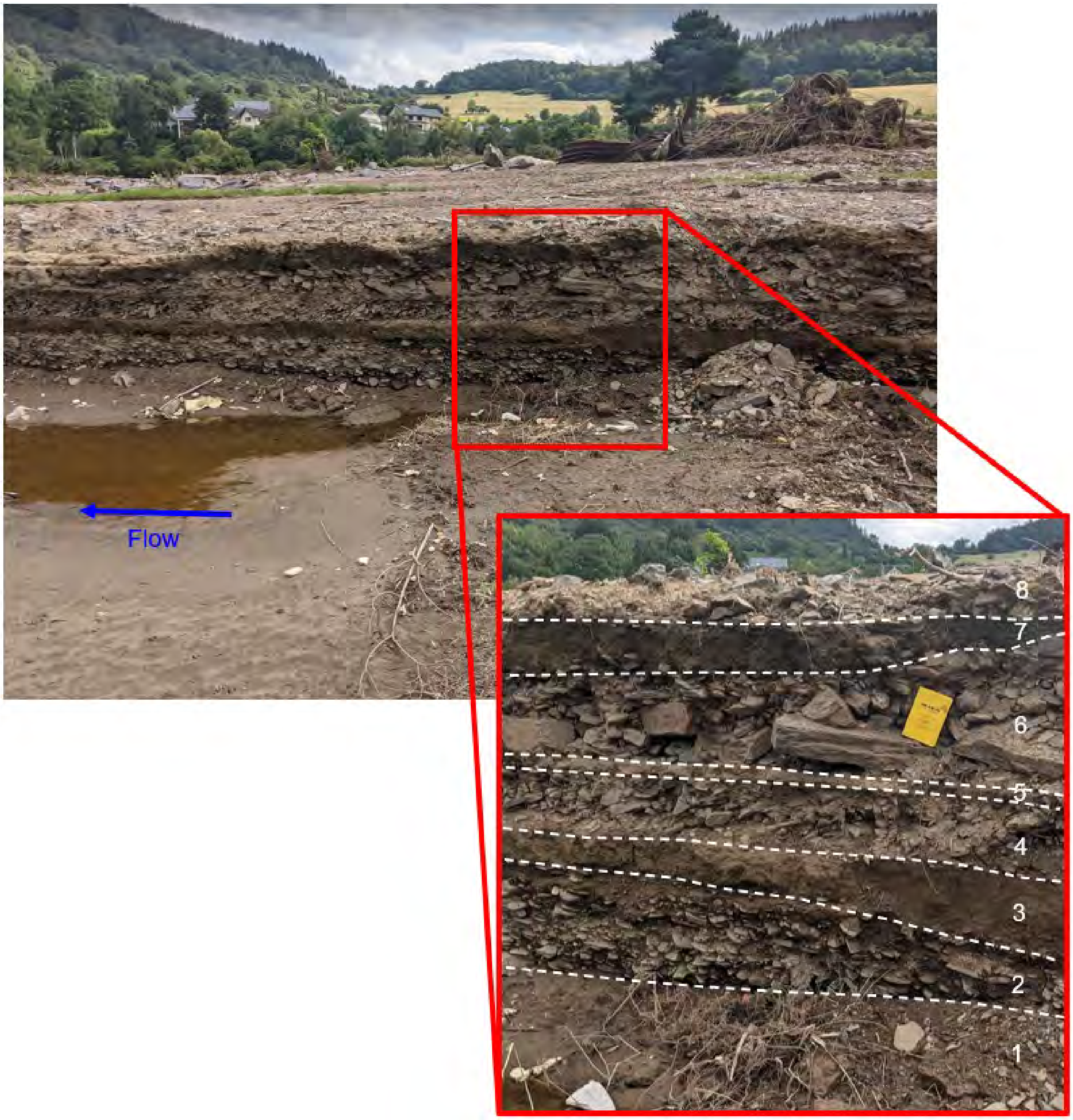


Figure 3.113. Bank erosion exposure at the Campground Gut Gut Pützfeld showing previously deposited sediments (50.4943691, 6.9822398).

The railroad bridge adjacent to the campground was also damaged, particularly its abutment areas. Figure 3.114 shows the bride from upstream (top) and downstream (bottom) direction. Figures 3.115 – 3.116 show three screenshots obtained from online video footage showing the bridge immediately after the flood, which highlights the amounts of debris and deadwood deposited on the bridge deck. Figure 3.117 shows close-up photographs of the damage near the bridge abutments.

Figure 3.114. Rail bridge at Campground Gut Pützfeld from upstream (top) and downstream (bottom photo) direction (50.4943691, 6.9822398).

Figure 3.115. Railroad bridge from downstream direction shortly after the flood showing massive amounts of debris and deadwood piled up around bridge structure, Source: https://www.youtube.com/watch?v=MSrJRXl6dQA

Figure 3.116. Railroad bridge shortly after the flood showing massive amounts of debris and deadwood piled up around bridge structure, Source: https://www.youtube.com/watch?v=MSrJRXl6dQA

Figure 3.117. Damage and Erosion around the bridge abutments. From downstream direction (Top left and right) and upstream direction (Bottom left and right abutment), (50.4943691, 6.9822398).

The bicycle and pedestrian bridge in close proximity to the campground was also damaged. This bridge is located on the hiking path to the Sancta Maria Immaculata chapel. The bridge is shown in its intact state in Figure 3.118. The bridge railing as well as part of the bridge deck was destroyed and washed away, and one of the arches was damaged as shown in Figures 3.119 and 3.120 bottom.

Figure 3.118. Bicycle bridge at street Mühlenaue, Photos by Heinz Grate, Source: https://www.aw-wiki.de/w/index.php?curid=67004

Figure 3.119. Bridge at Muehlenaue shortly after the flood, Source: Screen shot from online footage by EMS Media TV, accessed at: https://www.youtube.com/watch?v=MSrJRXl6dQA

Figure 3.120. Damage to bicycle bridge Mühlenaue in Pützfeld taken by the GEER team (50.49382, 6.97981128)

3.3.10. Altenburg, Altenahr

Altenburg is part of the municipality of Altenahr. The village is located between Altenahr and Kreuzberg at an elevation of 175 meters above sea level. Altenburg has about 600 inhabitants. Figure 3.121 shows a map of Altenburg. The circled bridges were inspected by the reconnaissance team. Figure 3.122 shows a before after aerial image of Altenburg, depicting the extent of the flood coverage. Figure 3.123 and 3.124 show photographs obtained from online sources depicting the flood situation immediately after the rainfall event (Figure 3.123) and within a week of the flood (Figure 3.124).

Figure 3.121. Map of Altenahr with Ahr bridges

Figure 3.122. Aerial view of Altenburg before and during flood event, Source: https://www.dw.com/en/flooding-in-germany-before-and-after-images-from-the-ahr-and-eifel-regions/a-58299008

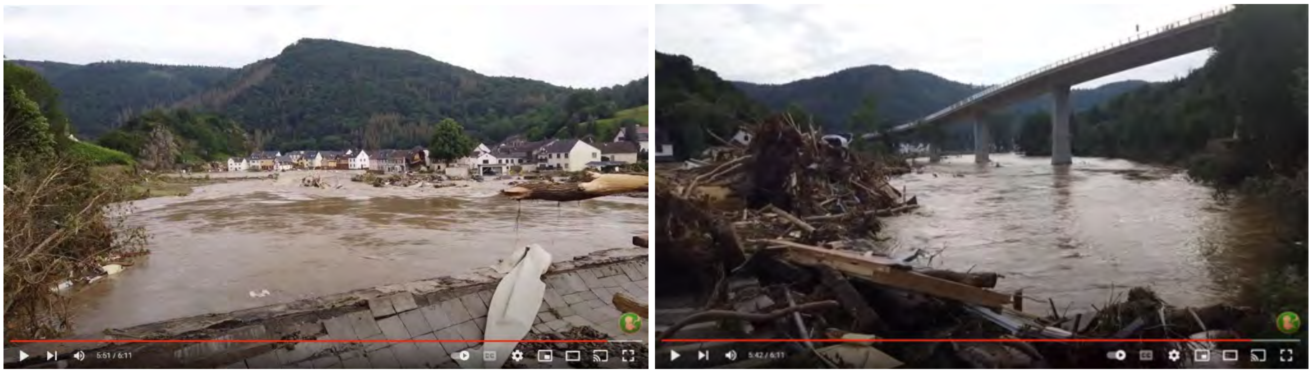


Figure 3.123. Close up few one day after the main flood event, Source: https://www.youtube.com/watch?v=g09YLvd4xzk

Figure 3.124. Aerial view of Altenburg shortly after the flood, Source: https://blasorchester-altenahr.hpage.com/aktuelles.html

Figure 3.125 shows photographs taken by the team in Altenburg. The bottom figure includes the high-water marks on the remaining residential houses along the main street in Altenburg.

Figure 3.125. Flood damage adjacent to the Ahr in Altenburg, houses along the main road 267 (50.5117204, 6.9842627)

Figure 3.126 shows bridge damage in Altenburg. This two-span road bridge was constructed with precast concrete deck segments, which were found to be intact and washed away /relocated to the riverbanks (as shown in Fig. 3.126, bottom left). Both abutments and the middle pier were found to be intact. Rising water levels lifted the bridge deck up as there was no rigid connection between the superstructure and foundation elements (i.e., gravity supports only).

Figure 3.126. Top: Road bridge in Altenburg before flood (Source: https://www.aw-wiki.de/w/index.php?curid=40670) After: Bridge damage in Altenburg (GPS: 50.511551, 6.985069)

Figure 3.127 shows the rail bridge in Altenburg. This bridge suffered no structural damage. The rail track on the bridge was completely destroyed (see Figure 3.128). The bridge in the background, a road bridge part of Bundesstrasse 267, suffered no damage (see Figure 3.128).

Figure 3.127. Rail bridge in Altenburg (foreground), road bridge along Bundesstrasse 267 (background), (50.5117204, 6.9842627)

Figure 3.128. Area surrounding road bridge along Highway 267 (50.51283427, 6.9842112)

3.3.11. Altenahr

Altenahr is a small town with a population of 1914 people in the district of Ahrweiler. Altenahr was heavily featured in the news and other media coverage due to its extended flood damage to infrastructure and its total number of fatalities (33), which was the second highest reported amongst any of the single districts (SWR.DE; https://www.swr.de/swraktuell/rheinland-pfalz/flut-in-ahrweiler-so-gross-ist-der-schaden-104.html) Altenahr has an elevation of about 170m, and an area of 15km^2. Its location is known through many local wineries and the town's fortress "Ahrburg". The team visited Altenahr several times, as the entrance into town was only possible through the route described within the previous pages. The tunnel which connects Altenahr with the remaining Ahr valley in downstream direction was severely damaged. The Ahr bend (Ahrschleife) in Altenahr contributed substantially to the heavy, localized damage and high number of fatalities. The team visited the campground Altenahr which is located between Altenburg and Altenahr.

3.3.11.1. Campground Altenahr, Railroad Bridge and Pedestrian Bridge

Both campgrounds in Altenahr (i.e., the Europacamping "Am alten Wehr", and the Campground "Viktoria-Station") were completely flooded. The team spoke with the owners of the campground Viktoria-Station who indicated that the campground will not reopen following clean up. Two bridges (a railroad bridge and a pedestrian bridge) next to the campground and depicted in Figure 3.129 experienced substantial damage (Figure 3.130). Hereby the first bridge in downstream direction (rail bridge) carried the heaviest impact load and consequently suffered the most damage.

Figure 3.129. Altenahr Campground before flood, Source: https://www.spottocamp.com/en/campsites/camping-schulz-altenahr-altenahraltenburg

Figure 3.130. Campground Altenahr at time of team’s visit, all camp infrastructure was destroyed (50.51427139, 6.9865368)

3.3.11.2. Railroad and Pedestrian bridge at Campground Altenahr Viktoria-Station

The rail and pedestrian bridge across the Ahr are depicted in Figure 3.131 prior to the flood. The rail bridge is upstream and the pedestrian bridge (formerly road bridge) is downstream. Consequently, the rail bridge was damaged most, catching much debris, camping caravans, tree logs and other items carried by the flood, as shown in Figure 3.132.

Figure 3.131. Bridges near campground Altenahr Viktoria-Station prior to the flood. Left: rail bridge source: https://www.aw-wiki.de/w/index.php?curid=67322, Right:pedestian/bicycle bridge: https://www.aw-wiki.de/w/index.php?curid=67323

Figure 3.132. View of damaged bridges near campground Viktoria-Station, Altenahr (photo: picture alliance/dpa)

Figure 3.133 shows a photograph taken by the team on August 11, 2021. The superstructure of the rail bridge was completely destroyed, debris and tree logs were still present around the bridge structure. The pedestrian bridge (formerly road bridge) was passable and structurally intact and used as emergency access between part of the town.

Figure 3.133. Photograph of damaged rail and pedestrian bridge on August 11, 202, (50.5147073, 6.9856677)

Figure 3.134. Photographs of the damaged rail bridge (top and center) and washed-out abutment region (bottom), (50.5147775, 6.98626321)

The abutment region of the rail bridge (Figure 3.134 bottom) was washed out and the rail tracks were hanging in the air. The abutment wall itself was intact but lacked any connection with any surrounding material. The bridge deck (Figure 3.134) was displaced laterally by at least 60 cm, the original placement should have been atop the concrete inlets in the pier walls, visible in Figure 3.135. In addition, the pier walls were tilted. This bridge was later removed.

Figure 3.135. Rail bridge: damage to bridge deck and tilted pier wall foundation(50.5147775, 6.98626321).

Figure 3.136 shows a panoramic view of both bridges presenting the massive damage to the rail bridge and the minimal damage to the pedestrian bridge. The pedestrian bridge is missing its railing. Also, shown in Figure 3.137, the pedestrian bridge did not suffer any damage at the foundation level. Much of the debris and material was stuck on the rail bridge, while water overtopped both bridges and the adjacent campground to make its way downstream.

Figure 3.136. View of both bridges on August 11, 2021, (50.5147775, 6.98626321).

Figure 3.137. Photo of largely intact pedestrian bridge in Altenahr (50.51483562, 6.98577135)

3.3.11.3. Bicycle bridge at Campground Altenahr Viktoria-Station

As shown in Figure 3.138, the adjacent bicycle bridge in downstream direction, just nearby the double bridge at Campground Viktoria-Station was heavily damaged and clogged with debris immediately following the flood. At the time of the team’s visit, this bridge was either removed or collapsed. Two tilted bridge pier walls were visible (Figure 3.139 and one abutment inland, which remained intact. The lightweight superstructure, a streel truss was completed removed. The bridge deck likely only rested on the intermediate supports as well as on the abutment structure to the left of Figure 3.139. The bridge was loaded with limited debris (smaller tree debris as shown in Figure 3.139), however, the tilt and damage to the foundation walls likely led to the demolition of the bridge.

Figure 3.138. Bicycle Bridge ("Seilbahnbruecke") near Campground Viktoria-Station prior to the flood. Source: https://www.aw-wiki.de/w/index.php?curid=51171

Figure 3.139. Destroyed bicycle bridge at the time of the team's visit (50.5152961, 6.9842002)

3.3.11.4. Altenahr Town and Ahr bridge

Figure 3.140 depicts the town of Altenahr. The yellow shaded areas were heavily damaged, and partially or fully destroyed. Some houses were washed away (Figure 3.141). Figures 3.141 – 3.145 demonstrate the extent of damage to the town of Altenahr, its businesses, infrastructure, residential housing and road and bridge structures. The only intact bridge within the town was the road bridge near the town center. Figure 3.141 shows online footage of the town center in the days after the flood. Streets were filled with cars, debris, and household objects.

Figure 3.140. Map showing town of Altenahr, highlighting damaged areas (yellow) and other landmarks

Figure 3.141. Photographs of the Main Road (Tunnelstrasse) in Altenahr shortly after the flood event. Source: https://newsrnd.com/life/2021-07-20-altenahr-after-the-flood-disaster--%C2%BBi-expect-that-we-will-still-find-bodies%C2%AB.HkxNHLlVAd.html (left) and https://www1.wdr.de/nachrichten/unwetter-nrw-starkregen124.html (right)

Figure 3.142 shows a photograph of a single family house near Seilbahnstrasse in Altenahr. This house was completed submerged and later on lifted up by the masses of water and transported away where it eventually crashed into another house. This and many other eyewitness documentaries of survivors describing their night at room and the chimney of their houses can be found in the source link to this photograph and demonstrate the horrific circumstances most people endured fighting for their lives. Figure 3.142 right shows an aerial photograph after the waters receded and rescue teams arrived in Altenahr.

Figure 3.142. Left: residential home in Altenahr completely submerged (Source: https://www.washingtonpost.com/world/2021/07/23/germany-floods-street-night/), Right: Aerial photograph in Altenahr showing damage around the Ahr river (Source: unknown)

Figure 3.143. Photograph taken from the road bridge in the town center looking at the Ahr and the adjacent "Hotel zur Post"; embankment damage on both sides; Train station to the right (50.5165073, 6.98911282)

Figure 3.143 shows a photograph along the main street in Altenahr. To the left is the destroyed "Hotel zur Post" and to the right is the train station. Severe embankment damage is visible on both sides. News sources describe the water level to the rook of both buildings. Figure 3.144 top shows photos of the Altenahr train station. The station building was standing but completely flooded, the train tracks were washed away. Photographs in the center depict the only remaining intact bridge in town and the embankment and riverbank destruction in upstream direction. The bottom row shows the inside and outside of houses along the main road (Tunnelstrasse).

Figure 3.144. Photographs of damage in Altenahr near town center (50.5165073, 6.98911282).

Figure 3.145 shows two photos of houses washed away at the foundation level. The bottom photos depicts houses flooded to the roof level.

Figure 3.145. Photos of damage and destruction in the town of Altenahr by the GEER team; top: houses destroyed to the foundation level, bottom: houses flooded until roof level (50.51671855, 6.9903993)

3.3.11.5. Altenahr Tunnel Entrance

The Altenahr tunnel is the infrastructure connection between Altenahr and the downstream remainder of the Ahr valley. The tunnel is the shortcut for rail, pedestrian and road traffic, while the Ahr river follows and extended bend through forest and nature. Figure 3.146 shows the tunnel entrance prior to the flood.

Figure 3.146. Aerial view of the tunnel entrance area before the flood. Source Top photo: https://de.wikipedia.org/wiki/Datei:Altenahr,_Engelslay-Tunnel.jpg, Bottom: photos by Heinz Grates, accessed at https://www.aw-wiki.de/index.php/Ahrbr%C3%BCcken_im_Kreis_Ahrweiler#Altenahr

Figure 3.147 shows the tunnel entrance area in Altenahr during the 2016 flood event. The water levels were substantially lower, even though considerable amounts of water was flowing through the tunnel.

Figure 3.147. Tunnel entrance area during the 2016 Flood event (Source: https://www.rhein-zeitung.de/cms_media/module_img/3015/1507856_1_mrvwallpaper_crnthight129t8036231756384735502img.jpg)

Since the Ahr travels through a narrow bend and extended turn (not visible in the Figure), the water level rise occurs very quickly and pushes water immediately through the tunnel. During the 2021 flood event the tunnel was nearly completely filled, the water level mark is within 1.0 to 1.5ft of the tunnel top (as observed by the team visiting the inside of the tunnel). Figures 3.148 – 3.149 show the tunnel entrance area along with the rail and bicycle/pedestrian bridge shortly after the night of the flood.

Figure 3.148. Aerial view of tunnel entrance in July 2021, shortly after the flood night (photo: Polizei Thueringen, accessed at https://www.mdr.de/nachrichten/deutschland/panorama/hochwasser-katastrophe-milliarden-schaden-bahn-strasse-100.html)

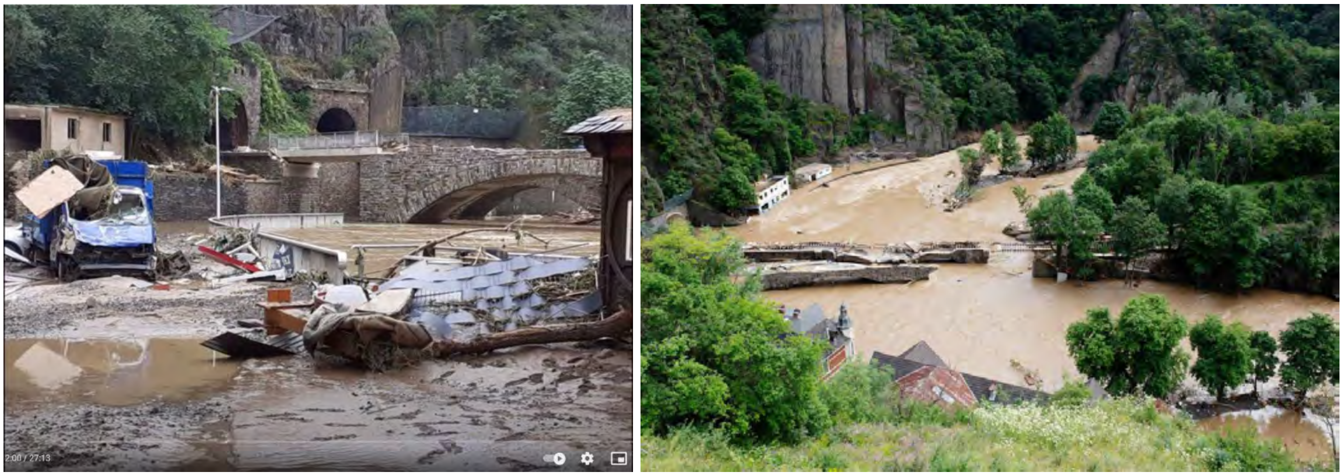


Figure 3.149. Online footage capturing the water and damage near the tunnel entrance, Source photo left: https://www.youtube.com/watch?v=0YdCiEqePJw, Photo right – source: https://img.zeit.de/gesellschaft/zeitgeschehen/2021-07/ahrweiler-unwetter-ueberschwemmung-notlage-nrw-reportage-teaser-2/original__1000x666

Even though much of the debris, such as cars and large pieces of wood were cleaned up, the area around the tunnel was still declared a high-risk area, with access to the public prohibited. Both bridges (rail and pedestrian) suffered severe and irreparable damage. While the middle piers of both bridges remained standing, the arches were largely destroyed and substantial erosion around the abutment areas left rail tracks tangling in the air (see Figure 3.150 and Figure 3.151).

Figure 3.150. Photograph of remainder of the pedestrian bridge at tunnel entrance (front) and the severely damaged rail bridge in the back (50.5164851, 6.99482486)

Figure 3.151 shows several additional photographs taken of the double bridge, showing the damage to the bridge deck and the wash out of the abutment area and the infill in the arches (Figure 3.151 center). The photos at the bottom show the damage to the street adjacent to the Ahr past the tunnel entrance.

Figure 3.151. Damage to old rail bridge near tunnel entrance and areas surrounding the bridge damage. Photos by GEER team in August 2021(50.5164851, 6.99482486).

Figure 3.152 shows the tunnel entrance area in October 2021. The rail bridge has been completely removed, only one arch of the pedestrian tunnel is still standing.

Figure 3.152. Tunnel Entrance, October 2021. Only one bridge arch remains, reconstruction of road access, one bridge was completely demolished. Source: unknown, GPS Coordinates: 50.51637961742962, 6.995167798855734.

3.4. Day 3-5: Ahrtal Part B: from Altenahr tunnel to Bad Neuenahr-Ahrweiler

3.4.1. Travel map

Figure 3.153 shows the stretch between Altenahr (tunnel exit) and Bad Neuenahr Ahrweiler. Almost all towns (as accessible) were inspected along the route. Table 3.4 lists the specific towns, includes landmarks such as bridge and other documented failures along with their GPS coordinates.

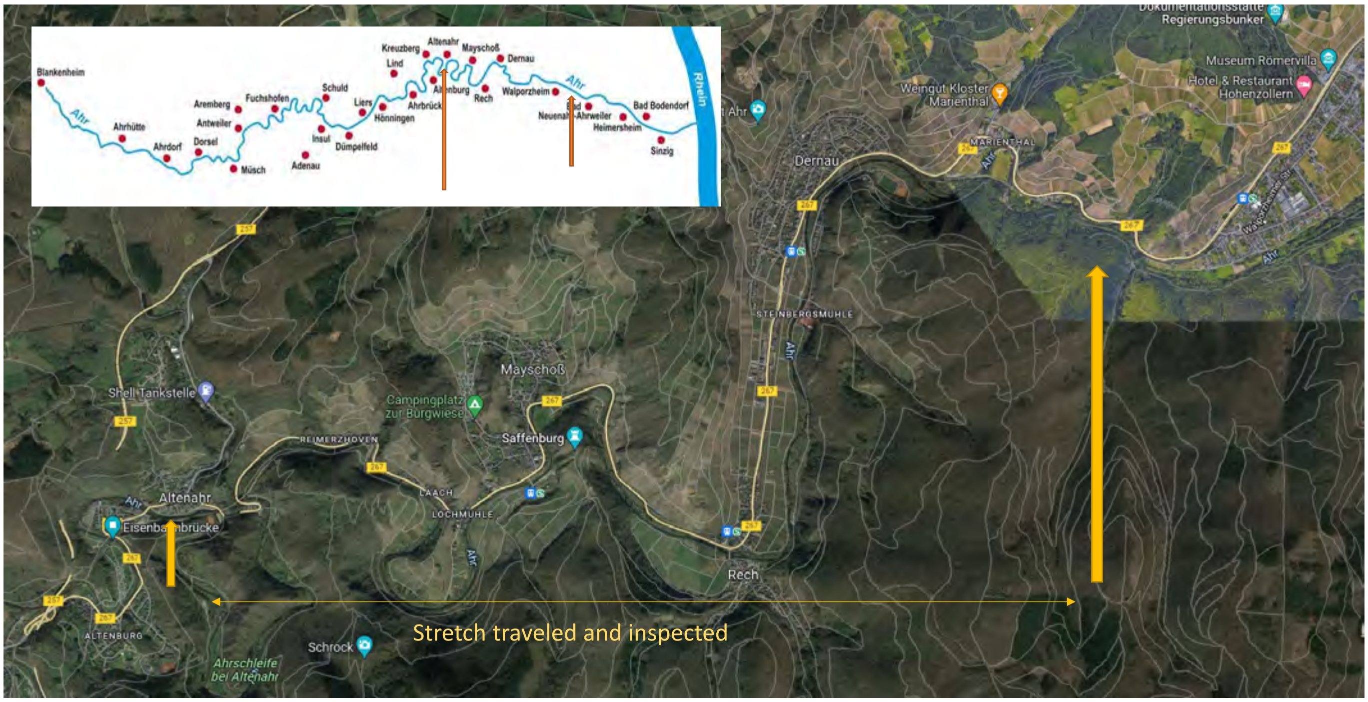


Figure 3.153. Reconnaissance Segment Altenahr to Bad Neuenahr-Ahrweiler

Table 3.4. Overview of locations visited between the Altenahr Tunnel Exit and Bad Neuenahr - Ahrweiler

Town	**Visited Places**	**Applied methods**	**GPS-coordinates**
Altenahr	Tunnel Exit	UAV images Lidar Photos	50.516779; 6.996648
Altenahr	Double Bridge at Tunnel Exit (“Zwillingsviadukt”)	Drone, Lidar	50.516993, 6.9966851
Reimerzhoven	Bicycle path bridge	Photos	50.518758; 7.006963
Mayschoss	Bridges near Hotel Bergischer Hof	Multispectral images, Lidar	50.518083; 7.026473
Rech	St Johannes von Nepomuk Brücke	Photos	50.514089, 7.0362482
Dernau	Weinbaubrücke	Photos	50.5336734, 7.045423
Marienthal		Photos	50.535642, 7.056949
Marienthal/Walporzheim	Bridge A Bridge B Bridge C	Photos	50.533641, 7.056369 50.533180, 7.059086 50.532218, 7.062409

3.4.2. Altenahr Tunnel Exit: Road and Bridge Damage

Figure 3.154 shows a Google Earth Image (March 2020) and a Google Street View of the tunnel exit (May 2021), followed by a photograph of the tunnel exit during the 100-year flood in 2016 (Fig. 3.155). Figure 3.156 shows the tunnel exit and surrounding area on August 13, 2021, approximately four weeks after the flood.

Figure 3.154. Tunnel exit east area before flood event (Sources: google maps, google earth and google street view)

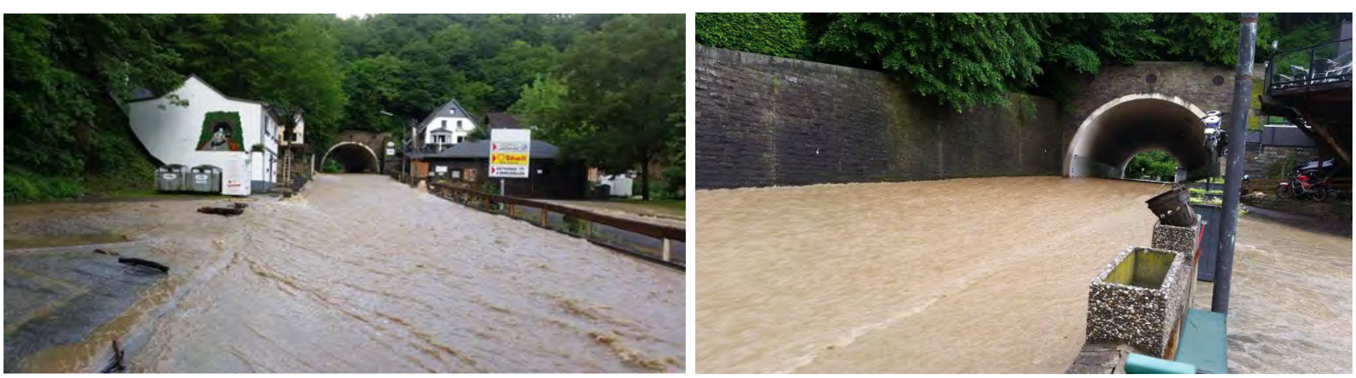


Figure 3.155. Photos of tunnel area during the 2016 flood,
Source:https://www.altenahr.de/index.php?id=26&publish[id]=9709&publish[mode]=overview&no_cache=1

Figure 3.156. Destroyed Tunnelstrasse @ the tunnel exit following the 2021 flood (50.51631664, 6.9968335)

Figure 3.157 shows a photograph taken inside the tunnel, indicating the water levels observed during the various flood events in the Ahr valley. The 2016 flood, a 100-yr return event, is marked at about 30 cm above the pedestrian walkway. Based on mud-colored traces visible inside the tunnel walls, the high water mark of the 2021 flood *within* the tunnel is estimated to be around 3.40 m -3.80 m.

The road damage and abrupt cut-off of the pavement is visible from the photographs taken inside the tunnel (Figures 3.156 right, and Figure 3.158 left) and at the tunnel exit edge (Figure 3.157, right). The cut-off was approximately 1-2 meters within the immediate vicinity of the tunnel exit and approximately 3-5 meters at distance (Figure 3.158). Figure 3.158 also shows the aerial extent of the damage surrounding the tunnel exit. It is estimated that the entire area shown in Figures 3.158 and 3.159 was submerged with water. Substantial erosion occurred underneath the street and near the residential housing adjacent to the tunnel. At the time of the teams' visit, the underlying rock appeared eroded and fractured near the surface as result of water pressure and flood forces (Figures 3.158 and 3.159).

Figure 3.157. Water elevation markers inside the Altenahr tunnel (left) and estimated water level during the 2021 flood event (right); (50.51631664, 6.9968335).

Figure 3.158. Cut-off of Tunnelstrasse at the Altenahr tunnel exit. View from inside the tunnel (left) and immediately outside the tunnel (right), (50.51631664, 6.9968335).

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Figure 3.159. Aerial view of tunnel exit one week after flood, source:Skyscrapercity.com (access not available anymore)

Figure 3.160. Aerial view of tunnel exit, with inlet figure showing pre-flood road alignment, photo: https://www.stuttgarter-zeitung.de/inhalt.vor-und-nach-der-flut-beeindruckendes-video-zeigt-die-zerstoerung-im-ahrtal.c6922fcb-b67a-41fe-bd62-b3748db25fec.html

Two of the adjacent residential structures to the right side of the tunnel exit (Figure 3.160) remained standing but were heavily scoured at the foundation level. Both structures were demolished after the flood. Immediately below the right-hand side buildings, another building was destroyed and washed away by the flood (Figure 3.161).

Figure 3.161. Left: extreme scour and erosion of the foundations of the residential buildings adjacent to the tunnel exit; right: washed out soil and rock just below the tunnel exit, causing a deep cut of 3+ meters, (50.5165261, 6.9975355)

Figure 3.162 shows the tunnel exit in October 2021. The footage was obtained through online video documentation. Except for one building to the left, all residential structures (or their remains) have been removed.

Figure 3.162. Tunnel Exit on October 24th, 2021. Screenshot obtained from https://www.youtube.com/watch?v=ol4SYAb_Olc

The tunnel street (Tunnelstrasse) was completely destroyed by the water efflux rushing out of the tunnel exit and exposed underlying bedrock to a depth of about 2-3 m. Near the tunnel exit a total of 4 bridges cross the Ahr river (Figure 3.163). Two of the bridges, (a) a road bridge to the wastewater treatment plant across the tunnel exit (shown in the orange frame in Figure 3.163), and (b) a pedestrian/bicycle bridge for the famous “Ahrradweg”, the popular bicycle path along the Ahr river, shown in the green frame in Figure 3.163. The large “double bridge”, located to the north of the tunnel consisted of two adjacent bridges, a rail bridge and a pedestrian/bicycle bridge that have their own separate tunnels. These two bridges suffered no major structural damage, except around the abutment area. Figure 3.164 shows drone imagery taken by the GEER team documenting debris deposit atop the bridge deck and along the rail line. Figure 3.165 shows the abutment area, where major erosion occurred, washing out all-natural soil adjacent to the first arch. No damage was observed around the middle piers of the bridge. Debris deposited atop the bridge was flushed through the tunnel and remained on the bridge deck (Figure 3.166).

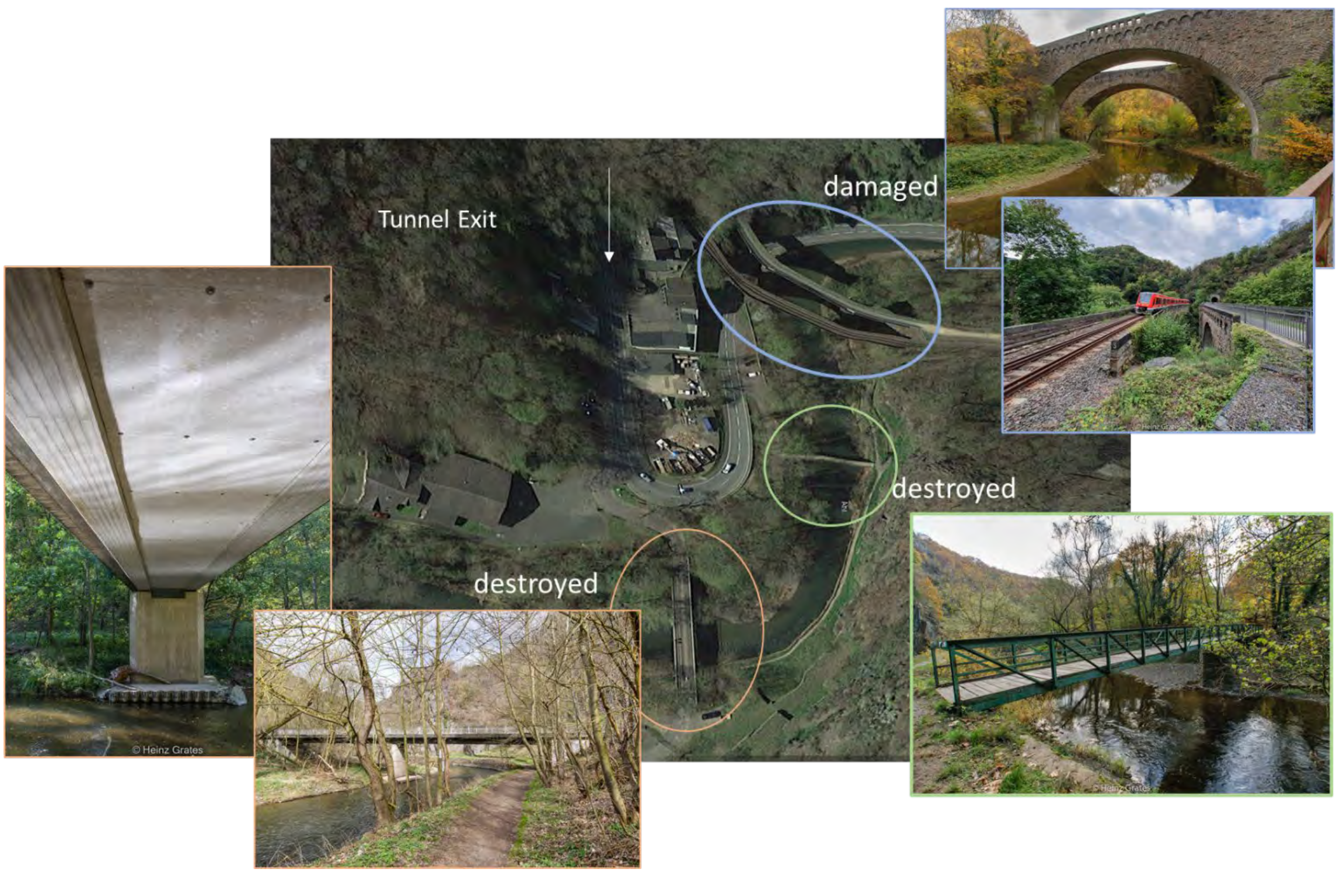

Figure 3.163. google maps excerpt of tunnel exit and surrounding bridges, two of which were washed away. Before flood photos: Heinz Grates, Source: https://www.aw-wiki.de/index.php/Ahrbr%C3%BCcken_im_Kreis_Ahrweiler

Figure 3.164. Aerial photograph of historic rail and pedestrian bridge at tunnel exit (50.5169260, 6.9970019)

Figure 3.165. Major erosion around bridge abutment areas (50.5169260, 6.9970019).

Figure 3.166. Photographs of “double bridge”, showing mud fields and tree clean-up work (top photo) as well as erosion around bridge abutment and along the riverbanks (bottom photos), (50.5169260, 6.9970019).

The wastewater plant adjacent to the tunnel exit was also severely damaged and still remains closed six months after the flood. The plant was located where water from the Ahr river (which flooded the narrow Ahr-bend (“Ahrschleife”) and the water flowing through the tunnel intersected. Figure 3.167 shows photos of the area around the treatment plant.

Figure 3.167. Aerial photograph of destroyed river and floodplains, as well as damaged wastewater treatment plant (50.51617525, 6.9989579).

3.4.2. Reimerzhoven (near Altenahr)

The village of Reimerzhoven is located on the Ahr River between Mayschoß and Altenahr, each of which is two kilometers away from Reimerzhoven. The settlement was founded in the 14th century as a winegrowers' village. It consists of about 40 houses and two streets. Its location is shown in Figure 3.168.

Figure 3.168. Location of Reimerzhoven and its bridges. Figure also shows the town of Laach.

Along the route from the Altenahr Tunnel to Reimerzhoven, massive amounts of debris were deposited along the riverbanks and within the embankment areas. Both bridges in Reimerzhoven were destroyed. The bridge shown in Figure 3.169 (top left) from upstream direction was completely washed away. Figure 3.169 top right shows the location of where the bridge was once standing. Figure 3.169 bottom shows the substantial amount of erosion along the riverbanks.

Figure 3.169. Location of pre-flood pedestrian bridge with aerial view of Reimerzhoven. Top left: bridge before flood (credit: Heinz Grates, Source: https://www.aw-wiki.de/index.php/Ahrbr%C3%BCcken_im_Kreis_Ahrweiler), Top right: flood damage and missing bridge, Bottom: global photo of area. Photo source: https://www.inforadio.de/dossier/2021/silvester/beitraege/flutkatastrophe-ahr-ahrtal-nordrhein-westfalen-rheinland-pfalz-loni-josten-reimerzhoven.html

Figure 3.170 shows the remains of the bridge depicted in Figure 3.169. Except for a middle pier and some abutment wall leftovers, little evidence indicates the once existing pedestrian bridge. Figure 3.170 shows debris and destruction around the Ahr river and its limited flood plains between Reimerzhofen and Laach. The Steep terrain on both sides of the Ahr river yielded high water levels as shown in Figures 3.171. Visible dirt lines indicate water elevation to be well in or above the 2nd story of the adjacent residential building. For typical German construction (story heights ~2.30m) this suggests a water elevation in the bottom photograph of Figure 3.172 of nearly 5.0 meters.

Figure 3.170. Remaining middle pier of pedestrian bridge in Reimerzhoven, and soil erosion near embankment (50.5195072, 7.004132)

Figure 3.171. Debris and deposits along the river, after the first major clean up. Photos take on the road between Reimerzhoven and Laach (50.5199710, 7.0070852)

Figure 3.172. Water elevation in Reimerzhoven, based on visible watermarks on buildings (50.5201175, 7.006573)

Figure 3.173 shows the second bridge, a bicycle bridge in Reimerzhoven. This bridge is a single span, cable stayed bicycle bridge with steel girders and steel deck. Photos in Figure 3.173 show the location of the bridge (top left), and photographs taken prior to the flood event.

Figure 3.173. Location of damaged bicycle bridge (top left) and pre-flood pictures of bridge, Source:

Figure 3.174 shows the bicycle bridge on August 13, 2021. The bridge was clearly damaged, the bridge deck was still connected to its abutment structure (this was a fixed structural connection due to the single, cable span mechanism), but the bridge deck was rotated in downstream direction. The bridge deck was bent down into the river at approximately midspan.

Figure 3.174. Bridge damage of the bicycle bridge in Reimerzhoven documented by the GEER team (50.5188435, 7.00714039)

3.4.3. Laach

Figure 3.168 included the district of Laach, which belongs to the wine town Mayschoss. Laach is located on the Mayschoss bicycle path (Mayschoss Radweg), which was known for its famous wood bridge. The construction of the 460,000 Euro bridge began in 2004 and was completed just before Easter 2005. It was inaugurated in July 2005. The approximately 30-meter-long structure had a clearance of about four meters and a width of 3.5 meters. In total, the original bridge was six meters high. The bridge spanned the Ahr River with a length of 29.20 meters. With its enormous longitudinal girders, it was considered the largest all-timber bridge in Germany, which is why it was the reference object of the European Timber Route (https://www.aw-wiki.de/index.php/St.-Anna-Br%C3%BCcke_Laach). Figure 3.175 shows the bridge before the flood event:

Figure 3.175. Bicycle bridge Laach prior to the 2021 flood, Source:

The remaining components of the bridge in Laach are shown in Figure 3.176. Figure 3.176 (bottom right) also shows the cut off and erosion, exposing the steep rock slopes adjacent to the river.

Figure 3.176. Remaining abutment structures of the pedestrian timber bridge Laach at the time of the team's visit (50.517824, 7.00952)

Figure 3.177 shows the devastation around the river between Laach and Mayschoss. Steep cuts are visible along the slopes adjacent to the river.

Figure 3.177. Damage and devastation along the Ahr river between Laach and Mayschoss. Thousands of tons of debris and trash are still to be removed (bottom photo) (50.5165985, 7.01311363)

3.4.4. Mayschoss

Mayschoss is a small town with less than thousand inhabitants (966), located at an elevation of only 124m and surrounded by Vineyards. Following the flood, Mayschoss was only accessible through air (Stern.de, 2021). Water levels in Mayschoss reached over nine meters, compared to the Ahr’s typical water table elevation (Stern.de, 2021).

3.4.4.1. Damage to residential housing and infrastructure in Mayschoss along Bundesstrasse 267

According to the municipality, around 158 of some 351 buildings in Mayschoß and Laach were damaged or completely destroyed. The Mayschoß-Altenahr winegrowers' cooperative, which claims to be the oldest winegrowers' cooperative in the world, was flooded. Almost all bridges were destroyed (SWR.de, 2022). Inhabitants were supported by military, which flew in food, drinking water and other essential supplies for 5 consecutive days. Thereafter an emergency road to and across Mayschoss was constructed and paved. Figure 3.178 (top left) shows the destroyed road in Mayschoss which cut the town’s access. Figure 3.178 depicts damage to residential and commercial buildings in Mayschoss. Mayschoss was one of the key wine towns in the Ahr Valley.

Figure 3.178. Damage in Mayschoss and cut-off of main access road. Sources: Top Left: https://www.augsburger-allgemeine.de/panorama/Katastrophen-Alle-fuer-alle-Wie-sich-ein-Dorf-aus-dem-Schlamm-kaempft-id60205721.html; https://www.rhein-zeitung.de/region/aus-den-lokalredaktionen/kreis-ahrweiler_artikel,-ueberleben-im-chaos-mayschoss-hat-es-organisiert-_arid,2285542.html; Photo bottom: https://www.swr.de/swraktuell/rheinland-pfalz/koblenz/mayschoss-nach-dem-hochwasser-100.html

Figure 3.179 shows the accumulation of household trash (primarily large appliances such as laundry machines, dishwashers, stoves and cabinets) collected for pick up nearby the residential buildings. Figure 3.179 (right) shows the church of Mayschoss which served as temporary storage and distribution center for donations for the flood victims.

Figure 3.179. Left:Trash collection in Mayschoss (photo by Boris Ressler/dpa, https://www.rheinpfalz.de/lokal/frankenthal_artikel,-hochwasser-gefahrstoffexperten-im-einsatz-_arid,5231883.html?reduced=true); Right: donation distribution in the Mayschoss church, photo by Juergen Tarrach, https://www.rhein-zeitung.de/region/aus-den-lokalredaktionen/kreis-ahrweiler_artikel,-ueberleben-im-chaos-mayschoss-hat-es-organisiert-_arid,2285542.html

In February 2022, seven months after the flood, the Mayschoss community was reconnected to the electricity and water networks, and public transportation into town was provisionally restored. The municipality has set up 20 Tiny Houses for those affected by the flood. According to the reconstruction staff, a total of 25 buildings in Mayschoß and Laach are affected by the demolition, some may not be rebuilt in the same place. The winegrowers' cooperative also has to demolish buildings (SWR.de, 2022). Figure 3.180 and 3.181 shows damage in Mayschoss recorded by the GEER team in August 2021.

Figure 3.180. Damage to residential and commercial buildings in Mayschoss (50.5184234, 7.0205426)

Figure 3.181. Top: Remains of a flooded winery in Mayschoss; Bottom: watermarks at several residential buildings along Bundesstrasse 267 in Mayschoss indicating water level rise during flood (50.52194645, 7.021036269)

Figure 3.182 shows a set of before-after images obtained from SWR.de:

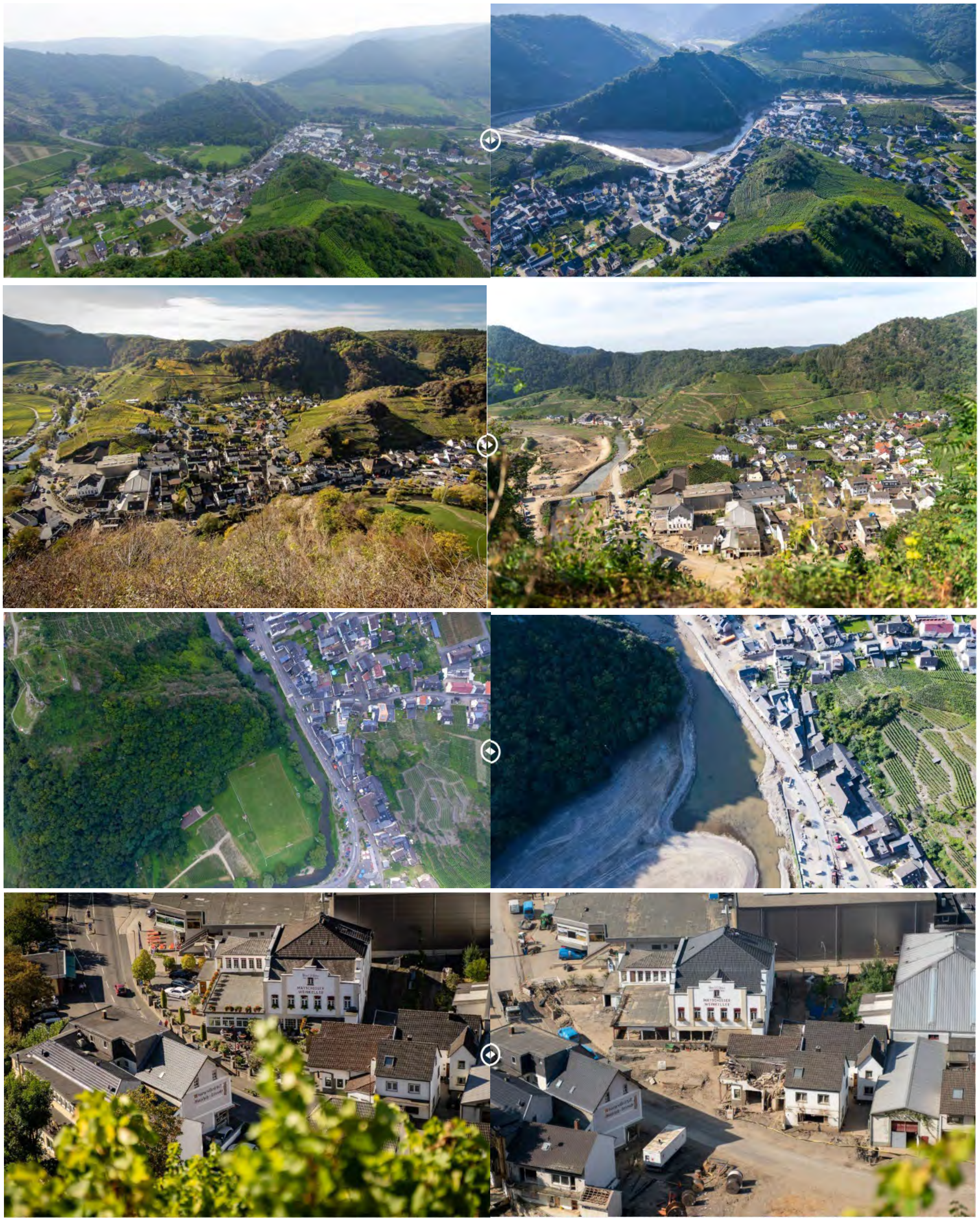

Figure 3.182. Before (left) and after (right) photos of Mayschoss (Source: swr.de)

3.4.4.2. Mayschoss, Bridge to train Station (Bahnhofsbruecke)

All bridges in Mayschoss were severely damaged. Figure 3.183 shows before/after photos of the road bride to the train station Mayschoss, which is locaed across the river, on the right hand side as shown in Fig. 3.183 bottom. The bridge was damaged due to debris deposits, however, remained structurally intact. The bridge deck, as well as the abutment areas appeared stable at the time of the team's visit. A temporary railing was installed, and the bridge was continued to be used (Figure 3.184).

Figure 3.183. Foto of Mayschoss, bridge to train station in background, Top: prior to the 2021 flood, photo by Heinz Grates via https://www.aw-wiki.de/index.php/Ahrbr%C3%BCcken_im_Kreis_Ahrweiler), bottom after the 2021 flood, Source: https://www.rheinpfalz.de/lokal/speyer_artikel,-flutkatastrophe-b%C3%BCrger-sollen-f%C3%BCr-mayscho%C3%9F-spenden-_arid,5231261.html

Figure 3.184. Bahnhofsbrücke Mayschoss on August 13, 2021 (50.51784531, 7.02004213)

3.4.4.3 Recycling of trees debris in Mayschoss

Figure 3.185 shows recycling operations in Mayschoss along the stretch between Mayschoss town, and Hotel Bergischer Hof. The large amounts of deadwood accumulated through the upstream stretch of the Ahr valley, was collected, cut, and chopped using large mobile woodchoppers. Mayschoss served as central recycling and redistribution hub to the Ahr valley.

Figure 3.185. Recycling operations along Bundesstrasse 267 in Mayschoss using mobile woodchoppers (50.51924, 7.0264184)

3.4.4.4. Mayschoss Double Bridge near Hotel Bergischer Hof

The building “Hotel Bergischer Hof”, previously run as a hotel served in recent years as residence to the family who once ran the Hotel business. The house was in the process of remodeling and served as landmark along the Bundesstrasse B267 towards Rech (Figure 3.186). Figure 3.187 shows a photograph of the Hotel prior to the flood, and post 2021 flooding.

Figure 3.186. Hotel Bergischer Hof and double bridge across the Ahr; Photo taken by Heinz Grates, Available through: https://www.aw-wiki.de/w/index.php?curid=75512

Figure 3.187. Historic Photo of Hotel Bergischer Hof (left, Source: https://oldthing.de/AK-Mayschoss-Hotel-Restaurant-Bergischer-Hof-Cafe-0042096931) and post-flood photo of Hotel Building (August 2021, 50.518393429, 7.026975)

The double bridge next to the “Hotel Bergischer Hof” consisted of the typical duo: a bicycle/pedestrian bridge next to the rail bridge (Figure 3.186). The predestrian bridge was location upstream of the rail bridge and consisted of a historic brick-arch bridge (Figure 3.188).

Figure 3.188. Rail and bicycle/pedestrian bridge at Hotel Bergischer Hof prior to flood. Photos by Heinz Grates, Source: https://www.aw-wiki.de/index.php/Ahrbr%C3%BCcken_im_Kreis_Ahrweiler#Mayscho.C3.9F

Figures 3.189 – 3.191 document the intense damage to both bridges. As shown in Figure 3.189, the upstream pedestrian bridge was completely destroyed, with only 1.5-arch remaining standing. The rest of the bridge was washed away, a few selected pieces of the bridge foundation remained visible in the riverbed. The rail bridge also suffered irreparable damage. The bride abutment constructed in the adjacent rock remained intact, along with one intermediate bridge support wall (Figure 3.189 and 3.190). The rest of the bridge supports laid in the river, part of the superstructure truss was washed onto the downstream shore (see Figure 3.191)

Figure 3.189. Destroyed rail and bicycle bridge at “Hotel Bergischer Hof” in Mayschoss. Photo taken by GEER team 2021(50.51818719, 7.02648801)

Figure 3.190. Panoramic view of destroyed rail bridge at Hotel Bergischer Hof. Photo Credit: Heinz Grates accessed through: https://www.aw-wiki.de/index.php/Ahrtalbahn-Br%C3%BCcke_Mayscho%C3%9F)

Figure 3.191. Damage around bridge showing destroyed rail tracks (top left, (50.51818719, 7.02648801)), Submerged bridge foundation components (top right), and aerial view taken several months later by Heinz Grates, Source: https://www.aw-wiki.de/w/thumb.php?f=Mayscho%C3%9F_-_Heinz_Grates_%28320%29.jpg&width=1200)

Figure 3.192 shows close-up photographs of both bridge superstructures. Photographs suggest that the superstructure was broken off and washed away due to the impact from debris and objects carried by the flood waters.

Figure 3.192. Remaining sections of the two bridges at Hotel Bergischer Hof, (50.51818719, 7.02648801).

<u>*3.4.5. Rech*</u>

Rech is a small municipality in the district of Ahrweiler with a population of 565 inhabitants. Rech is known for its wineries and its location along the famous "red wine hiking trail" (Rotweinwanderweg), which begins at the foot of the Are castle ruins in Altenahr and leads through the vineyards of Mayschoß, Rech, Dernau via Marienthal, Walporzheim, Ahrweiler, Bad Neuenahr, Heppingen, over the Landskrone to Lohrsdorf and to Bad Bodendorf. The total length is 34 km. The red wine hiking trail is probably one of the most frequented themed hiking trails in Germany. Rech was severely destroyed during the flood events and was closed off to public access for several days. The famous Ahr bridge "Nepomukbrücke", which connects both parts of Rech, was destroyed. Figure 3.193 shows damage in Rech.

Figure 3.193. Damage in Rech, Source: https://ga.de/fotos/region/flutkatastrophe-im-kreis-ahrweiler-bilder_bid-61312581#28

The Ahrbrücke (also called The St. John of Nepomuk Bridge) in Rech, is a stone arch bridge over the Ahr River. The road bridge connects the village center with the federal road B267. The structure has been a protected cultural monument since 1981. *(https://de.wikipedia.org/wiki/Ahrbr%C3%BCcke_(Rech).*
From 1723 to 1724, the municipality of Rech built two stone piers in the Ahr River, on which a three-span wooden beam bridge was placed. In 1759, the bridge structure was replaced by two arches made of quarry stones. After a flood in 1804, the addition of two arches followed. The flood of the Ahr on June 13, 1910 destroyed all smaller and eight large Ahr bridges. Only the bridges near Dernau and Rech were preserved. Extensive bridge renovation work was carried out in 2008. The construction costs amounted to 934,000 euros. The bridge, which is about 43 meters long and up to five meters high, is made of graywacke masonry and has four flat, 4.94-meter-wide basket arches. The two inner arches have a clear width of 8.40 meters each, the outer ones of 9.45 meters and 9.12 meters respectively. The pier widths vary between 1.85 meters and 2.92 meters. A 47-centimeter-thick, 76-centimeter-high brick parapet delimits the 4.0-meter-wide roadway. The bridge was severely damaged during the flood of the Ahr River on July 14-15, 2021. The fourth arch of the bridge was swept away along with a large part of the southern, right bank. Traffic crossing the Ahr was provisionally handled first by shuttle boats, then by an armored fast bridge until August 25, 2021. By January 2022, the town of Rech has determined that the Nepomuk Bridge will not be rebuilt. In addition, 13 plots of land may no longer be built on. Replacement sites are being sought for the owners. The traffic routing in the village is also being planned anew (SWR.de, 2022). Figures 3.194 and 3.195 show the bridge before and after the flood event.

Figure 3.194. Aerial view of Nepomuk Brücke in Rech prior to the 2021 flood, obtained through: https://www.bundeswehr.de/de/organisation/personal/fluthilfe-im-ahrtal-nachbar-helfer-soldat--5207408

Figure 3.195. Before photos of the Nepomuk bridge in Rech, Source: Adobe photostock, standard license (free)

Figure 3.196 – 3.198 show post-flood images depicting the destroyed Nepomuk bridge as well as two of the three emergency bridges erected in Rech. The part of town shown on the left-hand side in Figure 3.196 was cut-off by the flood and only accessed with helicopters during the first days of emergency response. A total of three emergency bridges were constructed in Rech by the German military as shown in Figure 3.198. Figure 3.199 (top and 2nd row) shows a temporary floating pedestrian bridge which was erected on July 23rd, within 6 days of the flood. This bridge enabled pedestrian access to the “cut-off” part of Rech. Later, two road bridges were constructed (shown in the back of Figure 3.198 and in Figure 3.199).

Figure 3.196. Post-flood aerial image of Rech and its Nepomuk bridge, Source: Deutsche Bundeswehr, https://www.bundeswehr.de/de/organisation/personal/fluthilfe-im-ahrtal-nachbar-helfer-soldat--5207408

Figure 3.197. After flood photos of the Nepomuk bridge in Rech, showing missing bridge arch and abutment structure (50.5141233, 7.03625453)

Figure 3.198. Rech and the destroyed Nepomuk bridge (middle) with a pedestrian emergency bridge (front) and two road bridges (background)

Figure 3.199. Photographs of the three emergency bridges in Rech. Sources: Bundeswehr.de

3.4.6. Dernau

The village of Dernau which is centrally located in the Ahr valley, within a short drive from Bad Neuenahr Ahrweiler, and famous for its wines. The town has a population of 1700 inhabitants (https://en.wikipedia.org/wiki/Dernau). Dernau is famous for its red wine production. Besides agriculture, tourism is a strong economic factor. According to the tourism association, around 90 percent of the citizens of Dernau were affected by the damage caused by the flood (SWR.de, Jan 2022). In addition, there was massive damage to the infrastructure. For example, the bridge over the Ahr was destroyed. Six months after the flood, 400 houses are still not habitable. 30 buildings have been demolished, with another 20 to follow, according to the municipality. The calculated damage amounts to 87.95 million euros, according to the municipality. In December, a container village for senior citizens was built, and since January there have also been 15 mobile homes and 13 Tiny Houses for residents who lost their homes in the flood (SWR.de, 2022). Figure 3.200 shows a photograph of the Ahr bridge in Dernau immediately after the flood. Figure 3.200 shows a photo taken by the GEER team in August 2021. Figure 3.202 shows a photograph of Dernau with two emergency bridges in place.

Figure 3.200. Dernau, Photo by Benjamin Westoff, Accessed through: https://ga.de/fotos/region/flutkatastrophe-im-kreis-ahrweiler-bilder_bid-61312581#58

Figure 3.201. Damaged Ahr bridge in Dernau on August 10th, 2021, documented by the GEER team (50.533719356, 7.0453862)

Figure 3.202. Damaged bridge with 2 emergency bridges (Jan 2022), Source: SWR.de, accessed through: https://www.swr.de/swraktuell/rheinland-pfalz/koblenz/dernau-nach-dem-hochwasser-100.html

3.4.7. Marienthal

Marienthal is located in the middle of the Ahr valley to the left of the river between Walporzheim and Dernau, surrounded by steep vineyards and forest. Marienthal is a small community with three wineries and just around 100 inhabitants, at an elevation of 120m above sea level. Two wineries have been destroyed and are closed. While vineyards are intact, both winemakers lost all equipment and business infrastructure to keep operations running. Figure 3.203 shows a google satellite image showing the towns of Marienthal and Walporzheim. Five bridges cross the Ahr river within the short distance (2.1km) between Marienthal and Walporzheim are damaged or destroyed. Marienthal itself has been heavily destroyed as shown in Figure 3.204. Marienthal had 105 inhabitants and recorded three fatalities due to the flood (https://www.hochwasserhilfe-marienthal.de/ein-erster-post-5/). 90% of all houses were flooded, at least to, and including the first story. Figure 3.204 shows severe damage to two buildings in Marienthal as well as the town's emergency medical office (bottom photos).

Figure 3.203. Location of Marienthal and bridges inspected around Marienthal

Figure 3. 204. Destroyed houses (top) and post-flood doctors office (bottom) in Marienthal (Source: https://www.hochwasserhilfe-marienthal.de/bildergalerie/)

The team inspected the rail bridge at various locations. Near the "Hotel zum Sänger", the team documented the bridge damage of two close-by bridges. The Hotel zum Sänger (white building shown in Figures 3.205 and 3.206 was evacuated. Residents reported water levels to be above the 2nd story. This suggested an estimated water level rise of up to (or more than) 7.0 meters. Emergency evacuation was performed by the fire department and Hotel staff using the latter shown in Figure 3.206, which was placed between the roof of the house and the adjacent slope of the vineyard. Eyewitnesses described seeing the hotel guests climbing out of the windows and crossing the floods on the latter, with water elevations being just 30cm below the latter. Figure 3.205 shows all buildings along the landmark and their location.

Figure 3.205. Damaged bridges and buildings near the "Hotel zum Sänger" between Marienthal and Walporzheim, Source: google maps overlain with photos by Geer team and Generalanzeiger Online

Figure 3.206. Water levels at the Hotel zum Sänger, Marienthal/Walporzheim

Three rail bridges within the short Ahr bend in Marienthal were inspected by the GEER team. Figure 3.207 show the locations of the bridges. "Bridge A" did experience some damage, but largely withstood the impact of the flood. Bridges B and C experienced irreparable damage and were later removed. Figure 3.208 shows the erosion along the Marienthaler Strasse, the main road shown in Figure 3.207. Figure 3.209 and 3.210 show damage to Bridge B, which consisted of displaced and tilted bridge pier walls, a washed-out left abutment, and displaced rail tracks. Three of the bridge supports appeared to be structurally stable. The pedestrian/bicycle deck was lifted and washed away.

Figure 3.207. Location of rail and bicycle bridges near Hotel zum Sänger

Figure 3. 208. Erosion along the Ahr and adjacent slopes between Marienthal and Walporzheim (50.5343798, 7.05975402)

Figure 3.209. Panoramic photographs of Bridge B (rail bridge) from upstream direction (top and center) and downstream (bottom) direction (50.5331621, 7.0592238).

Figure 3.210. Documentation of damage to rail bridge "B" in Marienthal/Walporzheim, (50.5331621, 7.0592238).

Figure 3.211 and 3.212 show the bride close by the Hotel zum Sänger as well as the residential and business buildings (Vinothek "Ahr") shown as "Bridge C" in Figure 3.207. This bridge, similarly to bridge "B" consisted of a rail deck and a pedestrian deck, resting next to each other on several brick support walls. Figure 3.211 shows photographs of the bridge prior to the flood obtained from online sources. A drone photo (Figure 3.212) of bridge C presents the extent of damage, which included completed erosion of the abutment areas, and heavy damage to the abutment structure in downstream direction left (shown on the right hand side in Figure 3.212). Several of the intermediate support walls tilted, rotated, and settled in the riverbed. The photograph also shows the massive erosion along the river to bedrock (see washed-out slopes on the left of Figure 3.212). Figure 3.213 depicts the damaged rail line approaching bridge "C" and the damage to the adjacent residential buildings.

Figure 3.211. Photos of the bridge near the “Hotel zum Sänger” between Marienthal and Walporzheim prior to the 2021 flood event (top: https://www.aw-wiki.de/w/index.php?curid=35163, Bottom left: https://www.aw-wiki.de/w/index.php?curid=67373, Bottom Right: https://www.aw-wiki.de/w/index.php?curid=39699)

Figure 3.212. Drone image of rail bridge at Hotel zum Sänger (50.532217, 7.0624500)

Figure 3.213. Damage documented around the rail bridge and adjacent residential building (50.532217, 7.0624500)

Figure 3.214 shows more photos of "bridge C" near the Hotel zum Sanger and depicts the severe tilt of the middle foundation support.

Substantial difference in elevation is visible around the deck and the water level, indicating rotation accompanied by settlement and soil erosion around the foundation element.

Figure 3.214. Rail bridge damage near Hotel zum Sanger, Marienthal/Walporzheim, (50.532217, 7.0624500).

3.5. Day 3-5: Ahrtal Part C: From Bad-Neuenahr Ahrweiler to Rhein river and Sinzig

3.5.1. Travel Route from Bad Neuenahr Ahrweiler to Sinzig

The team visited the Ahr river section from Bad Neuenahr-Ahrweiler to the Ahr-Rhine-confluence, close to Kripp, on August 12, 2021. The travel route is shown in Figure 3.215. Primarily, the bridges shown in Figure 3.215 and listed in Table 3.5 were examined. Smaller pedestrian bridges, including the Amseltal bridge (Bad Neuenahr-Ahrweiler), the pedestrian bridge in Sinzig, and the bicycle path bridge in Kripp, were completely destroyed as a result of the flood event. However, considerable damage was also reported at larger bridges.

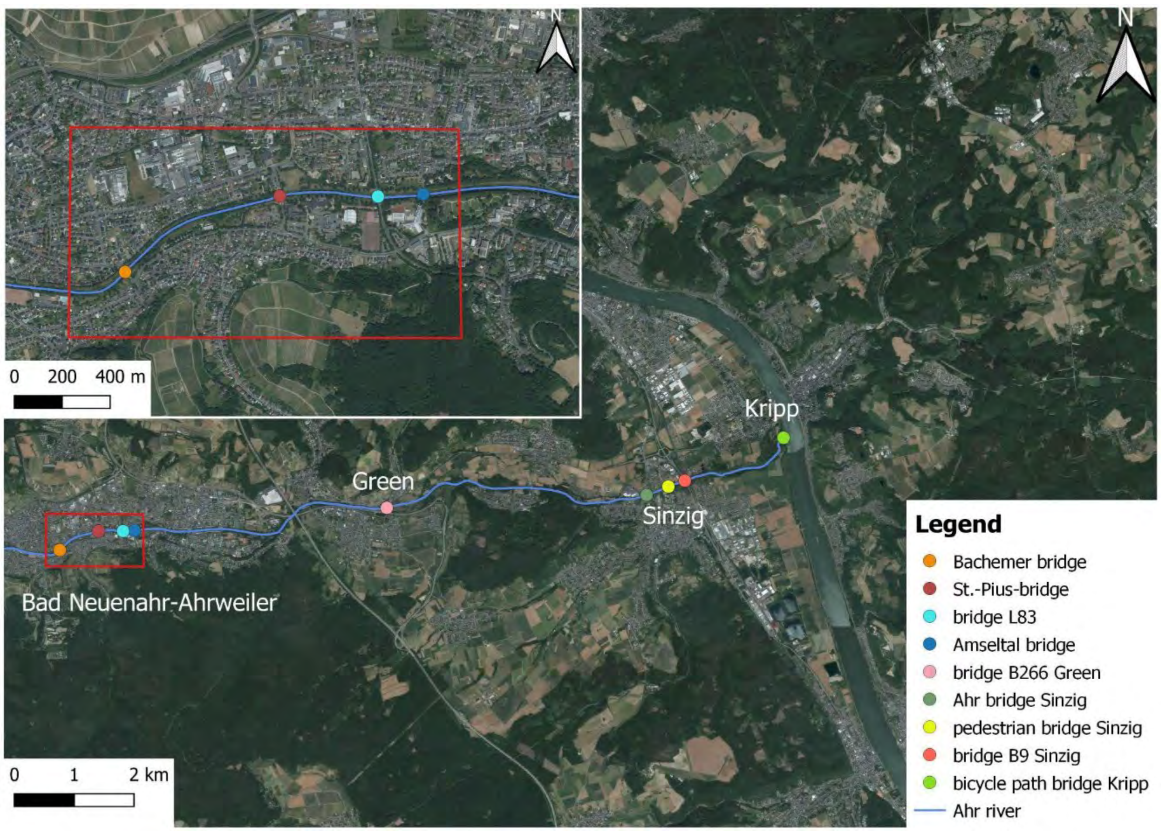

Figure 3.215. Examined bridges crossing the Ahr river in the section from Bad Neuenahr-Ahrweiler to Kripp (Rhine - Ahr Confluence)

Table 3.5. List of the examined bridges shown in Fig. 3.214 with related GPS-coordinates

Town	**Examined bridges**	**GPS-coordinates**
Bad Neuenahr-Ahrweiler	Bridge Bachemer Straße	50.539450; 7.106596
	St.-Pius-bridge	50.542463; 7.115642
	Bridge L83	50.542527; 7.121371
	Bridge Uhlandstraße	50.542624; 7.124038
	Bridge Otlerstrasse/Am Schwimmbad	50.53561; 7.10128
Green (Bad Neuenahr-Ahrweiler	Bridge B266	50.546220; 7.183492
Sinzig	Ahr bridge	50.549856; 7.244673
	Pedestrian bridge	50.551174; 7.249713
	Bridge B9	50.552182; 7.253561
Kripp	Bicycle path bridge	50.558957; 7.276552

3.5.2. Bad Neuenahr-Ahrweiler

In Bad Neuenahr-Ahrweiler, the damage along the Ahrallee was investigated between the Bachemer bridge and the Amseltal bridge. Since most of the buildings here are located at a considerable distance to the river, the damage to buildings appeared less severe than in narrower locations of the Ahr valley. Nevertheless, damage to buildings, especially undercutting of foundations, was considerable in this area as well. The GEER team observed traces or scour around buildings reaching down to basement and foundation levels, destroyed yards, and roads (Fig. 3.216). Substantial high-watermarks in excess of 2 meters were visible in the same area. (Fig. 3.217).

Figure 3.216. Residential building in Bad Neuenahr-Ahrweiler about 100 m from the Ahr river showing scour at corner of the building, destruction of yards and roads, and the original road just being temporarily replaced by a gravel road.

Figure 3.217. Residential area near the Ahr river, in Bad Neuenahr-Ahrweiler showing destruction of the road and high water marks on residential buildings in excess of 2 m. (50.5411069, 7.108835)

Of the four bridges in this section, the Bachemer Bridge and the Amseltal Bridge were completely destroyed by the flood (Figs. 3.218 and 3.219, respectively).

Figure 3.218. Left: Bachemer bridge before the flood event (source: https://www.aw-wiki.de/index.php/Ahrbr%C3%BCcken_im_Kreis_Ahrweiler); right: replacement bridge for the destroyed Bachemer bridge.

Figure 3.219. Left: Amseltal bridge before the flood event (source: https://www.aw-wiki.de/index.php/Ahrbr%C3%BCcken_im_Kreis_Ahrweiler); right: Destroyed Amseltal bridge at the time of the GEER visit (50.542624927, 7.124041563).

The bridge across the Bundesstrasse L83 was severely damaged. The accumulation of significant amounts of flotsam debris was documented shortly after the flood event. Riverbanks showed significant erosion around the bridge, and the underpass for pedestrians and cyclists was destroyed, requiring immediate stabilization of the bridge deck (Fig. 3.220). Figure 3.220 shows the bridge before the flood, immediately after the flood and at the time of the teams visit with damage to the bridge railing, significant sediment relocations at the riverbanks and within the riverbed, and the destruction and temporary stabilization of the pedestrian underpass part of the bridge.

Figure 3.220. L83 bridge Bad Neuenahr-Ahrweiler. Top left: prior to the flood event (source: https://www.aw-wiki.de/index.php/Ahrbr%C3%BCcken_im_Kreis_Ahrweiler); top right: significant deposition and accumulation of debris against and around the bridge during and shortly after the flood; bottom): the bridge at the time of the GEER team visit (50.542527; 7.121371)

At the St. Pius Bridge (Figure 3.221), scour was observed by the GEER team at the bridge pier that separates the pedestrian underpass from the river span. Despite the scour and damage to the bridge rails, this bridge was less severely damaged and was open to traffic at the time of the GEER team visit. Fig. 3.222 offers a close up at the scour. Responsible maybe a combination of efflux coming from a pipe that was exposed (Fig. 3.222) and shows a significant pool that appears likely associated to flow efflux, and of flow- bridge pier inter action creating scour particularly at the upstream river-side corner of the pier. Together, both processes may have formed the significant scour hole that is wrapping around the upstream side of the pier exposing gravelly substrata supporting the pier as well as a sheetpile construction towards the river side. It appears that the sheet pile wall succeeded to mitigate scour to undermine the pier.

Figure 3.221. St.-Pius bridge Bad Neuenahr-Ahrweiler. Top) Bridge before flood; bottom) observations by the GEER team on August 12, 2021 (50.542423, 7.115540328).

Figure 3.222. Close up of the St. Pius Bridge pier in Bad Neuenahr-Ahrweiler separating the pedestrian underpass part of the bridge from the river crossing span. Significant scour is observed wrapping around the upstream part of the pier (50.542423, 7.115540328).

The Otlerbruecke (Fig. 3.223) in Bad Neuenahr Ahrweiler, a cable span pedestrian bridge, exhibited a similar damage pattern as observed at the bicycle bridge in Reimerzhofen (see Section 3.3). Figure 3.223 (top left) shows the bridge prior to the flood event. Photographs on the top right and bottom left show the bridge at the time of the team's visit. The abutment structure and its connection to the superstructure piers on the right-hand side in downstream direction were still standing. The bridge deck was lifted up at its opposite support and rotated in the downstream direction, leading to full destruction of the bridge. Flood water levels substantially exceeded the clearance of the bridge deck. At the time of the team visit, the bridge deck was located at the riverbank with the cables still being connected to the bridge deck (Fig. 3.223 bottom left). The abutment wall appeared to be structurally intact at the time of the team's inspection (Fig. 3.223 bottom right).

Figure 3.223. Otlerbruecke, Bad Neuenahr Ahrweiler. top left) before the flood event top right & bottom left) destroyed bridge deck, rotated counterclockwise in downstream direction on August 12, 2021; bottom right) bridge abutment (downstream left), structurally intact at the time of the team's visit (50.53874, 7.1013125)

<u>3.5.3. Green</u>

In the town of Green, the Ahr river is fringed by railway tracks and the Landskroner Strasse to the North and by the federal highway 266 (B266) to the North with sometimes less than 20 m between the river and the railway tracks and as little as 10 m between the river and the highway. During the flood event, the riverbanks eroded so severely that erosion led to road damage to B266 and the riverbanks reached the railway tracks (Fig. 3.224). Overall, the river appears to be relocated in terms of a shift to the South approaching B266, while sediment deposits seem to have accumulated on the northern side (Figs. 3.225 and 3.226). Resulting road damage was significant (Fig. 3.224), particularly to a small asphalt road paralleling B266 between the highway and the river in some sections. However, railway track damage was also observed along short sections (Fig. 3.226). Local authorities recognized the risk to bridges and applied gravel and riprap scour protection and abutment stabilization (Fig. 3.226). It is unknown to the GEER team when the action was taken, but the lack of any vegetation or debris or erosion suggested a most recent deposit post flood to possibly address a detected scour hole.

Figure 3.224. Overview image showing the Ahr river, undermining of B266 (left) and the railway tracks on August 12, 2021, after the flood (50.5468469, 7.1817397).

Figure 3.225. Shift of the Ahr river to adjacent to the B266 and associated road damage (50.5465709, 7.1828458).

Figure 3.226. Rail damage (top) and embankment wall damage (bottom) along both sides of the Ahr river (50.547131515, 7.176075868).

Figure 3.227. Recent gravel and riprap deposits supporting the bridge abutments in Green (50.5470057, 7.18318548).

3.5.4. Sinzig

The section between the Kölner Straße bridge (Fig. 3.228) and the B9 bridge, both crossing the Ahr, was investigated in Sinzig by the GEER team. Only minor damage was caused to Koelner Strasse bridge as a result of the flood event. However, significant scour was documented under the northern arch spanning from the abutment to the first bridge pier over the river bank and around the northern bridge pier. A scour depth of consistently ~ 60 cm was reported (lpm.rlp.de). Riprap was filled into the scour hole and into an erosion channel that suggests severe flow from the upstream northern riverbank through the northernmost arch of the bridge, likely serving the load-bearing capacity of the pier (Fig. 3.229). It appears that reinforced soil around the abutment of the bridge mitigated scour at the abutment. The bridge was reopened to traffic on August 12, the same day as the investigation by the GEER team (lpm.rlp.de).

Figure 3.228. Koelner Strasse bridge crossing the Ahr in Sinzig (left, source: https://www.aw-wiki.de/index.php/Ahrbr%C3%BCcken_im_Kreis_Ahrweiler) before the flood event and (right) at the time of the GEER-visit (August 12).

Figure 3.229. Infill of the scour hole and of an erosion channel suggesting flow from the top of the upstream northern riverbank down through the northernmost bridge arch (50.549856, 7.244673).

A pedestrian bridge between Koelner Strasse and B9 was completely destroyed by the flood (Figure 3.230). Significant debris, mostly trees and vegetation were deposited in the original location of the bridge (Fig. 3.230).

Figure 3.230. Pedestrian bridge Sinzig before the flood (left, photo by Heinz Grate @ https://www.aw-wiki.de/index.php/Ahrbr%C3%BCcken_im_Kreis_Ahrweiler) and on August 12, 2021 (50.551174; 7.249713).

The federal highway 9 (B9) bridge in Sinzig experienced significant damage during the flood event (Fig. 3.231). The bridge piers of this bridge are typically located on the riverbanks and not exposed to flow. However, soil deposits suggest the significant expansion of the Ahr width during the flood event reaching a water treatment facility just downstream of the bridge (Fig. 3.231). Soil deposits may also suggest that significant flow, possibly enhanced by the presence of asphalt-bicycle ways leading from higher grounds to the river plain may have contributed to the more focused damage at the southern bridge pier. A significant scour hole formed, and the southern bridge tilted, leading to sagging and breaking of the bridge deck (Figs. 3.231 and 3.232). The railway bridge downstream of the B9 bridge seemed less impacted with traffic ongoing.

Figure 3.231. B9 bridge in Sinzig (left) shortly after the flood event, Source: blick-aktuell.de;

At the time of the GEER team visit on August 12, 2021, the failed upstream bridge deck was removed and soil preparation and stabilization for reconstruction was ongoing (Fig. 3.232).

Figure 3.232. Left: Removed damaged bridge deck of the B9 in Sinzig on August 12, 2021, northern riverbank. Right: Active soil preparation and infill ongoing on the southern riverbank side (50.55218, 7.253561)

The GEER team also inspected the downstream southern riverbank bridge pier. Erosion exposed sheetpile wall reinforcement around the foundation caps to a soil depth of about one meter around the entire pile (Fig. 3.233). Asphalt and cobble-concrete reinforcement along a pedestrian path was damaged, but also in some instances still in place. Erosion is also clearly visible towards the railway bridge piles; however, erosion seems to not have reached to critical levels here.

Figure 3.233. Sinzig B9 bridge downstream southern bridge pier at the time of the team visit (August 12) with the railway bridge in the background (50.55218, 7.253561).

3.5.5. Kripp

The confluence of the Ahr river to the river Rhine in Kripp-Remagen was investigated on August 12. At that time it appeared like business as usual in Kripp including active ferry and other river traffic on the Rhine. The confluence area Ahr-Rhine classifies as a nature reserve (nature reserve "Mündungsgebiet der Ahr") with development limited to recreational bicycle paths. A small wooden bridge connected the bicycle path across the Ahr and parallel to the Rhine (Fig. 3.234). This bridge was completely destroyed by the flood (Fig. 3.235). Large amounts of debris were deposited around this location. The bridge abutments seemed still in place and stable; however, the bridge pier was clearly tilted forward. This may suggest to be a result of severe scour that eroded the soil directly adjacent upstream of the pier, possibly undermining the pier if on shallow foundations so that the pier was able to slip and tilt into its own scour hole (Fig. 3.236).

Figure 3.234. Aerial image of the Ahr estuary

Figure 3.235. Bicycle path bridge across the Ahr before the flood (left, source: https://www.aw-wiki.de/index.php/Ahrbr%C3%BCcken_im_Kreis_Ahrweiler) and on August 12, 2021 (right), (50.558957; 7.276552).

Figure 3.236. Tilted bridge pier of Ahr-Rhine confluence bicycle bridge (50.558957; 7.276552).

3.6 Belgium – Valley of the river Vesdre, Liege – Pepinster – Verviers

3.6.1. Introduction to the flood in Belgium

In Belgium, the provinces of Hainaut, Namur, Liège, Luxembourg, Walloon Brabant, Limburg and the Brussels-Capital Region were affected. In addition to significant material damage, 39 victims lost their lives during these floods. Over 20,000 people in the southern region Wallonia were without electricity. Others lacked clean water. Two weeks after this natural disaster, the deadliest in the country's history, the Walloon Government recognizes the floods of 14, 15 and 16 July as a public natural disaster in 209 municipalities. In particular, the valley of the Vesdre river was heavily affected and therefore was visited on the sixth day of the mission. Figure 3.237 (left) shows a map of Belgium and the location of the Meuse river, and Figure 3.236 (right) illustrates the catchment of the river Vesdre (Bruwier *et al.*, 2015). Table 3.6 provides an overview of the places visited during the reconnaissance mission.

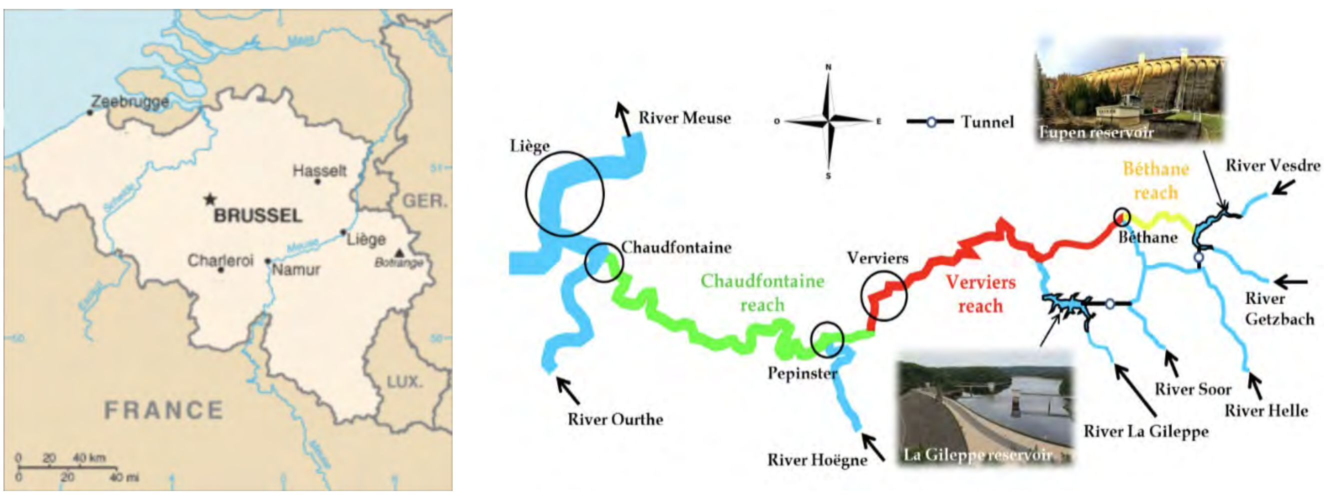

Figure 3.237. (Left) Map of Belgium showing the Meuse river (right) Vesdre valley from upstream of the Eupen reservoir to the mouth into the River Ourthe, which flows into the River Meuse (from Bruwier et al., 2015).

The water level of the Meuse river elevated in the city of Liege from 1.2m (July 14) to 4.01m (July 15) (Figure 3.238). The Meuse is a major European river flowing through France, Belgium and the Netherlands over a total length of 925 kilometers before draining in the North Sea. In Belgium, approximately 1,000 residents close to the riverbanks were asked to evacuate the area. The districts of Chênée and Angleur in the south of Liege, close to where the Ourthe river (a right tributary to the river Meuse) flows into the mainstem, were heavily affected.

Figure 3.238. Meuse river water level. River flood alerts in Belgium as of 16 July 2021. Image: Voies Hydrauliques Wallonie. Source: https://floodlist.com/europe/floods-belgium-july-2021 https://www.reuters.com/business/environment/belgium-warns-against-travel-flood-death-toll-hits-14-2021-07-16/

On July 15, 2021, the authorities of the city of Liège asked all residents near or near the Meuse and Ourthe to evacuate their homes and go to safety. The Liège police circulated there to help people evacuate. In addition, shop owners were asked to close their businesses and let their employees return home safely. During the night from Wednesday to Thursday, a crew of 8 firefighters from Antwerp left to provide assistance to the province of Liège. Among them, five divers with boats as well as rescue equipment would help the army to evacuate victims from their homes or locate missing persons. France has also sent 40 civil security rescuers. A convoy of 103 firefighters and 26 Austrian boats were sent as reinforcements to secure the victims of Liège. A curfew was decreed by the mayor of Verviers, Muriel Targnon, for the night of July 14 to 15 as well as that of July 15 to 16, from 9 p.m., as a measure to stop the looting that took place in the abandoned stores and houses. Concerns regarding the Tihange Nuclear power plant, one of the two Nuclear energy production sites in Belgium and located on the banks of the Meuse river, were addressed by the Federal Agency for Nuclear Control. On July 16, they reassured the population by declaring that “The risk of flooding around the Tihange nuclear power plant remains under control and there is no immediate danger”. Evacuations were also carried out in neighboring Chaudfontaine situated to the south of the city of Liège due to the overflowing Vesdre river, which is a right tributary to the river Ourthe. In this part of the Vesdre river, the water increased by 3.5m within 24 hours (Figure 3.239). As of 16 July, at least 3 fatalities were reported in nearby Trooz, while another person died in Aywaille to the south of Chaudfontaine.

Figure 3.239. Vesdre river water level at Chaudfontaine. River flood alerts in Belgium as of 16 July 2021. Image: Voies Hydrauliques Wallonie. https://floodlist.com/europe/floods-belgium-july-2021 https://www.reuters.com/business/environment/belgium-warns-against-travel-flood-death-toll-hits-14-2021-07-16/

Flooding along the Vesdre river also caused widespread damage in Pepinster and the neighboring town of Verviers. A bridge and several houses collapsed in Pepinster. Three people were swept away and reported missing after a small boat capsized during a rescue operation. As of 16 July, 1 fatality was reported in Pepinster and 6 in Verviers. Further east flood damage and fatalities were also reported in Eupen, where the Vesdre river jumped from under 0.6m to 2.98m in the space of a few hours between 13 and 14 July.

Within 48 hours, the Eupen dam reservoir accumulated an additional 13.4 million m3, more than half Lake Eupen's normal capacity. As the dam had reached its maximum capacity, it could not store any more incoming water. Thus, large water flows were released from the Eupen dam into the Vesdre River. First at five cubic meters per second, then 10, then 15, leading to eventually a flow of 45 cubic meters per second, which in combination with the rainfall raised water levels downstream (Figure 3.240). It is reported that the river flow reached 150 cubic meters per second; enough to fill an Olympic swimming pool in 16 seconds (https://www.politico.eu/article/unnatural-disaster-the-german-belgian-floods-climate-change/)

In total, more than 21,000 people are without electricity in the south of Belgium due weather damage to infrastructure (SPglobal.com, 2021). Drinking water supply has been interrupted in the municipalities of Huy and Marchin in the province of Liège. Other rivers across the Walloon region remained above danger levels.

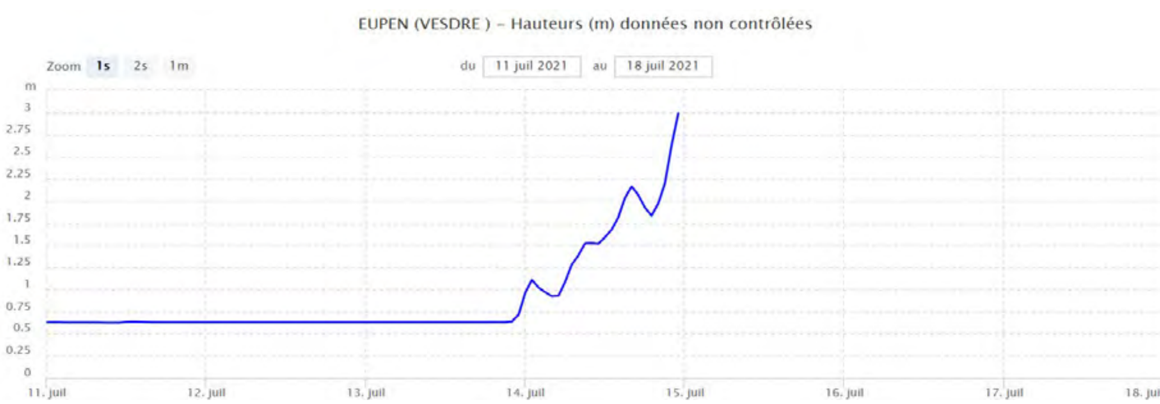

Figure 3.240. Vesdre river water level at Eupen. River flood alerts in Belgium as of 16 July 2021. Image: Voies Hydrauliques Wallonie. Source: https://floodlist.com/europe/floods-belgium-july-2021 https://www.reuters.com/business/environment/belgium-warns-against-travel-flood-death-toll-hits-14-2021-07-16/

3.6.2. Reconnaissance Travel Map, Belgium

The reconnaissance effort included documentation of flood related damages between Liege and Eupen, and Liege and Roermond, along distances of approximately 50 km (Figure 3.241) and 80 km (Figure 3.242), respectively. Detailed information including exact locations and types of damages are shown in Table 3.6.

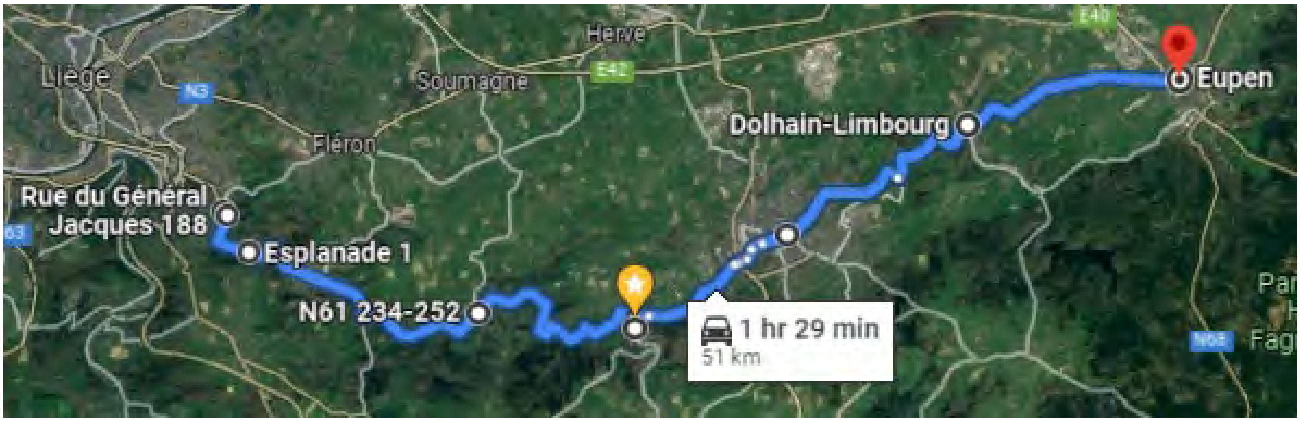

Figure 3.241. Reconnaissance route taken to document flooding effects between Liege and Eupen along a distance of approximately 50 km.

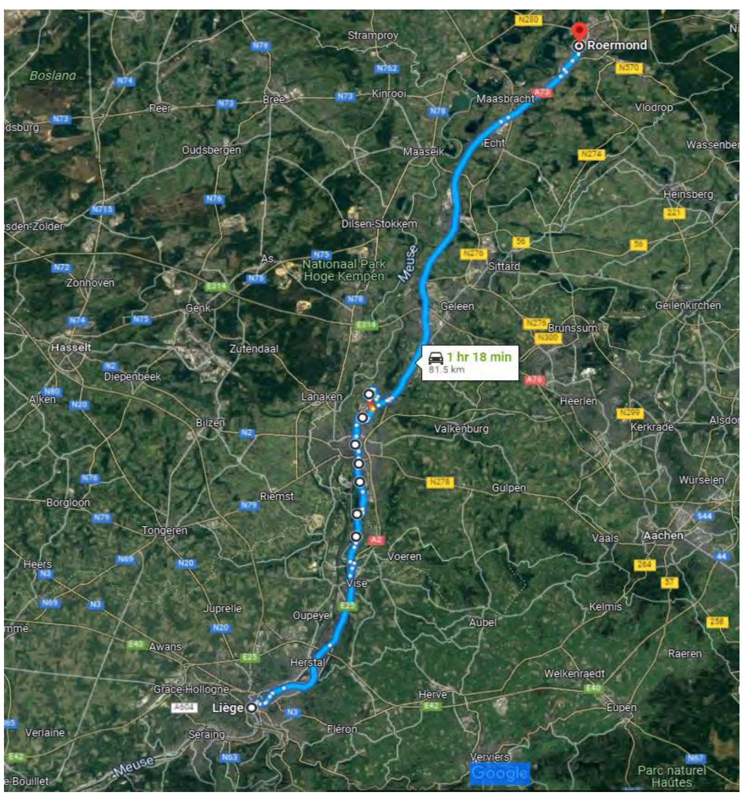

Figure 3.242. Reconnaissance route taken on day 7 between Liege and Roermond, about 80 km along the river Meuse.

Table 3.6. Overview of locations visited between in the Vesdre Valley

Town	**Visited Places**	**Applied methods**	**GPS-coordinates**
Liege	Bridge “Pont du Lhonneux”	Photos	50.609965, 5.619422
Chaudfontaine	Railway embankment, Railway station River banks, Water/Coca Cola factory Railway bridge	Photos	50° 35' 50.95" N, 5° 37' 53.98" E 50° 35' 13.02" N, 5° 38' 29.67" E 50° 35' 10.57" N, 5° 38' 58.81" E
Trooz	Slope failure, railway embankment	Lidar Photos	50°34'44.7"N, 5°40'02.3"E 50° 34' 12.34" N, 5° 44' 13.68" E
Nessonvaux	Centre Protestant de Nessonvaux collapse near bridge, along the Vesdre river		50°34'27.4"N, 5°44'33.5"E
Goffontaine (Pepinster)	River side, bridge collapse		50°33'58.4"N, 5°45'46.1"E 50°33'53.0"N 5°46'49.0"E
Pepinster	City center and river banks		50°34'08.8"N, 5°48'12.3"E
Dolhain, Limbourg, 32 Av. Reine Astrid	Road Collapse		50.615619748678334, 5.92693217102927
Eupen	Flooded Swimming pool and washed out riverbanks		50°36'54.4"N, 6°02'42.3"E

3.6.3. Liege: Damage at "Pont du Lhonneux"

Substantial damage around the bridge Pont du L'honneux (50.609965, 5.619422) was observed along the pedestrian walkway, the bridge support walls, and the surrounding embankment walls (Figure 3.243). Even though substantial cracking was visible in one of the support walls, (see Figure 3.243 bottom), the bridge remained in use. The bridge support walls consisted of masonry walls, an outlet for wastewater is visible in Figure 3.243 top right.

Figure 3.243. Bridge "Pont du L'honneux" in Liege (50.609966, 5.6194468).

Damage along the embankment wall is shown in more detail in Figure 3.244. The pedestrian walkway was eroded, the deck and fill material missing. Figure 3.244 shows the exposed utility lines near the bride, along with debris washed into the gap.

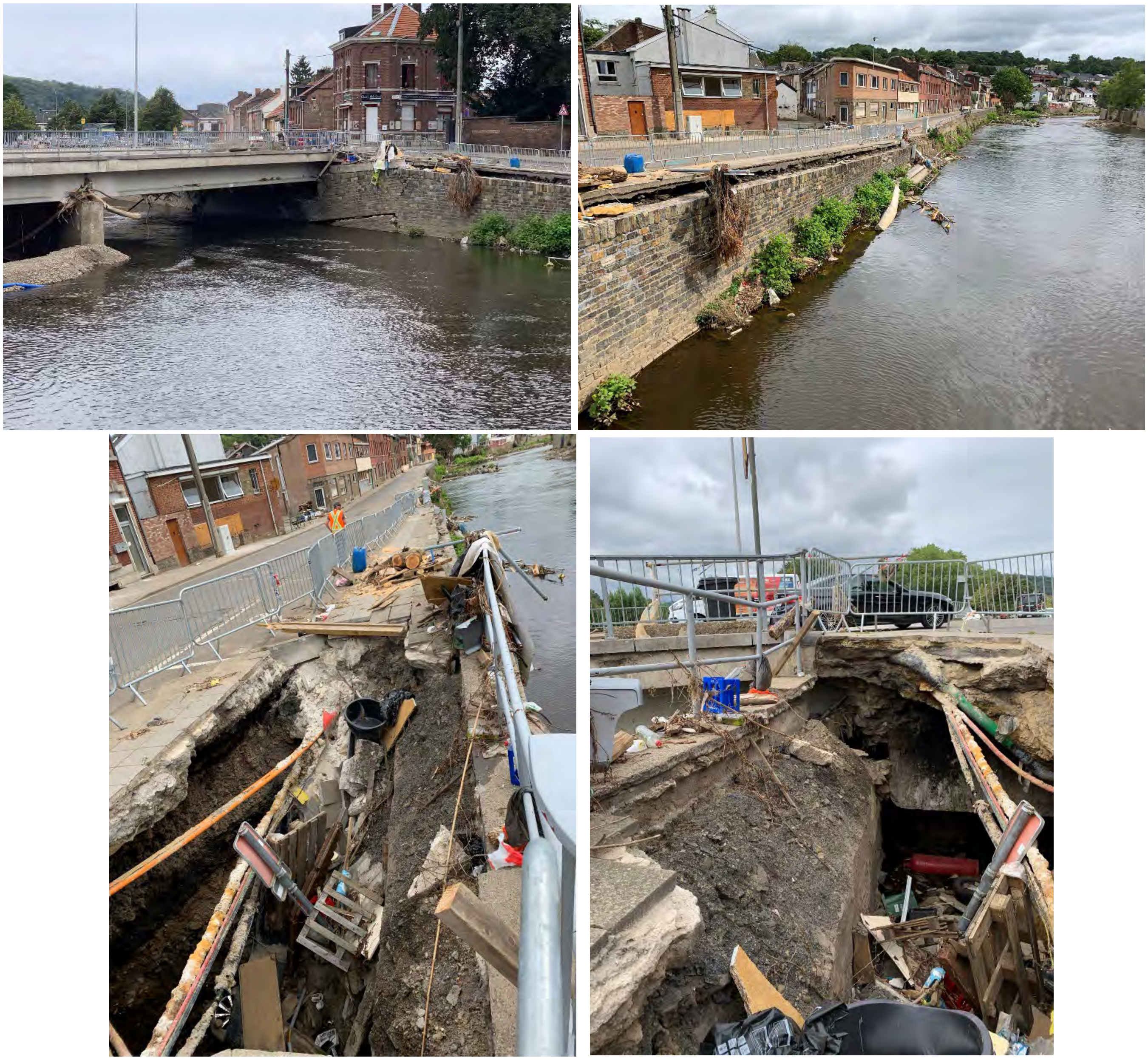

Figure 3.244. Pont du L'honneux damage: left embankment wall in upstream direction(50.609966, 5.6194468).

3.6.4. Rail and Embankment damage between Liege and Chaudfontaine

Railway 37, which connects Liège with the border at Aachen and follows the valley of the Vesdre, was heavily affected by the flooding events on July 15. Several sections of track and a bridge were destabilized or swept away. Heavy rainfall and mass flooding across Belgium disrupted rail traffic and damaged the railway infrastructure. Large parts of the rail network in southern Belgium were unusable and tracks were swept away. About 20 railway lines across the provinces of Liège, Namur, Luxembourg, Walloon Brabant and Hainaut were closed (Figure 3.245). The different colors in Figure 3.245 indicate the planned dates of reopening as of July 18th (Green: in service, Yellow: 19/7, Pink: 26/7, Red: 2/8, Blue: 9/8, Purple: 30/8). Many lines were blocked, mudslides washed away the ballast, railway embankments collapsed, and electrical installations were damaged (Figure 3.246). Train traffic between Welkenraedt and the border resumed two days after the flooding, as on line 49 to Eupen thanks to a diversion via lines 40, 24 and 39 (i.e., by making the detour between Liège-Guillemins and Welkenraedt by Visé and Montzen).

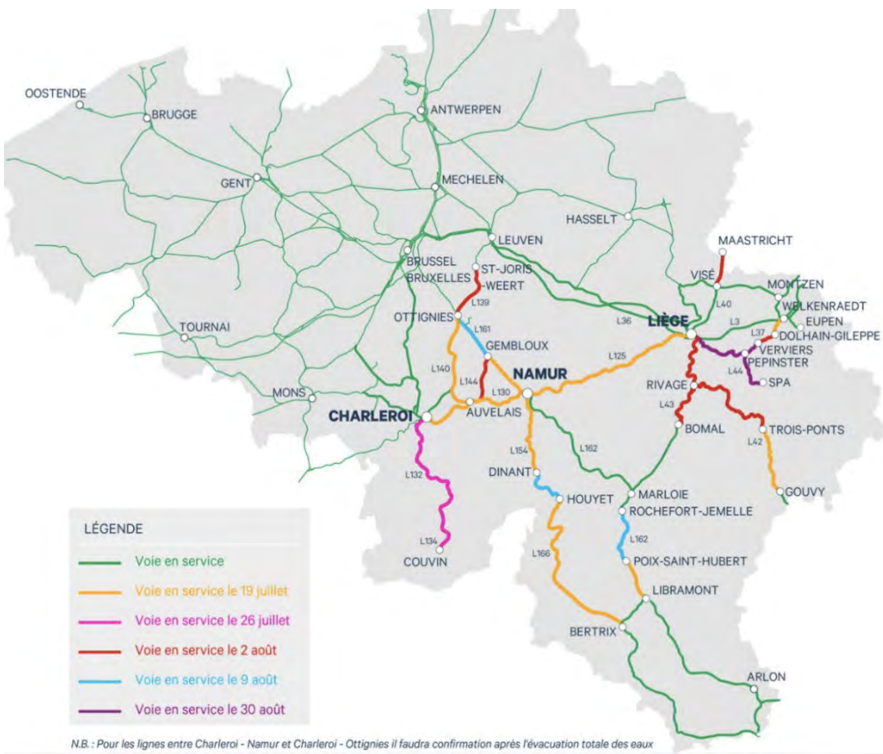

Figure 3.245. Map showing the disrupted railway lines across Belgium (https://www.rfc-northsea-med.eu/en/actualite/important-update-concerning-exceptional-flooding-infrabel-network).

Figure 3.246 shows embankment failure in Chaudfontaine, where the flooding eroded the foot of the embankment, laying bare the inner structure of rubblized soil. As done along large parts of railway line 37, the embankment was later repaired by Infrabel, the Belgian government-owned public railway network infrastructure. The repair works involve the use of stacked heavy rocks, arranged along the embankments to consolidate them in the event of new heavy rains and flooding. A similar repair philosophy has been adopted for the entire Belgian railway network, where an early estimate from Infrabel, dated July 19th 2021, predicted repair costs would exceed 50 million euros (https://www.lecho.be/entreprises/transport/la-facture-des-inondations-s-alourdit-pour-infrabel/10325815.html).

Figure 3.246. Embankment failure along railway 37 near Chaudfontaine (50° 35' 51.58" N, 5° 37' 53.38" E); top: before the flooding (June 2019, Source Google street view), Center and Bottom left: Failure documented by the GEER team, Bottom right: after repair works (October 2021, source google street view)

3.6.3. Chaudfontaine

The GEER reconnaissance team visited the banks of the Vesdre river, near Rue de La Vesdre Chaudfontaine (Figure 3.247). While there was no structural damage to the houses that may provide direct risk to their stability, the water level had reached about 2 m high on the facade. Along the riverbanks, the GEER team observed failure of the retaining walls, calving of the river banks, and fresh sediment deposits on shore, as depicted in Figure 3.247. It was unclear what caused the retaining wall to fall: this could possibly have been caused by a water level difference between the river and the street, causing excessive moments in the unreinforced natural stone masonry wall. The failure mode of the wall does not suggest that the foundation of the wall has been eroded, since the wall tilted towards the riverbank.

Figure 3.247. Vesdre riverbank (Rue de la Vesdre, Chaudfontaine, 50° 35' 47.65" N, 5° 38' 0.01" E)

More apparent damage was observed in the vicinity of Chaudfontaine Railway station (Esplanade, Chaudfontaine). Figure 3.248 shows damaged glass balustrade of the “Rive Droite” Restaurant and damaged houses on the left bank of the Vesdre river (50°35'08.2"N 5°38'42.5"E). Furthermore, there are pronounced failures of the retaining walls near the banks (in particular in front of the Grand Casino Chaudfontaine-Liège, closed down), with a tilting of the wall combined with erosion and deposition of debris along the banks.

Figure 3.248. Embankment damage along the river near Chaudfontaine center (50° 35' 10.71" N, 5° 38' 34.46" E)

At the same site, the Railway station of Verviers is located at about 80 m from the Vesdre river, heavy damage had occurred at the railway embankment, causing a failure that also triggered the collapse of an L-shaped wall panel that supported the railway platform (Figure 3.249). Renovation of the railway embankment had already started, in a similar fashion as the other visited locations along railway line 37, by means of massive blockwork masonry.

Figure 3.249. Railway embankment failure at Chaudfontaine Railway station; indication of water level during the flooding (exact location 50° 35' 13.02" N, 5° 38' 29.67" E)

Figure 3.250 shows the damage to the railway bridge at Avenue des Thermes, from Chaudfontaine to Liège. The railway bridge also included a small pedestrian bridge that was washed away. The red arrow in the upper photo shows the location of the pedestrian bridge. This pedestrian crossing was a later addition to the historic masonry bridge, at a lower level. There was no visual damage to the old masonry bridge, while the bridge abutments have been reinforced after the events by Infrabel.

Figure 3.250. Bridge at Avenue des Thermes, from Chaudfontaine to Liège, Wallonia (exact location 50° 35' 9.44" N, 5° 38' 56.41" E). Top: Bridge before damage from April 2021, bottom: at the time of the GEER visit

Figure 3.251 shows heavily damaged houses between the railway station and the railway bridge Chaudfontaine.

Figure 3.251. Building and fence on 124 Av. des Thermes (from Chaudfontaine to Liège, Wallonia: exact location 50° 35' 9.44" N, 5° 38' 56.41" E)

Figure 3.252 shows heavy damage to the retaining wall of the Vesdre river bank that caused tilting of the wall. Clear signs of erosion of the backfill layer can be observed, which also triggered the guard rails and parapets to fail. There is also visible damage to the access bridge to the Chaudfontaine water bottling plant, part of the Coca-Cola company. The factory itself was not visited during the GEER mission, since it had just restarted operation after being forced to stop the activities in the wake of the events. The ground floor of the plant was heavily affected, with water levels raising over a height of 2 m (confirmed by the GEER team, Figure 3.252 bottom). The wells and the boreholes used to bring the water to the plant site, are located on the first floor (where bottling takes place) and were not affected by the flood. (https://www.retaildetail.eu/en/news/food/chaudfontaine-expects-stock-shortages-after-floods)

Figure 3.252. Damage and water level in the area in front of the Coca-Cola Enterprises site in Chaudfontaine (50.58746206, 5.6503174)

3.6.6. District of Trooz

3.6.6.1. Railbridge and Roadbridge Rue Franklin Roosevelt, Nessonvaux

Figure 3.253 shows the damage to the abutments and ongoing repair works to the railway bridge over the Vesdre river in Trooz (50°34'12.3"N, 5°44'13.7"E), which is also a historic masonry arch bridge composed of natural stone and brickwork. Similar to the railway bridge in Chaudfontaine, there was no visible damage to the railway bridge, but the flooding caused the embankment near the abutment to erode, leaving the abutments exposed so that railway traffic could not pass without causing further damage to the bridge and embankments. These crucial repair works were implemented with high priority, as a part of the entire retrofitting and renovation of railway line 37, as discussed above.

Figure 3.253. Bridge abutment failure. (50° 34' 12.34" N, 5° 44' 13.68" E)

The road bridge in front of the rail bridge experienced damage along the abutment areas as shown in Figure 3.254. The bridge allowed for one-sided crossing. Figure 3.254 right shows damage to the bridge deck due to failure of the abutment's underneath. Figures 3.254 shows damage and washout of the pedestrian walkway and along the highway. Utility pipelines are exposed in Figure 3.254 bottom center.

Figure 3.254. Damage of the road bridge along Rue Franklin Roosevelt (50°34'12.3"N, 5°44'13.7"E)

3.6.6.2 Protestant Church in Nessonvaux

The collapse of part of the *Centre Protestant de Nessonvaux* located at the banks of the Vesdre river was observed during the GEER mission in the town of Nessonvaux (Figures 3.255 – 3.257**,** exact location 50° 34' 26.88" N, 5° 44' 32.23" E). The flooded river washed out the soil underneath the abutment, which subsequently caused the collapse of the entire abutment wingwall (Figures 3.256 and 3.257). Evidence of water rise during the event is illustrated in Figure B18. The abutment backfill is then exposed and is consequently washed out. At the same time the erosion of the foundation soil allows the building's foundation to be washed out. This in its turn, causes the building's facade and its side along the riverbank to collapse. The damage included part of the road, uncovering utility lines (gas, electricity lines). During the GEER mission, the road was (partially) closed due to the damage involved at this particular location.

Figure 3.255. Photographs before (left - google maps) and after (right) damages in the Centre Protestant de Nessonvaux near a Vesdre river bridge abutment in Nessonvaux (50.574176, 5.742544)

Figure 3.256. Panoramic view of damage to the protestant church "Centre Protestant de Nessonvaux" and soil erosion along the Vesdre riverbank, August 2021 (50.574176, 5.742544).

Figure 3.257. Aerial view of Centre Protestant de Nessonvaux and bridge abutment damage. Wingwall structural damage and soil erosion (top). Evidence of high-water level during the event (bottom), (50.574176, 5.742544).

Figure 3.258 shows the damage to the abutment area on the other side of the bridge (50.573807, 5.742468). This involves both structural damage of the abutment wingwalls, and erosion of the abutment backfill. In particular, the top-right photograph shows the substantial erosion to the riverbanks and damage to the adjacent road. The top left photograph shows the damage to the bridge abutment area diagonally across from the house depicted in the photograph at the bottom.

Figure 3.258. Damage of abutment and wingwall area on the other side of the road bridge, (50.574176, 5.742544).

3.6.6.3. Road Bridge in Trooz

Figure 3.259 shows a road bridge damage in Trooz, Belgium, which was caused by the flooding of the river Vesdre. The two-span reinforced concrete bridge experienced loss of global stability driven by excessive settlements and tilting of the single middle pier. Comparing the photographs before (top left, source: google maps) and after the flooding event (bottom left), helps identify the level of damage. A lidar scan is additionally included to provide an overview of the damage.

Figure 3.259. Photographs and point cloud model (13.5 million points) obtained from LiDAR scanning (Location: Trooz, Belgium 50.571160, 5.689884, Rue de Verviers 6, 4870 Trooz & Ry Fenderie)

3.6.6.4. Louheau Bridge and Floodplains

Figure 3.260 shows the damaged Louheau bridge which links Trooz to Pepinster via Nessonvaux on the road N61. The central bridge pier experienced evident settlements, likely caused by the scouring of its foundation. The bridge was closed during the GEER mission. A photo from google streets dated in April 2021 is also included to provide an image of the bridge prior to experiencing the heavy floods. The top photograph shows the google street view prior to the flood, pictures at the bottom document the damage observed by the GEER team.

Figure 3.260. Damage to Louheau bridge which links Pepinster to Trooz via Nessonvaux on the N61 in Wallonia, Belgium. Excessive settlement of the middle pier foundation (top). Before flooding (source: google street, April 2021). Exact location 50°34'1.32"N, 5°46'56.

The flood plains adjacent to the river experienced substantial erosion and soil redeposition. Figure 3.261 shows an aerial image of the downstream area. Several vehicles, which have been carried by the flood waters and have been deposited in the adjacent field are also shown in the photographs. Two trajectories are visible in Figure 3.261 (bottom), suggesting that the depositional debris cut through the top soil layers and spread across a larger area in the field. As shown in more detail in Figure 3.262, the flood debris consisted of primarily natural materials (large gravels, including small rocks).

Figure 3.261. River deposition into adjacent floodplains of the river Vesdre near Louheau bridge (N61 linking Pepinster to Trooz via Nessonvaux). Exact location 50°34'1.32"N, 5°46'56.72"E

Figure 3.262. Depositional material near Louheau bridge (N61 linking Pepinster to Trooz via Nessonvaux). Exact location 50°34'1.32"N, 5°46'56.72"E

The heavily damaged Louheau bridge has been demolished for safety reasons and has been recently replaced by a temporary steel bridge (Figure 3.263). This reflects the effort of the Wallonie Infrastructures SPW to reopen this section of road to traffic as quickly as possible. This temporary bridge has a single span and the same dimensions as the old bridge with 2 traffic lanes and 2 sidewalks (Figure 3.263, right).

Figure 3.263. Post-flood reconstruction of the Louheau bridge on the N61 which links Pepinster to Trooz via Nessonvaux, in Wallonia, Belgium; Source: https://infrastructures.wallonie.be/news/reconstruction-post-inondations-pose-dun-pont-provisoire-a-louheau-pou

3.6.7. Pepinster

The city of Pepinster was very heavily affected by the events, and received a lot of media coverage, in particular featuring the large damage to housing and infrastructure. At the end of July 2021, structural engineers have examined the stability of dozens of buildings in and around Pepinster. Approximately 50 buildings did not pass the test and must be demolished. The orange dots on the map in Figure 3.264 indicate buildings that must be demolished. Among these, there are buildings which include several residential units and garages.

Houses in the Rue Hubert Halet street along the Vesdre river are scheduled for demolition. On the other hand, houses at 41, 43 and 45 Rue Hubert Halet have collapsed totally. The Hoegne and Vesdre rivers burst their banks and lead to severe damages in the city center. Aerial photos best illustrate the level and extent of damage (Figures 3.265, 3.266).

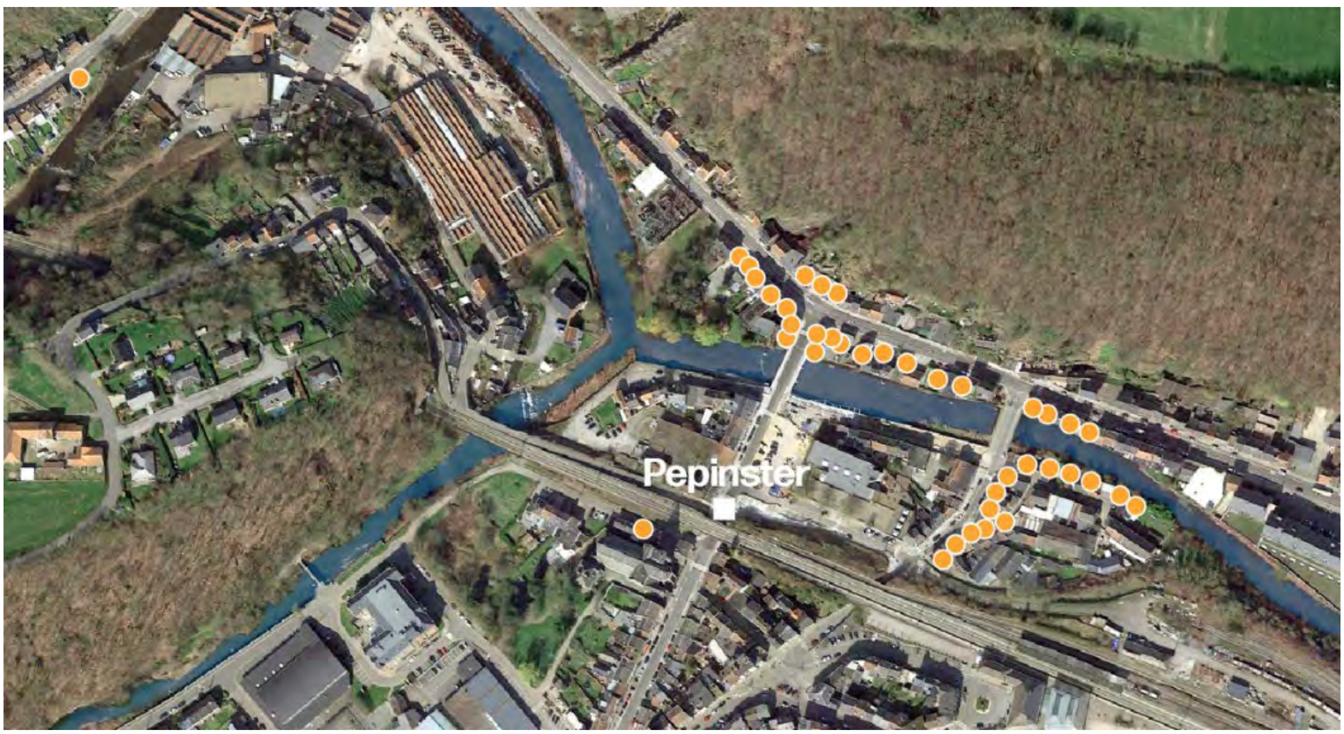

Figure 3.264. Locations of 50 properties to be demolished in the center of Pepinster; Source: https://www.vrt.be/vrtnws/nl/2021/07/30/burgemeester-pepinster-beveelt-afbraak-van-50-tal-woningen-na-zw/)

Figure 3.265. Aerial photos of damage in Pepinster, at Rue "Pont Walrand", (50.569710, 5.804977).

Figure 3.266. Drone footage of residential damage in Pepinster (50.569710, 5.804977).

The GEER team observed collapsed buildings and/or facades, with debris and waste scattered around the city center (Figure 3.267). The houses that were not structurally affected, were during the reconnaissance mission under renovation (e.g., removing wetted plaster layers in ground floors, restoring gas and electricity lines).

Figure 3.267. Photographs of flood damage in Pepinster (top: residential destruction, middle: embankment failure, bottom: road and foundation failures), (50.569710, 5.804977).

A comparative photo, which further illustrates the level of damage is shown in Figure 3.268. The buildings in the right photos have vanished (top) or have experienced severe damages (bottom) during the flood events.

Figure 3.268. Post- (left) and pre- (right) flood damages to buildings and infrastructure along Rue Hubert Halet in Pepinster, Belgium (top 50° 34' 11.14" N, 5° 48' 19.42" E and bottom 50° 34' 11.43" N, 5° 48' 20.25" E)

High water levels reached in the city center have been measured according to evidence, as shown in Figure 3.269. Additional footage of the flood damage and debris deposition in Pepinster is gathered from the news. Figure 3.270 shows soon after the floods cars washed out.

Figure 3.269. Documentation of high water levels during flooding in Pepinster (left photo:50° 34' 10.59'' N, 5° 48' 26.94'' E, right photo 50° 34' 11.43'' N, 5° 48' 26.06'' E

Figure 3.270. Top: a damaged vehicle is seen next to the river, following heavy rainfalls, in Pepinster, Belgium, July 16, 2021. Bottom: Vehicles damaged by heavy rainfalls are pictured in Pepinster, Belgium, July 16, 2021; Source: REUTERS/Yves Herman https://www.reuters.com/business/environment/belgium-warns-against-travel-flood-death-toll-hits-14-2021-07-16/

3.6.8. Verviers

The N61 urban motorway between Dolhain and Verviers was closed for several weeks following the floods. The reason is the road collapse next to the river Vesdre as shown in Figure 3.271 (location: 50.616650, 5.927750). Most likely, the foundation soil under the wall retaining the road embankment eroded, the wall collapsed, and the embankment backfill was washed out, resulting in the collapse of the road deck as shown in the photographs. Soon after the damage, the City of Limbourg decided to ban traffic in both directions.

Figure 3.271. Road failure in N61 urban motorway between Dolhain and Verviers, along the river Vesdre. Top photograph source:https://lameuse-verviers.sudinfo.be/814356/article/2021-08-01/la-n61-entre-dolhain-et-verviers-fermee-plusieurs-semaines-suite-aux-inondations. Bottom Photograph source: https://www.lavenir.net/cnt/dmf20210731_01601829/la-nationale-entre-dolhain-et-verviers-est-fermee

Damage to residential housing in Verviers is reported in Figures 3.272 and was collected from media sources shortly after the flood.

Figure 3.272. Top left: A partially destroyed house following heavy rainfalls, in Ensival, Verviers, Belgium, July 16th, Top right: Wreckage lies on the river, following heavy rainfalls in Verviers, Source: https://www.reuters.com/business/environment/belgium-warns-against-travel-flood-death-toll-hits-14-2021-07-16/

<u>*3.6.9. Eupen*</u>

Figure 3.273 (left) shows a gravity wall failure along the Hill river/stream in the suburbs of Eupen, at Hutte. The Hill rises near the highest point in Belgium, the Signal de Botrange and empties into the Vesdre (Weser) at Eupen, 25 km further north. It is evident that there is no access to the parking lot at the back of the *Arbeitsamt der Deutschsprachigen Gemeinschaft Belgiens* building (right photo). Additional damage is shown in Figure 3.273 bottom. Part of the parking lot in front of the building has vanished due to the foundation soil being washed out. Utility lines have been uncovered and the traffic has been blocked due to debris blocking the bridge deck.

Figure 3.273. Top: Gravity wall failure in Eupen (exact location: 50.614888, 6.045164), Bottom: Parking lot collapse due to river bank being washed out and traffic interrupted. Main entrance of the Arbeitsamt der Deutschsprachigen Gemeinschaft Belgiens, Eupen in Belgium. Source: https://www.grenzecho.net/59306/artikel/2021-07-21/arbeitsamt-der-dg-zieht-vorubergehend-die-oberstadt

3.7. Liege and the river Meuse

The water level of Meuse river in Liege, Belgium rose 2.81 meters from July 14 to July 15, which resulted in an evacuation of over 1000 people in residential areas near the river. The Monsin Dam is located only 5 km upstream of Liege's city center and at one point had only two out of six sluice gates operational. Due to the fear of a potential failure of the Monsin dam the entire city of Liege was encouraged to evacuate on July 15th, but not required. The majority of infrastructure damage along the Meuse river was located in Dutch regions of the river and is addressed more comprehensively in the following section. Figure 3.274 show the flooding along the riverbanks of the Meuse river in Liege.

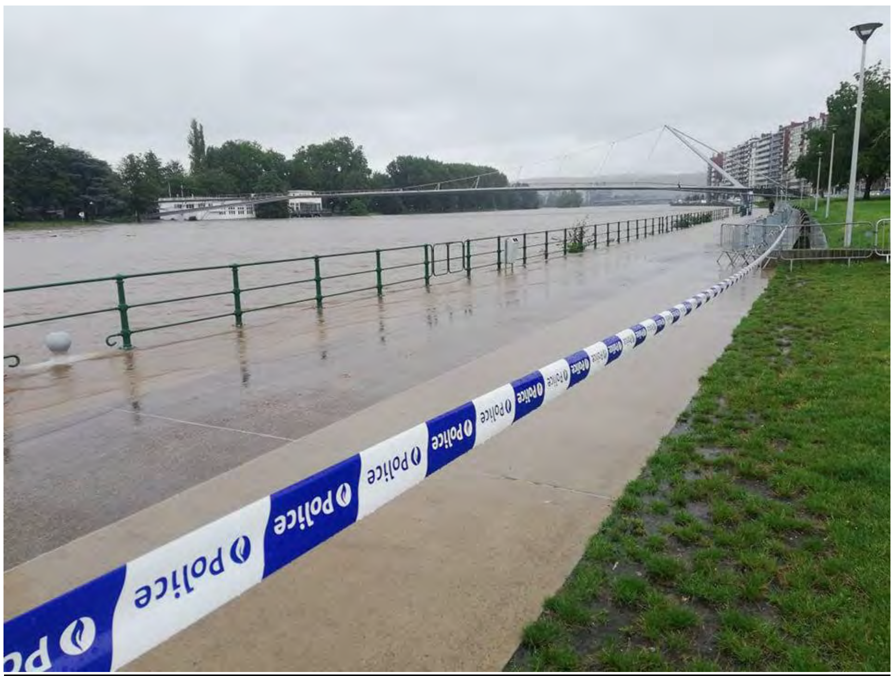

Figure 3.274. Flooding along the banks of the Meuse River in Liege, Belgium. Photo: Ville de Liege https://floodlist.com/europe/floods-belgium-july-2021

3.7.1. Role of the Eupen dam and criticism

After the flooding, criticism was raised that the Eupen dam should have been emptied as a preventive measure. According to local news outlets (https://henry.wallonie.be/home/communiques--actualites/communiques-de-presse/presses/presse.html) the mayors of Limbourg and Chaudfontaine evacuated the areas around the Vesdre on Wednesday 14 July at 2 pm. On Wednesday July 14 at 5 p.m., the Eupen dam has been opened to keep the water level in the dam constant, in order to protect the dam. A few hours later, Eupen, Dolhain, Verviers, Pepinster and other localities located along the Vesdre (Nessonvaux, Fraipont, Trooz, Chaudfontaine, Vaux-sous-Chèvremont), and two sections of Liège (Chênée and Angleur)) were flooded on Thursday July 15 around 3 or 4.

3.8. Observations in the Netherlands: Flood region Limburg

3.8.1. Introduction

Large areas in the province of Limburg (Netherlands) were affected by extreme rainfall and floods. The GEER team visited the province and met with the Dutch Waterboard in Roermond, Province Limburg. In addition, Dutch team members participated in an independent fact-finding study in collaboration with Delft University of Technology, Deltares, HKV Consultants, VU Amsterdam, University of Utrecht, KNMI, Wageningen University and Research, Erasmus MC and University of Twente. This parallel project was commissioned and supported by the Dutch Expertise Network Flood Risk (ENW) and is published here: https://klimaatadaptatienederland.nl/en/@250648/rapport-hoogwater-2021-feiten-en-duiding/.

The regional water authority Limburg and Rijkswaterstaat (Directorate General of Infrastructure and Water) also contributed by providing information, accompanying field visits and participating in interviews. Figure 3.275 shows the flood areas and its rivers.

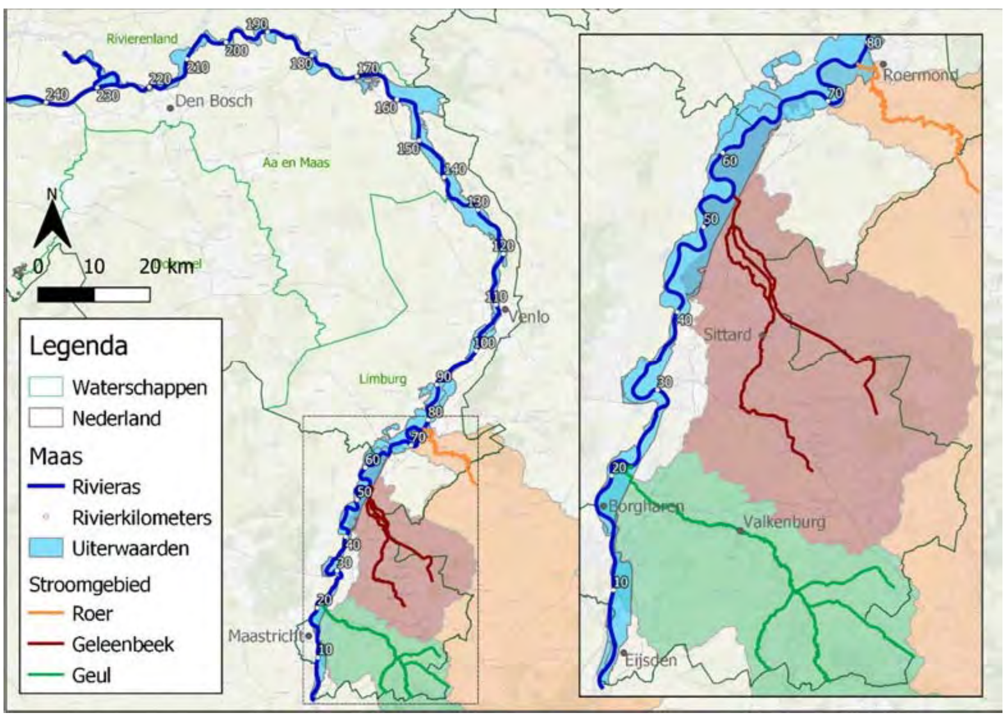

Figure 3.275. Flood areas in the Netherlands. Source: Rapport Hoogwater 2021 Feiten en Duiding.

3.8.2. Roermond

The main flood defenses along the biggest river in the region, the Meuse River, did not breach. Some incidents such as sand-boils, overflow of an embankment, and damage to a weir were reported and observed by the GEER team. In the local river system, two non-primary nor regional flood defenses were breached:

an emergency embankment near Horn and an embankment close to the city of Roermond. As a part of the defense against rising water levels, Waterschap Limburg, the water board for the province of Limburg, placed rows of sandbags along the banks of the Roer river. This provided extra protection against flooding and, according to interviews with Waterschap Limburg personnel, was a significant reason that damage was not more catastrophic.

Flood damages in Roermond were concentrated along the beginning of the Roer river, a tributary of the Meuse river. Observations of damage began only 1.3km from the intersection of the Roer and Meuse rivers and were generally not life threatening. Peak water levels on the Meuse river in Roermond and down to Liege were generally lower than models estimated for the magnitude of the rainfall event that occurred. The lower than predicted water levels resulted in no loss of life in the Netherlands and lower estimates of the value of damage, which is estimated to be around 600 million euros for the Netherlands. The lower water levels on the Meuse are being credited to the 5 billion Euro “Meuse Works” program, which was completed in 1997. This program was a part of a large project in southern Netherlands which consisted of the construction of storm surge barriers, dams, dykes, levees, and locks in order to protect major rivers from rising sea levels and flooding events. Figures 3.276 and 3.277 show the effects of flooding near Roermond on August 18th, approximately one month after the rainfall event. Water levels rose to the heights of the banks of the two rivers but did not breach the banks and result in widespread flooding. A nearby fish migration system was damaged in the process but had since been restored by the time of the visit.

Figure 3.276. Intersection of the Roer and Hambeek rivers in Roemond, Netherlands. Water rose to the banks of the river but did not reach the roads or the power station nearby. (51°11'06.4"N 5°59'19.2"E)

Figure 3.277. Approx. 50 meters from the intersection of the Roer and Hambeek rivers, a road bridge shows no signs of scour along the piers or embankment. Water levels did not breach the deck. (51°11'06.6"N 5°59'19.4"E)

Figure 3.278 (left) shows the Roer river lock system, which is 1 km away from the intersection of the Roer and Meuse rivers. The lock system was closed at the onset of the flooding to protect the city of Roermond from flooding. Water levels reached the top of the concrete portion of the structure on July 17th, which resulted in a piping failure behind the right door and leaking through the center doors. Due to the closing of the lock doors, discharge from the Roer was therefore redirected towards the western Hambeek river. In the 1990's, an additional spillway called the Green River was built to accommodate future flood waters, however the Green River was not utilized in this scenario due to instability. A concrete top would have needed to be excavated first to activate it, which there was no time for. Figure 3.278 (right) shows the high-water mark along a row of bushes.

Figure 3.278. Left: Open river lock system on the Roer river (51°11'13.1"N 5°58'51.3"E); Right: High water marks shown on bushes in a residential yard near a 2-m dyke failure along the Roer river, which was repaired by the time of visit (51°11'08.3"N 5°59'04.0"E).

3.8.3. Valkenburg

Of the 600 million Euro in estimated damages throughout the Netherlands, 470 million Euro in damage were concentrated in the city of Valkenburg. The Geul river runs through the city center damaging over 700 buildings in the city and displaced around 700 families (The Associated Press (2021), accessed through: https://www.seattletimes.com/business/470-million-flood-damage-bill-in-hard-hit-dutch-town/).

This section documents damage due to the flooding of the Geul river in the city of Valkenburg. Figure 3.279 shows high water marks visible on various structures, the GEER team member used for reference is 1.88m tall. Figure 3.280 shows damage to a masonry retaining wall structure. The retaining was structurally still intact, outside façade bricks seem to have detached and fell into the riverbed.

Figure 3.279. Left: High water mark on a building in the city center of Valkenburg (50°51'50.2"N 5°50'03.3"E), Right: High water mark along a residential building along the Geul river, Location 50°51'53.0"N 5°49'48.4"E

Figure 3.280. Retaining wall failure along the Geul river in Valkenburg (50°51'54.3"N 5°49'49.8"E)

In a residential area just west of the city center of Valkenburg on the Geul river, a two-lane road bridge with sidewalks on either side was overtopped and destroyed (Figure 3.281). There was no center pier of the bridge, but excessive scour to both abutments resulted in settlement and ultimately failure. In the aftermath, riprap scour protection was added to the abutments of the bridge to prevent further erosion to the fill. A temporary pedestrian bridge was constructed. Figure 3.281 shows the google earth image of the two-lane road bridge prior to the flood.

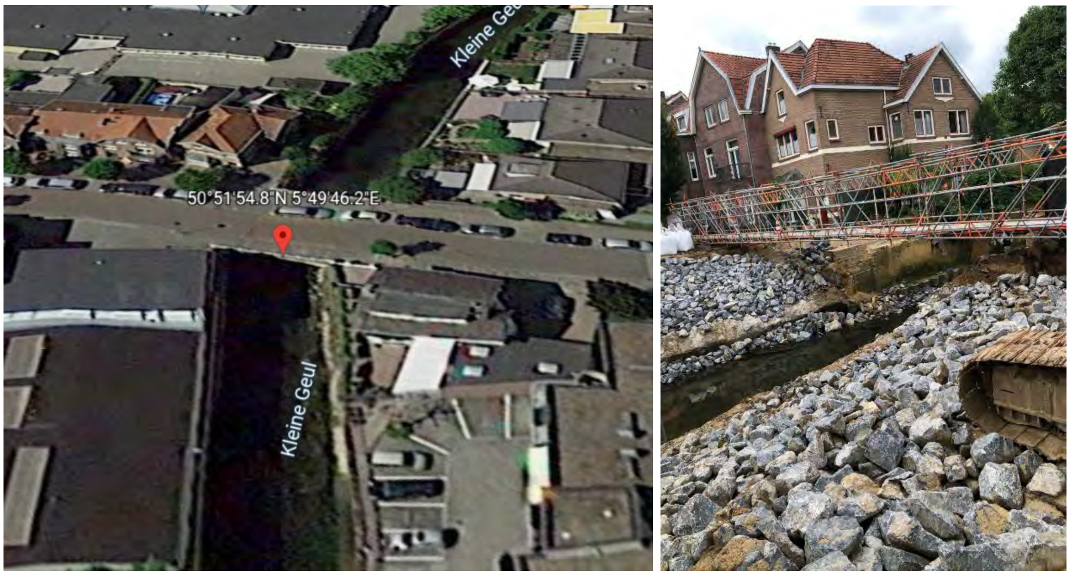

Figure 3.281. Temporary pedestrian bridge in place of a destroyed two-lane bridge (50°51'54.8"N 5°49'46.2"E)

4. Summary

July 2021 was the record-breaking month of flood disasters documented in the past decades. 124 flood events were recorded across 385 locations, in more than 20 countries globally (Davies, 2021; accessed through floodlist.com). More than 920 people have lost their lives including 230 in Belgium and western Germany in mid-July; 192 in Mumbai and Maharashtra, India, in late July 2021; 113 in Nuristan Province, Afghanistan in late July; and 99 in Henan Province, China, late July.

The 2021 Western European floods were also the most severe floods in Europe in the 21st century. Similar damage in central Europe was only recorded during the 1804 and 1910 flood events in the Ahr region. The Ahr is the northernmost tributary of the Rhine River, located in the Rhenish Slate Mountains (Rheinisches Schiefergebirge). With a length of 90 km and a catchment area of 900 km^2 it is situated inside a low mountain range and has created deep-seated valleys and steep slopes. This is mainly due to the relatively large altitude differences and short flow lengths between the sources and mouths of the main river and its tributaries (Seel, 1983). Besides the severe damage caused by the river Ahr in Germany, other major flooded regions included the catchments of the rivers Erft, Urft, and Wupper (all in Germany), the rivers Vesdre and Meuse and its smaller tributaries (in Belgium) and the river Meuse and Geul (in the Netherlands).

A team from the Geotechnical Extreme Events Reconnaissance (GEER) Association, supported by NSF, was deployed to gather perishable data, and document the impacts of the flooding. The team documented extensive scour damage to foundation systems, earth retention structures adjacent to rivers, progressive riverbank failures, and head-cutting in overtopped earthen structures, bridge-, road-, rail-, and utility infrastructure damage, and damage to residential and commercial buildings as well as local businesses. The majority of this damage is documented in this report and supplemented with information collected from online sources. Beyond traditional, aerial, and satellite photography presented herein, the team also collected data via on-ground lidar, multispectral imaging, soil sampling, and in-situ measurements. This data is stored and publicly accessible (along with all other imagery) at doi: 10.17603/ds2-0ddt-ss87. An accompanying outreach video for high-school and early university level students has been produced by team member Kees van Ginkel and can be accessed here: https://youtu.be/vtluiFhaHeA .

The reconnaissance team leads (A. Lemnitzer & N. Stark) would like to thank all participants from the United States, Germany, Belgium, and the Netherlands for their contributions and their on-site participation. We gratefully acknowledge the support from local agencies and administrators who made our field access possible. The GEER association (especially the GEER president Prof. Dr. David Frost) is gratefully acknowledged for their valuable assistance and unconditional support, including all financial support received to make this data collection successful. The NSF Rapid facility has provided and arranged for the equipment for this deployment and has been wonderful to work with.

With the success of this first data collection, the US team members have secured external funding (NSF) to conduct a Phase 2 deployment in co-sponsorship with GEER and collaboration with colleagues in Germany. Data collected during the Phase 2 deployment will be presented in a separate report.

5. References

Much information presented in the GEER report has been supplemented with news reports obtain from media sources, on-site testimonies, video material and eye-witness reports, as well as official agencies in Germany, Belgium, and the Netherlands. News sources are acknowledged when respective content was cited and referred to in the text. These references are not listed here as a full web-link was made available through within the figure captions. The following short list includes academic sources and outlets that are citable or have been collected through other research efforts.

Bruwier, M., Erpicum, S., Pirotton, M., Archambeau, P., and Dewals, B. J. (2015). Assessing the operation rules of a reservoir system based on a detailed modelling chain, Nat. Hazards Earth Syst. Sci., 15, 365–379, https://doi.org/10.5194/nhess-15-365-2015, 2015

Junghänel T., P. Bissolli, J. Daßler, R. Fleckenstein, F. Imbery, W. Janssen, F. Kaspar, K. Lengfeld, T. Leppelt, M. Rauthe, A. Rauthe-Schöch, M. Rocek, E. Walawender und E. Weigl. "Hydro-klimatologische Einordnung der Stark- und Dauerniederschläge in Teilen Deutschlands im Zusammenhang mit dem Tiefdruckgebiet „Bernd" vom 12. bis 19. Juli 2021", Stand: 21.07.2021, Bericht, Deutscher Wetterdienst, accessible at: https://www.dwd.de/DE/leistungen/besondereereignisse/niederschlag/20210721_bericht_starkniederschlaege_tief_bernd.pdf?__blob=publicationFile&v=6

EDNHnews.de (2021).: https://ednh.news/why-have-the-floods-in-europe-been-so-deadly/

WDR.de (2021): https://www1.wdr.de/nachrichten/rheinland/duisburg-messstationen-pegelstaende-nrw-100.html

Floodlist.com (2021): https://floodlist.com/asia/world-floods-july-2021

EPA. (2021). https://eifeler-presse-agentur.de/2021/10/a1-a61-einbau-einer-neuen-fahrbahn/

LANUV (2021): Online-Angebot Landesamt für Natur, Umwelt und Verbraucherschutz (LANUV) NRW https://www.lanuv.nrw.de/umwelt/wasser/niederschlag/niederschlag-online

Meyer, W. (1993). Die Geologie der Umgebung von Altenahr. Beitraege Landpflege Rheinland--Pfalz, 16, 77-84, available at https://lfu.rlp.de/fileadmin/lfu/Downloads/DrBuechs/Band1/2_1Meyer.pdf

Mrasek, V. (2021). https://www.deutschlandfunk.de/unwetterkatastrophe-in-erftstadt-blessem-die- erft-soll.676.de.html?dram:article_id=500838

Munich Re (2022): Hurricanes, cold waves, tornadoes: Weather disasters in USA dominate natural disaster losses in 2021, Munich Re. https://www.munichre.com/en/company/media-relations/media-information-and-corporate-news/media-information/2022/natural-disaster-losses-2021.html

RTBF (2021): Inondations de juillet 2021: 71,746 dossiers d'indemnisation introduits auprès des assureurs (*71,746 loss claims filed according to insurers*). Radio Télévision Belge Francophone https://www.rtbf.be/article/inondations-de-juillet-2021-71746-dossiers-dindemnisation-introduits-aupres-des-assureurs-10868318 (in French)

Seel, K.A. (1983), Die Ahr und ihre Hochwässer in alten Quellen, Heimatjahrbuch des Kreises Ahrweiler 1983, availble at https://relaunch.kreis-ahrweiler.de/kvar/VT/hjb1983/hjb1983.25.htm

Spglobal.com (2021). https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/electric-power/071621-over-21000-without-power-in-belgium-after-river-meuse-bursts-banks