Impact of a potential extreme rainfall event in the Bornbach catchment

Numerical modeling case study

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Summary

In the framework of the EU Interreg program BEGIN LSBG wants to investigate the feasibility and efficiency of blue green infrastructure measures in order to use synergies between flood prevention, natural design, and liveable inner-city space in the context of extreme weather events. This report describes the set-up and application of a numerical model of the urban catchment area of the Bornbach, north of Hamburg Airport, using the Delft3D Flexible Mesh Suite. By means of a direct rainfall simulation, the model was used to investigate what consequences the extreme precipitation event that hit the western part of Germany in July 2021 would have for this urban area. Furthermore, the impact and functioning of decentralized blue green infrastructure measures were analysed, and a rough estimate of expected damage was made.

The set of retention measures analysed in this study was too small to have a significant effect on maximum water depths and thus on expected damage for the simulated extreme event. For such an event, a bigger retention volume is needed. To protect the areas of value in the Bornbach catchment, a larger number of retention measures should be placed further upstream in the catchment. Increasing the volume at the locations tested in the current study would have only little influence on areas of value in the Bornbach catchment, but it would help to reduce flooding from the downstream creeks, e.g. Tarpenbeek. If retention measures are placed close to the creek it is important to keep them outside areas that are inundated from the creeks in order to keep the volume available for storing rainfall.

In a heavily urbanized environment as the Bornbach catchment it is difficult to find suitable locations large enough for green retention areas. It might be necessary to combine these with other measures such as raingardens, permeable paving, green roofs, and water squares in order to achieve sufficient mitigation of flooding.

The area close to the creek in the central part of the Bornbach catchment is flood prone due to its topography. For such areas, adaptive construction and design, such as flood-proof buildings is recommended.

Contents

1 Introduction

1.1 Background

The Landesbetrieb für Straßen, Brücken und Gewässer (LSBG) is a company of the Free and Hanseatic City of Hamburg. Its core tasks include, amongst others, water bodies and flood protection. These include the planning and construction of water bodies and flood protection systems as well as the implementation of the EU Flood Risk Management Directive (Hochwasserrisikomanagement-Richtlinie, HWRM-RL) in Hamburg. In addition, the supervision of public flood protection and HafenCity, dike defence, and the maintenance of flood protection systems are essential tasks.

LSBG is one of the partners in the EU Interreg project BEGIN[1], which unites cities, citizens, and stakeholders through the co-creation of blue and green infrastructure projects in 10 EU cities, reducing flood risk by up to 30% and improving liveability. One of the central themes of this project is the consideration of decentralized retention measures in urban areas. In Hamburg, great importance is attached to the development of the so-called "Blue Green Infrastructure", i.e. synergies are sought between flood prevention, natural design, and liveable inner-city space (multifunctional spatial design). At the same time, metropolises like Hamburg have to prepare for the ever-increasing threat of extreme rain events. The devastating flood catastrophe in July 2021 in the Ahr valley in North Rhine Westphalia, Germany, triggered by a series of heavy rain events, has once again underlined the urgency of the tasks of LSBG.

1.2 Assignment

Deltares was assigned the tasks i) to build a two-dimensional numerical model of the urban catchment area of the Bornbach north of Hamburg Airport (ca. 7 km^2, Figure 2.1), ii) testing application of the model for flood hazard assessment, and iii) to evaluate the effect of a pre-selected set of measures. The modelling is made using the Delft3D Flexible Mesh Suite (Deltares, 2021). By means of a direct rainfall simulation, the model is used to investigate the consequences of an extreme precipitation event as the one that which hit North Rhine-Westphalia in July 2021. Furthermore, the impact and functioning of decentralized blue green infrastructure measures is to be calculated.

1.3 Report outline

Chapter 2 describes how and with what data the numerical model was set up. The model results are checked for plausibility in chapter 3, followed by a brief analysis of the efficiency of the blue green infrastructure measures as well as a rough estimate of expected damage. Chapter 4 presents conclusions and recommendations.

1.4 Acknowledgement

This study is co-funded by Interreg North Sea Region via the Project BEGIN (Blue-Green Infrastructure through Social Innovation), which aims to support existing grey infrastructure to cope with extreme weather events and improve disaster resilience in urban environments.

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[1] See e.g. BEGIN, Interreg VB North Sea Region Programme for a description of the project.

2 Model set-up

2.1 Modelled area

The Bornbach is a creek in the north of the city of Hamburg in Germany (Figure 2.1). It is approximately 6 km long and its urban catchment area is approximately 7 km^2. The creek starts close to the border with Schleswig-Holstein. From there, it takes a course in a south-westerly direction, crossing several retention basins and larger roads and railroads. The main tributaries are the Pannsgraben and the Tweeltenbek in the upper reaches. The Bornbach flows into the Tarpenbek via the Krohnstieg retention basin, which then passes under a runway of the airport a little further downstream. The catchment area itself is partly characterized by dense urban development and a well-developed transport network, but also has numerous green areas, e.g. in the form of allotment gardens and parks.

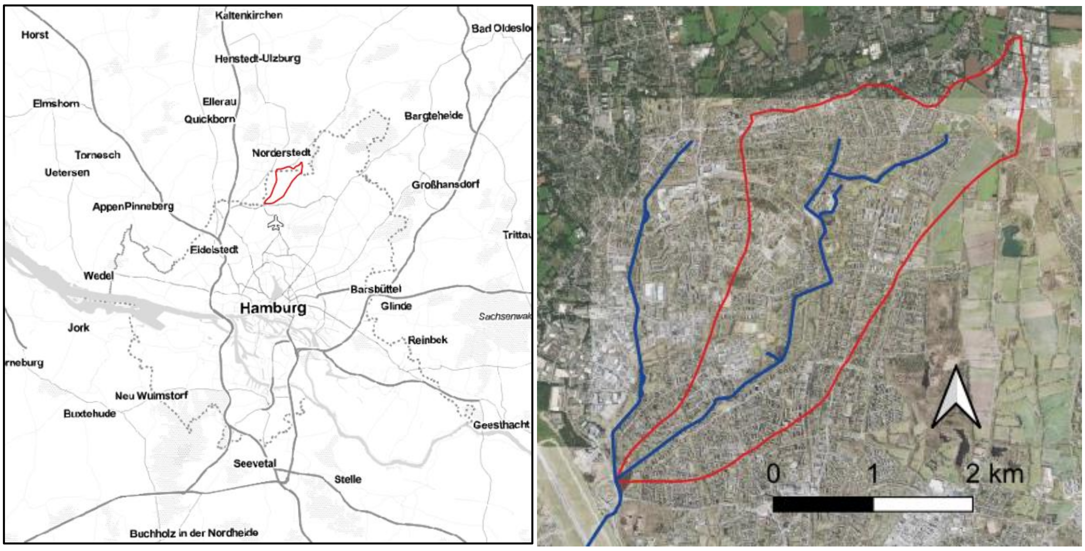


Figure 2.1 Bornbach catchment.

2.2 Available data

Table 2.1 gives an overview of the available data and how it was used for the model set-up. The following paragraphs explain the use of the data in more detail.

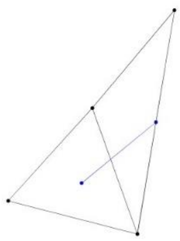
Table 2.1 Overview of available data.

dataset	used for which part of the model
DGM1: digital elevation model, resolution 1m x 1m	terrain elevation
shapefile catchment delineation	model extent
shapefiles centerlines of the creeks Bornbach, Tweltenbeek, Pannsgraben and Diekmoorgraben	location of the creeks (used for grid generation: curvilinear 2D grid and 1D grid)
land use data (ATKIS), extract of data for City of Hamburg and federal state Schleswig Holstein	roughness
shapefile of building footprints	roofs
cross-section survey data Bornbach, Tweeltenbek, Diekmoorgraben, Pannsgraben (Excel file)	cross-sections, hydraulic structures
photos of maps, and reports of/about the existing retention basins along Bornbach	dimensions of retention basins and their outlet structures
rainfall intensity time series (mm/min)	model forcing
shapefiles of expected main flow paths and depressions in the terrain according to the GIS flow path analysis conducted by Hamburg Wasser[2]	plausibility check of model results
shapefile average indicative values for areas of types “industry and commerce” and “residential area”	simplified damage calculation

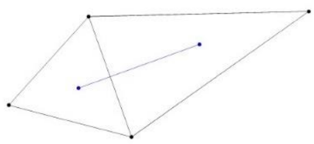
2.3 Computational grid

For direct rainfall modeling on catchment scale with Delft3D Flexible Mesh, Deltares has good experience with using regular grids consisting of squared grid cells. These are computationally more efficient, because less cells are needed then when using triangular cells at the same spatial resolution. Furthermore, squared cells perfectly fulfill the recommendations for Delft3D Flexible Mesh regarding orthogonality and smoothness (see Figure 2.2):

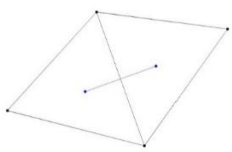
- The line connecting the cell centres of two neighbouring cells should be perpendicular to the edge between the two cells.
- Two neighbouring cells should have similar sizes (in surface area).



(a) Perfect smoothness, but poor orthogonality.



(b) Perfect orthogonality, but poor smoothness



(c) Perfect orthogonality and smoothness

Figure 2.2 Orthogonality and smoothness in Delft3D Flexible Mesh

[2] https://geoportal-hamburg.de/geo-online/
Subject data: Umwelt und Klima → Starkregengefahrenkarte Hamburg

Depending on the topography, the squared grid cells can be refined locally where necessary, as shown in the example in Figure 2.3, where elevated roads and urban areas are modelled with a finer resolution than flat agricultural areas. The same approach is applied to the Bornbach catchment in this study.

Figure 2.3 Example of a regular grid with local refinements.

German federal state Baden-Württemberg has defined guidelines for direct rainfall modeling of extreme events, which, amongst others, defines requirements for the grid resolution (LUBW, 2020). These depend on the type of the applied numerical solver. For a finite volume method as implemented in Delft3D Flexible Mesh, it recommends using:

- within urban areas and along striking flow features: a maximum of 25 m² cell size, and an average of 2-5 m² cell size, with exceptions possible for polygons of buildings
- outside of urban areas and no significant striking flow features: a maximum of 50 m² cell size, and an average of 25 m² cell size.

The first would apply to the urban Bornbach catchment. Since the available elevation data is a 1 m x 1 m Digital Elevation Model (DEM), using grid cells smaller than 1 m x 1 m is not recommended. A finer resolution mesh would require access to the raw laserscanning data, which are often available at a sub 1 metre resolution.

For the creeks themselves, two options are available in Delft3D Flexible Mesh. They can either be included in the 2D grid of the entire catchment using an appropriately small cell size, or they can be modelled as 1D branches that are coupled to the 2D grid of the catchment as shown in Figure 2.4.

Deltares

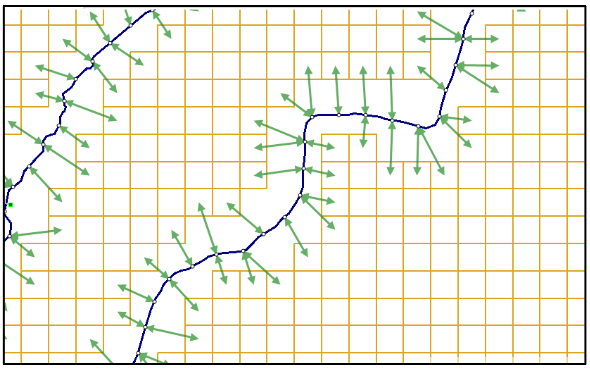


Figure 2.4 Example of a coupled 1D-2D grid.

For computational efficiency, the latter is preferable, since it allows for a detailed representation of the creeks' cross-sections without having to use a very fine grid resolution around the creeks. Since the model of the Bornbach is supposed to be used for other applications that require a 3D approach, however, the creeks were first implemented with a 2D grid that can be easily extended to 3D by adding the desired number of layers. However, during the grid-testing phase, this fully 2D-grid approach needed extremely small simulation time steps, which made it impossible to get results within the tight run time of the project. Therefore, the 1D2D approach was adapted, in which the creeks are modeled in 1D and the terrain is modelled in 2D. A description of the fully 2D grid was provided to LSBG as a separate technical note.

The 1D2D coupled grid is presented in Figure 2.5. The catchment is covered with a 2D grid composed of quadratic cells of 5 m x 5 m (orange coloured cells in the figure). The area covered by the available cross-sections of the creeks was cut out of that grid. The creeks themselves (dark blue lines and green nodes in the figure) are represented by their centre line, which was derived from available shapefiles that were corrected slightly based on the available high-resolution DEM. Computational grid points were created at a 10 m spacing. The 2D grid cells at the edge of the creeks were coupled to the 1D computational points by means of 1D2D links (green arrows in the figure).

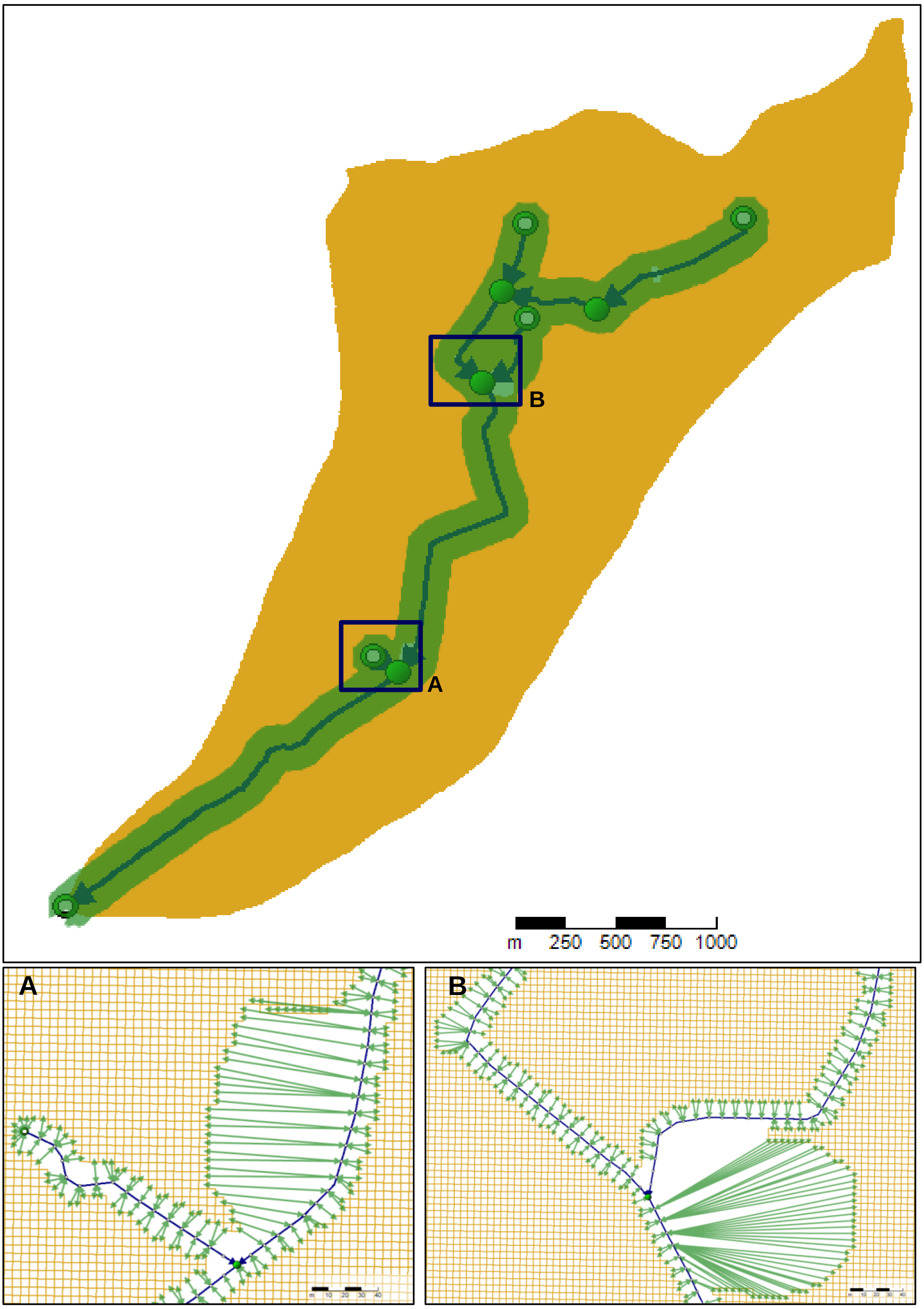


Figure 2.5 Top panel: Full 1D2D grid – blue & green for coverage by 1D, and orange area covered by 2D. Bottom panels: selected details of the coupling at the mouth of Diekmoorgraben and retention basin Diekmoor (A) and the mouth of Tweeltenbek and retention basins Solferinstraße and Kiwittsmoor (B).

2.4 Elevation and bathymetry

The terrain elevation in the catchment was derived from a 1 m x 1 m DEM and projected on the grid by grid cell averaging. The DEM was checked for elevated line elements such as roads and railroads and openings in those. The most prominent longitudinal feature is the railroad that crosses the catchment from south to north-west (Figure 2.6). The railroad is wide enough (about 18 m) to be captured in a 5 m by 5 m grid, so no extra line element had to be included in the model. Other roads do not present significant flow obstacles to wildly flowing water. Where roads cross the railroad, openings are already incorporated in the DEM, so no further postprocessing was needed.

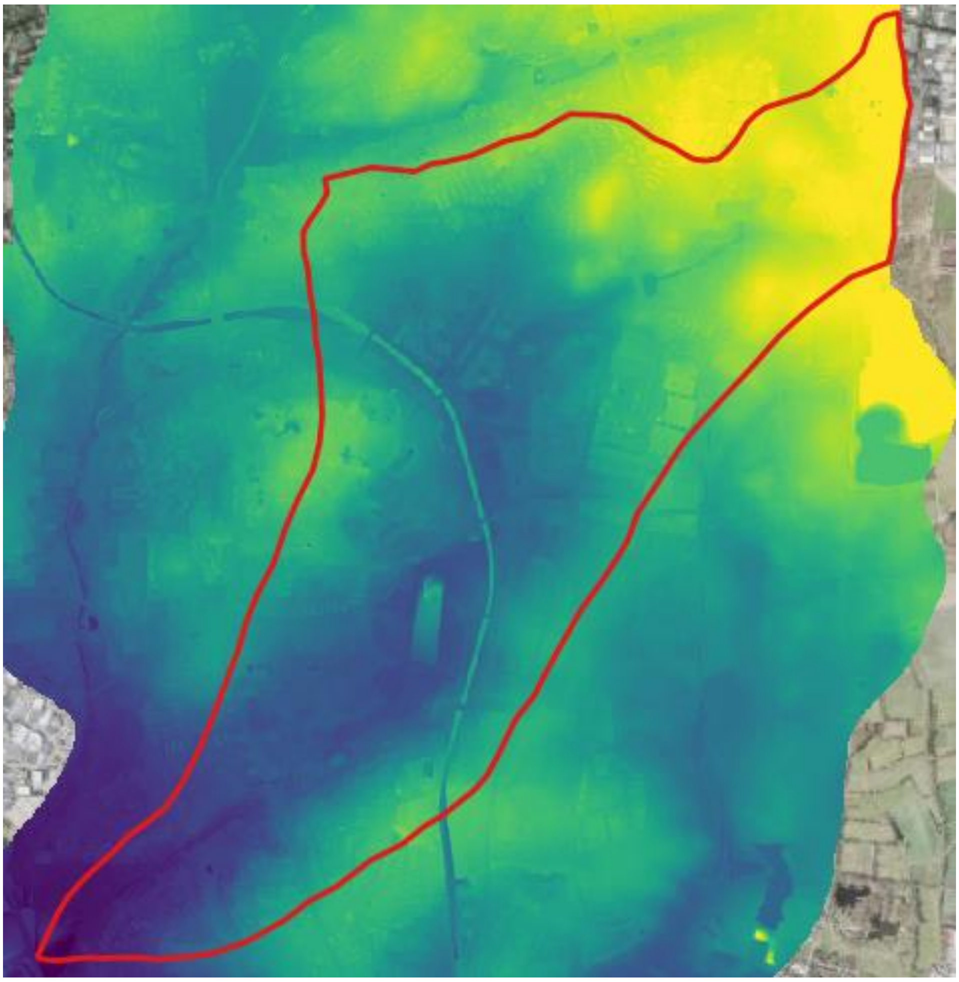


Figure 2.6 Elevation in 1 m by 1 m DEM.

For the creeks, cross-section data was available. It was composed of "open profiles" for the main creeks and "closed profiles" for structures such as culverts. The data for "open profiles" was used to define the cross-sections of the 1D model. Elements such as culverts were implemented into the model as hydraulic structures (section 2.7 and Figure 2.8). Additional cross-sections were introduced to describe the bathymetry of the retention basins (Figure 2.8). Figure 2.7 presents the locations of all implemented cross-sections. On computational points in between cross-sections, the bathymetry is interpolated based on conveyance tables (Deltares, 2021).

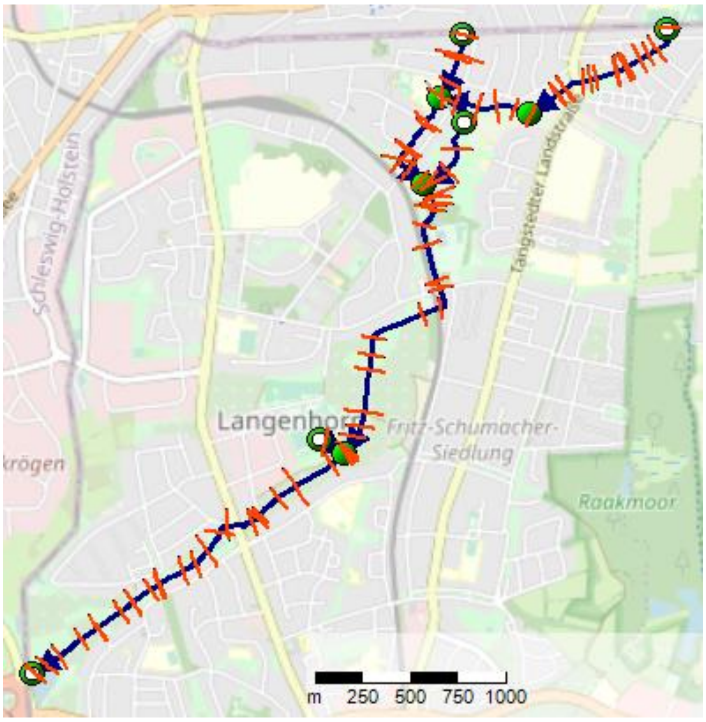


Figure 2.7 Cross-sections (red lines) on the branches of the creeks (blue lines).

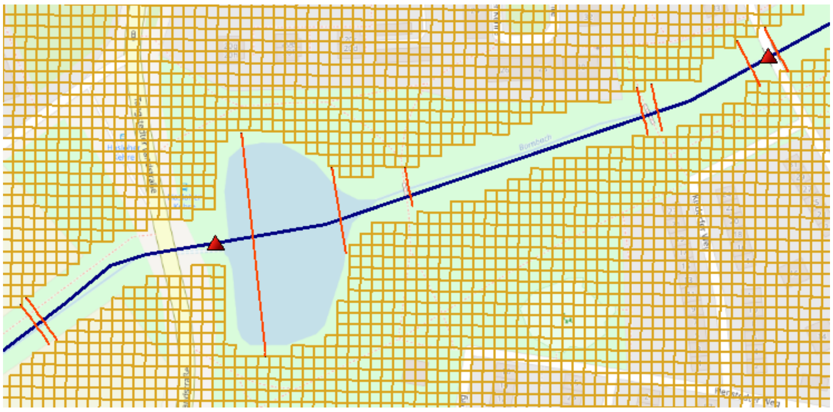


Figure 2.8 Cross-sections (red lines) and hydraulic structures (red triangles) in and around retention basin Heidberg.

2.5 Land use

ATKIS data was provided as land use information, together with a recommendation of which roughness coefficients to use for which land use class taken from LUBW (2020, appendices 1a, b and c). Table 2.2 lists the classes found in the catchment, the recommended value ranges and the values used in the model. For the model, these were converted to Manning values by calculating the inverse, since Delft3D Flexible Mesh does not allow values of type Gauckler-Manning-Strickler. The 1D creeks were set with a constant roughness of $n = 0.04\ s/m^{1/3}$.

Table 2.2 Roughness coefficients for different land use types.

recommended (LUBW, 2020, appendices 1a, b and c)			**provided shapefile (ATKIS data)**		
Land use class	**thin water layer <2 cm** k_{Str} **(m$^{1/3}$/s)**	**> 10 cm** **n (s/m$^{1/3}$)**	**Land use class**	**value applied in Delft3D FM model** **Strickler** k_{Str} **(m$^{1/3}$/s)**	**Manning n (s/m$^{1/3}$)**
Crop land	8-12	15-30	agricultural grounds (“Landwirtschaft”)	16	0.062
Woods, groves, deciduous or coniferous forests	3-6	5-20	Woods, groves, stockpiles (“Wald, Gehölz, Halde”)	8.5	0.118
Grassland, meadows and pastures	5-10	20-35	Area without vegetation, cemetery („Unland Vegetationslose Fläche, Friedhof“)	16	0.062
Lawn	3-8	20-35	Sports grounds, recreational areas („Sport Freizeit und Erholungsfläche“)	15	0.066
Residential area	6-15	10-20	Residential areas, commercial areas, areas of mixed use („Wohnbaufläche, Industrie und Gewerbefläche, Fläche Besonderer Funktionaler Prägung, Fläche Gemischte Nutzung“)	12.8	0.078
Watercourses, lakes	15-35		Watercourses, lakes (“Fließgewässer, Stehendes Gewässer”)	25	0.040
Roads, paths (asphalt)	40-60		Roads, paths, squares (“Straßenverkehr, Weg, Platz”)	50	0.020
Roads, paths (paved)	30-50		Railroad lines (“Bahnverkehr”)	40	0.025

2.6 Retention basins

There are five inline retention basins in the catchment (Figure 2.9):

- Heidberg
- Solferinstraße
- Kiwittsmoor
- Diekmoor
- and Krohnstieg at the downstream end of the catchment.

It is assumed that the DEM contains the standard water level at these basins. The bathymetry at the basins was estimated as being 80 cm below that surface. At the outlet of each basin, a hydraulic structure representing the outlet structure was defined. These structures are modelled using the general structures type (of Delft3D FM). They are described by setting a crest level, width, a gate lower edge, and gate top level. The general structure type in Delft3D FM is able to represent underflow (through e.g. a culvert) as well as overtopping (e.g. of a bridge). The dimensions of the structures in the model were based on the data available from the “closed profiles” (section 2.4).

Retention basin Krohnstieg is located at the downstream end of the model. Therefore, no outlet structure was implemented here. Instead the downstream model boundary is placed at the retention basin.

Figure 2.9 Retention (turquoise areas) basins in the Bornbach catchment (black line: catchment delineation, blue lines: creeks).

2.7 Hydraulic structures

Apart from the outlets of retention basins, all bridges of (rail)roads across the creek were modelled as hydraulic structures. For these, we used the general structure type as well.

2.8 Buildings

In a heavily populated urban area, buildings cover a significant part of the catchment. As such they ought to be incorporated in the models. The building footprints are added to the model via a shapefile. The shapefile provided by LSBG (Table 2.1) contains individual polygons for all the roofs of the buildings within the city of Hamburg (Figure 2.10). A small upstream part of the catchment is situated in the state Schleswig-Holstein. For this part of the catchment, buildings were not implemented in the model due to lack of data.

Cells within a building polygon are blocked, so no flow can pass through these cells. When defining roofs within the model, all roofs are assumed to be horizontal roofs with a 10 cm high border (default value) surrounding the edges of the roofs. As such the roofs provide temporary storage of rainwater. When this storage is filled with water, additional precipitation will overflow the roofs, and will be added to the neighbouring pixels. The assumption is also considered valid for tilted roofs, as most of these are equipped with rain gutters.

Figure 2.10 Location of the roofs (red polygons) with OpenStreetMap as background. Left figure shows different roof types (isolated small roofs, isolated large roofs, and connected individual roofs). Right figure shows where roof data is lacking: north of the border between Hamburg and Schleswig-Holstein.

2.9 Boundary conditions

2.9.1 Rainfall event

The model is forced with an extreme rainfall event, which was observed in July 2021 at Wipperfürth Gardeweg in North Rhine Westphalia/Germany. Figure 2.11 shows the observed rainfall intensity. The event represents 165 mm within 48 h, including several individual intense cloudburst sub events. In the model, rain falls onto the entire model extent, including the 1D part, in which the area considered for rainfall is determined by the maximum width of the cross-sections and the length of the flow links[3].

The model is only fed by rainfall, i.e. no discharge enters the model at the upstream boundaries of the creeks and baseflow was neglected. However, an initial water depth in the creeks and retention basins was applied (see Section 2.10).

Hydrological processes such as infiltration or evaporation are not taken into account to allow representation of a worst-case cloud burst scenario.

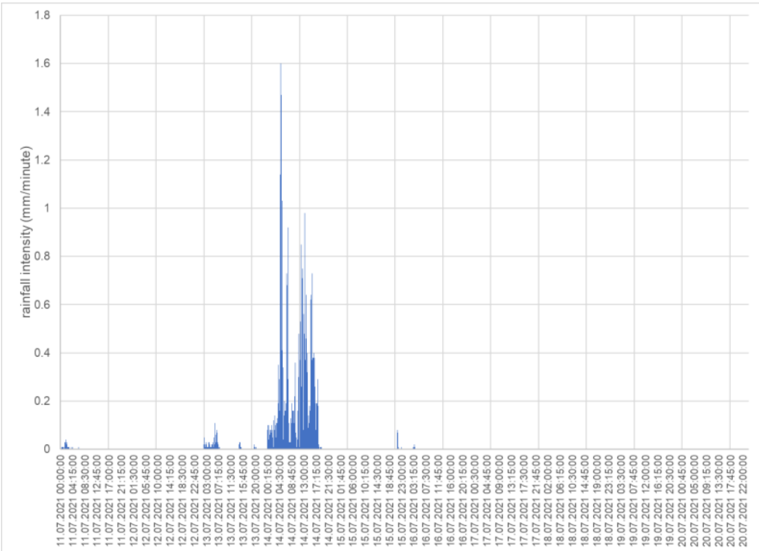


Figure 2.11 Observed rainfall intensity at Wipperfürth-Gardeweg, July 2021.

[3] pieces of branch between two calculation points

2.9.2 Downstream boundary

A water level of 13,75 m AOD was applied as downstream water level, both on the 1D and the 2D models. This means the water level in retention basin Krohnstieg is assumed to stay constant during the entire rainfall event. Simulation results show that this assumption does not significantly influence the discharge of water through the creeks or overland flow upstream of the basin during a rainfall event.

2.10 Initial conditions

The creeks and the retention basins are filled with water at the start of each simulation. To this end, and initial water depth of 80 cm was defined in the basins and 30 cm in the creeks. The rest of the catchment is assumed to be dry initially.

2.11 Blue-green infrastructure measures

Next to the reference simulation, a simulation with measures for potential blue-green infrastructure was performed. The functional design of these structures is to temporarily store rainwater in order to minimize and attenuate the peak water levels. Five potential example locations were determined for testing purposes and allowed to have a maximum dimension of 20 by 40 meters, with a storage depth of 2 meters. Accordingly, five storage basins were defined following the maximum dimensions. Locations were optimized such that they are situated at a location without buildings and/or other important infrastructure (see Figure 2.12). The storage infrastructure was allowed to be situated on space currently reserved for parking lots. Since some locations had sloping terrain, the depression of the storage basin was set equal to 2 meters beneath the invert level value within the 20x40 meter rectangle. This means that, locally, the resulting depression would be larger than 2 meters, but ensures that at least 2 meters of water can be stored across the entire basin.

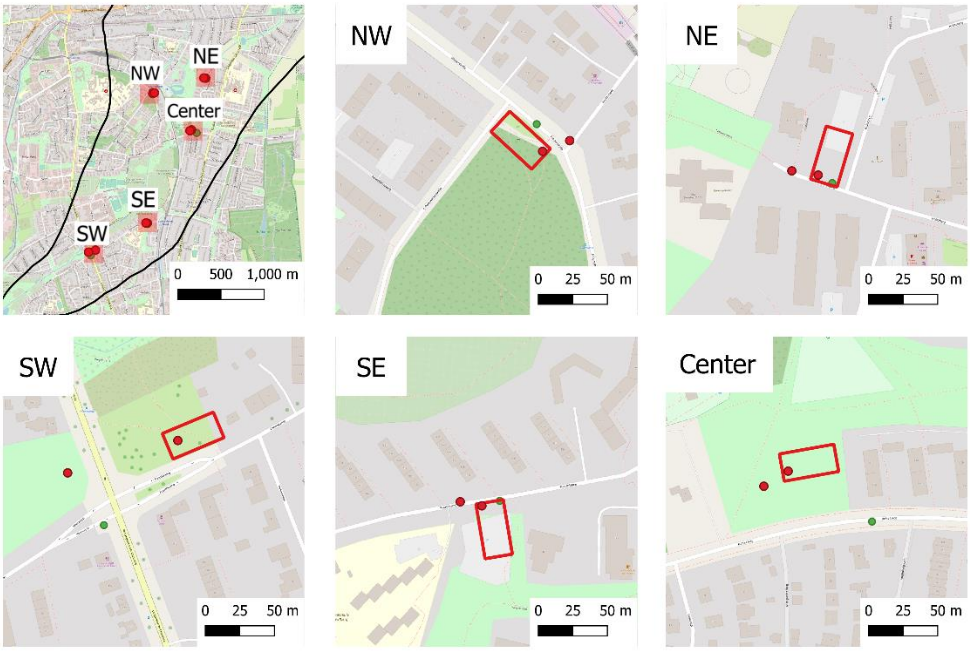


Figure 2.12 Location of the five potential infrastructure measures. Labels in the top left corner indicate the names of the five basins, linked to their relative position within the basin. Green dots indicate the provided locations by LBSG, red rectangles the resulting 20x40m basins, and the red dots the input (within the rectangle) and output (outside the rectangle) location of the added pumps.

To prevent water from simply filling up these basins, pumps (*Source-Sinks*) were added to extract water from these basins to a downstream location (throttle flow). A source (point where water will be extracted) and a sink (point where water is released) were defined for each location. For the SE location, the sink (exit point) was placed relatively far from the storage infrastructure to prevent water from flowing back into the depression. Each pump had a maximum allowed throttle flow, which for the purpose of this study was defined as 17 l/s per hectare of upstream area[4]. Based on the streamlines from the reference simulation, we estimated the upstream area of each location, and defined a maximum allowed discharge for the pumps (see Table 2.3).

Table 2.3 Statistics for the five potential blue-green infrastructure measures

Infrastructure measure name (location)	Minimum bed level (mAOD)	Bed level of measure (mAOD)	Upstream area (ha)	Maximum pump discharge (m^3/s)
NW	23.40	21.40	11	0.19
NE	22.78	20.78	10.5	0.18
SE	20.49	18.49	15	0.26
SW	19.18	17.18	35[5]	0.61
Center	21.10	19.10	27.5	0.47

Adding these measures to the model slightly changed the flow pattern, either resulting from the depressions subtracted from the existing bed level, or through the implementation of the *Source-Sinks* pumping the water out of these depressions. This resulted in the flow patterns around the five locations as presented in Figure 2.13.

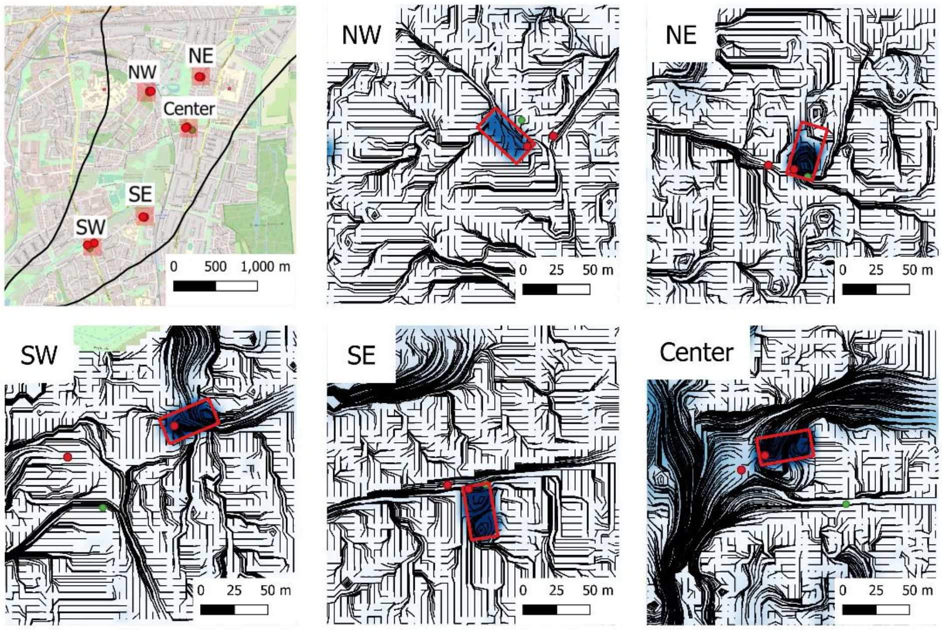


Figure 2.13 Streamlines around the five locations at 2021-07-14 15:00:00. Black lines indicate the flow direction of water at that timestep, coloured background indicates the water depth (white equals to 0 meters, dark blue to +2 meters).

[4] More recent guidelines in Hamburg have expressed a preference for reducing this value to 10 l/s*ha.

[5] Please note that the full upstream area of the SE location is included in the upstream area of SW

3 Results and analysis

3.1 Plausibility check

A proper calibration of the model was impossible, since

a) There is no flow gauge available in the catchment, and
b) there are no observed data available in neighbouring/donor catchments for a similarly extreme event.

Instead, the model results were checked for plausibility.

3.1.1 Simulation of “as is” situation

A comparison between the GIS flow path analysis conducted by Hamburg Wasser (Table 2.1) with streamlines simulated with the model shows many similarities between the two products (Figure 3.1). Naturally, the streamlines from the GIS flowpath analysis do not show an equally dense flow network as the model results. This comparison shows that the model correctly simulates the path water follows when landed on the surface. In many locations, water follows the structure of the road network, as this likely provides that path of least resistance. Even in less urban areas, the streamlines show good correlation. This highlights that the model correctly simulates the conditions in different areas, and the spatial resolution of 5x5 meter is sufficient to do so.

Figure 3.1 Comparison between a GIS flowpath analysis (red) and simulated streamlines (green), with OpenStreetMap as background. Left figure shows the area around Diekmoor, right figure shows the urban area southwest of the Langenhorn Nord station.

Figure 3.2 compares the maximum water depth in the catchment to the location of depressions in the terrain (flowpath analysis) and roofs. Apart from very small sinks these are nicely captured in the model. It also becomes visible that roofs also store some water (section 2.8). The extent of the areas with significant water depth exceed the sinks of the flowpath analysis especially in between houses and close to the creek. This makes sense in this very extreme scenario where significant flooding occurs directly by overtopping of the creek itself.

The effect of some rooftoops appears to be represented less accurately by the model, the storage effect of some of them is not visible in the results. An optimization of the rooftop functionality feature is currently under investigation by the Deltares software developers.

Figure 3.3 shows the calculated water levels in Bornbach creek at different times during the simulation. At the beginning of the simulation (t0), an initial water depth is applied as described in section 2.10 (dark blue line). After some spin-up with only little rainfall, a natural water level profile is reached (light blue line). Water depth is generally low, apart from locations that are influenced by structures (dashed vertical lines), in the retention basins (bold vertical lines) and in the central part of the creek between chainages 3250 and 4400, which has a rather low-lying bed. The results are in line with the expected flooding results.

The extreme rainfall causes the water depths in the creek to increase significantly, to water depths of more than 1 m in the central part. Figure 3.4 shows that in this area significant flooding takes place around the creek, which has been observed in reality as well.

Figure 3.5 shows results of the model's water balance. It shows that nearly all the water in the model comes from precipitation (apart from the initial water depth in the creeks), and that the total (numerical) volume error is several orders of magnitude smaller than the total volume in the model, i.e. the error is small.

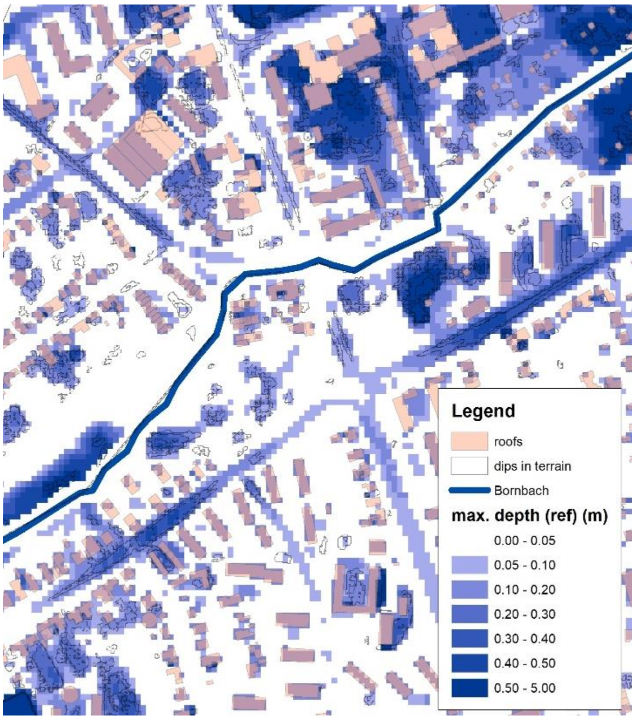


Figure 3.2 Maximum water depth in the catchment compared to the location of dips in the terrain and roofs.

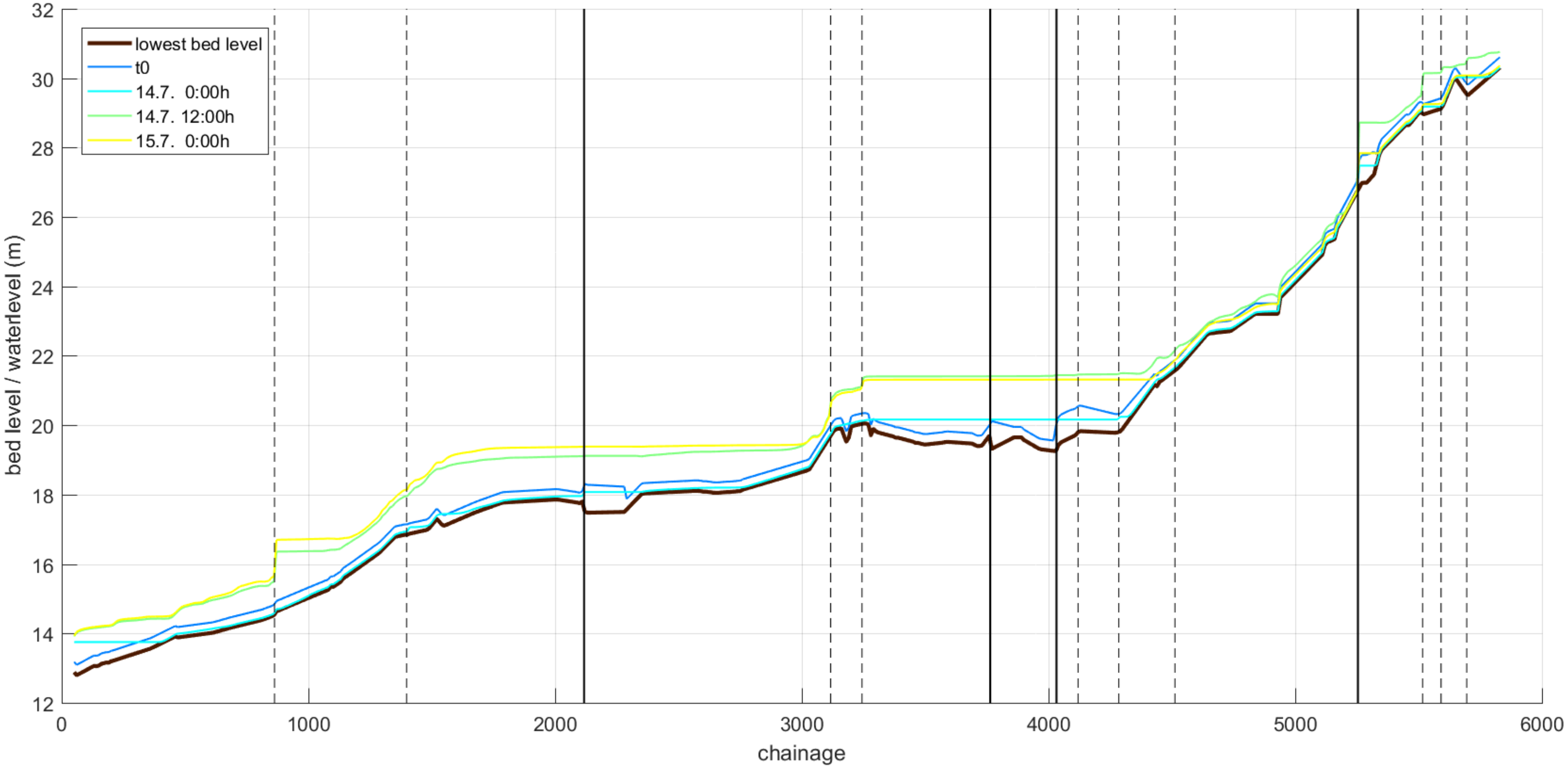


Figure 3.3 Bed level (thick brown line, deepest point) and calculated water levels in Bornbach (1D model).

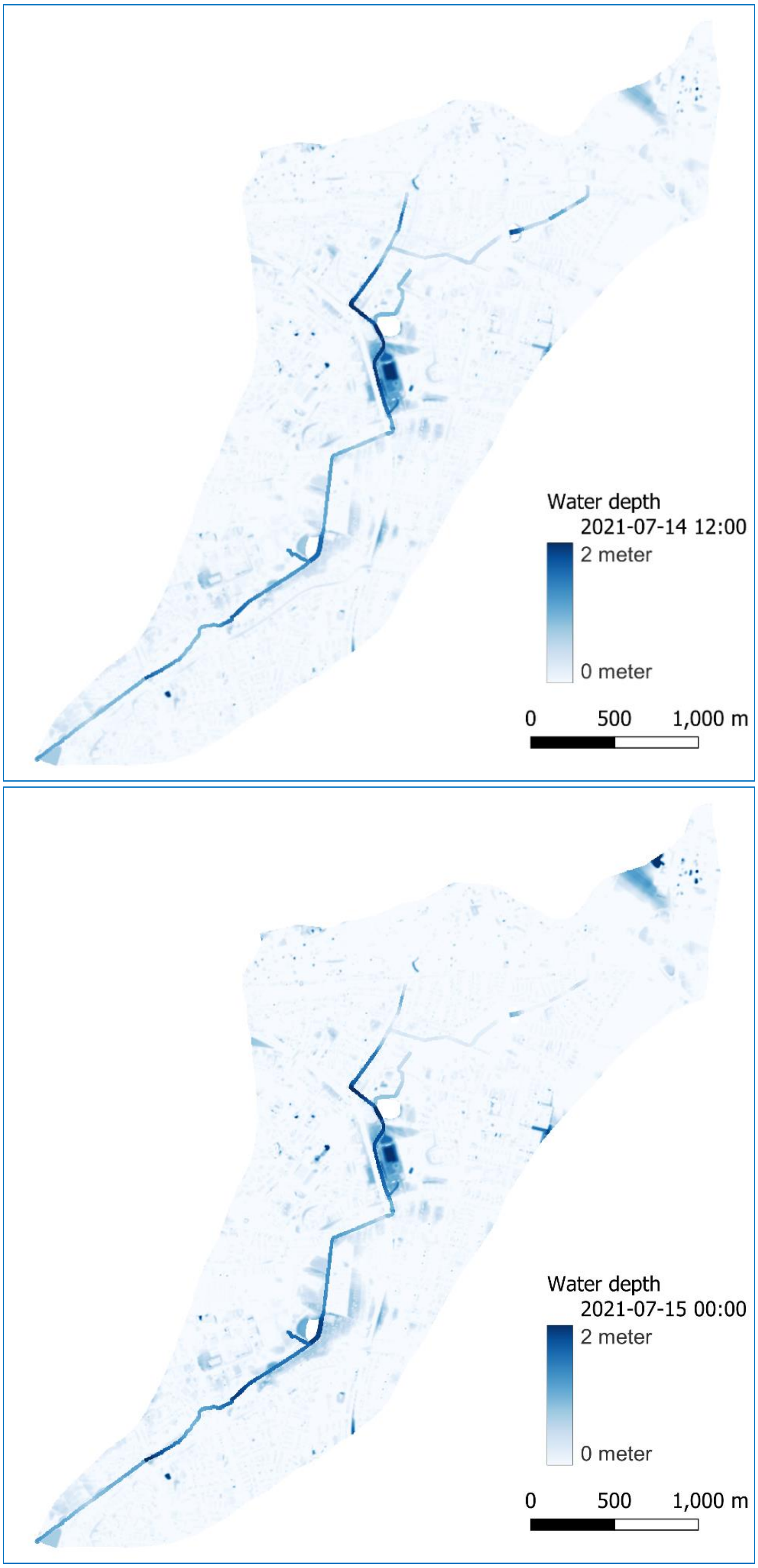


Figure 3.4 Water depths in Bornbach catchment halfway through and at the end of the extreme precipitation event.

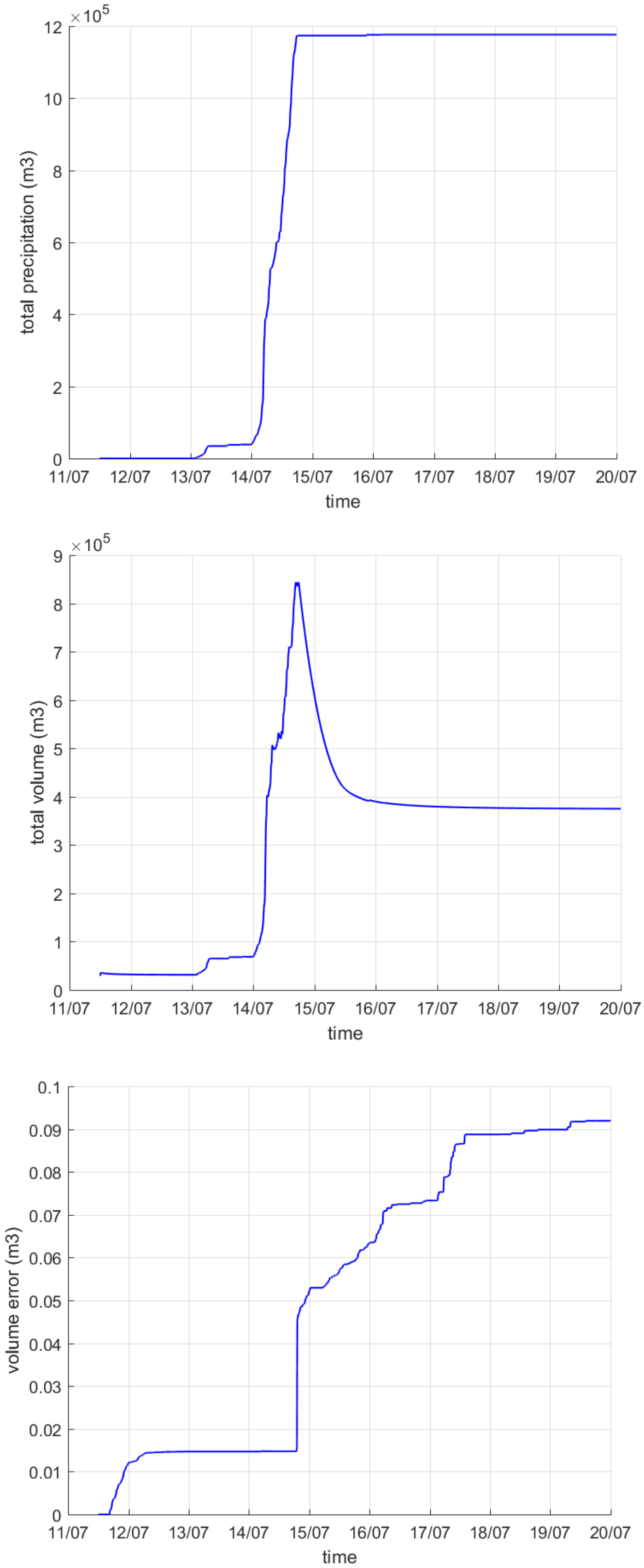


Figure 3.5 Total amount of precipitation onto the model (top), total volume of water in the model (centre) and volume error (bottom) in m³.

3.1.2 Simulation scenario with storage areas

Figure 3.6 shows time series of water depths during the filling up and emptying process of the retention basins, and Figure 3.7 presents the throttle flow. Please note that this is the flow through the implemented source-sinks (i.e. the throttle flow) only. Once the basins are filled and inflow to the basins exceeds the maximum throttle flow, overtopping of the basins will occur, and the total outflow of the basins will be much higher than the maximum throttle flow.

As expected, the throttle flow only reaches its prescribed value if enough water is available in the retention basins. The measure in the center of the catchment (called “Center” in Figure 2.12) is located next to the inundation area of Bornbach creek. It does not empty quickly after the rainfall event, because it is not only filled by rainfall on the catchment upstream of the measure but also by the discharge in the creek.

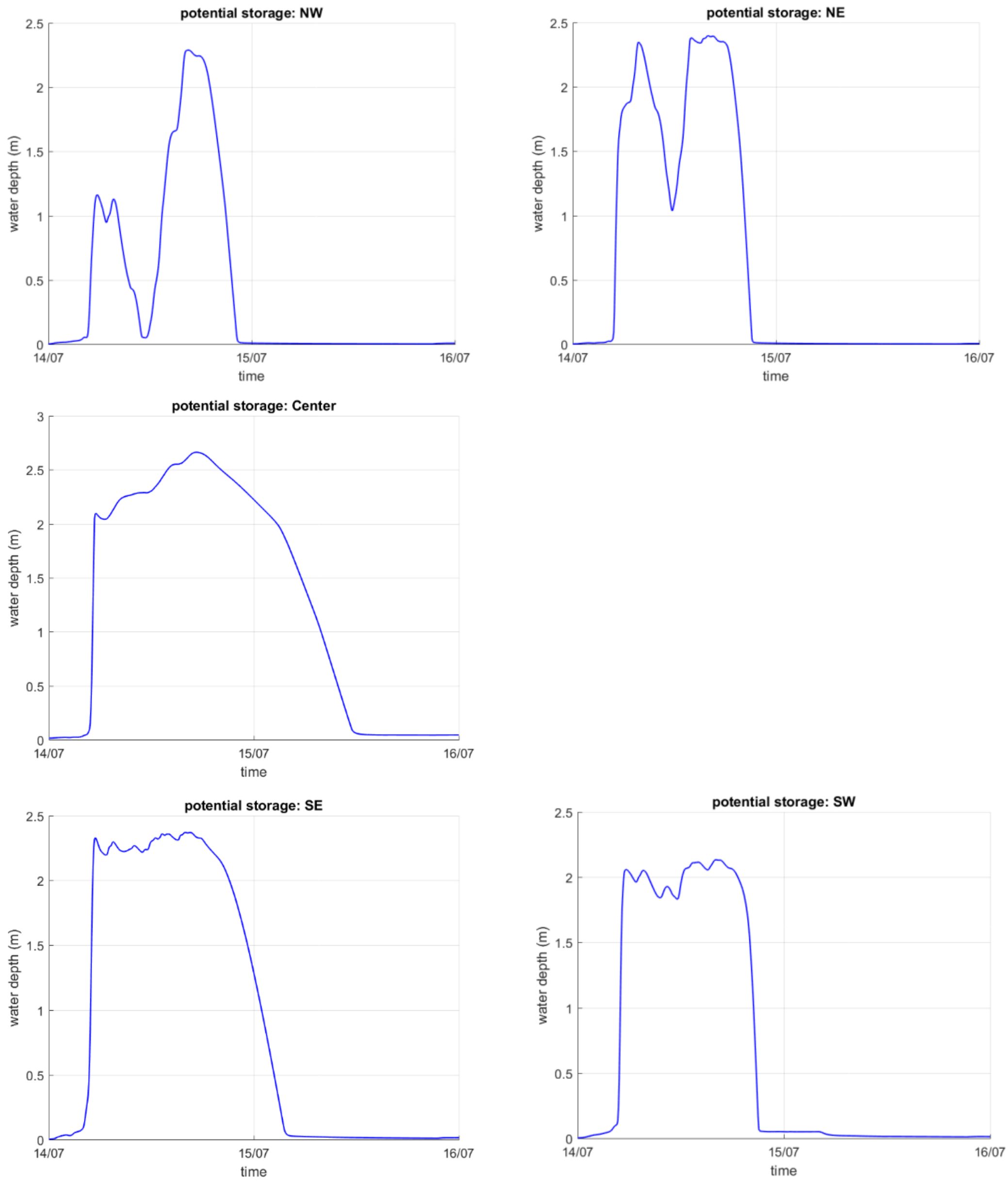


Figure 3.6 Filling of the potential storage areas.

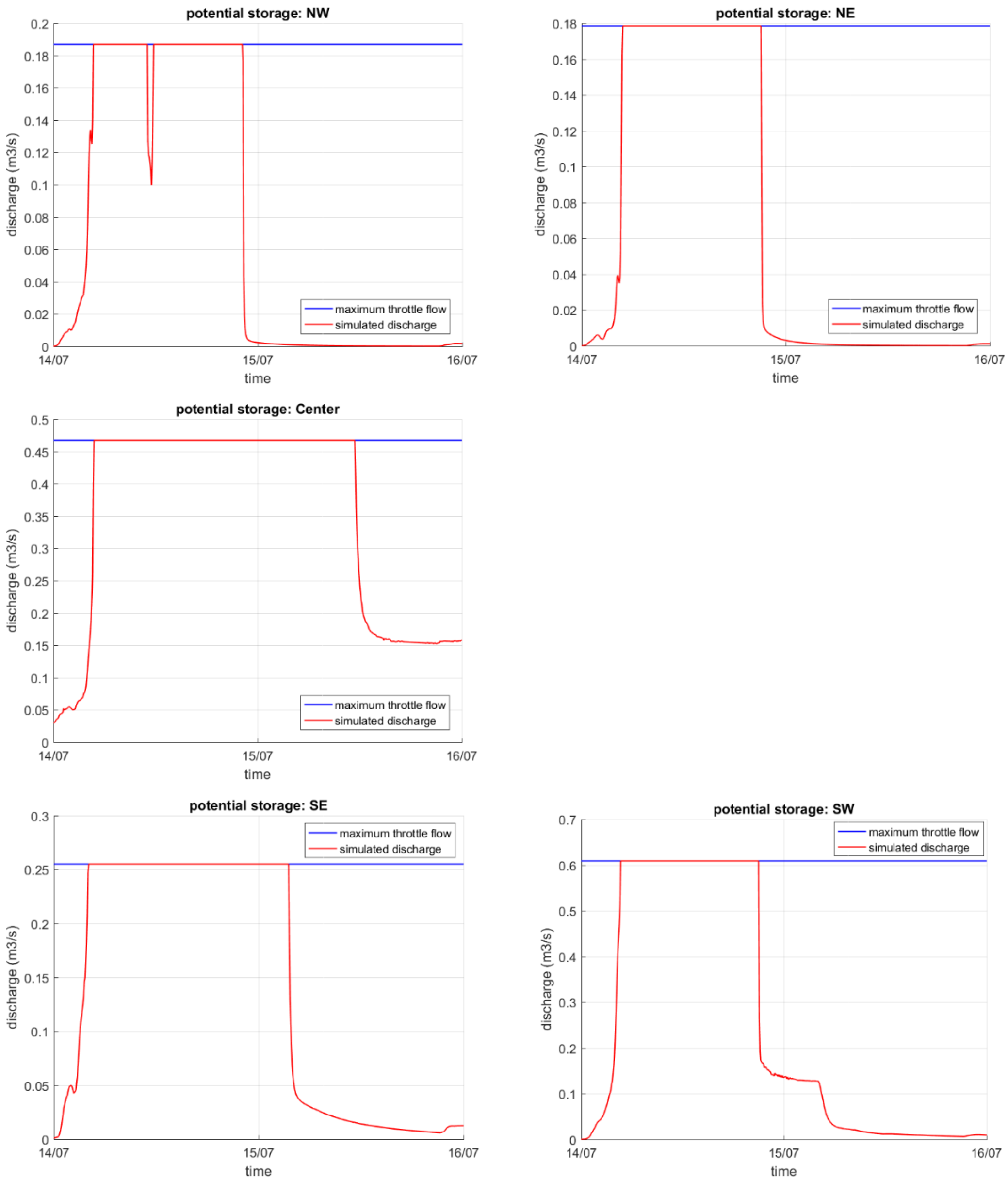


Figure 3.7 Throttle flow out of the potential storage areas.

3.2 Efficiency of the blue-green infrastructure measures

Figure 3.9 presents the influence of the retention measures on the discharge through Bornbach creek at selected locations. The locations are shown on a map in Figure 3.8. The streamlines in the same figure illustrate where the throttle flow out of the retention measures reaches the creek close to the selected locations[6].

Filling of the potential retention measures occurs relatively fast, and only in the case of the two northernmost measures the throttle flow is large enough to partially empty the basins again at mid-day of 14^{th} of July, when the rainfall temporarily drops (see Figure 3.6 and Figure 3.7).

[6] Since there are no output locations for discharge in Tweeltenbek creek, where the water of retention NE ends up, chainage 3770 on Bornbach creek, downstream of the confluence with Tweeltenbek, is chosen as representative location to evaluate the influence of that measure.

The measures have their maximum effect on the discharge in the creek while the retention measures are filled. The maximum retention effect therefore occurs before the discharge peak in the creek and the end of the rainfall event. Figure 3.9 indicates that the total reduction of discharge in the creek is limited. During the periods when the throttle flow exceeds the inflow of rainwater from upstream in the catchment, e.g. around mid-day on July 14th, the discharge in the creeks is higher in the situation with retention areas than in the as-is situation, because the basins are slowly emptied then, and therefore inflow to the creek is temporarily increased.

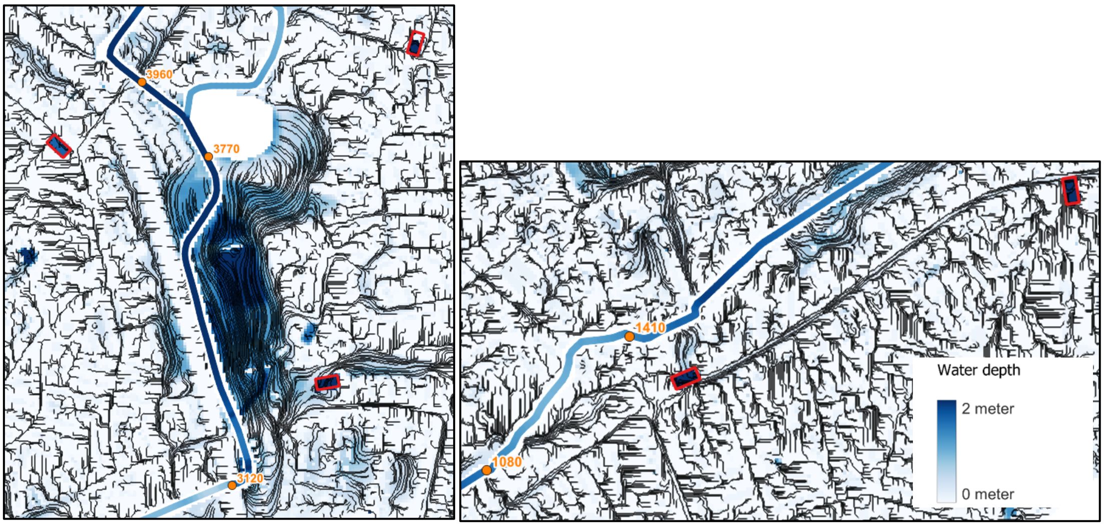


Figure 3.8 Water depth and streamlines (black lines) around the retention measures (red rectangles) on July 14th, 15h00.

Figure 3.10 presents the difference in maximum water depth in the catchment as well as water depth difference at two specific moments in time. Depth differences generally stay within the order of a few centimetres; the extent and value change in time, though.

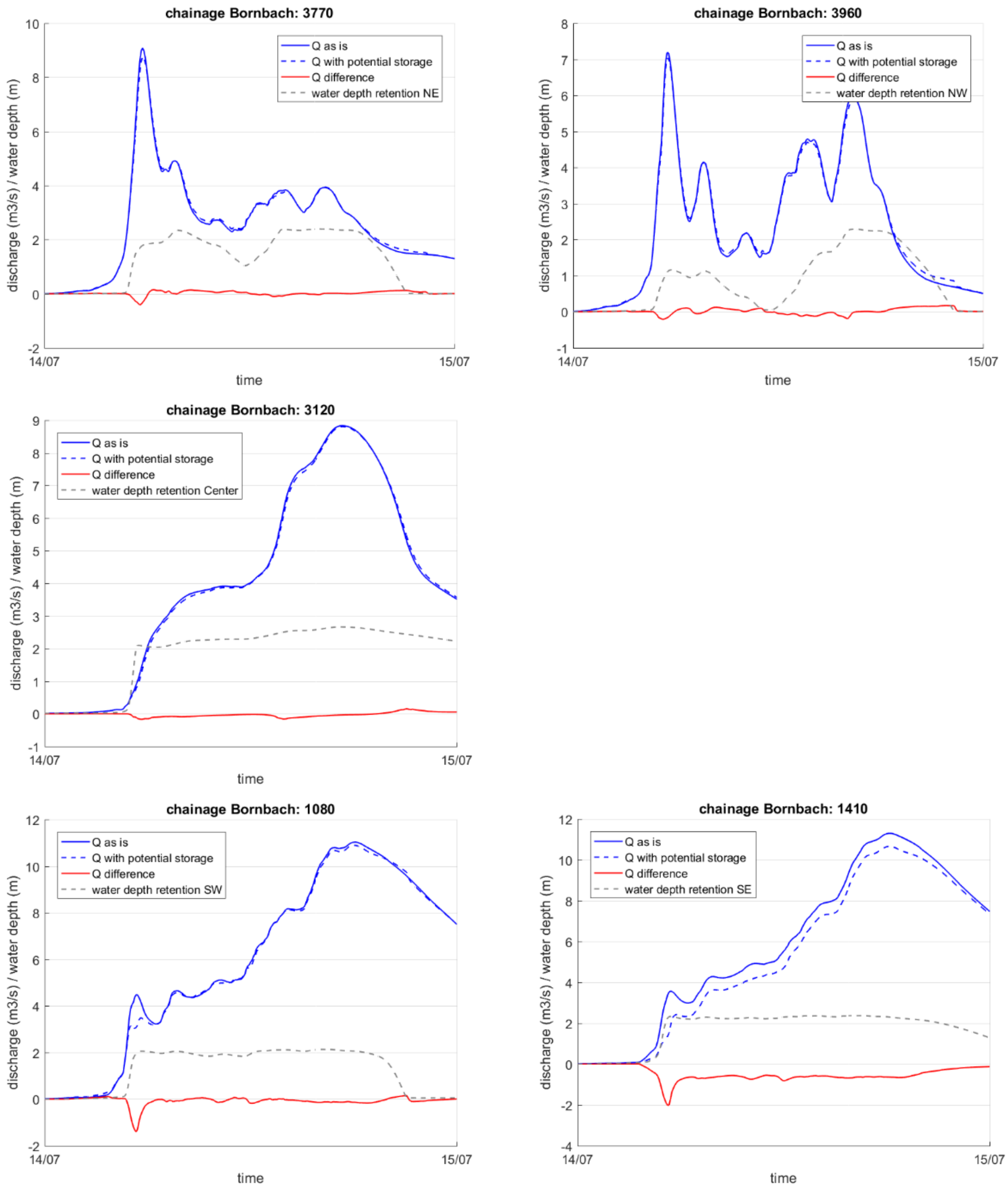


Figure 3.9 Influence on the potential retention measures on discharge in Bornbach creek at selected locations.

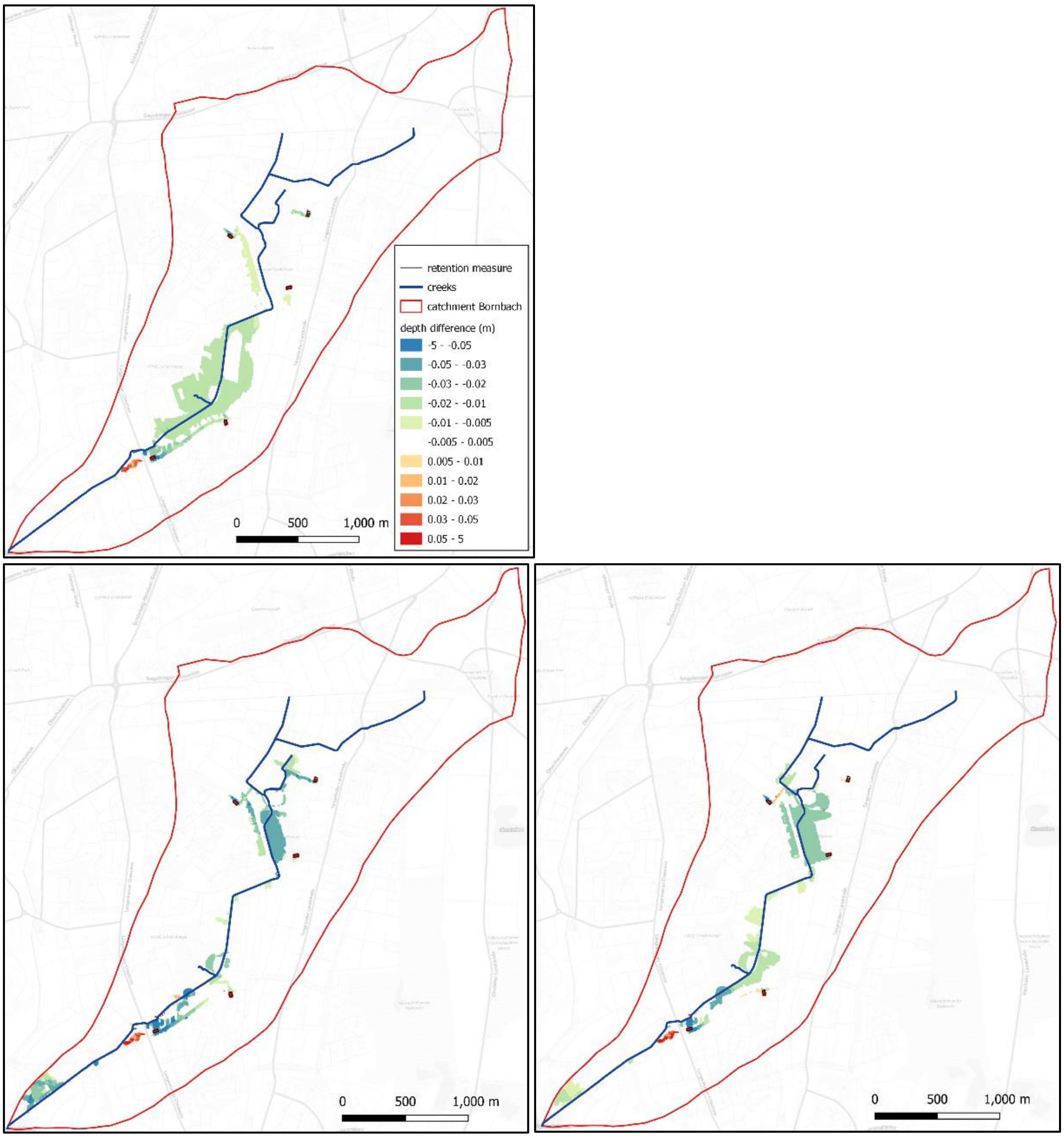


Figure 3.10 Difference in maximum water level (top) and water level difference at 14th of July, 5h30 (bottom left) and 8h00 (bottom right).

3.3 Simplified calculation of damage

The economic consequences of such an extreme rainfall event for the Bornbach catchment are estimated using a simplified damage calculation. Damage is assumed to be caused by water depths that exceed 5 cm. These areas were extracted from the maximum water depth that was reached during the simulation period and then intersected with areas covered by land use types “industry and commerce” and “residential area” (see Figure 3.11). The resulting surface areas were multiplied with an indicative damage per square meter provided by LSBG. This means that 100% damage is assumed if water depths exceed 5 cm.

The indicative damage per square meter is based on standardized plot values from BORIS[7], extrapolated to 2021 from the last available value from 2017 and combined with land use data. Damage is calculated only for the reference case, because the maximum flood extent does not differ significantly in the case with retention measures.

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[7] Boris.HH (geoportal-hamburg.de)

This results in an indicative damage of about 741 Million Euro, of which about one quarter is damage to industry and commerce, and three quarters is damage to residential areas.

Table 3.1 Indicative damage caused by an extreme rainfall event in the Bornbach catchment.

type of area	area flooded with max. depth of more than 5 cm (m²)	damage (EUR/m²)	damage (Mio. EUR)
industry and commerce (Industrie und Gewerbe)	251350	705	177
residential area (Wohnbaufläche)	834267	676	564
		total:	741

As stated above, areas flooded with maximum water depth > 5 cm are considered to be damaged. Figure 3.11 compares the extent of these areas to the areas of value (industry/commerce and residential) for the reference situation as well as the situation with retention measures. As expected, differences in extent occur only downstream of the measures, i.e. close to the creeks. This is mostly outside the areas of valuable assets. Overall, the difference in flood extents between the "as is" situation and the scenario including retention basins is small. Figure 3.12 shows that, as can also be seen from the figures of water level difference (Figure 3.10), the influence of the retention measures differs at different moments in time. On 14th of July, around 5h30, the southern and central basins have reached maximum volume capacity and have approximately their maximum effect on flow retention.

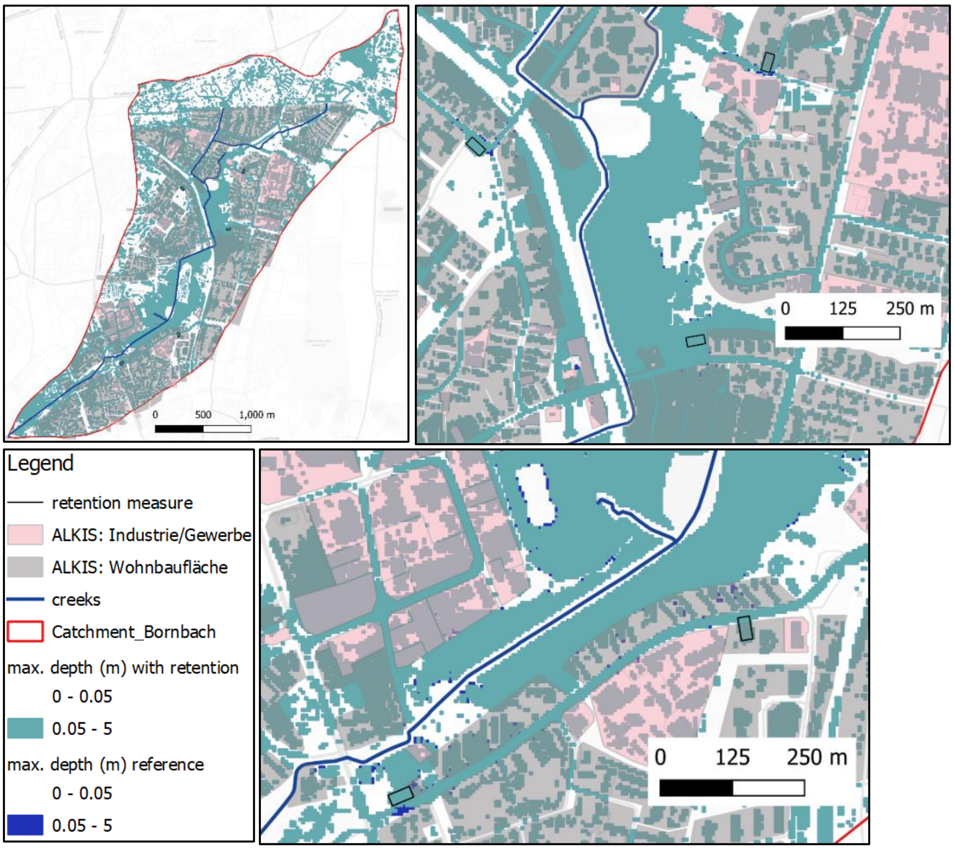

Figure 3.11 Extent of the area flooded with maximum water depth > 5 cm compared to the areas of value (ALKIS: Industrie/Gewerbe = industry and commerce, Wohnbaufläche = residential area). Dark blue pixels represent the areas in which the extent is reduced by the retention measures.

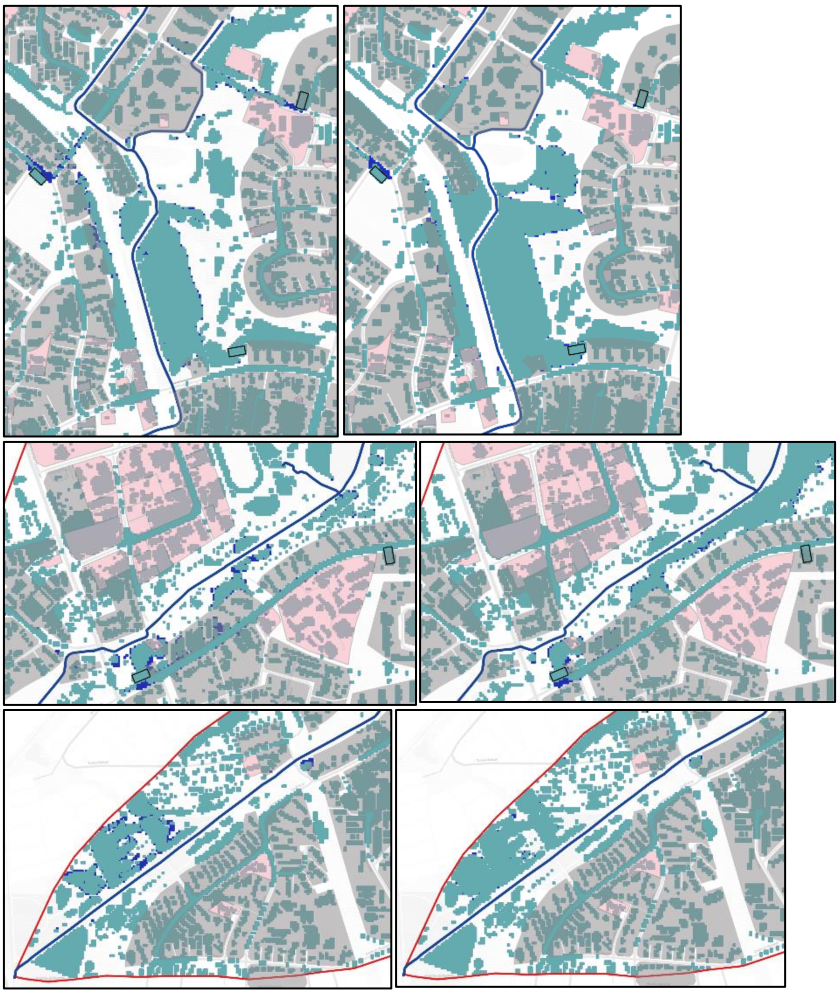

Figure 3.12 Difference in extent of the area with water depth > 5 cm at different locations in the catchment on 14th of July, 5h30 (left) and 8h00 (right).

4 Conclusions and recommendations

In the first phase of the study[8], we tested two different approaches for modelling extreme events using the direct rainfall method, the first is a pure 2D model and the second is a coupled 1D2D model. The pure 2D model needed extremely small simulation time steps to produce stable model results, which made it impossible to get results within the tight run time of the project. Therefore, a coupled 1D2D model was selected for the analysis. In that model, the creeks were modeled in 1D and the terrain was modelled in 2D. This is computationally much more efficient than a purely 2D model, since it allows for a detailed representation of the creeks' cross-sections without having to use a very fine grid resolution around the creeks. The model is forced with the extreme rainfall event, that was observed in July 2021 in North Rhine Westphalia/Germany. A plausibility check demonstrated that the model functions as intended. Next to the as-is situation, a model version with blue-green infrastructure measures was set-up. Five retention basins (example locations and dimensions only) were implemented in the model to temporarily store rainwater. They are intended to attenuate the peak water levels. Locations were selected such that they are situated at a location without buildings and/or other important infrastructure

The model simulations showed that filling of the potential retention measures happens rather quickly, and that their storage capacity is exceeded well before the extreme rainfall event finishes. Therefore, their effect on maximum water depths, for this extreme event, is limited. At the early stages of the event, the measures have a clear reducing effect on the discharge in the creek, but their influence on the extent of the area with significant water depths is local. In order to achieve a more significant effect for an extreme event such as the one of July 2021, a larger total retention volume is needed, i.e. a higher number of storage areas or bigger storage volumes would need to be implemented. Retention measures of the size implemented in this study should be located further upstream, where the accumulated flood volume is likely to be lower.

This study presents a first analysis of the potential effect of decentralized blue-green infrastructure elements in the Bornbach catchment. Further modelling would be required to optimize their number, size and locations.

Retention measures mostly influence flooding downstream of the storage areas. In the current study, the measures were placed rather far downstream, close to the creek, while the residential and industrial/commercial areas are mainly located further upstream in the catchment. Therefore, the total expected damage is not reduced significantly by these measures. To protect infrastructure in the Bornbach catchment itself, measures should be placed further upstream in the catchment. So from this point of view, preferably a larger number of retention basins should be placed further upstream, rather than increasing the volume at the locations analyzed in this study.

Measures close to the creek can, however, help to reduce the discharge further downstream in the creeks. Thus, they may protect those areas, i.e. along the Tarpenbeek creek, which receives the discharge from Bornbach catchment. If retention measures are placed close to the creek, it is important to keep them outside areas that are inundated from the creeks in order to keep the volume available for storing rainfall.

[8] The study is complemented with a water quality study (separate report).

In a heavily urbanized environment as the Bornbach catchment, it is difficult to find suitable locations large enough for green retention areas. It might be necessary to combine these with other measures such as raingardens, permeable paving, green roofs, or water squares; in order to achieve sufficient mitigation of flooding.

The area close to the creek in the central part of the Bornbach catchment is flood prone due to its topography. For this area, and other such areas, adaptive construction and design such as flood-proof buildings is recommended.

5 References

Deltares (2021): Delft3D FM Suite 1D2D. User Manual. Draft version, 20th January 2022.

LUBW (2020): Leitfaden Kommunales Starkregenrisikomanagement in Baden-Württemberg.

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