# Transfer and extension of experience from urban heavy rain flood risk warning

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# Abstract

The high variability of local intense rainfall events and the short response time of flow in urban catchments demand improved methods in flood warning systems. A key aspect of success is the improvement of short-term forecasts of heavy rainfall by combining ensembles of radar nowcasts with numerical weather prediction ensembles. This paper presents results from this approach in the context of the urban fluvial water management and flood warning system in Hamburg since 2019 and extends its conclusions to other application fields. New challenges from this operational context are being investigated in another research project focusing on the city of Hanover. The topics of improved spatial rainfall data resolution, use of ensemble information from radar nowcasts for pluvial flood warning in connection with sewer load and possible solutions for real-time applications in the urban context are tackled.

Experiences from both projects illustrate the importance of applying real-time measurements and ensemble forecasts in connection with a clear open information strategy. Data quality and resolution are crucial aspects in this context, making the combination of different data sources potentially significant for improving the outcome.


# 1 Introduction

Small urban catchments are characterised by a short response time and a high damage potential. Combined with the high variability of local heavy rain events, flood forecasts and warnings are a challenging task (Schellart et al., 2014, Thorndal et al., 2017). Current studies describe the forecast quality of different nowcast methods, numerical weather predictions and combined forecasts. Several studies highlight the benefit of using NWP ensembles for run-off simulations and flood warnings in small to medium size catchments and of radar-based ensemble nowcasts (e. g. Smith et al., 2014). In water management practice, resources are limited and trade-offs between simple and more complex solutions need to be found. Against this background, it is crucial to assess the added value of radar-based ensemble nowcasts and of NWP ensemble forecasts for urban flood warning. We first present an evaluation of an operational warning system for the city of Hamburg which was updated with combined ensemble forecasts in 2019. In a second step, we discuss the potential for improvements of such an online system, on the example of a digital twin project for the city of Hanover in Germany. Here, new ways ahead are being developed and operationally tested.

# 2 Operational Flood Warning System in Hamburg

## 2.1 General context

The Hanseatic City of Hamburg is situated at the mouth of the Elbe river, in the influence range of the North Sea tides which may be even increased in amplitude by the river mouth. At the same time, drainage of natural rivers and of the sewer system become critical with very high tides so that a risk of inland flooding exists. This was the base scenario of the StucK project “Long term drainage management of tide-influenced coastal urban areas with consideration of climate change” (2016–2019), funded by the Federal Ministry of Education and Research in Germany, with the objective to improve the current warning situation in view of the tidal context. The results have been implemented in the WaBiHa system (Warndienst Binnenhochwasser Hamburg – warning service for fluvial floods in Hamburg) and are increasingly being transferred to other application sites.

## 2.2 Precipitation module

The basis of the precipitation nowcasts are

- Radar data from 4 German Weather Service (DWD) radar stations: Boostedt, Rostock, Hanover and Borkum. The basic radar product is a polar measurement (Plan Position Indicator – PPI) with a spatial resolution of 250 m x 1° and a 5-minute time step.
- Rain gauge measurements of 400 stations (DWD in Northern Germany with time step between 5 minutes and 1 hour)

The radar data are processed and corrected with the software SCOUT (hydro & meteo 2009), using numerous filter and correction methods (Jasper-Tönnies & Jessen, 2014). The rain gauge measurements are continuously used for the adjustment of radar measured rainfall sums, based on data of the past 3 hours. A composite with a resolution of 1 km x 1 km is produced every 5 min from the data of the four radar stations. An example of the adjusted composite is shown in Fig. 1.

The radar composites of the last 30 min serve as input for calculating nowcasts with a lead time of 1–3 h. The nowcast method is based on a cell-tracking algorithm, tracking rain cells with a minimum size of 20 grid points above a reflectivity threshold. Cells are tracked based on their position and size, and displacement vectors are determined. These vectors are used to approximate the 2D advection field. A Semi-Lagrange scheme is used to forecast the advection of the rainfall field. Additionally, growth and decay of rain cells are extrapolated. The method is a further development of the nowcast described by Tessendorf and Einfalt (2012).

The ensembles are created through variation of the individual cell properties. Thus, the past development of the cells’ properties as well as their uncertainties are determining the degree of variation for the ensemble.

A joint evaluation of the forecast quality of the ensemble nowcasts, the deterministic COSMO-DE, and the ensemble forecasts COSMO-DE-EPS was performed. The ensemble nowcasts and COSMO-DE-EPS outperform the deterministic forecast (Jasper-Tönnies et al., 2018).

## 2.3 Real-Time warning

The real-time warning system WaBiHa combines the current warning level at 39 water level gauges with the warning levels from the precipitation measurements and the forecasts. The three independently determined warning levels are used to derive a general warning level, for each of the water level gauge specific subcatchments. The real time warning level is publicly displayed on the WaBiHa platform www.wabiha.de and changes of warning levels are emailed to relevant users within the city administration.

The updated warning system WaBiHa with ensemble nowcast based warnings has been operational since 2019. An evaluation of the highest 35 events in a 6-month-period with exceedances of warning levels at the water level gauges revealed that in 66% of the events a correct warning was issued based on the precipitation forecasts at least 6 hours ahead. The overall hit rate was 77% while the false alarm ratio in the same time period was 40%. Misses of the warning system were partly due to missing incoming data. These results represent a major step forward compared to the previous warning system which was solely based on the deterministic COSMO-DE forecast.

## 2.4 Further updates and consequences

The public WaBiHa portal has had a relaunch in early 2022, now integrating the new ICON-D2-EPS NWP data, and is being visited a few thousand times per day during flooding events. The approach to make relevant information public, also displaying data in form of maps and time series has proven to be successful. This goes in line with a movement towards open data, a strategy that we strongly support.

The warnings for three relevant water level gauges are also transmitted to the direct public warning apps NINA (https://www.bbk.bund.de/DE/Warnung-Vorsorge/Warn-App-NINA/warn-app-nina_node.html) and KATWARN (https://www.katwarn.de/) through the federal flood warning service LHP. Thus, every citizen in Hamburg with one of these two mobile phone applications receives a direct warning when a warning level is reached.

Warning systems building upon the experience from Hamburg have now been established for the city of Bremen (www.starkregenpartnerschaft.de), for parts of North Rhine-Westphalia (without public website yet) and are under construction for the cities of Flensburg and Cologne.

# 3 Research and development for a detailed online forecast in the city of Hanover

In order to explore next steps beyond the operational scheme established in Hamburg, two elements of practical use are under research in a new project: the use of smaller grid cells for the radar-based rainfall information, and the assessment of the flood potential by heavy rain. Within the ZwillE project (Research project funded by the German Federal Ministry of Education and Research) aiming at creating a digital twin of the water flows within the city of Hanover, Germany, these elements are being analysed in order to provide further refinements and extensions for operational warnings.

## 3.1 Radar measurement

Since a few years, the German radars are measuring precipitation with a spatial resolution of 250 m x1°. In the vicinity of a radar, this provides the possibility to gain more spatial information on the rainfall. Since the closest weather radar to the city of Hanover is located at Hanover airport, the conditions for testing this possibility are good.

After correction e. g. for clutter, beam blockage and advection, the data are being adjusted using a dense network of 17 ground stations from DWD and the city of Hanover (drainage organisation of Hanover – Stadtentwässerung Hanover (SEH)).

### 3.1.1 Improved rain sums

Deriving rain sums from radar measurements is one step to locally approach rain gauge measurements. The rain sums are used as a basis for radar-rain gauge adjustment procedures and are also useful for further calculations and visualisation. In order to achieve improved radar rain sums, we

- use the high-resolution original data on the 250m x 1° grid instead of a coarser composite grid
- conduct an advection correction on the fine polar grid

as is described by Jasper-Tönnies et al. (2014). The effects of the increased resolution (250 m x 1° versus 1 km x 1 km) in combination with the advection correction are evaluated.

### 3.1.2 Automatic rain gauge check

An automatic check of the incoming rain gauge data is implemented (Fennig et al., 2022) to account for measurement errors. In addition to fixed thresholds and a comparison with data from neighboured stations to find inconsistent and unplausible data, a comparison between radar and rain gauge data is conducted. Unplausible measurements are excluded from the radar-rain gauge adjustment. The impact of the rain gauge check in the real-time environment is investigated.

### 3.1.3 Radar-rain gauge adjustment optimised for real-time applications

A « quasi-adjustment » is performed in real-time with the software SCOUT, enabling adjustment procedures with factor and difference fields. Both, factors and differences to correct for differences between radar and rain gauge measurements are determined spatially, resolved for each point on the radar grid. Several innovations have been implemented:

- A flexible adapting algorithm in dependence on the number of modelling stations with valid precipitation information and their distance to the considered grid point
- An underlying error model: For radar and rain gauge measurements, assumptions over the measurement inaccuracy are considered, in dependence on the measured precipitation intensity. A linear regression function is computed to map radar precipitation sums to the precipitation measured by the rain gauges.

- Advection correction of the adjustment parameters: Since rain gauge measurements are only available for a past period, a past period (we use up to 3 hours) is considered where overlapping radar and rain gauge data are available. The resulting adjustment fields are valid for this past period. In order to achieve the best possible correction for the current radar measurement, an advection of the adjustment fields is calculated to consider the spatio-temporal movement of the precipitation field. The methods of cell detection and advection from nowcasting are used for this procedure. The advection of the calibration field on the grid is calculated using the Semi-Lagrange method.

# 3.2 Ensemble nowcasts

The polar data from this radar are transformed into a rectangular grid of 500 m x 500 m, providing four times more information than the usual grid of 1 km x 1 km. The rectangular grid is helpful for further processing in nowcast and in intersection with flow information.

On this basis, ensemble nowcasts with a forecast horizon of up to two hours are calculated, as described in section 2.2 above.

Furthermore, the adjustment information is also being projected into the future so that both informations are available for the nowcasts on a 500 m x 500 m grid.

For forecasts beyond the horizon of two hours, a blending of the nowcast with the NWP ICON-D2-EPS is performed, weighting the nowcast heavier just after two hours and fading out the weight until a forecast horizon of four hours. Forecasts that are going further are then solely dependent on the NWP data, up to a horizon of 48 hours.

Special and new features are:

- The consideration and advection of adjustment parameters, deriving « quasi-adjusted » nowcasts.
- Ensemble-nowcasts allowing for the quantification of uncertainties which can also be transferred to impact models. They are generated by varying initial forecast conditions and by an estimation of the uncertainty as function of the variance of the observed variables during the past 30 min.
- The lead time of the nowcasts is extended by a blending procedure (Jasper-Tönnies et al., 2018) blending ensemble nowcasts with the ensemble numerical weather forecasts ICON-D2-EPS of the DWD
- A fast calculation of nowcast ensembles and blended ensembles in less than 5 min.
- Calculation of nowcasts with an increased spatial resolution related to the increased resolution of the radar scans.

For the evaluation of QPE, QPF and derived products, a real-time simulator is used, simulating the process chain and the actual data availability in the corresponding real-time environment.

# 3.3 Post event analysis within a case study

## 3.3.1 Description of the situation

A case study presenting the post event analysis of a heavy rainfall event having occurred on the 16th of June 2020 (Fig. 2), will demonstrate aspects of the use of the presented forecast information.

During this event, several streets and numerous cellars were flooded, the emergency services had a large number of interventions (Fig. 3), and combined sewer overflow into the creeks and rivers has been observed. The radar data showed a strong spatial gradient of the rainfall amount around the centre of heavy rain.

## 3.3.2 Methods for Analysis

In Germany, the rainstorm severity index RSI (Schmitt & Scheid, 2020) is a popular tool for the description of the severity of a rainfall event. This index permits to communicate the severity of a rainstorm without direct reference to return periods. However, there is a one-to-one translation of the twelve index values into return periods in the index classes 1 to 7. Beyond, the event is statistically less frequent than once in 100 years.

For applications in Germany, the extreme value statistics in vigour is KOSTRA-DWD 2020 (www.dwd.de/kostra) since January 2023. Thus, there is a clear structure for communicating rainfall severity of individual rain events.

Since the pure rainfall amount is not directly related to flooding, further steps need to be taken to analyse an event and its threat to human action and property. Floodways, soil conditions, topography and land use play an important role in risk assessment. An outline for a hydrometeorological event analysis have been described by Einfalt & Scheibel (2019).

## 3.3.3 First results

The event from section 3.3.1 has been further investigated. An assessment in terms of RSI showed a decrease in severity from RSI 7 (extreme rainfall) down to RSI 1 (ordinary rainfall) within 2 km distance. Observed flooded areas and emergency interventions are fitting well to the spatial distribution of heavy rain from the adjusted radar data.

It becomes obvious that a single rain gauge is not capable of representing such a spatially heterogeneous rainfall event.

Nowcasts which were calculated after the event clearly demonstrated that the ensemble approach can envelop the expected rainfall amount within the coming hour. This is not the case for a simpler deterministic nowcast.

A link between Pluvial Flood Risk Maps (Starkregengefahrenkarten) and the current rainfall amounts is currently under way in order to better assess the risk associated with the rainfall amount. Such maps are a prerequisite for flood resilience measures (e.g. Löwe & Arnbjerg-Nielsen, 2020).

## 3.3.4 Conclusions from the case study

This case study illustrates that a fine scale, high quality assessment of inundation risk through heavy rainfall has high requirements on data resolution, quality and fast availability. Limits of the current measurement devices as well as technology become more obvious, as are remaining uncertainties of measurement and forecast. These elements have to be taken into account before releasing the results from such calculations to the public. However, the potential has been demonstrated in which way such systems and approaches can improve the flood resilience of urban areas based on a well-tailored warning system.

## 4 Conclusions and outlook

The application of real-time forecasts is a useful feature for the reduction of flood risk for the population, in particular in connection with a clear open information strategy. In this context, data quality is a crucial factor and the combination of different data sources as well as the use of ensemble forecasts can significantly improve the outcome. The WaBiHa system, with different stages of extension, modernisation and publication, has proven to be beneficial for the city of Hamburg since 2013. Similar approaches are now being established at other locations.

Further benefits are currently being investigated in the ZwillE project with the development of high-resolution ensemble nowcasts and their link to pluvial flood risk maps. The resilience of the urban population can be strengthened based on this additional information, available in real time.

Other open points are

- Extension of the nowcast horizon through data fusion with satellite information
- Usefulness of non-standard sensors for a spatially denser information
- Effect of the variability of precipitation within a radar pixel of 1 km x 1 km (or 500 m x 500 m)

These are investigated in other projects and regularly exposed to discussion at the Urban Rain symposium (https://urbanrain.ethz.ch/).

## Declarations

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Competing interests

The authors have no relevant financial or non-financial interests to disclose.

Author contributions

TE (corresponding author) and AT have created the manuscript and performed data analysis as well as the formulation of conclusions; BC contributed with figures and data analyses. All authors read and approved the final manuscript.

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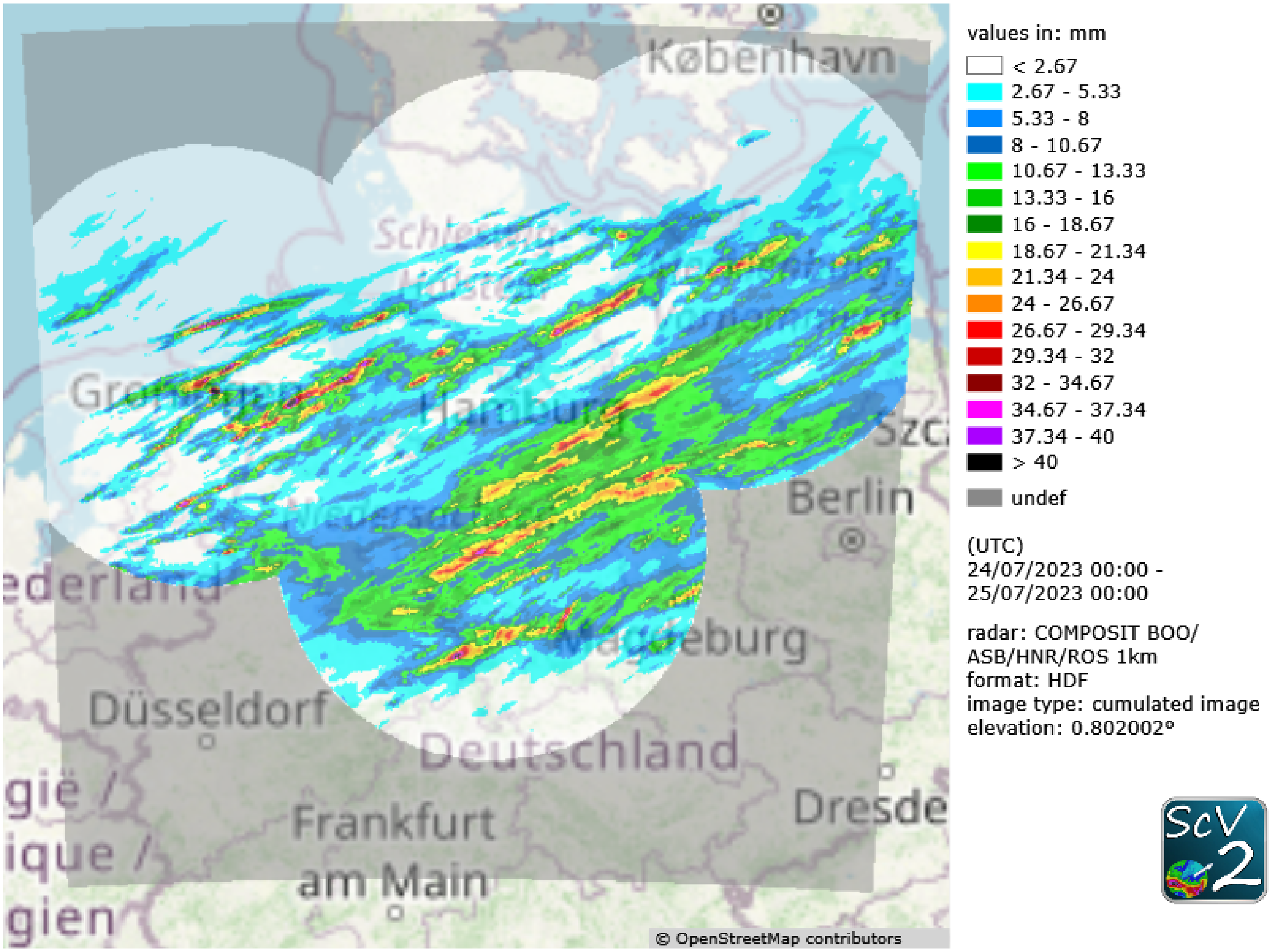
# Figures




## Figure 1

Adjusted radar composite of Northern Germany, daily rain sum of the 24th July 2023 rain event in mm.

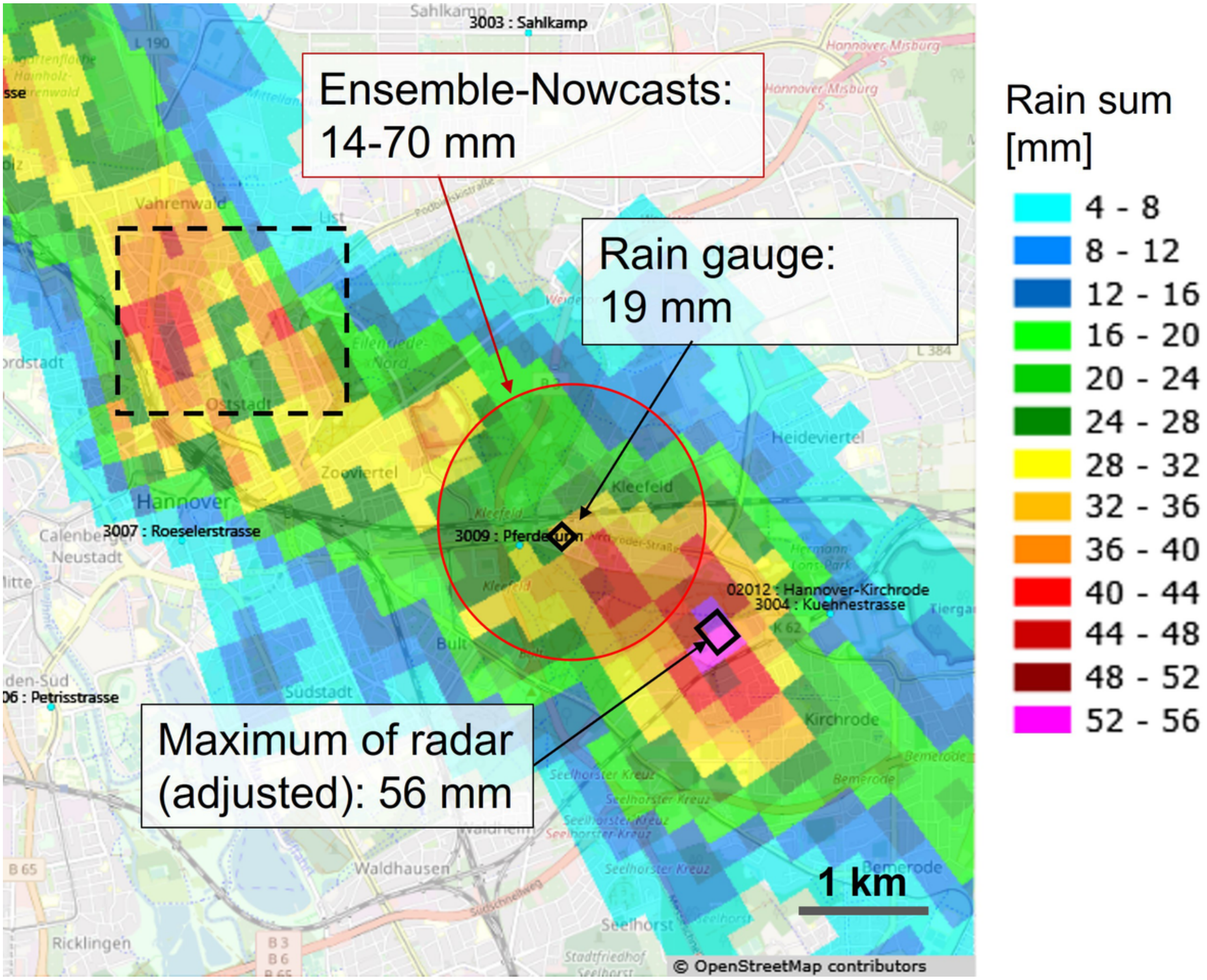



**Figure 2**

Radar-based precipitation amount for the hour 13:40 – 14:40 UTC on 16 June 2020, radar data corrected and adjusted with the available rain gauge stations by the SCOUT software. Radar data resolution: 250 m x 1°.

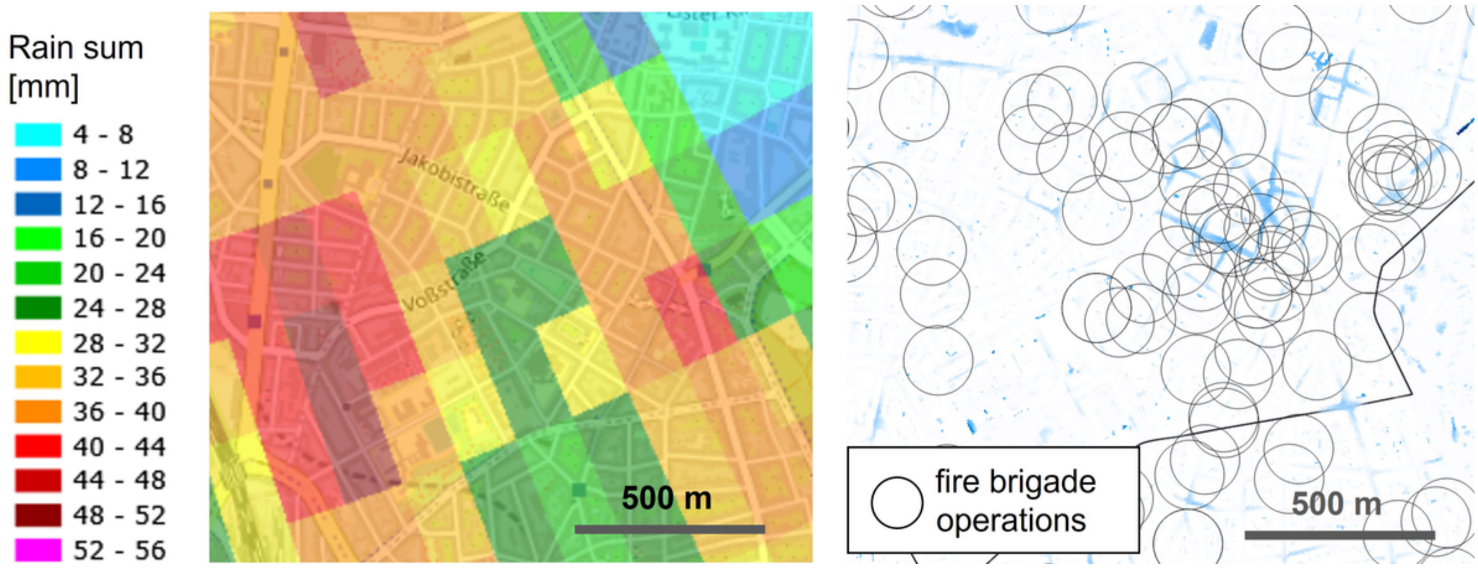



**Figure 3**

Left: Precipitation sum from radar, zoomed section from Figure 1. Right: Expected flooding for a flood with a return period of 50 years (in blue) and actual fire brigade emergency operations during the event of 16-17 June 2020 (circles – blurred locations due to data privacy limitations)