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Radar long term event time series for hydrodynamic discharge modelling

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Abstract

The relevance of non-uniform rainfall for the results of urban drainage design is often insufficiently discussed and underestimated. Using the example of the combined sewer system model of the city of Basel, the influence of non-uniform rainfall on the discharge behaviour is investigated based on a high-quality radar long-term event time series. The results are compared with a uniform rainfall from a single rain gauge observation. The radar rainfall analysis shows a clear pattern in the spatial rainfall distribution with lower rainfall heights in the heavily paved city centre compared to the neighbouring settlement areas in the transition area to natural, unsealed surfaces. The differences for the total rainfall height are about 10%; for statistical heavy rainfall heights of convective events, the differences are more pronounced and amount to 30% - 40%. The small-scale spatial rainfall distribution has also an effect on the results of the hydrodynamic pollution discharge modelling. In the overall view of the drainage system, the pollution discharge for ammonium (NH_4 kg /a) is reduced by 15% compared to the uniform rainfall from the rain gauge; the number of discharge days is reduced by 11%.

Highlights

- High-quality radar long-term event time series of 1.884 events, period 2001 – 2020
- Urban effect on areal rainfall distribution
- Comparison of radar and gauge rainfall on the results of hydrodynamic pollution discharge modelling.

Introduction

Hydrological and hydrodynamical models are used to verify and to assess the pollution of receiving waters from combined sewer overflows. The set up of the models is carried out with a high level of detail, especially with respect to the connected areas. It is also necessary to collect extensive data to determine the dry weather runoff from wastewater and extraneous water and its pollutants.

In contrast to this high degree of detail rain gauge information are still used today for dimensioning and verification of urban drainage systems (UDS). However, especially in an event-based view as required for detailed modelling of the discharge behaviour this point information is without spatial significance, which no longer matches the level of detail required today for surface information in the urban drainage models (UDM). Various studies show that the mean deviation of several rain gauge observations from their mean value on the microscale α (<< 2.5 km) is in the order of 20 % (Fiener and Auersbach, 2009; Pedersen et al., 2009; Peleg et al., 2013). In addition, the spatial variability of the extent of the rain structures (mesoscale gamma < 25 km) must be considered. Significant precipitation

gradients in the spatial distribution are to be expected, especially for the short-lasting convective precipitation processes for durations D < 60 min (Thorndahl et al. 2019).
Nevertheless, in design practice, it is assumed for simplicity's sake that the rain gauge information can be extrapolated (uniform rainfall). A critical discussion of this simplification is often omitted, as long-term, temporally parallel rainfall time series from several locally valid stations are often not available. An alternative are radar rainfall data, which are available with a temporal discretisation of 5 min and a spatial resolution of 0.5 km grid size over long periods of more than 20 years. To investigate the influence of radar rainfall data (non-uniform rainfall) on the discharge behaviour of the drainage system of the city of Basel, a long-term radar event time series of high-quality radar rainfall data is created. The results of the rainfall-runoff simulation with non-uniform radar rainfall input are compared with the results from uniform rainfall with a single rain gauge for the same event times.

Methodology

Comments on the required quality of radar data for application in UDM

Rainfall runoff processes in urban areas are highly dynamic due to the high degree of impervious areas and accelerated runoff transport in the sewers. In addition, the topological sub-catchment areas upstream of pumping stations or relief structures are small compared to a typical cartesian radar resolution of 1,0 km² and often range in size from a few hectares to very few square kilometres. Therefore, the radar data must have a high temporal resolution (dt ≤ 5 min), a fine scale spatial resolution (optimal: 0,25 km²) and as well a high degree of correctness and quantitative precision.
The limiting factor in the use of radar data is the radar signal attenuation caused by the rainfall itself (Hitschfeld and Bordan, 1954). When the radar signal passes through a rain structure, the electromagnetic energy is scattered by the raindrops and increasingly attenuated (Figure 1, left) As a result, the radar measurement perceives the intensity at distance r_2 to be lower than at distance r_1. The influence of attenuation increases exponentially with rainfall intensity > 10 mm/hr (≈ 40 dBZ).

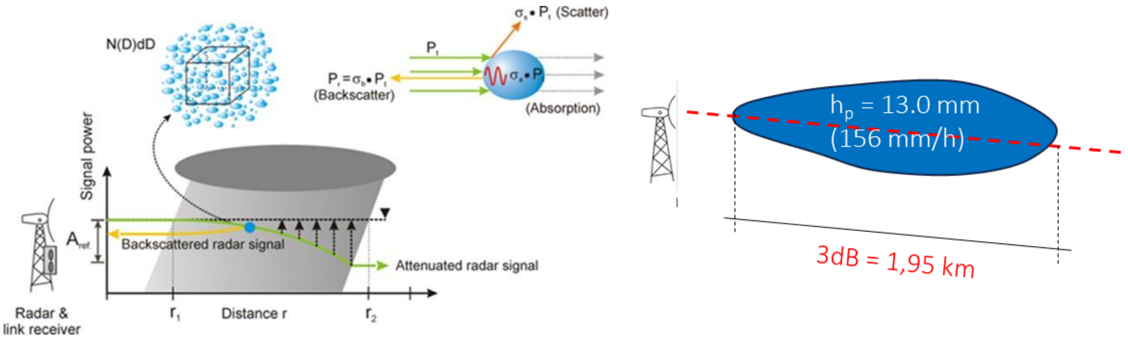

Figure 1. Schematic sketch of radar signal attenuation (left) and path integrated attenuation according to **Table** 1 (right)

To explain the relevance of radar signal attenuation in the context of UDS design according to rule EN 752, **Table 1** contains statistical rainfall as a function of the recurrence interval for the duration D = 5 min and D = 60 min.

Table 1. Statistical rainfall depending on recurrence interval (T) and duration level from KOSTRA-DWD 2020 for the region of the city of Basel and specific attenuation (2-way) at C-Band frequency

	Recurrence interval T (frequency 1 in n years)									
	Design frequency relevant for UDS									
Duration D	**1 a**	**2 a**	**3 a**	**5 a**	**10 a**	**20 a**	**30 a**	**50 a**	**100 a**	**Unit**
5 min	8,6	10,4	11,5	**13**	15,1	17,2	18,7	20,5	23,2	mm
	103,2	124,8	138	**156**	181,2	206,4	224,4	246	278,4	mm/hr
	0,95	1,18	1,33	**1,54**	1,83	2,13	2,35	2,62	3,02	dB/km
60 min	18,5	22,4	24,9	28	32,6	37,3	40,4	44,5	50,3	mm
										(mm/hr)
	0,13	0,16	0,18	0,21	0,25	0,29	0,32	0,36	0,41	dB/km

For the recurrence interval T = 5 a and the duration D = 5 min, the statistical rainfall is $h_P = 13.0$ mm (blue) and corresponds to an intensity of 156 mm/hr (black). This intensity generates a specific 2-way attenuation of k = 1.54 dB/km (red). Because a value of 3dB on a logarithmic scale implies a halving of the signal power, a rain structure with a rain intensity of 156 mm/h already generates such a high attenuation over a length of 1.95 km (Figure 1, right). The overall view clearly shows that the attenuation increases as a function of the rain intensity; the strongest attenuation is observed for the shortest duration with the highest return period and the highest intensity.

The radar signal attenuation has an extreme effect on the conversion of radar reflectivity (Z) into the target figure rainfall intensity (R), too. Figure 2 shows the exponential dependence of rainfall intensity on radar reflectivity. Depicted is the R-Z relationship according to Marshall and Palmer (MP, 1948) as well as event-specific R-Z relationships that are characteristic for stratiform and convective event types. The exponential increase in rain intensities for reflectivity > 40 dBZ is striking. The influence of the attenuation correction becomes clear in the derivation of the rain intensities for discrete values of reflectivity using the MP R-Z relationship: for example, an attenuation correction of 3 dB from 50 to 53 dBZ results in an increase in rain intensity from 49 mm/hr to 93 mm/hr (ΔR = 26 mm/hr). The use of the convective R-Z relation results in 50 dBZ = 55 mm/hr and 53 dBZ = 93 mm/hr (ΔR = 38 mm/hr).

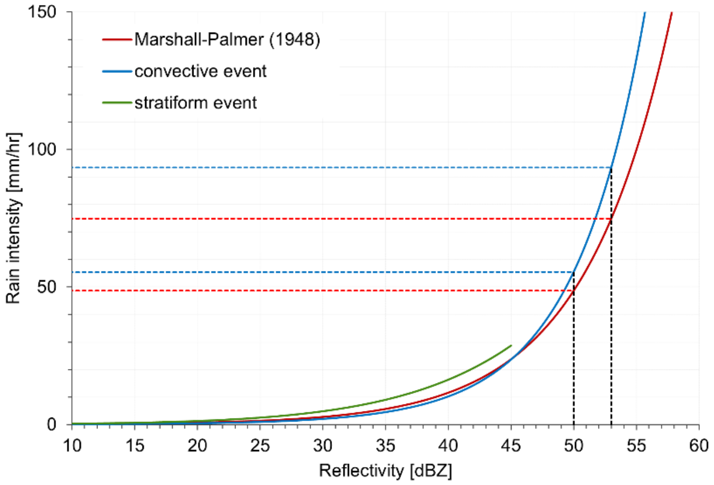

Figure 2. Influence of attenuation on the derivation of rain intensity using different R-Z relations

The previous observations on the extent of radar signal attenuation over short distances and its influence on the derivation of precipitation intensity illustrate the problem of systematic underestimation of radar-measured precipitation if it is not corrected for attenuation. The standard procedure for processing radar rainfall data is the adjustment to rain gauge observations with the aid of station-specific correction factors. With knowledge of the above discussed physical attenuation influences, however, it becomes clear that these adjustment methods are very limited in their effectiveness and the quality of the adjustment depends very much on the event character and the density of the rain gauge network. This also means that the adjustment methods in unobserved areas are always highly erroneous with increasing distance from the rain gauge (Schleiss et al. 2020).

Long term radar rainfall time series

In a first step, a list of relevant events to discharge from the UDS of the city of Basel was compiled in accordance with the VSA 2019 guideline for the period 2001- 2020. Based on radar and rain gauge data 1,884 events were identified (94/a). For these events a detailed processing of the radar data was carried out to use the data as a direct input for the UDM. The data processing is subdivided in two phases and is performed for each time step of the radar observation (dt = 5min).

Phase I comprises a correction of physical influences on the radar rainfall measurement including clutter filtering, wet radome attenuation correction, correction of the radar signal attenuation (Krämer and Verworn 2009), conversion of the radar reflectivity (Z) into rainfall intensity (R) and spatiotemporal interpolation of the radar data to 1-minute values. In Phase II a time-stepwise adjustment of the radar rainfall data to the ground measurements is applied using a mean-field bias factor.

As a result of the processing cartesian gridded high quality radar data with a spatial resolution of 500 x 500 metres are provided. Figure 3, left shows the radar location in relation to the catchment area of the city of Basel and the rain gauge.

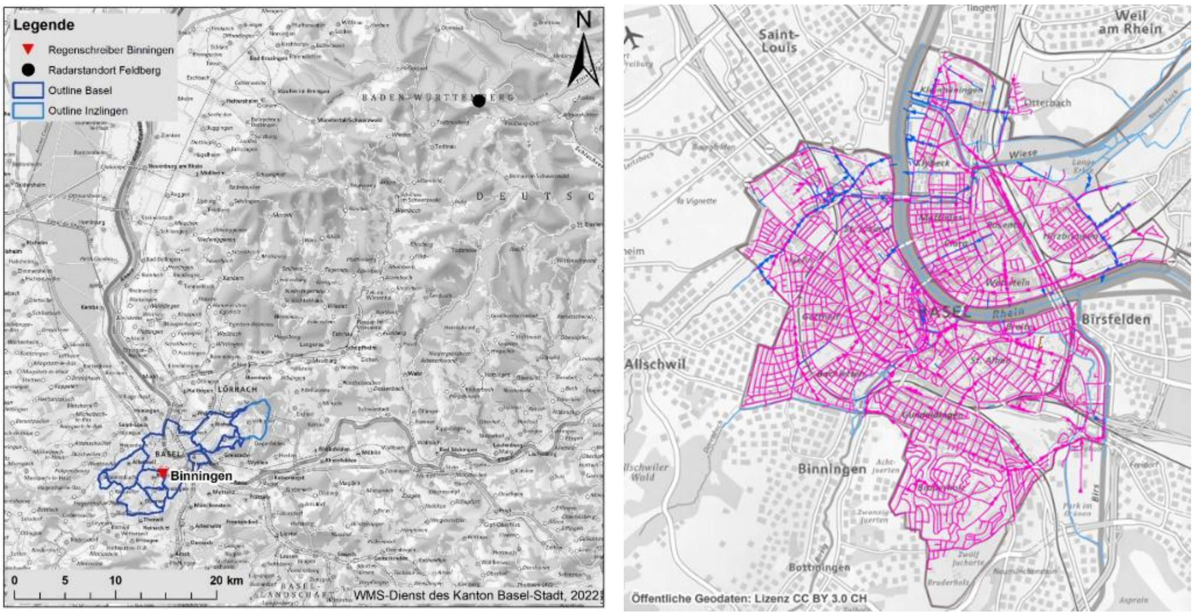

Figure 3. left: radar site (black circle) operated by the German Weather Service and rain gauge (red triangle) operated by Meteo Swiss in the city of Basel, in blue: runoff and discharge contributing catchments of the city of Basel and surrounding communities to the wastewater treatment plant of the city of Basel; right: combined sewer system of the city of Basel.

Case study

The city of Basel is predominantly drained using a combined sewer system. For hydraulic, technical and economic reasons, the drainage system of the urban area includes 72 relief structures through which the combined water can be discharged into the river Rhine in wet weather. According to the VSA-Guideline (2019) ‘Wastewater management in rainy weather, Module B’, the limit value to be complied with at all discharge points is 2% of the total annual ammonium load. Taking these requirements into account, the UDS of the city of Basel is evaluated in terms of emissions using two modelling scenarios:

a) uniform, homogenous rainfall derived from the rain gauge Binningen (Figure 3) and
b) non-uniform, inhomogeneous rainfall by the application the radar long-time event series.

Both rainfall scenarios include the same 1,884 events. The comparison is carried out for the annual mean values of the target figures average discharge load of ammonium (kg NH4-N per year) and discharge frequency (days per year).

Hydrodynamic pollution load modelling

The UDS of the city of Basel (Figure 3, right) has a length of 380 km and a connected paved area of 1,787 ha. The profile heights of the sewers vary between 150 mm and 3500 mm. The mean dry weather inflow QT,aM to the Basel WWTP is 743 l/s. In addition, the catchment areas from the neighbouring municipalities (Figure 3, left) discharging into the sewer system of the city of Basel are represented by simplified substitute systems for 17 relief points with a connected paved area of 531 ha.

Due to the complex, meshed network structure, some of which contains backwater, the rainfall runoff simulation are carried out using the HYSTEM-EXTRAN hydrodynamic rainfall runoff and pollutant load model. The pollution loads in the sewer network are calculated using the one-dimensional convection-dispersion-mass transport differential equation. The drainage model was calibrated based on rainfall-runoff measurements. In addition, to simulate the discharge loads, the target figure ammonium nitrogen (NH_4-N) must be defined in the model. For this purpose, the average long-term NH_4-N load from the quality sampling of the influent of the Basel WWTP from 2019 to 2021 was analysed. This includes 111 days with quality sampling and 57 days with dry weather. The evaluation is carried out for the TN load in dry weather, as no values were collected for NH_4-N.

Results and discussion

Rainfall results

To illustrate the inhomogeneity of rainfall as seen by radar Figure 4 shows two events of different characteristics. For the convective event of 10th May 2018, the high spatial variability of the rainfall ranging between 5 mm and 85 mm is evident. The variability becomes particularly clear in the hydrograph comparison between the observations of the rain gauge (in red), the radar centre grid element corresponding to the rain gauge coordinate (in black) and the hydrographs of the surrounding grid elements (in grey, with the best fitting element in blue). Note that the grid length is only 500 m. This contrasts with the event period from 30th April to 2nd May 2015, which is characterised by uniform, long-lasting rainfall of low and medium intensity. The quantitative range of rainfall heights of the surrounding grid elements is also very low.

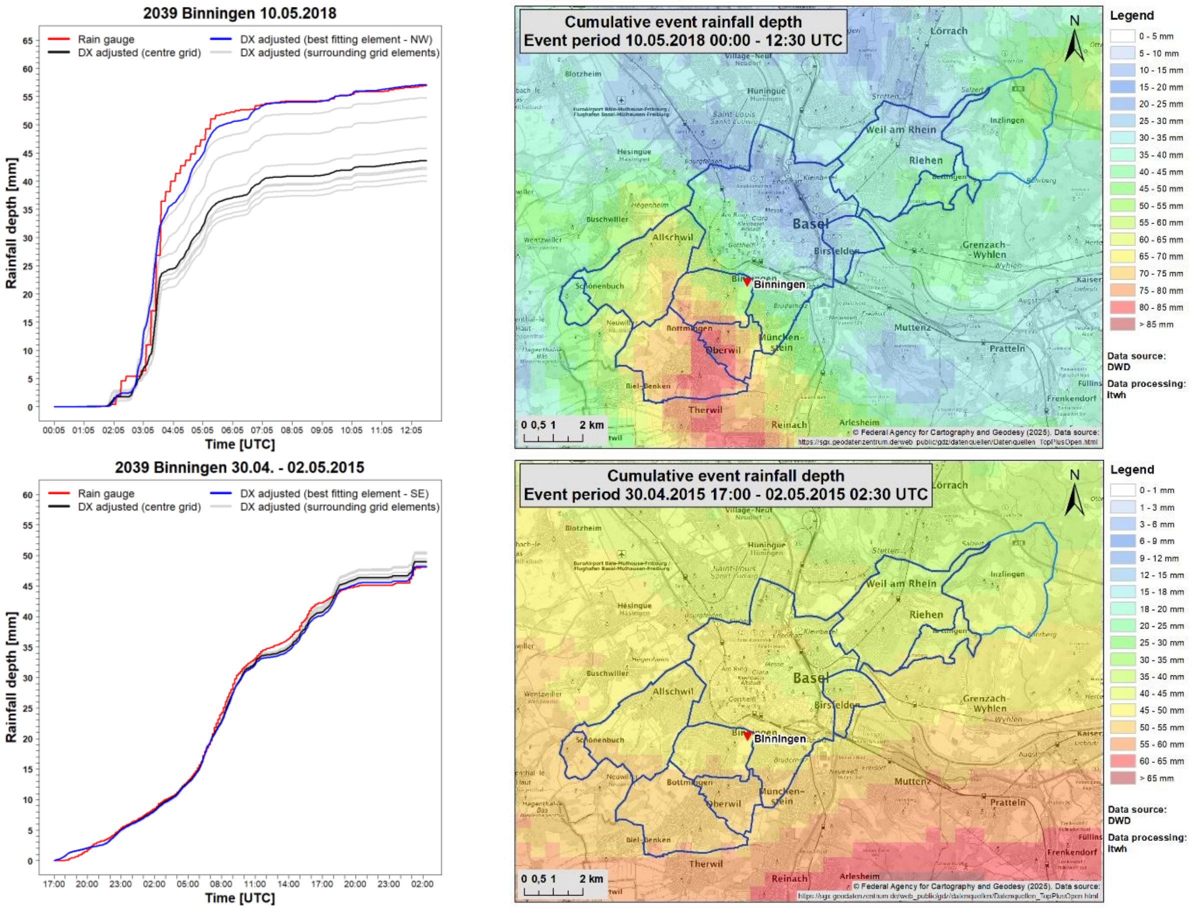

Figure 4. Radar rainfall, left: convective, 10th. May 2018, right: stratiform 30thApril - 2nd May 2015.

To gain further insights into the spatial rainfall distribution, the radar long-term time series was analysed for rainfall events with a return period T > 1a. For each individual grid element (grid length: 500m × 500m) in the urban area, a partial time series of the heavy rainfall was formed in accordance with DWA-A 531 (2012). The partial time series were formed independently of the events, i.e. spatially and temporally independent of the rainfall structures and values of the neighbouring radar grids.

Figure 5 shows the results of the radar rainfall heights for the return period T = 1 a and the duration levels D = 15 min, D = 60 min, D = 180 min and D = 720 min. The spatial distribution of the statistical radar rainfall shows low rainfall heights (light blue) in the city centre of Basel while the southern and western surrounding communities and north-east of Bettingen show higher rainfall (dark blue) for the durations D = 15 min, D = 60 min and D =180 min. For the duration D = 720 min, an increasing uniformity of the spatial rainfall structures compared to the short durations can be observed, which can be attributed to an increasing influence of stratiform events. The results for the return period T = 5 a (not depicted) show a consistent pattern with minimum values in the urban area of Basel in contrast to the surrounding area; however, the spatial differences in the envious rainfall are more pronounced.

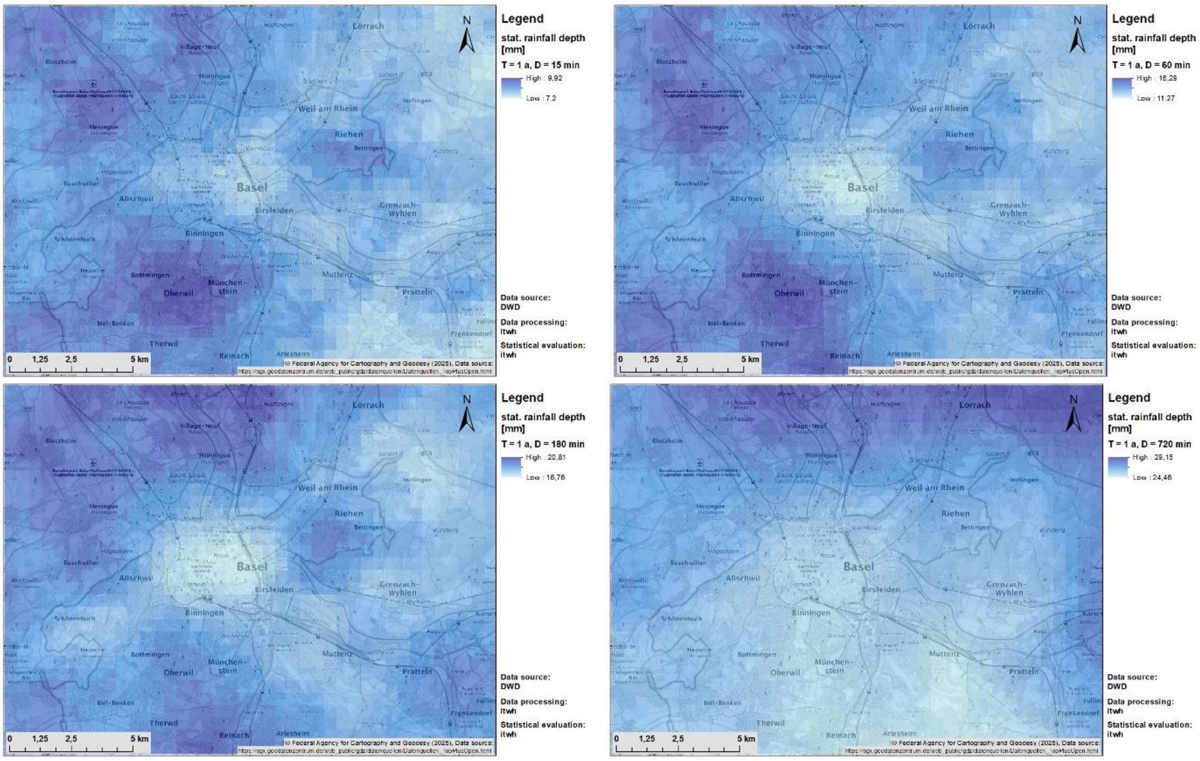

Figure 5. Areal distribution of statistical radar rainfall for the city of Basel, basis: 1,884 events form the period 2001 – 2021 for the return period T = 1a for the durations D = 15 min, D = 60min, D = 180 min and D = 720 min.

Table 2 summarises the range of minimum and maximum values of rainfall heights for the return periods T = 1 a and T = 5a. The relative differences for the return period T = 1 a indicate a steady decline of the relative differences from -30 % for duration level D =15 min to -14% for D = 720 min. In case of the higher return period T = 5 a the differences are higher and the relative values range between -43 % and -18 %. The maximum differences (-43%) are found for D = 60 and D = 180 min.

Table 2. Min and max values for statistical rainfall heights, the relative differences are related to the maximum as basis

	Duration D = 15 min			D = 60 min			D = 180 min			D = 720 min		
Return Period	Min [mm]	Max [mm]	Dif. [%]	Min [mm]	Max [mm]	Dif. [%]	Min [mm]	Max [mm]	Dif. [%]	Min [mm]	Max [mm]	Dif. [%]
T = 1 a	7	10	- 30	11	16	- 25	17	21	- 19	24	29	- 14
T = 5 a	10	15	- 33	16	28	- 43	23	40	- 43	36	44	- 18

Results of hydrodynamic modelling

To analyse the influence of the rainfall type on the results of the pollution load modelling for the target variables discharge load and discharge frequency, all 1884 events of the rain gauge and radar long-term event time series were simulated.

The modelling results of the pollutant load show that the ammonium discharges at all combined sewer structures are lower in case of non-uniform radar rainfall than with the uniform rainfall from the single rain gauge (**Figure 6**). The average difference for the area under consideration is 15.2% (2,036 kg NH_4/a). For the average number of calendar days with discharges, the results for the radar rainfall data are approx. 11% lower than for the uniform gauge rainfall.

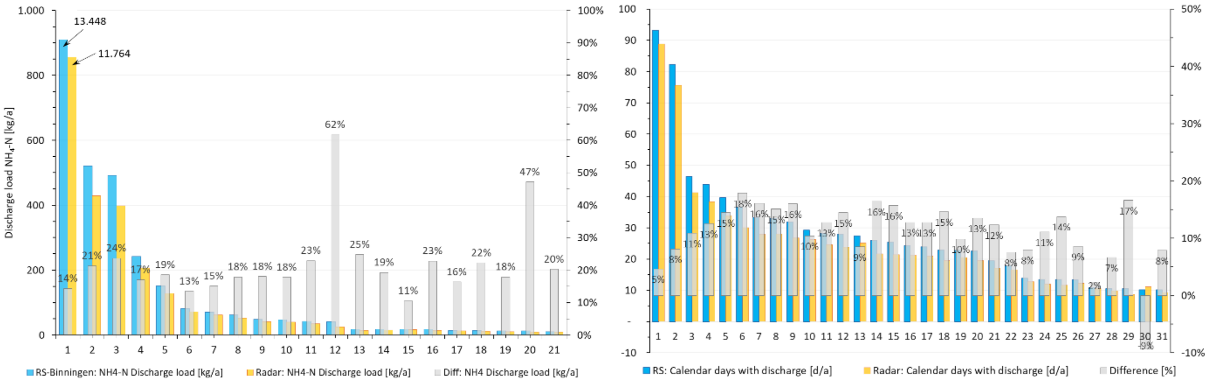

Figure 6. Simulated discharge loads NH_4-N using rain gauge and radar rainfall as input to the hydrodynamic model (left) and days with discharge (right) for different relief sites into the river Rhine

Further analyses have shown that the deviations in discharge volumes tend to increase the smaller the catchment areas of the combined sewer system become. The effects of equalisation due to longer flow times in the catchment area tend to decrease with the size of the area. In addition, the differences increase the further away the discharge facilities are from the city centre. This also becomes clear from a spatial analysis of the statistical radar rainfall (Figure 5). The rainfall in the city centre is noticeably lower than in the surrounding area.

Conclusions and future work

The analysis of radar rainfall data over long-term periods (here: 1,884 events of the period 2001 – 2020) involves a clear change of perspective on rainfall processes in urban areas: It becomes apparent that the convective events relevant to the UDS design are very dynamic and small-scale and often cannot be adequately mapped by rain gauge measurements.

Obviously, urban areas influence the climate on the micro- and mesoscale due to their surface properties, which have changed compared to the natural initial state, so that the rainfall process itself is influenced by the settlement areas. In this case of the city of Basel, the rainfall relevant for the assessment of UDS is lower in the city centre than in the neighbouring residential areas in the surrounding countryside. The characteristics are dependent on the return period T and the duration D. While the differences in rainfall between minimum and maximum increase with increasing return period T, a levelling out of the spatial differences can be observed as the duration D increases. For the short durations (D ≤ 180 min), which are dominated by convective precipitation processes, strongly pronounced gradients can be observed (30 % - 40 % within 2 km). For stratiform events, which are characteristic of long durations (D = 720 min), the differences and gradients are less pronounced (14 % - 18 % within 10 km). These findings are confirmed by studies on other cities based on analogue data and approach (Krämer et al. 2023, Krämer et al. 2024). One possible explanation of this phenomenon is the increased air temperature and changed humidity in the urban area compared to the surrounding area and the resulting amplification in rainfall in the downwind region of the respective event (Kingfield et al. 2018, Liu and Niyogy, 2019).

With knowledge of the above-mentioned context, the fundamental question of the validity and spatial relevance of long-term rain gauge observations, which have been used as a basis for the design and verification of the UDS, arises.

The areal differences in rainfall are also reflected in the results of the UDM concerning the discharge behaviour. The results demonstrate that the use of radar rainfall data as a rainfall input for urban drainage models enables a more realistic representation of the discharge behaviour of drainage systems, which leads to a significant and systematic reduction of the discharged pollution load at the magnitude of 15% (in average) compared to the uniform rainfall assumption by the rain gauge; the number of days with discharge is reduced on average in the order of 11%. For engineers and municipal decision-makers, the question of how to deal with the potential hydraulic-hydrological reserves in the drainage systems will therefore be an important issue in the future. This applies in particular to the climate change, where an increase in statistical design rainfall in the order of 5%-10% is forecast for the short-term future up to the year 2050 and an increase of 15%-25% for the long-term future up to the year 2100 (Ebers et al. 2024) which may require structural adaptions of the UDS.

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