

Ready for the flood? Assessing the applicability of pluvial flood mapping based on the worst urban flood in Sweden

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HIGHLIGHTS

- The space–time evolution of an extreme rainfall and urban flooding is reconstructed.
- The reconstruction is successfully validated using municipal and citizen observations.
- Conventional pluvial flood mapping is useful also for far more extreme rainfall events.

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ABSTRACT

Pluvial flood mapping is a common way to identify locations at risk of being flooded in connection with an extreme short-duration rainfall. As rainfall extremes are expected to intensify in a warmer climate, more and more cities and municipalities are performing pluvial flood mapping, in Sweden and elsewhere. Often a rainfall with a return period of 100–200 years is used in the mapping, and the main question underlying this study is to which extent such conventional flood mapping can provide useful indications also of the consequences of a far more severe rainfall. To investigate this question we use the worst urban flooding in Sweden to date as a case study. In Aug 2021, a record-breaking rainfall with a return period > 1000 years hit Gävle city on the east coast, resulting in widespread flooding and massive damages. We reconstruct the space–time evolution of this event by combining different rainfall observations and using them as input to a high-resolution hydrodynamic model. The reconstruction was overall successfully validated using municipal and citizen observations. Different representations of the rainfall had limited impact on the average flood response, but distinct local differences were found. Comparing the reconstructed flooding with the results from a conventional 100-year flood mapping revealed that overall the worst flooded locations during the actual event were also pointed out in the conventional mapping, albeit with some differences. We recommend to always include assessments of fluxes and water velocities as well as sensitivity tests of very extreme rainfalls in pluvial flood mapping.

Practical implications

A main consequence of the global warming is the intensification of rainfall extremes. Short-duration extremes, with very high intensities for a couple of hours or so, may lead to so-called pluvial flooding, that is, accumulation of rainfall water in low-lying areas when the infiltration capacity of the ground (and the sewer system) is insufficient. The risk of pluvial flooding is particularly high in cities with a large fraction of

impervious surface (roads, parking lots, etc.).

Cities thus need to adapt to the increased pluvial flood hazard, for example by reducing the impervious fraction and/or by constructing some nature-based solutions (ponds, rain gardens, etc.). One key component of this adaptation is pluvial flood mapping, a climate service where the flood response to a very heavy rainfall is estimated by numerical (hydrodynamic) modelling, in order to identify locations and activities at risk, and thereby guide the implementation of adaptation

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measures. The main output of pluvial flood mapping is a map of the city showing the maximum inundation depths following an extreme rainfall, for example a statistical 100-year rainfall (that is, a rainfall of a magnitude that is reached only once in 100 years, as an average over a very long time period) upscaled to represent future climate. Many cities in Sweden and elsewhere have performed pluvial flood mapping in recent years, as a response to growing concerns over the future flood hazard.

Some notable limitations associated with pluvial flood mapping are that (i) the rainfall input is generally represented in a very simplified form (so-called design storms), (ii) the accuracy of the modelling result is seldom possible to evaluate and (iii) it remains unknown what will happen if an even more extreme rainfall happens. In this study we have tackled these limitations by an in-depth investigation of the most severe urban pluvial flood in Sweden so far, which took place in Gävle city in Aug 2021. The rainfall, with an estimated return period of > 1000 years, was reconstructed using measurements from gauges and weather radar and used as input to a hydrodynamic model. The resulting pluvial flood map was compared with water level observations during the event as well as with post-event municipal flood reports. We also compared the pluvial flood map from the event with the map from a conventional 100-year modelling, in order to assess to which extent the conventional map represents the impacts also of a far more severe rainfall.

The results related to the above three limitations, which effectively constitute the main practical implications of the study, may be summarized as follows.

- Overall, the flood response to a simplified rainfall input (spatially homogeneous, idealized hyetograph) turned out to be relatively similar to the flood response to a detailed rainfall input with realistic variation in space and time. However, potentially significant local differences were found which indicate limitations in the simplified approach.
- The evaluation of the simulated flooding in 2021 against observations and reports was generally positive with water levels well reproduced and reported damages well in line with the flood map. This supports the use of urban hydrodynamic modelling also for representing the flood impacts of very extreme rainfalls.
- Overall, the worst affected locations during the 2021 flood were also pointed out as risk areas in the conventional 100-year pluvial flood map, indicating that conventional mapping does represent spatial patterns of exposure also of far more severe rainfalls. However, it is highly recommended to (i) investigate not only maximum water depths but also fluxes and velocities, which provide important complementary information, and (ii) whenever possible perform at least some sensitivity tests to assess the impacts of a very extreme rainfall.

Introduction

Climate change generates new and reinforces existing risks in society (IPCC, 2022), and climate-related impacts are increasing, particularly in urban areas around the world (Dodman et al., 2022). The global costs of extreme weather that are attributable to climate change are estimated to US\$ 143 billion annually, of which flood impacts account for a significant part (Newman and Noy, 2023). Currently about 23% of the world population are directly exposed to flooding (Rentschler et al. 2022), which is anticipated to increase over time. Urban pluvial flooding here represents a significant hazard, already affecting millions of people globally, but whose scope and consequences are difficult to predict (Allegrì et al. 2024). In northern Europe, the pluvial flood event in Copenhagen, Denmark, 2011 was an eye-opener, showcasing damage to infrastructure, private and public buildings and business, generating insurance claims of more than 800 million EUR. Similarly, many Swedish cities have experienced pluvial flood events during the last decade (Knös et al., 2022). The unpredictability of such past events and

anticipated changes stress the need for reliable decision-support for pluvial flood hazard to enable actions to mitigate and manage flood impacts (Sörensen et al. 2024).

A direct and largely undisputed consequence of global warming is that short-duration rainfall extremes will become intensified, primarily as a warmer atmosphere can hold more moisture but also as higher temperatures generally favour generation of convective rainfall. On daily and multi-daily time scales, a positive trend since the 1950s have been found in most parts of the world, with northern Europe being pointed out as a hot-spot (IPCC, 2021). On sub-daily scales, historical trends are generally difficult to confirm, largely because of too short records, and both increases and decreases have been found depending on region and historical period (e.g. Willems et al., 2012). The future change in short-duration extremes is generally expressed in terms of a climate factor, representing the expected relative future change of the depth (or intensity) of a rainfall with a certain return period and duration (e.g. Willems et al., 2012); a climate factor 1.3 corresponds to a 30% increase. Current climate factors for the Nordic countries, estimated from Regional Climate Model (RCM) projection ensembles, are in the range 1.2–1.4 for a time horizon until the end of the century, and recent analyses of very high-resolution convective-permitting RCMs indicate somewhat higher climate factors in the region (Dyrddal et al., 2023).

This outlook, together with the experiences from recent events, makes increased rainfall extremes and resulting flooding the most worrying consequence of the global warming among stakeholders in Sweden (Glaas et al. 2022; Hjerpe et al. 2025) as well as in other countries. To respond to this threat, many cities and municipalities in Sweden perform urban pluvial flood mapping, i.e. scenario simulations aimed to estimate the resulting pluvial flooding in cities from a rainfall with a long return period (typically 100 years in Sweden). Different types of pluvial flood mapping methods exist, ranging from rapid methods such as simple static topographical analysis or fill and spill models (McDonnell et al., 2021), to fully distributed methods such as surface 2D hydrodynamic or coupled 1D/2D surface-sewer modelling (e.g. Schmitt and Scheid, 2020; MSB, 2023). Coupled surface-sewer models, when accurately representing the sewer networks, can capture the flow dynamics in a more detailed way by also representing flows not strictly coupled to topography. Neglecting the sewer network and its drainage capacity can lead to overestimation of flood extent (Martins et al., 2018; Palla et al., 2018). On the other hand, flood extent may become underestimated since surcharging manholes, not represented in the model, can significantly contribute to surface flow and flooding (Montalvo et al., 2024). However, when comprehensive data for calibration and validation of a sewer system is unavailable, its effect can be approximated in hydrodynamic 2D models by deduction of precipitation according to the capacity of the sewage system. Although the full dynamics are not captured in this way, the probability for overestimation is still much reduced (Oberauer and Lehmann, 2024).

The model results are typically expressed as maps of maximum inundation depth in all locations within the model domain. Together with maps of sensitive buildings and infrastructure, vulnerability and adaptation analysis may be performed. Besides local applications, there are a few examples of generalized pluvial flood mapping performed for a number of cities in Europe (Guerreiro et al., 2017; Essenfelder et al., 2022).

Despite their widespread use and obvious value, assessments of the actual realism and precision of urban pluvial flood maps by reconstructions of historical events are rare. Courty et al. (2017) used the Itzī model to reconstruct an urban pluvial flood in Hull, UK, in 2007, and the results were compared with observed flood extents. Zhang et al. (2021) evaluated the results from the DHMUrban hydrodynamic model for a heavy rainfall over Shenzhen City, China, in 2018, using reported inundation depths at two locations. As in Courty et al. (2017), actual rainfall observations from one gauge were used in the simulation. Lu et al. (2022) reconstructed a fluvial flood in Shanghai, China, caused by typhoon Fitow in 2013. Different precipitation data as well as model

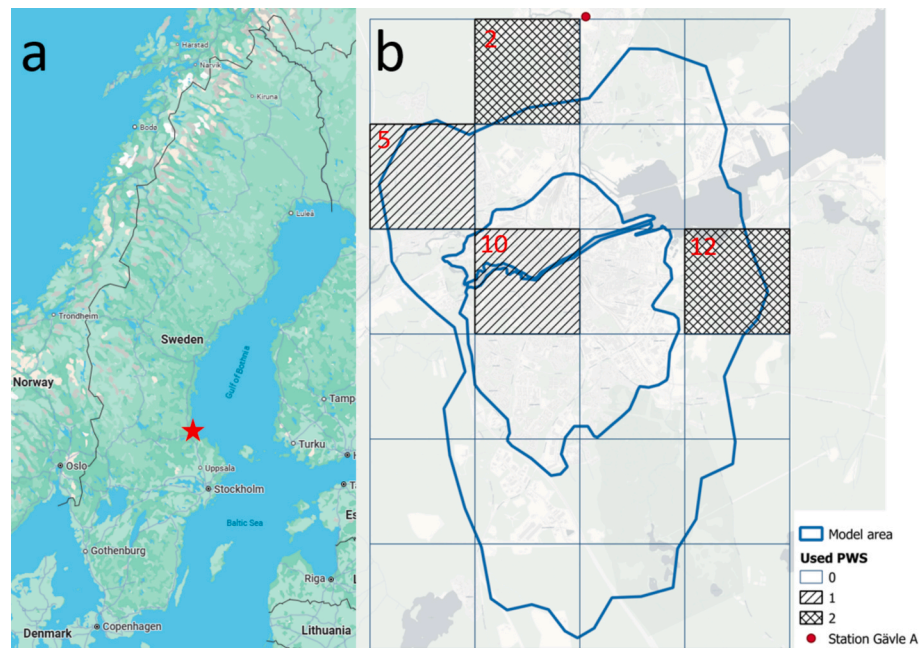


Fig. 1. The location of Gävle marked by a red star (a). The hydrodynamic model boundaries, station Gävle A and the HIPRAD grid (b). Grid cells with PWS inside them have patterns indicating the number contained PWS (0–2) and the grid cell numbers (2, 5, 10, 12) are used for identification in the results. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

evaluation scales were used when evaluating the results in 34 locations. Iliadis et al. (2023) evaluated the results of the CityCAT model (Glenis et al., 2018) for an event in London, UK, in 2021. Fourteen observation points were used and the rainfall input was in the form of an idealized hyetograph. In all the above studies, an overall reasonable agreement with reported water depths was found despite a range of uncertainties related to e.g. the description of the rainfall input, the treatment of sewers and the credibility of the flood observations. Besides these studies including an explicit pluvial component, several reconstructions of historical urban floods of primarily fluvial nature have been reported (e.g. Mignot et al., 2006; Neal et al., 2009; Segura-Beltrán et al., 2016).

A key component of historical reconstruction of pluvial floods is an accurate representation or reconstruction of the rainfall. Generally, the spatial and, often considered more importantly, temporal resolution of the rainfall input has a distinct impact on the results of hydrodynamic models (e.g. Ochoa-Rodriguez et al., 2015; Sieg et al., 2023). Xing et al. (2021), in a global sensitivity analysis of urban pluvial flood modelling, concluded that the rainfall input is of primary importance for the quality of the output. Lu et al. (2022), in their Shanghai study, found that an improved rainfall product based on radar-gauge fusion overall provided a better reproduction of observed flooding than using radar and gauge data separately. In a follow-up study of Courty et al. (2017), Courty et al. (2018) however found no clear improvement in the reproduction of the Hull flood when using spatially variable rainfall based on radar-gauge merging instead of spatially uniform rainfall based on a single gauge. The inconclusive result was suspected due to a low spatial variability of the rainfall field.

An aspect of urban pluvial flood mapping that we have not seen covered in the literature is to which degree the results of a standardized mapping can be used to assess the impacts of a much more severe storm. Say that a return period of 100 years was used in the mapping, what if a much more severe storm happens? How relevant is the 100-year map for describing the character of that flooding? Can the 100-year map be somehow upscaled to estimate the consequences also of a worst-case scenario, at least in a qualitative sense? This prospect is conceivably highly dependent on the local urban environment, e.g. the presence of physical flow barriers that lead to nonlinear impacts when exceeded. Even so, in light of the increase in extreme rainfalls, and thus also

record-breaking storms (and pluvial floods), we believe investigations in this direction are needed to improve our preparedness for the consequences of potentially catastrophic floods (e.g. Sieg et al., 2023).

In Aug 2021, the most damaging urban pluvial flooding to date in Sweden occurred in the city of Gävle, central Sweden, following a record-breaking rainfall event with an estimated return period of up to a few thousand years. The objective of this study is to use this unique case to assess the applicability of pluvial flood mapping, both by reconstructions of the flooding event and by comparison with generalized mapping. The following main research questions are addresses, in priority order.

1. To what extent can the information in generalized pluvial flood mapping be used to assess the characteristics also of a far more severe urban pluvial flood?
2. How well can a truly extreme urban pluvial flood be reproduced by hydrodynamic modelling forced with a full space-time reconstruction of the extreme rainfall?
3. What are the effects on the pluvial flood mapping of using a simplified representation of the extreme rainfall in time (design-type hyetograph) as well as in space (domain average)?

The Gävle event

On 17 Aug, 2021, a warm air mass associated with a low pressure system moved in over southern Sweden, became stationary and generated large amounts of rain in parts of central Sweden. In the evening and during the following night, a new partial low pressure system developed and intensified over the Bothnian Sea. This resulted in a dramatic intensification of the rainfall in the eastern parts of central Sweden, mainly in provinces Gästrikland and eastern Dalarna, especially around and just after midnight between 17 and 18 Aug. Between 06:00 17 Aug and 06:00 18 Aug (local time), 161.6 mm was recorded in the meteorological station just north of Gävle city (Fig. 2.1). Out of this amount, 121 mm fell in the 3-hour period from 21:45 to 00:45, and for durations between 2 and 12 h this event generated the largest amounts ever recorded in the national Swedish network of automatic gauges (around 130 stations in operation since the mid-1990s) (SMHI, 2025). Based on

regional Depth-Duration-Frequency (DDF) statistics (Olsson et al., 2019), the return period is estimated to up to several thousand years (although with a huge uncertainty range). Observations from private weather stations in central Gävle indicate even higher amounts there, with up to 200 mm in 24 h.

Heavy rainfall was forecasted before the event and a class-1 warning was issued already on 15 Aug, of up to 100 mm of rain from p.m. 17 Aug and 24 h ahead, although over a rather large region covering counties Gävleborg (including Gävle city), Dalarna, Uppsala and Västmanland. In the morning of 17 Aug, the warning was upgraded to class 2 in counties Gävleborg and Dalarna. Class-2 warnings of heavy rainfall, which is the highest warning category for rainfall implying risk of serious consequences for society and public danger, are very rare and are issued on average less than once per year in Sweden (Yang et al., 2025). Even if the total rainfall amounts were somewhat underestimated, the early warnings were considered overall successful given the extreme nature of the event (Glaas et al., 2024).

In light of the warnings, a regional preparedness conference was held on 17 Aug p.m. followed by e.g. cleaning of storm drains and information about the warnings being distributed to property owners. Despite the preparations, the pluvial flooding in Gävle city became very severe with large consequences. These were not only caused by the extreme rainfall amounts around midnight, but also the preceding rainfall of around 40 mm during daytime on 17 Aug which effectively led to saturated conditions in many pervious areas. While personal injuries and social impacts were minor, conceivably because the worst flooding happened at night and very early morning, nearly 7 000 insurance claims were made afterwards at a total damage cost of around 160 MEUR (Finansinspektionen, 2023). Furthermore, bridges collapsed, roads were undermined and underpasses were inundated with potential consequence for rescue services and urgent transportation. For more information about the event and societal impacts, with focus on the vulnerability of municipal welfare services, see Glaas et al. (2024).

Material

Rainfall observations and statistics

Rainfall observations from the event have been obtained from three different sources. The most reliable source is believed to be the automatic meteorological station in the national SMHI network, located some 4 km north of central Gävle (Fig. 1). The gauge is of weighing type (Geonor) and 15-min accumulations during the event are available.

Furthermore, gridded 15-min observations from the HIPRAD product (HIgh-resolution Precipitation from gauge-adjusted weather RADar; Berg et al., 2016) are used in the analysis. In HIPRAD, 15-min accumulations from weather radar composites in a national 2×2 km² grid are scaled against a sliding 30-day period of accumulated daily values from the PTHBV product (Precipitation and Temperature for the HBV model; Johansson and Chen 2003). In PTHBV, daily precipitation observations are interpolated by optimal interpolation, taking topography and winds into account, and transformed into a national grid. By this scaling, radar artefacts are greatly reduced and long-term accumulations preserved while maintaining a high spatio-temporal resolution.

The final source of rainfall observations are 5-min registrations from in total 13 personal weather stations (PWS, of type Netatmo). The potential of non-conventional and crowdsourced data for flood-related analysis and management has been stressed and demonstrated in several studies (e.g. Caumont et al. 2021; Chen et al. 2022; Nyberg et al. 2022), but this is to our knowledge the first time PWS observations are used in historical flood reconstruction. Out of the 13 available PWS, seven were discarded either because they exhibited a doubtful performance during the event or because they were located very close to a HIPRAD grid cell border. Accumulated rainfall during the event in all PWS is shown in Fig. S1 in the Supplement.

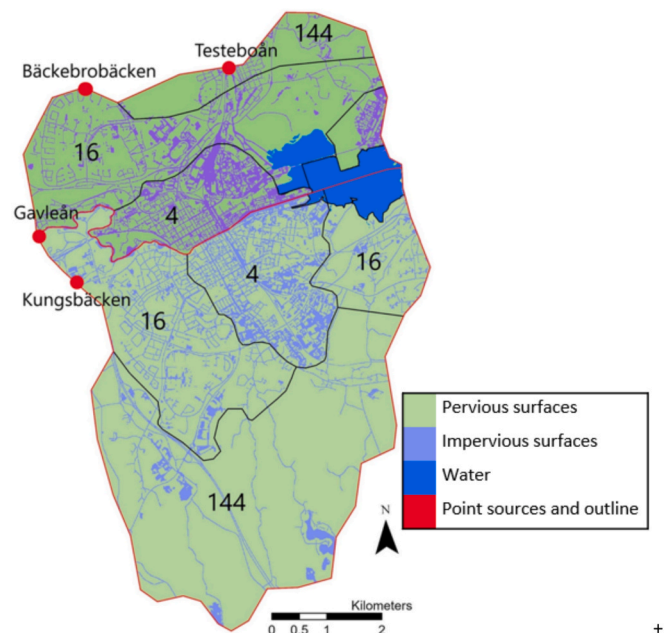


Fig. 2. Model area of in total 54 km² parted in pervious surfaces in green and impervious surfaces in purple. Resolution of different parts written in m² and point sources marked with red dots. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Hydrodynamic modelling

MIKE 21 Flow Model FM (DHI, 2020) has been used to set up a 2D hydrodynamic model over Gävle to reconstruct the flooding event. The fully distributed surface model was selected instead of a hydrostatic model to enable the representation of velocities and flow directions. This choice aligns with Swedish standards, as one of the objectives of this study was to compare the Gävle event with the routinely performed flood mapping (MSB, 2023). Since comprehensive data on the sewer network was not available for the whole city of Gävle simulated in the study, the representation of the network was instead made by deducting precipitation corresponding to the intensity of a 5-year block rain. The assumed drainage capacity of the sewer system was based on local assessment and Swedish recommendations for stormwater systems (Svenskt Vatten, 2016).

Model boundaries were chosen so small catchments around Gävle were included and the upstream contributions from the larger catchments that were cut off were included as point sources at the borders of the model area (Fig. 2). The watercourses crossing the model border that were added as point sources were Gävleån, Testeboån, Bäckebrobacken and Kungsbäcken, where modelled discharge volumes from 17–18 Aug from SMHI's hydrological model S-HYPE (Swedish national set-up of the model HYdrological Predictions for the Environment; Strömqvist et al., 2012) were used. In total the model had an area of 54 km² and was parted in two through Gävleån river in a northern part of 18 km² and a southern part of 36 km², to reduce computational time. Since there is no water exchange between the two parts this does not affect the results.

MIKE 21 Flow Model FM enables the use of a flexible mesh and different resolution was used for different parts of the model ranging from 4 m² to 144 m² with 4 m² for the urban central parts, 16 m² for the urban but less central parts and 144 m² for surrounding areas that contributed to the general flow but where flooding was not evaluated.

The model was prepared from 1 × 1 m DEM based on the Swedish Mapping, Cadastral and Land Registration Authority Lantmäteriet's GSD-elevation data (markhöjdmödel, April 2021) and a property map (Lantmäteriet, 2025). To better represent flow paths, the DEM was

Table 1
Model parameters.

Parameter	Pervious surfaces	Impervious surfaces
Infiltration rate	36 mm/h	0.001 mm/h
Leakage rate	0.40 mm/h	0.01 mm/h
Porosity	0.40	0.01
Layer depth	0.30 m	0.01 m
Manning number	2 m ^{1/3} /s	50 m ^{1/3} /s

modified by removing bridges, viaducts and surface over culverts. Buildings were not included in the original elevation dataset, instead their presence was approximated by elevating known building locations from the property map by 2 m to more correctly describe the flow paths.

Surface material was simplified to be described as pervious or impervious surfaces with different infiltration rate, leakage rate, porosity and Manning number. The parameter values were chosen to fit with the general guidelines with the aim to represent a standard practice in Sweden. The values for infiltration and porosity lie in between the recommended values by the Swedish Civil Contingencies Agency (MSB, 2023) for sand and till, which are the most common soil types in the model area, and the Manning number values are in line with the recommendations for impervious surfaces and forested areas and farmland (Table 1).

Conventional pluvial flood mapping

The conventional pluvial flood mapping was made using a 6-hour

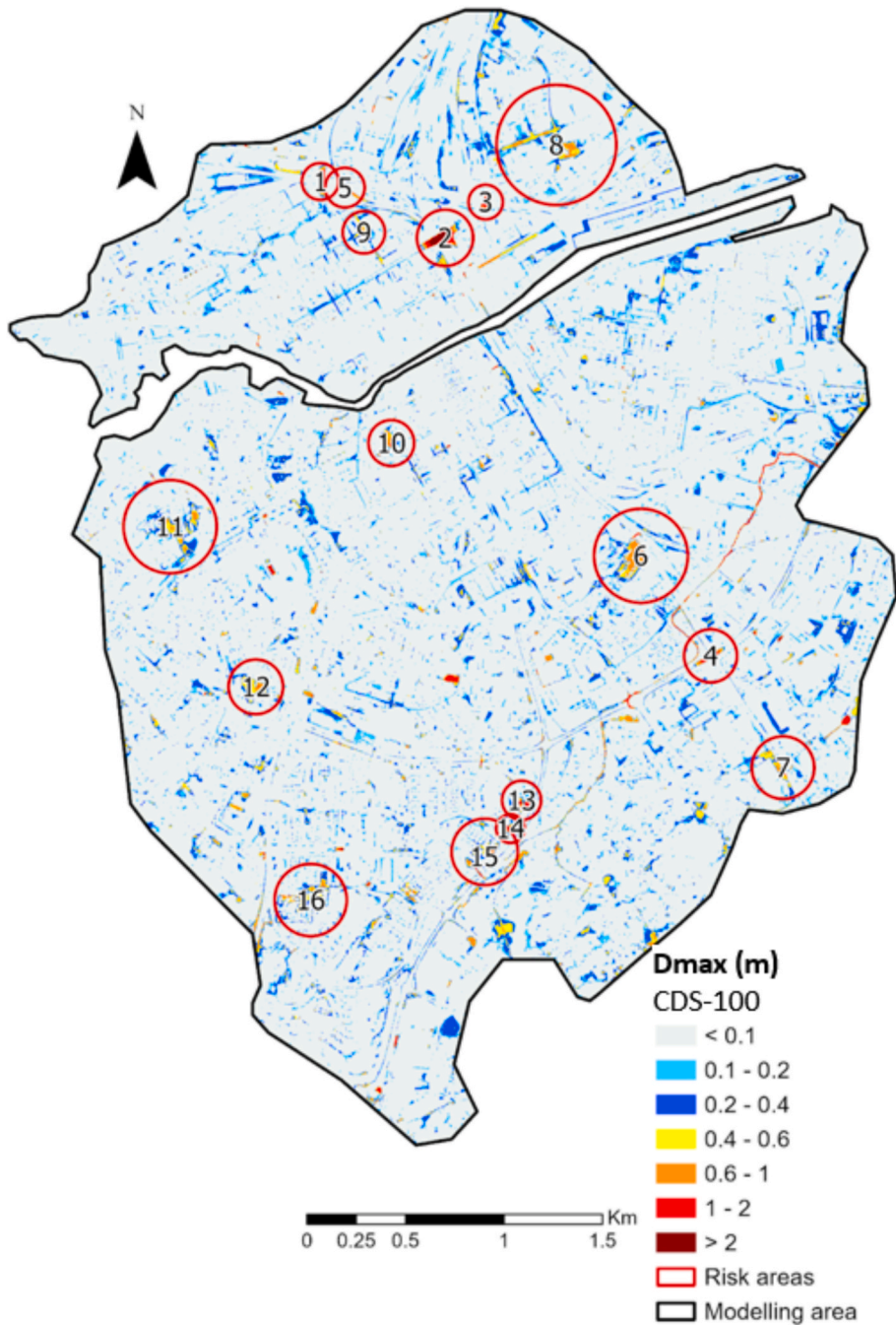


Fig. 3. Pluvial flood map corresponding to simulation CDS-100. The 16 identified risk areas are marked with red circles, approximately covering the extent of the corresponding flooding. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Chicago Design Storm (CDS) (Keifer and Chu, 1957) with a 100 year return period as input to the MIKE 21 model described in section 3.2. The corresponding rainfall depth is 60.3 mm, based on national Depth-Duration-Frequency (DDF) statistics (Olsson et al., 2017). This depth was multiplied by a climate factor of 1.4, in order to represent DDF statistics in the period 2071-2100 under an assumption of Representative Concentration Pathway (RCP) 8.5 (Olsson et al., 2017). The CDS was defined with a 5 min time step and every 5-min depth was applied uniformly on the model domain. The entire procedure follows the national recommendations for pluvial flood mapping (MSB, 2023), which is common practice in a Swedish context and also in line with international recommendations although practices vary (e.g. Welten et al., 2024).

The resulting pluvial flood map is shown in Fig. 3 and in the following we will refer to this simulation as CDS-100. Locations with an estimated maximum water depth during the event (D_{max}) exceeding 1 m are found in all parts of the domain, the most notable ones in the northern sub-domain. The 16 main locations at risk as identified by the conventional mapping are shown by circles in Fig. 3. The 16 locations were selected based on the conventional mapping, prioritizing areas with extensive flooding and water depths exceeding 0.5 m. Non-sensitive areas, such as green areas or watercourses with minimal impact on surrounding areas, were excluded. A more detailed description of the 16 locations is provided in section 5.2.2 below, where the results are compared with a reconstruction of the 2021 flood.

Methods

Forcing data generation

A reconstruction of the rainfall event was made by first extracting the entire space-time sequence (15 min and $2 \times 2 \text{ km}^2$) over the domain from the HIPRAD product (section 3.1). In an additional scaling step, the HIPRAD sequence was adjusted (scaled) to match the observations in station Gävle A. This scaling was done by a mean field bias adjustment (MFB), with a correction factor derived from a 1-h moving average ratio between the station measured rain sequence and the HIPRAD estimated rain sequence from the same location; a weighted mean from the four radar cells around the station. This correction factor, with a value for every hour, was then multiplied with the HIPRAD data from the whole model area to get the adjusted data, hereafter denoted HIPRAD^a. This method assumes that there is a uniform systematic multiplicative error in the radar data, introduced in the radar rainfall estimates from the reflectivity, and thus that this error can be decreased by multiplying all the radar data with a factor correcting this bias (McKee and Binns 2016; Ochoa-Rodriguez et al. 2019). The final sequence used in the model simulations (section 4.2) has a duration of 6 h.

To complement the full space-time reconstruction, and assess the influence of spatial variability in hydrodynamic simulation of pluvial floods, two hyetographs were generated. The first represents the mean value over the domain in each 15-min time step during the 6-h duration, resulting in a total depth of 155 mm. The second hyetograph is an implementation of the event in the form of a CDS, with the same total depth, duration and time step.

Model simulations

The pluvial flooding generated by the rainfall was reconstructed using the adjusted spatio-temporal rainfall sequence from the event, HIPRAD^a (section 4.1), as a forcing to the model set-up over Gävle (section 3.2). To generate a representative initial soil saturation state, the model was initially forced by a “pre-rain” consisting of the spatio-temporal HIPRAD^a sequence recorded 00:00-20:00 on 17 Aug. The pre-rain gave a saturation of 44-49% in the model, which was used as initial conditions for all the following simulations. The most intense part of the rain took place 20:00-02:00 and the spatio-temporal adjusted

HIPRAD^a from 20:00-02:00 was simulated using initial conditions from pre-rain, additionally including the inflows from the watercourses crossing the model borders (Fig. 2).

Additionally, flood simulations were performed using spatially uniform rainfall depths following the mean and CDS hyetographs, described in section 4.1. Thus, three different simulations based on the reconstructed rainfall were performed (and compared with the CDS-100 simulation), which will be referred to as follows:

- REC-ST: forced by adjusted spatio-temporal HIPRAD^a;
- REC-UM: forced by spatially uniform mean hyetograph based on HIPRAD^a;
- REC-UC: forced by spatially uniform CDS hyetograph based on HIPRAD^a

From the hydrodynamic simulations, we mainly use the parameter D_{max} (m), i.e. maximum water depth during the flooding, for evaluation and comparison between simulations. For some evaluation also water depth (m) at a specific time in a specific location was extracted from the simulations. Finally, for estimating DEFRA ratings (section 4.3.3), maximum flow velocities (m/s) in all grid cells were used.

Evaluation

Rainfall

The 11 Netatmo stations classified as functional (section 3.1) were considered eligible for independent validation of the scaled HIPRAD^a sequence (section 4.1). A requirement was that the station(s) would be located close to the centre of the HIPRAD grid cell, which resulted in five stations being disqualified. Out of the remaining six stations, two pairs of stations were located close to the centre of the same grid cell; in this case their average value for each time step was used. Overall evaluation is thus made in four grid cells (Fig. 1), where 15-min time series during the event were compared and evaluated with respect to similarity in terms of total depth, maximum depth and shape of hyetograph.

Reconstructed flooding (REC-ST)

For the simulation REC-ST, i.e. representing the full spatio-temporal rainfall sequence, validation of modelled water depths was performed by comparing with observed water depths derived from images and observations from the flooding event at six locations. At four locations, water depth could be derived from photos by using the DEM and recognizing objects or constructions in the photo that could be attributed with a coordinate in a web map service. From the elevation the water level reaches in a specific point, the flood depth in a depression the same water body is filling may be estimated. Measurements on site were available at two locations; one high water mark on a facade and one window that the water level was reaching on a photo. The modelled and observed water depths were compared at the time of the photo or observation.

Furthermore, data was delivered by the municipal property company Gavlefastigheter with information regarding confirmed flooded buildings and a full list of their properties with information about building type. Additional data regarding damaged critical infrastructure was delivered by staff at the municipal planning department. In all, this provided an overview of damaged objects deemed by the municipality as Vital Societal Functions (VSF) and Critical Infrastructure (CI). These objects were extracted from reconstructed flood mapping of maximal water depth (D_{max}) to assess the accuracy of the reported conditions for these areas.

Comparative evaluation of conventional flood mapping (CDS-100) and reconstructed flooding (REC-ST)

Besides visual inspection and comparison of the different simulations, we perform general assessments of the different simulations in terms of flood extent and DEFRA rating.

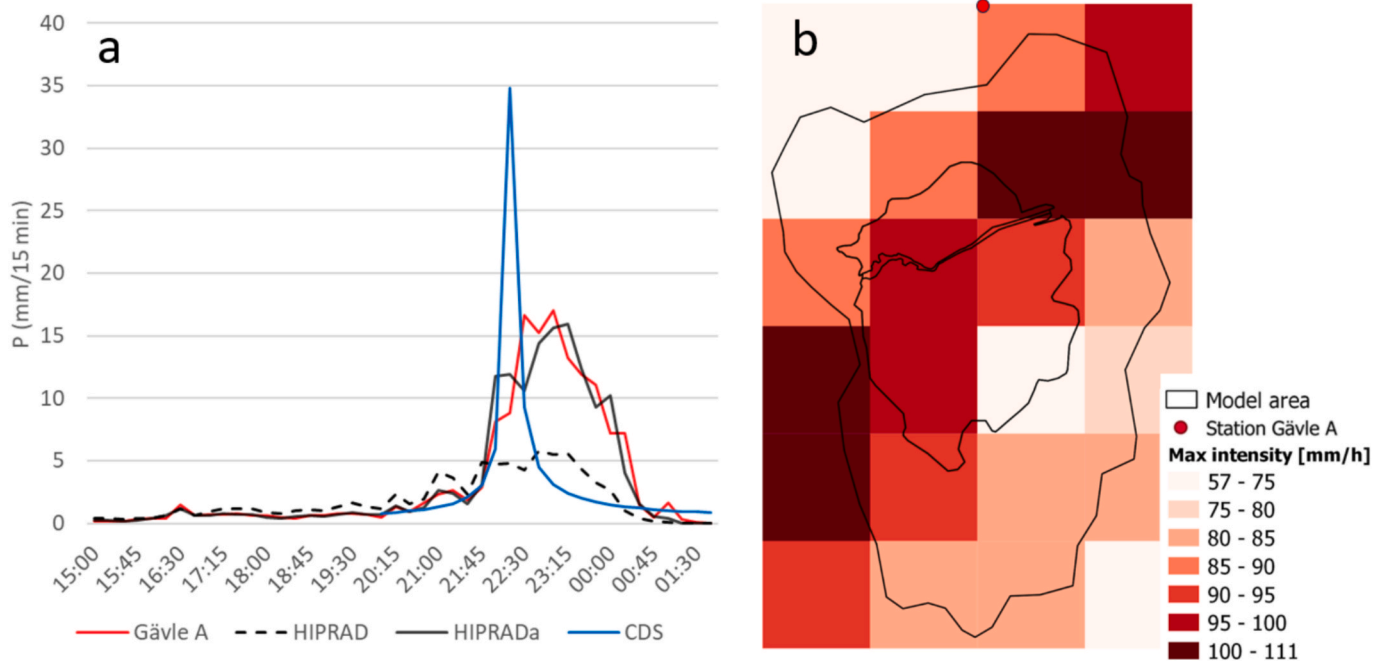


Fig. 4. Time series of 15-min accumulations during the event in station Gävle A and as mean values over the domain in HIPRAD, HIPRAD^a and HIPRAD^b converted into CDS shape (a). Maximum intensities in the different radar grid cells as estimated by HIPRAD^a (b).

- Flood extent: The percentage of flooded area was determined by measuring the size of the flooded area at various water depth levels and calculating each level as a percentage of the total flooded area.
- DEFRA rating: To assess the direct risks to human life, a methodology developed by the UK Department for Environment, Food & Rural Affairs (DEFRA, 2006) was used. This approach categorizes areas mapped for cloudburst flooding into four hazard levels: “no danger” (rating < 0.75), “danger to some” (0.75-1.25), “danger to most” (1.25-2.5) and “danger to all” (> 2.5). The classification is based on calculated water depths and flow velocities, which are combined to evaluate the level of hazard.

The above evaluations were used to (i) quantify the difference between the 100-year mapping and the reconstructed 2021 event, respectively, in terms of flood impacts, as well as (ii) to assess the sensitivity of pluvial flood mapping to the spatio-temporal representation of the rainfall forcing. The latter issue was quantitatively investigated in a contingency table analysis of simulations REC-UM and REC-UC, based on the DEFRA rating and with simulation REC-ST as benchmark. In the analysis, looping over all grid cells in the hydrodynamic model the entries (A-D) in the contingency table were summed as follows.

- if DEFRA(ST) $\geq$ 0.75 & DEFRA(UM/UC) $\geq$ 0.75 $\rightarrow$ true positive (A)
- If DEFRA(ST) < 0.75 & DEFRA(UM/UC) $\geq$ 0.75 $\rightarrow$ false positive (B)
- If DEFRA(ST) $\geq$ 0.75 & DEFRA(UM/UC) < 0.75 $\rightarrow$ false negative (C)
- If DEFRA(ST) < 0.75 & DEFRA(UM/UC) < 0.75 $\rightarrow$ true negative (D)

Three corresponding metrics were calculated (Nurmi, 2003):

- Hit Rate (HR): $A/(A+C)$ (range: 0-1; perfect score: 1)
- False Alarm Ratio (FAR): $B/(A+B)$ (range: 0-1; perfect score: 0)
- Critical Success Index (CSI): $A/(A+B+C)$ (range: 0-1; perfect score: 1)

To furthermore assess the extent to which the conventional mapping represents the impacts of a much worse event, two key questions were formulated.

1. What actually happened, according to REC-ST, in the main risk areas pointed out in CDS-100; were they all (severely) flooded?
2. Were there in REC-ST (severe) impacts in areas that were not pointed out in CDS-100?

To answer the first question, in all 16 hot spots found in CDS-100 (Fig. 3) we compared simulations CDS-100 and REC-ST in terms of Dmax and DEFRA rating. The second question was answered by mapping out the areas in which Dmax < 0.1 in CDS-100, implying no significant flood hazard, and Dmax > 0.5 in REC-ST, implying significant material damage as well as personal safety risks (the limits are established in Swedish pluvial flood mapping practice; e.g. MSB, 2023).

Results

Rainfall

The observed hyetograph of the event in station Gävle A shows the more or less continuous rainfall during 17 Aug, followed by the dramatic peak just before midnight (Fig. 4). The original HIPRAD observations (HIPRAD) in the grid cell covering the Gävle A station well agree with the station data until the peak reaches an intensity of ~ 5 mm/15 min, after which HIPRAD remains on this level and drops to near zero earlier than the station data. This type of underestimation of short-duration rainfall peaks in radar-based observations is not unusual and frequent local adjustment, as performed here, is generally recommended (Schleiss et al., 2020). After adjustment, the HIPRAD^a observations at the station location very well correspond to the station observations throughout the event.

The comparison of maximum and total 15-min depths in HIPRAD^a grid cells and PWS stations, respectively (Fig. 1b), reveals an overall good agreement between the two (Table 2). In terms of total depth, PWS is lower than HIPRAD^a in three cells and on average PWS recorded 8.2% less. A general underestimation by PWS of type Netatmo of $\sim 10\%$ has been previously found, when comparing with more professional measurements (de Vos et al., 2019). In terms of maximum 15-min depth the difference is smaller, 5.8% on average, with PWS being higher in two cells and HIPRAD^a in two. The event hyetographs (Fig. 5) confirm an

Table 2

Total (TOT) and maximum 15-min (MAX) depth (mm) for the event in four HIPRAD grid cells (Fig. 1b) as observed by HIPRAD^a and PWS, respectively.

	Cell 2		Cell 5		Cell 10		Cell 12	
	HIPRAD ^a	PWS	HIPRAD ^a	PWS	HIPRAD ^a	PWS	HIPRAD ^a	PWS
TOT	139.3	142.9	145.9	142.1	172.5	145.7	140.8	116.3
MAX	18.1	17.1	17.7	18.1	24.2	19.0	20.5	20.9

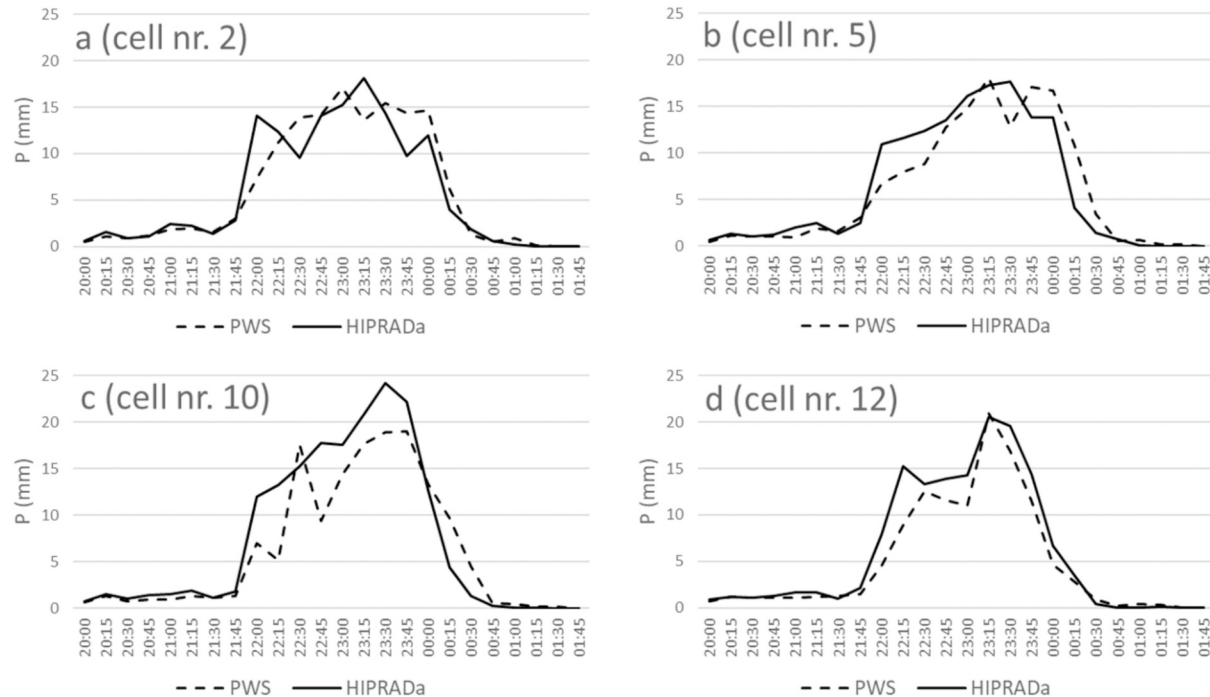


Fig. 5. Time series of 15-min accumulations during the event in four HIPRAD grid cells and corresponding PWS. Grid cell numbers in the titles refer to Fig. 1b.

overall close agreement also in terms of the temporal evolution, despite some differences in single time steps. We conclude that the PWS observations could be successfully used to evaluate and, to some extent, validate the adjusted HIPRAD^a sequence.

Flooding

Validation of reconstructed flooding

Validation of reconstructed flooding (REC-ST) was performed by comparing depth information derived from available photos or measurements in different points with the simulated water depth at the corresponding time and location. The observation points are denoted A-F in Fig. 6 and there is also a seventh point located outside the domain (Campus in Table 3). In point A, the observation is based on a measurement of high water marks on a house and in point F it is based on water reaching up to a nearby roundabout at its highest level; all the other points are based on photos combined with DEM analysis or photo combined with measurement of flooded objects in the photo. As shown in Table 3, the agreement is generally very good with only a few cm (and %) difference between the observed and simulated depths. The observations in points F and Campus are considered to be more uncertain and are therefore presented as ranges, thus the agreement is also less quantifiable.

Further validation was made by comparison with post-flood municipal documentation of Vital Societal Functions (VSI) and Critical Infrastructure (CI) that either were or were not affected by flooding during the event. Seven examples of VSI and CI that were affected are shown in Fig. 7. In all cases, the simulated D_{max} is at least ~0.5 m and in half of the cases >1 m. The viaduct in Fig. 7c shows particularly high water

depth, almost 5 m. This is naturally a deep low point and the road acts as a channel accumulating flow to the area. There is confirmation of it being flooded but no knowledge about the actual depth. Another area that shows great water depth is the pre-school in Fig. 7a with a depth at about 1.5 m. This property is part of a larger area highly affected by flooding that shows up in both conventional and reconstructed mapping, see number 16 in Fig. 6. Number 4 in Fig. 6 is the same flooded road as seen in Fig. 7c and Fig. 7g is located in connection with the flooded area number 6 in Fig. 6.

Fig. 8 shows six cases of VSF and CI that were confirmed non-flooded. The simulated D_{max} is overall limited, although in two cases it reaches ~0.5 m and in one case (Fig. 8a) >1 m. The existence of standing water in e.g. some areas with health care (Fig. 8a) is likely due to closed areas in the terrain model where the water gets trapped. The buildings in this area are very close to each other and the accuracy of the terrain model might be insufficient here. It is likely that the runoff in reality was diverted to some other location either on the surface, with smaller structures than the terrain model resolution can handle, or through storm water systems not represented in the model. The same reasoning can be applied Figs. 8d and 8f, whereas the areas in Figs. 8b, 8c and 8e do not have buildings as close to each other and therefore it is less likely that water gets trapped by a misinterpretation of the terrain.

Pluvial flood maps corresponding to simulations REC-UM and REC-UC are shown in the Supplement (Figs. S2 and S3). Based on visual inspection, they are similar to the REC-ST map (Fig. 6). Further analysis is made in Section 5.2.2.

Comparison between conventional flood mapping and reconstructed flooding

From only a visual comparison of the results from the conventional

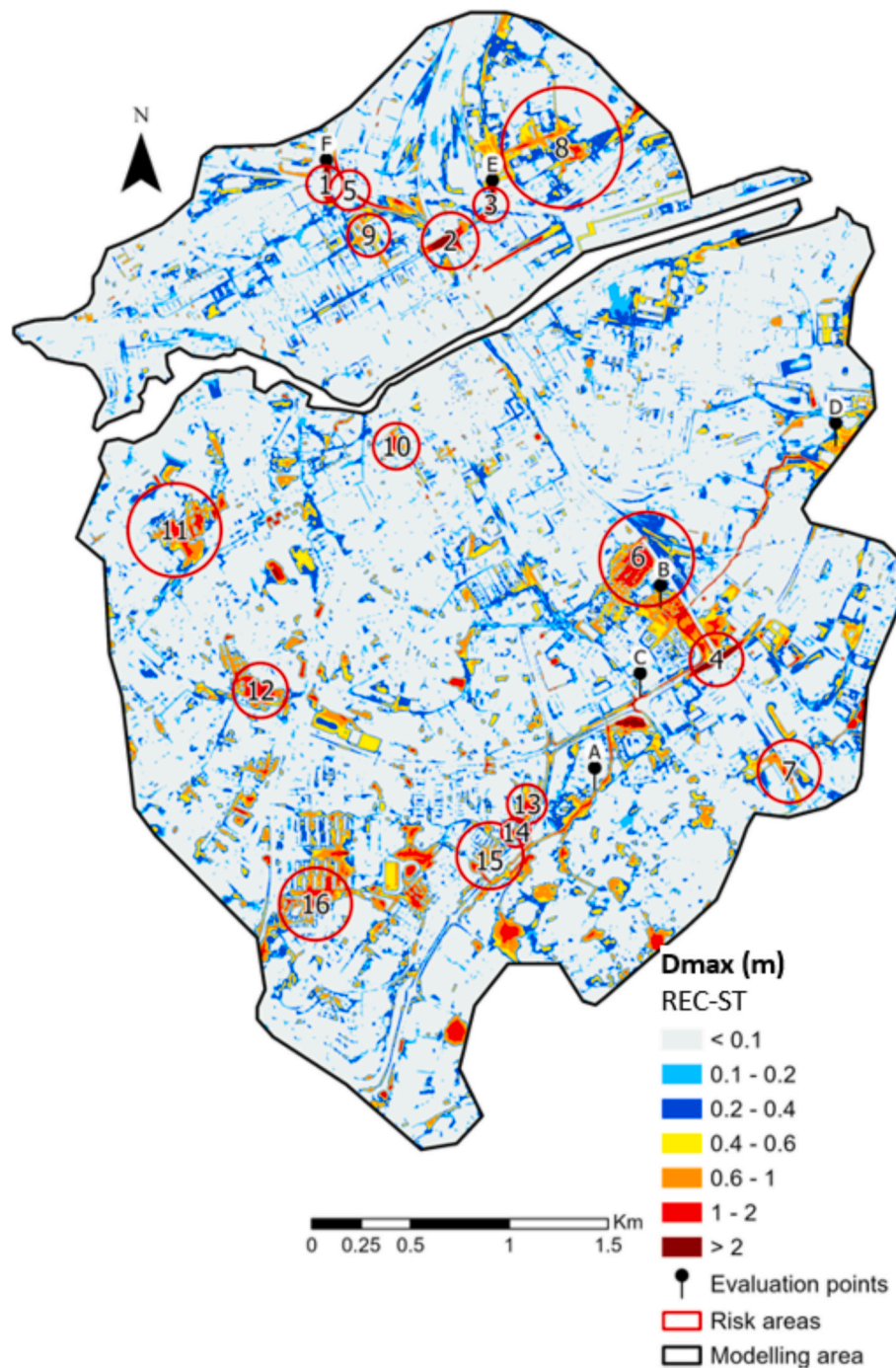


Fig. 6. Pluvial flood map corresponding to simulation REC-ST. The 16 identified risk areas are marked with red circles, approximately covering the extent of the flooding in CDS-100. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

mapping (CDS-100; Fig. 3) and the reconstructed flooding based in space-time varying rainfall (REC-ST; Fig. 6), it is obvious that the flooding during the 2021 event greatly exceeded the 100-year flood mapping. Areas with $D_{\max} > 1$ m are clearly both more numerous and more spatially extended in simulation REC-ST. A map showing the differences between $D_{\max}$ in simulations CDS-100 and REC-ST is provided as Fig. S4 in the Supplement. In many areas, $D_{\max}$ is > 0.5 m larger in REC-ST.

A more detailed comparison between the simulations is made in Fig. 9. In CDS-100, $D_{\max}$ exceeds 0.1 m in 12% of the total flooded area and 1 m in only 0.2% of the area (Fig. 9a). In REC-ST, on the other hand, $D_{\max} > 0.1$ in almost 30% of the area and 1 m is exceeded in 1.5%. In

terms of DEFRA rating (Fig. 9b), almost 2 ha are classified as “danger to some” (0.75–1.25 in Fig. 9b), almost 1 ha as “danger to most” (1.25–2.5) and 0.3 ha as “danger to all” (> 2.5). The corresponding areas in simulation REC-ST are 11.2, 3.6 and 1.7 ha, which correspond to a 500% increase on average.

Fig. 9 furthermore illustrates the differences between simulations REC-ST, REC-UM and REC-UC, representing different ways to describe the rainfall (section 4.2). Overall, on average over the domain, the differences are small, although there is a tendency of REC-ST to have slightly higher values than the other simulations. A complementary picture is given by the results from the contingency table analysis, shown in Table 4. In terms of all three metrics, simulation REC-UM

Table 3

Evaluation points (A-F shown in Fig. 6) with corresponding estimated depth, time of observation, corresponding simulated depth and their difference.

Point	Estimated real depth (m)	Time of observation	Simulated depth (m)	Difference (% of real depth)
House in Hemlingby (A)	1.06	At maximum	1.07	0.9%
Allotment garden (B)	0.85	07:55	0.82	3.5%
Hemsta roundabout (C)	2.45	07:54	2.37	3.3%
Coop Brynäs (D)	0.49	10:12	0.51	4.1%
Viaduct Strömsbrov. (E)	2.87	10:30	2.92	1.7%
Viaduct Kungsgatan (F)	2.70–3.00	At maximum	3.03	1–12%
Campus (not shown)	0.3–0.45	08:00	0.43	4–43%

agrees clearly better with REC-ST than what REC-UC does. This indicates that while the average error introduced when gradually simplifying the space-time variability of the rainfall is rather small (Fig. 9), the local precision is negatively impacted (which can also be seen in detailed comparison of Figs. S7–S9).

The 16 main locations at risk as identified by the conventional mapping (Fig. 3) are listed in Table 5. Most of the identified locations concern housing but also roads, railroads and one preschool are pointed out. In the conventional mapping, Dmax ranges from 0.81 m to 3.26 m, i. e. all locations are well above the 0.5 m limit representing major flood hazard. For half of the locations, a DEFRA rating of yellow or higher was found in the conventional mapping. In the reconstructed flooding, Dmax is substantially higher in all locations. The difference ranges between 0.2 m and >3 m (the latter in location 4), with an average of 0.9 m. All locations except two have a DEFRA rating of yellow or higher in simulation REC-ST. The remaining two locations (7 and 14) are the ones with the least difference between the CDS-100 and REC-ST simulations, only ~0.2 m. The basin draining to these areas appears to be rather small, thus the accumulated effects of the increased rainfall volume becomes limited. The highest differences of 2–3 m are found in locations 3 and 4, also locations 5 and 11 stand out with a difference of ~1.25 m. These areas are mainly connected to larger basins and concentrated flow paths, leading to non-linear accumulation effects when rainfall volume increases. The worst impacts in terms of both Dmax and DEFRA code was found for road sections (locations 1–4), especially two underpasses (1–2), but also some railroad sections (5–6) stand out with severe DEFRA ratings. In terms of confirmed impacts, we do not have information for all 16 locations but more than one third were flooded, some of which overlap with the locations in Fig. 7.

Concerning areas without flood hazard (Dmax<0.1 m) in the conventional mapping but with major flood hazard in the reconstructed flooding (Dmax>0.5 m), these are mapped in Fig. 10. In the northern sub-domain, areas are found mainly around or close to risk locations 3 and 5 identified in the conventional mapping. In the southern sub-domain, extended areas are found around or close to risk locations 4, 11 and 16. Some areas are however not in the immediate vicinity of identified risk locations, e.g. west of location 16 as well as in between locations 4 and 13. One factor behind the differences is conceivably the spatially varied rainfall in simulation REC-ST, compared to the spatially uniform CDS-100 simulation. As shown in Fig. 4b, the REC-ST rainfall is characterized by elevated amounts in the northern and western part of the domain, which may explain some of the pink areas in these parts of the domain (Fig. 10).

An additional way to shed light on the differences between the identified locations in simulations CDS-100 and REC-ST, and for explaining the non-linear increase in water depth in some areas, is to study the flux (i.e. flow rate per unit area) in the two simulations. This flux may be displayed in maps of maximum flux (unit: l/s/m) attained during the flooding and are provided as Figs. S5 (CDS-100) and S6 (REC-ST) in the Supplement. The locations with the largest difference (pink areas in Fig. 10) tend to be placed in areas connected to concentrated flow paths, often in areas where the flow path drains (Fig. S6). This can explain the non-linear behaviour of increase in water depth since runoff accumulates here. The locations with the smallest difference measured have rather small watersheds connected to them, thus the increase in generated runoff is less. Furthermore, the increase in DEFRA ratings imply that the areas with larger difference in water depths also are connected to concentrated flow paths since there is an increase in DEFRA rating that not only considers water depth but also velocity. For example, location 7 is not connected to a larger draining watershed or clear flow path and is not given any indications of hazard in the DEFRA rating for any of the mappings (Table 4).

Discussion

In this study, we have attempted to reconstruct a major urban flood in order to assess the realism and applicability of standardized pluvial flood mapping. This effort has included a range of challenges that we discuss in the following.

The initial challenge was to reconstruct the flood-generating rainfall, with sufficient accuracy to capture the highest short-term intensities as well as the substantial spatio-temporal variability. As there were no measurements made by the city itself, we had to resort primarily to data from the national observation system of SMHI. The situation with 15-min C-band weather radar data over the domain complemented with a 15-min official rain gauge relatively close by rather well represents the “baseline rainfall data” available in Sweden. A rather straight-forward scaling of the space-time radar sequence against the official gauge turned out to be overall very well supported by independent PWS observations. This highlights the potential value of PWS data, as well as other opportunistic rainfall data (e.g. Olsson et al., 2025), for providing an added value in post-analysis of heavy rainfall and flooding events.

There are a number of uncertainties associated with pluvial flood modelling, many of which are related to accuracy levels that can be selected in different parts of the modelling. It is a trade-off between on one hand time and resources and on the other hand the expected added value given by the improved accuracy. A simplification made in this case is the representation of the stormwater system only as a deduction of the rainfall. This estimation is uncertain in general and furthermore the capacity of the stormwater system can change during a flooding event, e.g. as stormwater drains can get clogged and manholes may surcharge, potentially causing both over- and underestimation of flood extent. However, the accuracy in the description of the stormwater system is of less importance when modelling extreme rainfalls, such as the one in this study, since the capacity of the system is very small compared to the rainfall volume. Another simplification is to only distinguish between pervious and impervious surfaces, respectively, when setting the values of spatially varied input such as infiltration rate and Manning numbers. These values can vary between different soil types, but in urban areas top soil and filling material are often used with an infiltration capacity that differs from the theoretical capacity of the soil type (MSB, 2023). A generalised partitioning in pervious and impervious areas captures the most important differences. Finally, the initial saturation exerts a significant control on the flood response. In this reconstruction we estimated it by simulation using the actual preceding rain, which appears to have worked well, but it should be emphasized that the flood impacts might have differed substantially for other soil saturation levels. Generally, in pluvial flood mapping it is highly recommended to always perform a sensitivity analysis to different saturation levels.

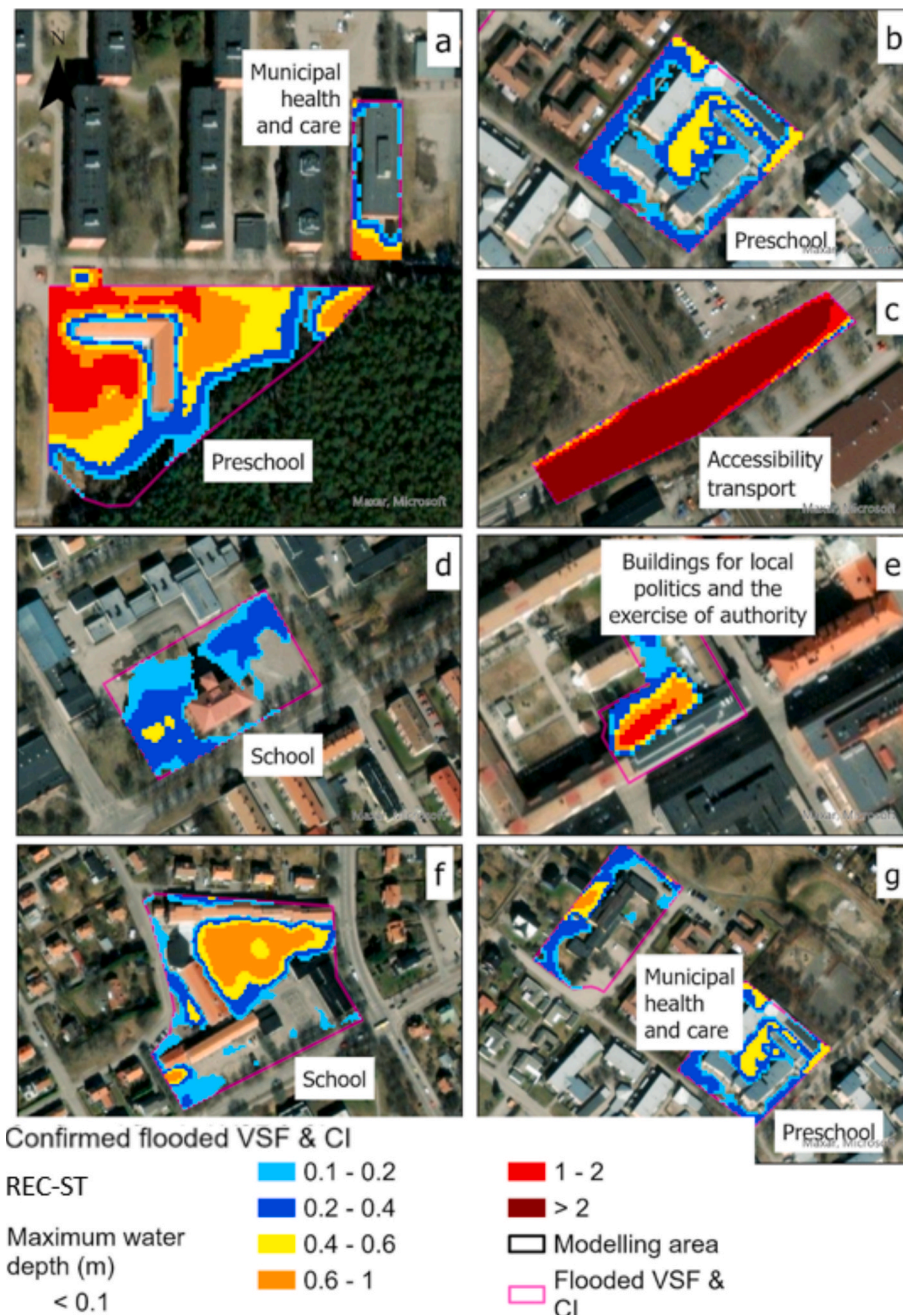


Fig. 7. Examples of Vital Societal Functions (VSF) and Critical Infrastructure (CI) that were confirmed damaged and the corresponding results from simulation REC-ST.

Although we consider the collected data used for validation in this study to be unusually good for this type of event, the number of points is admittedly limited and the information partly of qualitative nature. Despite these limitations the validation turned out overall acceptable, indicating that the hydrodynamic model was able to reconstruct this major flood. We foresee better documentation of future events now that everyone is walking around with a camera, opening up new possibilities to obtain crowdsourced validation data of pluvial floods.

Concerning the comparison between the conventional mapping (CDS-100) and the reconstructed flooding (REC-ST), there was as expected a large difference in the simulated maximum water depths as well as the severity in terms of DEFRA ratings. The locations identified with the highest flood hazard in the conventional mapping were indeed heavily affected also in the reconstructed flooding, although to somewhat various degree. Additional major flooding in the reconstructed

simulation mainly occurred in connection to the locations identified in the conventional mapping, with some exceptions. All in all, this indicates that the results from standardized conventional pluvial flood mapping can be used also to make a general assessment of the main locations at risk also following a much heavier rainfall, although the potential impacts are substantially more severe.

When assessing not only the water depth but velocity (e.g. in the DEFRA rating) as well as flux, the differences between conventional and reconstructed mappings were sometimes more pronounced. These differences may be important especially related to how the information is used when planning for actions or measures. While conventional mapping (CDS-100) successfully identifies flooded areas to a certain degree, prioritizing measures solely on water depths may lead to actions in areas where high water levels do not necessarily translate to significant risk or hazard. On the other hand, if using mainly DEFRA ratings derived from

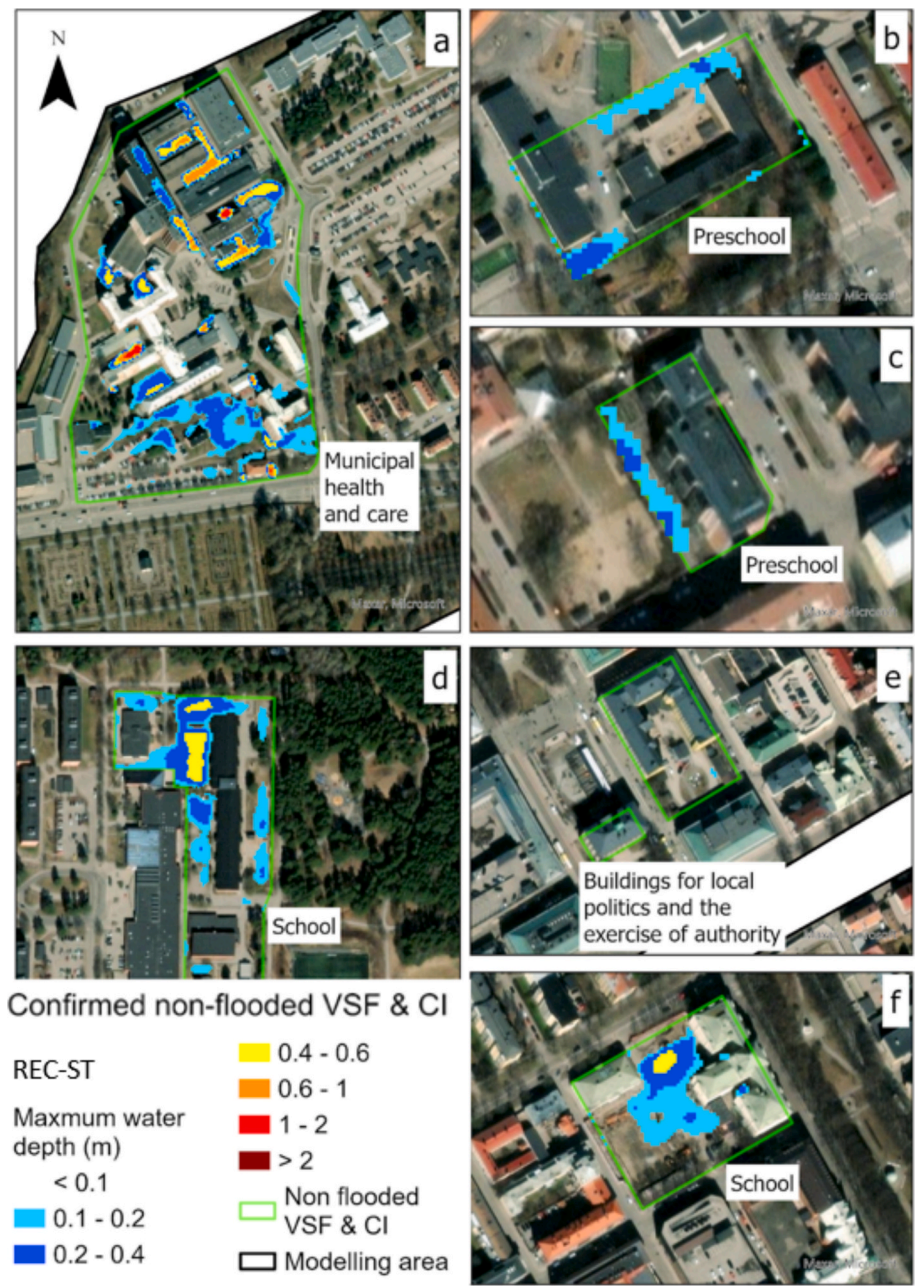


Fig. 8. Confirmed non-flooded buildings and the corresponding results from REC-ST.

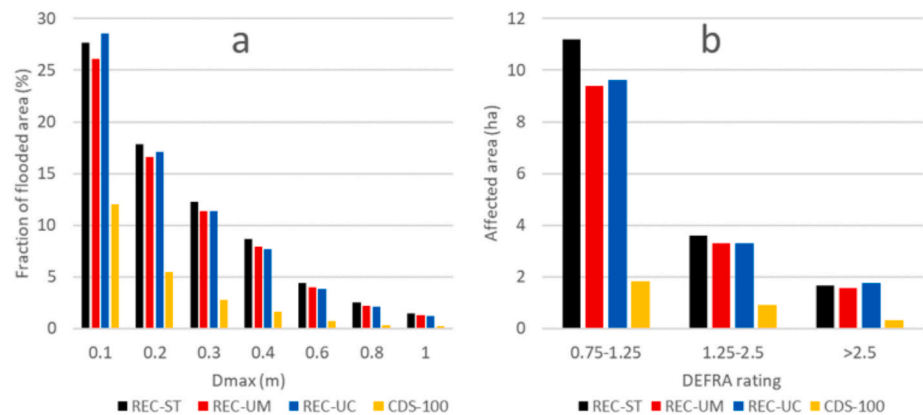


Fig. 9. Distributions of fraction of flooded area (a) and DEFRA rating (b) in the different simulations.

Table 4

Hit Rate (HR), False Alarm Rate (FAR) and Critical Success Index (CSI) from a comparison of REC-ST with REC-UM and REC-UC, respectively.

	HR	FAR	CSI
REC-UM	0.82	0.04	0.80
REC-UC	0.78	0.11	0.71

Table 5

Selection of key locations identified with major flood hazard in the conventional mapping (CDS-100); location numbers refer to the map shown in Fig. 3. Dmax and DEFRA rating are given for both conventional mapping (CDS-100) and reconstructed flooding (REC-ST). A DEFRA rating inside parentheses denote that only a small area is affected.

Location	Type	CDS-100	REC-ST
		Dmax (m)/DEFRA rating	Dmax (m)/DEFRA rating
1	Road	2.17/red	3.16/red
2	Road	3.26/red	3.97/red
3	Road	1.41/orange	3.27/red
4	Road	1.75/orange	4.78/red
5	Railroad	1.15/yellow	2.40/red
6	Railroad	1.67/orange	2.10/orange
7	Railroad/ Housing	1.37/-	1.59/-
8	Housing	0.81/-	1.19/yellow
9	Housing	0.83/-	1.12/yellow
10	Housing	1.19/-	1.66/yellow
11	Housing	1.00/-	2.23/yellow
12	Housing	1.01/-	2.12/orange
13	Housing	1.56/(yellow)	2.32/yellow
14	Housing	0.89/-	1.10/-
15	Housing	1.30/(red)	1.71/yellow (red)
16	Preschool	1.02/-	1.57/yellow (orange)

conventional mapping there is a risk of overlooking areas that could become hazardous during more extreme rainfall. This highlights the importance of a balanced approach that considers both water depth and flood dynamics to ensure effective and targeted flood prevention strategies.

A result of this study that was touched upon in connection with Fig. 9, but deserves more attention, is the difference between the three simulations representing different ways to represent and simplify the actual rainfall in 2021 (Fig. 4a); REC-ST (full spatio-temporal variability), REC-UM (spatially uniform with actual hyetograph) and REC-UC (spatially uniform with CDS-shaped hyetograph). To complement the pluvial flood maps, maps of the differences between Dmax in the three simulations are provided as Figs. S7-S9 in the Supplement. They show that locally Dmax can differ substantially between the simulations, even if the overall patterns are similar as shown in Fig. 9). This is also evident from the contingency table analysis (Table 4). In many locations, Dmax in simulation REC-ST is >0.3 m deeper than in simulation REC-UM (Fig. S7). Simulation REC-UM is overall closer to REC-ST than simulation REC-UC. The difference between Dmax in REC-UM and REC-UC, respectively is generally within ± 0.3 m.

These results imply that not only are spatial variations of the rainfall important, but also the temporal variations and therefore the choice of hyetograph is important when modelling and preparing for extreme rainfall events. If taking both spatial and temporal variability into account, the number of possible scenarios are almost indefinite but in real-world situations only one or a few scenarios can be considered because of limited resources. Still, the awareness of plausible large local deviations from the results based on one standardized hyetograph is worthwhile contemplating when planning for extreme rainfall events. Finally, although the spatial and temporal variations turned out to be of importance, the study still shows us that the choice of rain depth (i.e. return period) is of higher importance in the pluvial flood mapping. While conventional pluvial flood mapping (CDS-100) cannot represent

all features of a far more severe event (REC-ST), for obvious reasons, the former does provide a very useful starting point from where to explore consequences of very extreme rainfalls. If budget allows, complementing conventional mapping with some form of “worst case” mapping will provide additional information about vulnerable locations and objects, information that will support preparedness and adaptation actions.

Conclusions

The responses to our three research questions, as well as the main messages from this study, can be formulated as follows.

1. The conventional pluvial flood mapping, representing a rainfall with a 100-year return period, overall provided a useful picture also of the spatial patterns of exposure during the much more severe event in 2021. The main locations identified with a high flood hazard in the conventional flood mapping were also highly affected in the reconstructed flooding, although (importantly) to a much more severe degree. Additional flooding in the reconstructed simulation occurred mainly in connection to locations identified in the conventional mapping.
2. The severe urban flood in Gävle 2021 could be reconstructed with acceptable accuracy by hydrodynamic modelling forced with a full space-time reconstruction of the rainfall event. We emphasize that citizen science played a key role in the reconstruction, both for validating the rainfall sequence by PWS observations and for validating the simulated water depths from photos taken during the flood.
3. A gradual simplification of the rainfall from full space-time variability, through an actual hyetograph with spatially uniform mean depths to a spatially uniform CDS hyetograph did not substantially change the domain average results from the flood mapping, however distinct local differences were found. This indicates that while the rainfall depth or, equivalently, the return period in this case dominated the outcome of the mapping, the spatio-temporal representation of the rainfall is important for local accuracy in the flood impact.

We thus conclude that hydrodynamic modelling is able to reproduce major urban flooding with a good accuracy. Furthermore, conventional pluvial flood mapping can to some extent be “upscaled”, to detect locations at risk for major impacts caused by a rainfall with a far longer return period than in the conventional mapping. However, areas that pose an elevated risk during more extreme rainfall events may be overlooked when relying solely on conventional depth-based mapping, and therefore additional information in terms of fluxes and flow velocities are important to consider. Furthermore, we recommend that at least sensitivity tests involving e.g. very long return periods and fully saturated conditions are carried out whenever possible, for proper understanding of the major risks involved. In addition, the distinct local flood differences appearing when using spatio-temporally varied and uniform rainfall input, respectively, implies that this is an important aspect to consider as well as further investigate, not least in light of potential future changes in the spatial structure of rainfall extremes.

Finally, it must be emphasized that this was a case study in a specific city, with a specific model, of a specific event. We encourage more reconstructions of well-monitored major floods to advance our understanding of the pros and cons of pluvial flood mapping, in particular related to the consequences of very extreme rainfall events. Adapting cities to short-duration rainfall extremes and pluvial floods will undoubtedly remain a major challenge in the foreseeable future, with pluvial flood mapping being the primary supporting tool.

Data statement

Rainfall observations from the station Gävle A are openly available from <https://www.smhi.se/data/hitta-data-for-en-plats/ladda-ner-vad>

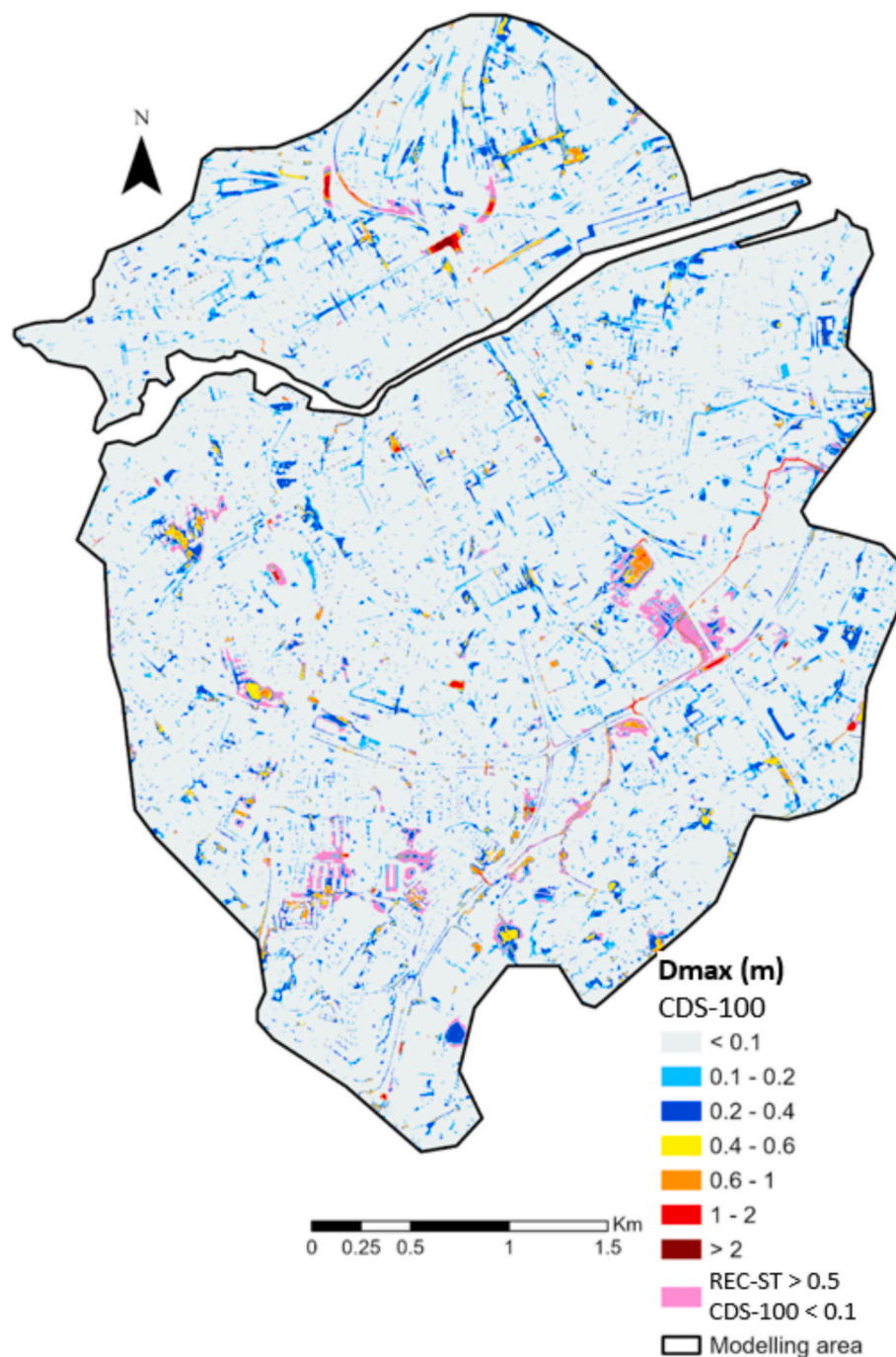


Fig. 10. Pluvial flood map from CDS-100 as well as areas (in pink) where no flood hazard was found in CDS-100 ($D_{\max} < 0.1$ m) but major flood hazard was found in REC-ST ($D_{\max} > 0.5$ m). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

erobervationer/precipitation15MinutesSum/107420. Other observations or simulations from the study are not publicly available but sharing will be considered upon request.

CRediT authorship contribution statement

Jonas Olsson: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Conceptualization. **Johan Kjellin:** Writing – review & editing, Validation, Methodology, Investigation, Conceptualization. **Sara Tunjic Ekeröth:** Writing – review & editing, Visualization, Investigation, Data curation. **Fanny Jeppson Stahl:** Writing – review & editing, Visualization, Investigation, Data curation. **Erik Glaas:** Writing – review & editing, Validation,

Methodology.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.cliser.2026.100645>.

Data availability

Data will be made available on request.

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