Reply to editor and reviewers

Dear editor

Please find details below on how we have implemented different reviewer suggestions in the manuscript. Minor corrections, typos, etc. are only corrected in the document (see track changes). Replies are marked with yellow.

On behalf of the authors
Søren Thorndahl

Handling Editor: Chris Onof suggests a minor revision with the comments:
Comments to the Author:
The reviews are very positive. I agree with Remko Uijlenhoet's comment about the problem with the length of the paper. However, as you correctly point out in the reply, it is not easy to take out whole sections without affecting the flow of the logic of the paper. I suggest therefore that you consider whether there are a few paragraphs containing less important material that could be taken out without affecting the structure of the whole.
Once this is done, and other minor corrections are carried out, this paper will be publishable

We have restructured parts of the paper and deleted paragraphs here end there in order to reduce the length of the paper. Moreover we have deleted parts of section 2 and added some parts to the introduction and the state of the art section. Some new references have been added and some sentences have been rephrased in order to make them shorter and clearer to the point.

Comments from R. Uijlenhoet
GENERAL REMARK
- This review paper, although dealing with relevant issues, has become quite lengthy, sometimes reading more as a report than as a scientific paper. Would it be possible to significantly reduce the length of the text, using the saved space to add one or two examples of urban hydrological applications of weather radar, which are currently lacking?

See comment to editor.

SPECIFIC REMARKS
- P.2, "the significant growth [in the number of papers]": How does the growth in this specific subject area compare to the overall growth of papers in the mentioned databases? In other words, is the reported growth merely a reflection of the overall increase in the number of publications, or is the relative proportion of papers in this subject area increasing with respect to other topics?

A paragraph has been added comparing the growth in hydrology in general to the growth in radar related publications.

- P.3, "journal papers such as": See also: Delrieu, G., I. Braud, A. Berne, M. Borga, B. Boudevillain, F. Fabry, J. Freer, E. Gaume, E. Nakakita, A. Seed, P. Tabary, and R. Uijlenhoet, 2009: Weather radar and hydrology. Adv. Water Resour., 32, 969–974, doi:10.1016/j.advwatres.2009.03.006.

Reference added

- P.5, "the radial resolution (or range resolution) is a function of the pulse and wavelength": In principle, the range resolution is equal to half the pulse length, independent of wavelength. See any radar meteorology textbook, such as Louis Battan's classic "Radar Observation of the Atmosphere" (University of Chicago Press, 1973).

A paragraph is added and ref is included

You probably mean the so-called maximum unambiguous range?
- P.5, "each radar scanline is subdivided into a fixed/selected number of range bins": For pulsed radars, the number of range bins is determined by the ratio of the maximum unambiguous range and the range resolution (i.e. half the pulse length). For frequency modulated - continuous wave (FM-CW) radars, the number of range bins is typically fixed at some power of 2 (e.g. 512).

Clarification has been added, but the point on FM-CW is omitted.

- P.5, "Small, local X-band radars with non-parabolic antennas": Many X-band rainfall radars still employ parabolic dish antennas. The angular resolution of a parabolic dish antenna is proportional to lambda / D, where lambda is the employed radar wavelength and D the antenna diameter. In other words, the larger the antenna (at a fixed wavelength), the more focused the beam. On the other hand, for a given antenna size, the larger the wavelength, the less focused the radar beam. X-band is about 3 cm, C-band 5-6 cm and S-band _10 cm. Hence, for a given antenna size, the beam width at Xband is _3 times smaller than at S-band. Or, for an X-band radar the antenna can be 3 times smaller than at S-band to achieve the same angular resolution.

Good point. We were addressing this point only to ship-radars which have been applied fore some applications within urban hydrology. I think it will be too much to include more detailed information here.

- P.5, "larger opening angles": In some urban hydrological studies, refurbished ship radars are being used as rain radars. Such radars employ the typical horizontal antenna shapes we know from ships. Such antennas produce so-called fan beams, with a small angular resolution in the horizontal direction, but quite a large angular resolution in the vertical direction. In other words, the shape of the radar beam is highly asymmetrical in this case, effectively integrating rainfall over a large vertical distance.

Yes. These refs are all related to these types of radars. Point on the large vertical distance has been added

- P.5, "X-band radars function with both higher spatial and temporal resolution": This is typically because X-band radars require smaller antennas than C- and S-band radars to achieve the same angular resolution. Smaller antennas are much easier to rotate quickly, thereby increasing the effective temporal resolution with which the rainfall field is being sampled.

Good point. This has been added to the text

- P.5, "different volume scans": Rather than "different volume scans" I would say "scans at different elevation angles" (comprising one volume scan).

Corrected

P.6, "methods to interpolate between radar images": The classic reference on this topic is: Frederic Fabry, Aldo Bellon, Mike R. Duncan, Geoffrey L. Austin (1994): High resolution rainfall measurements by radar for very small basins: the sampling problem reexamined. J. Hydrol. 161 (1-4), 415-428

This reference has been added

- P.7, "a relation between the temporal and the spatial resolution": Extrapolating the results of Van de Beek et al. (2012) leads to r = 5 t ˆ 0.3 for summer conditions in the Netherlands. See: Van de Beek, C.Z., H. Leijnse, P.J.J.F. Torfs, and R. Uijlenhoet, 2012: Seasonal semivariance of Dutch rainfall at hourly to daily scales. Adv. Water Resour., 45, 76–85, doi:10.1016/j.advwatres.2012.03.023.

This point has been added

- P.8, "the power-law parameters will vary with the DSD": I would say: "... vary with the DSD shape". If they would vary with the DSD they would vary continuously and that is not the case. However, Z-R relations do vary if the general shape of the DSD changes (e.g. from exponential to gamma).

Corrected

- P.9, "under the assumption that the radar field has a homogeneous DSD": This is not the only tacit assumption. Another one is that there are no systematic range effects in the radar rainfall retrievals (e.g. due to an increasing beam height in combination with the vertical reflectivity profile, or due to attenuation).

Good point, this is added

- P.9, "1 gauge per 10-20 km2 for urban areas": Berne et al. (2004) also provide numbers concerning the required spatial rainfall resolution for urban hydrological applications. You have referred to this before.

Yes – but this is related to the number of required gauges to perform adjustment – so I don’t think the Berne et al (2004) is relevant here.

- P.10, "adjusted or merged with rain gauge network data": However, the employed adjustment or merging methods are often quite straightforward, consisting of a combination of a mean field bias correction and a range-dependent correction. This approach is applied a.o. at SMHI (see the work of Daniel Michelson) and KNMI (the work of Iwan Holleman). I think UKMO uses a similar approach. In other words, I have the impression that geostatistical merging methods are largely limited to the academic community.

Good point. I added the following: The majority of operational products are based on rather simple range and MFB approaches as described in section 3.2.2 (e.g. Gjertsen et al., 2004).

- P.12, "leaving accurate radar rainfall adjustment less crucial": I am not so sure about this. Even a small but persistent bias, if lasting long enough, can be detrimental for hydrological simulations (e.g. rainfall-runoff modeling), even if the model is uncertain.
See e.g.:
Brauer, C.C., A. Overeem, H. Leijnse, and R. Uijlenhoet, 2016: The effect of differences between rainfall measurement techniques on groundwater and discharge simulations in a lowland catchment. Hydrol. Proc., 30, 3885–3900, doi:10.1002/hyp.10898.

The point is here that if you calibrate your hydrological model against flow, water level, obs. etc. a small defect on the rainfall input might blend in with other uncertainties.

- P.12: Classical references on this topic are:
Austin, G.L. and Bellon, A., 1974. The use of digital weather radar records for shortterm precipitation forcasting. Q. J. R. Meteorol. Soc., 100: 658-664.
Einfalt, T., Denoeux, T. and Jacquet, G., 1990. A radar rainfall forecasting method designed for hydrological purposes. J. Hydrol., 14:229-244.

Added

- P.13: I would also add SBMcast:

Berenguer, M., C. Corral, R. Sánchez-Diezma, D. Sempere-Torres, 2005: Hydrological validation of a radar-based nowcasting technique. *J. Hydrometeor*, 6, 532–549. doi: http://dx.doi.org/10.1175/JHM433.1.

Berenguer, M., D. Sempere-Torres, and G.S. Pegram, 2011: SBMcast – An ensemble nowcasting technique to assess the uncertainty in rainfall forecasts by Lagrangian extrapolation. *J. Hydrol.*, 404, 226–240, doi:10.1016/j.jhydrol.2011.04.033.

added

- P.16: Is it really necessary to mention both "frequency" and "risk", or would only "risk" suffice?

Rephased

- P.10, 18: I would use "operational" rather than "commercially produced". Many national meteorological services are not commercial at all.

Good point.We will use “operational”

Comments from Dan Wright

Interactive comment on “Weather radar rainfall data in urban hydrology” by Søren Thorndahl et al. D. Wright (Referee) danielb.wright@wisc.edu Received and published: 2 December 2016 Review of HESS-2016-517: “Weather Radar Data in Urban Hydrology” by Thorndahl et al. The authors present a review of weather radar technological and methodological advances in light of more than a decade of progress since the well-known Einfalt et al. (2004) review. The paper is a pleasure to read and represents a useful update on the state of the knowledge. I have only minor comments, mainly grammatical, that the authors should address prior to publication.

Introduction: I do think it would be useful to mention what “urban hydrology” means, though perhaps the authors think it is self-evident. Later in the paper, a number of specific application topics are mentioned, but perhaps a brief list belongs in the introduction.

The following is added:

Where Einfalt et al. (2004) used the term ”urban drainage” we extend the terminology to “urban hydrology”. Thereby, we do not only encounter design, analysis, and management of urban drainage system, but also urban hydrological modelling/prediction as well as management of and interaction between different parts of the whole urban water cycle, i.e. urban drainage systems, flood prone areas, rivers and streams, ground water, etc.

Pg.6 line 17-18: I understand this “fishbone” idea, but if the authors have a figure available that demonstrates it, they could consider including it in the paper.

I don’t think we have the space in the paper to include a figure relating to this term but we have alaborated the description

Pg.9 line 31-Pg.10 line 1: Wright et al. (JAWRA 2014) also examined the role of gage density in MFB estimation.

A paragraph including this reference is added

Sections 3.2.2 and 3.2.3: It seems strange that these are separate sections-the content of section 3.2.3 seems to naturally fit within the scope of Section 3.2.2. I am also surprised that range effects don’t appear in this discussion, and possible solutions such as approaches based on the vertical reflectivity profile. In addition, it is perhaps worth noting that MFB has an implicit range adjustment feature, in that, at least for storms that don’t cover a large portion of the radar coverage, the gages reporting positive rain will be spatially close to each other, i.e. at similar distance from the radar, and thus the computed MFB will be in some sense “tailored” to compensate for range dependent bias. This could be worth mentioning, as MFB is sometimes viewed as being overly simplistic when in fact, for this reason and others, it works quite well.

Sections are joined and issues with MFB is added and a paragraph is added to the conclusion:

"Conventional MFB adjustment has an implicit range adjustment feature, in that, at least for storms that do not cover a large portion of the radar coverage, the gauges reporting positive rain will be within a close distance to each other and at similar distance from the radar, and thus the computed MFB will be in some sense compensate for range dependent bias. "

"In many studies simple mean field bias adjustment between radar and rain gauges has proven sufficient and robust which is probably also the reason that this method is applied in many operational systems. At present, the more advanced geostatistical approached to bias adjustment are mostly applied within the research community."

Section 3.2.4: I object to the wording "commercial radar rainfall products." Perhaps "commercial" has a different implication in Europe but in North America it implies that the product would be available for purchase from some private-sector. While such products certainly exist, the authors refer to products produced by government agencies that, at least in the United States, are available free of charge.

This has been changed. See suggestion from other reviewer

Section 4.1: The first paragraph of this section is at times hard to follow. I'm not sure what the sentence on pg.14 lines 20-22 is trying to say. Is it that climate projections from GCMs are "spatially distributed"? Or that we need to understand the spatial nature of precipitation extremes in a changing climate? Please reword as needed. If the intended meaning is that GCM outputs are spatially distributed, I would argue that this isn't the case, due to their coarse resolution. Instead, I would argue that they are "spatially averaged," and so the relevant methods needed to use such information revolve around using radar (or other methods) to disaggregate these coarse spatial averages to finer scales. I'm also having a hard time understand the sentences on pg.14 lines 22-29, regarding the connection between Area Reduction Factors (ARF) and GCM outputs, point-based historical data, etc. These are all relevant issues, but the connections need to be clearer. If the authors wish to mention work related to ARF estimation using radar, they could consider the work of Durrans et al., (2002) and Wright et al. (2014).

We have rephrased the whole section!

Section 4.4: I think it is worth mentioning past work and future potential for assimilation of radar data into short-term numerical weather forecasts. Great potential here, I recently reviewed a paper (not yet published) with an urban application using NCAR's DART system that showed excellent results in an urban setting.

More refs are added

The authors don't say a lot in the review about the future: data assimilation, refinement of dual-polarization algorithms, phased array technology, etc. Consider including a brief mention and references.

This is actually some of the issues we discarded in order to shorten the paper.

Weather radar rainfall data in urban hydrology

Søren Thorndahl[1], Thomas Einfalt[2], Patrick Willems[3], Jesper Ellerbæk Nielsen[1], Marie-Claire ten Veldhuis[4], Karsten Arnbjerg-Nielsen[5], Michael R. Rasmussen[1], Peter Molnar[6]

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Correspondence to: Søren Thorndahl (st@civil.aau.dk)

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Abstract. Application of weather radar data in urban hydrological applications has evolved significantly during the past decade as an alternative to traditional rainfall observations with rain gauges. Advances in radar hardware, data processing, numerical models, and emerging fields within urban hydrology necessitate an updated review of the state of the art on such radar rainfall data and applications. Three key areas with significant advances over the past decade, have been identified: 1) temporal and spatial resolution of rainfall data required for different types of hydrological applications, 2) rainfall estimation, radar data adjustment and data quality, and 3) nowcasting of radar rainfall and real-time applications. Based on these three fields of research, the paper provides recommendations based on an updated overview of shortcomings, gains, and novel developments in relation to urban hydrological applications. The paper also reviews how the focus in urban hydrology research has shifted over the last decade to fields such as climate change impacts, resilience of urban areas to hydrological extremes, and on-line prediction/warning systems. It is discussed how radar rainfall data can add value to the aforementioned emerging fields in current and future applications, but also to the analysis of integrated water systems.

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1 Introduction

In 2003 the International Group on Urban Rainfall (IGUR) under the IWA/IAHR Joint Committee on Urban Drainage initiated joint work on the status and development on using radar rainfall data within in the context of urban drainage. This led to a review paper entitled: "*Towards a roadmap for use of radar rainfall data in urban drainage*" which was published in *Journal of Hydrology* by Einfalt et al. (2004). The paper highlighted the state of the art at the time in weather radar hardware and data processing, as well as methods and challenges in the application of radar rainfall data in urban drainage.

However, the foundation upon which the original paper was based has significantly changed during the past one and a half decade. This is partly due to the rapid developments in radar hardware, signal and data processing; the development of new

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methods for data processing and analysis; advancements in urban runoff modelling incorporating more complex hydrological processes, etc.

The purpose of the current paper remains the same as the one by Einfalt et al. (2004), i.e. to bridge the gap between current precipitation measurements and suitable precipitation information for operation and design of urban drainage systems. Schilling (1991) and Einfalt et al. (2004) summarized these needs as follows: at least 20 years of recordings without data gaps, a volumetric accuracy of less than 3 %, and a spatio-temporal resolution of 1 km^2 and 1 minute, respectively. Where Einfalt et al. (2004) used the term "urban drainage" we extend the terminology to "urban hydrology". Thereby, we do not only encounter design, analysis, and management of urban drainage systems, but also urban hydrological modelling/prediction as well as management of and interaction between different parts of the whole urban water cycle, i.e. urban drainage systems, flood prone areas, rivers and streams, ground water, etc.

The scientific interest within the field is evident from the number of publications for specific search strings in different scientific databases. Figure 1 shows the number of publications registered under the keywords "*radar + urban drainage*" and "*radar + urban hydrology*" in the databases *Scopus (Elsevier)* and *Web of Science (Thomson Reuters)* for each year in the period 1980-2015. Out of a total of 142 published papers in *Scopus* with keywords "*radar + urban drainage*", 37 are from 2004 and earlier and 105 are published after 2004. The corresponding numbers for the keywords "*radar + urban hydrology*" are 56 before 2004 and 85 after 2004. Searching for "*hydrology*" in general in the aforementioned databases shows a somewhat linear growth from 1980 to 2015 (not shown), whereas the increase in the number of publications within "*radar + urban drainage*" and "*radar + urban hydrology*" is more exponential, which indicates a faster growth with regards to the latter. This significant growth covers both an increase in applications of weather radar data in urban hydrology, but also continuous improvement and development of methods, algorithms, instrumentation, etc. for estimating rainfall from radar data.

Table 1 presents the three most cited papers according to *Scopus* and *Web of Science* with the keywords "*radar + urban drainage*". Both Schilling (1991) and Einfalt et al. (2004) are review papers providing recommendations on the use of radar data within urban hydrology. The reason for the many citations should probably be found in a need for guidelines in terms of data resolution, rainfall estimation, and applications. Both papers provide a look into the future of radar rainfall in urban hydrology, emphasize that the application of radar rainfall is under development, and the examples of applications are rather sparse. Einfalt et al. (2004) lists a wide range of hydrological applications showing the clear potential for the use of radar data. Since 2004, many such hydrological applications have been implemented and tested in both innovation/research projects and in operational applications. This paper will therefore provide an updated overview of some of the listed potential hydrological applications from Einfalt et al. (2004) and their current status in terms of documented applications.

Climate change and consequently increase in extreme rainfall have been a significant catalyst for the development in urban hydrological models over the past decade. There is a need to be able to simulate current and future loads on drainage systems and to fully utilize the capacity of drainage systems in order to accommodate for climate change. Furthermore, integrated hydrological models (e.g. integrated urban drainage, river, and inundation models) have become standard tools, e.g. to

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simulate inundation risks in urban areas. The use of more detailed and distributed models increased the demand for good quality, high resolution inputs, which promotes the use of radar rainfall data in urban hydrology.

In addition to the higher demand for precise local rainfall data, technological developments in hardware as well as data processing and quality have changed significantly since the publication of the papers in Table 1. These form the starting basis of this paper, which aims to provide a review on the major technical developments during the past decade, with particular focus on the most ground breaking applications and cases, from where updated recommendations are distilled for the applications of radar rainfall data in urban hydrology. Given that many of the new developments are still within innovation projects by research communities, this review also aims to expand the new knowledge to the industry and water companies. Confidence in radar data is provided and possibilities of applications in urban hydrology and urban drainage are being mapped.

We structure the review based on the following three key areas of research that are identified as being central in a large majority of the publications within the field of radar rainfall application in urban hydrology:

- Temporal and spatial resolution of radar data (Section 2.1)
- Rainfall estimation, radar data adjustment and quality (Section 2.2)
- Nowcasting of radar rainfall (Section 2.3)

We approach these key areas from two sides. Initially, in Section 3 we review state of the art within the three key areas respectively, focusing on the radar and radar-rainfall related issues. Secondly, we will end each sub-section by reviewing the impacts of each of the key areas on applications within urban hydrological modelling. The second part of the paper focuses on the value of applying radar rainfall in urban hydrology giving examples of applications (Section 3). Finally, in Section 4, we present our subjective views on what is needed and what can be recommended for current and future applications of radar rainfall data in urban hydrology.

2 State of the art in radar rainfall estimation for urban hydrological applications

Urban hydrology is characterized by fast runoff and short response times on impervious surfaces, thus small time and space scales compared to rural hydrology. Rainfall data for urban hydrology is therefore required to resolve these spatial and temporal scales sufficiently. However, following Willems (2001), Thorndahl et al. (2008), Schellart et al. (2012b), and others, the errors in such rainfall input data are one of the most important sources of uncertainty in (urban) hydrological models. For example, for a sewer system model in Belgium, it was shown by Willems and Berlamont (1999) that about 20 % of the total uncertainty in the downstream sewer throughflow discharges could be explained by the spatial variability of the rainfall and about 20-25% by the rainfall measurement errors, consisting in their case of rain gauge calibration errors, rainfall intensity resolution errors and errors by wind and local disturbances. For extreme events, e.g. flash flooding, uncertainties related to spatial variability and rainfall measurement errors are expected to be even larger (e.g. Berne et al., 2004; Hossain

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Slettet: and to provide confidence in radar data. With potential users (scientists, water utility companies, consultantconsultancy companies, authorities) of radar rainfall data within the field of urban hydrology as the main target group, this paper will provide an overview of the state of the art in radar rainfall in urban hydrology and urban drainage. In this context we have identified

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Slettet: <#>**Paper outline**¶
Since the first use of radars for precipitation measurement, there has been a rapid development and improvement of weather radar hardware, signal processing, software etc., but the fundamental principles of applying weather radar for precipitation measurements has not changed significantly. We therefore refer to the existing literature on the fundamentals of radar and atmosphere physics e.g. antennas, frequencies, bandwidths, polarization, data correction: e.g. attenuation, clutter removal, and reflectivity-rainfall conversion. These fundamentals are indeed crucial for the quality of rainfall estimation and should definitely not be disregarded by users of …

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et al., 2004; Brauer et al., 2016). Hence there is a need for high quality and high resolution rainfall inputs into urban hydrological models in order to reduce uncertainty in hydrological response. Radar rainfall data are ideal in that respect. Since the first use of radars for precipitation measurement, there has been a rapid development and improvement of weather radar hardware, signal processing, software etc., but the fundamental principles of applying weather radar for precipitation measurements have not changed significantly. We therefore refer to the existing literature on the fundamentals of radar and atmosphere physics e.g. antennas, frequencies, bandwidths, polarization, data correction: e.g. attenuation, clutter removal, and reflectivity-rainfall conversion. These fundamentals are indeed crucial for the quality of rainfall estimation and should definitely not be disregarded by users of radar rainfall, but they are omitted from the paper since they have been discussed in depth in primers such as Doviak and Zrnić (1993), Collier (1996), Bringi and Chandrasekar (2001), Meischner (2004), Michaelides (2008), and Rinehart (2010). Furthermore, there are pioneering and significant journal papers such as Marshall and Palmer (1945), Austin and Austin (1974), Wilson and Brandes (1979), Smith and Krajewski (1991), Krajewski and Smith (2002), Einfalt et al. (2004), Delrieu et al. (2009), Krajewski et al. (2010), Villarini and Krajewski (2010), and Berne and Krajewski (2013) which also provide general information on specifications and applications of radar rainfall. Also, VDI (2014) and ISO (2017) have produced a standard on precipitation measurement by radar. In the following, we focus on new developments in applications of radar in urban hydrology, and start the discussion from the temporal and spatial resolution needs.

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Slettet: for urban hydrology is therefore required to resolve these spatial and temporal scales sufficiently. In the following sections, we review and discuss the state of the art with regard to temporal and spatial resolution of radar data

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2.1 Temporal and spatial resolution of radar data

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Flyttet opad [2]: Urban hydrology is characterized by fast runoff and short response times on impervious surfaces, thus small time and space scales compared to rural hydrology.

Flyttet opad [3]: Radar rainfall data for urban hydrology is therefore required to resolve these spatial and temporal scales sufficiently. In the following sections, we review and discuss the state of the art with regard to temporal and spatial resolution of radar data.

2.1.1 Temporal resolution

The temporal resolution of radar data is governed by the scanning strategy of the radar. A radar scanning the atmosphere in different elevations to generate a full azimuthal volume scan can take up to several minutes depending on rotational speed and the number of scanning elevations. Radar collects instantaneous samples of rain rates (estimated from reflectivities), unlike rain gauges, which accumulate rainfall over a given time interval. Some radars operate with intermediate dedicated Doppler scans for each volume scan, hence doubling the time between two consecutive reflectivity scans. Operational meteorological S-,C-, and X-band radars usually provide reflectivity scans with a temporal resolution of 5-15 minutes (Table 2), whereas research radars dedicated to high resolution rainfall monitoring in specific areas and specific elevations are reported to provide data resolutions down to 15 sec (e.g. van de Beek et al., 2010; Mishra et al., 2016).

2.1.2 Spatial resolution

The main strength of radars for rainfall estimation is their capability to provide spatially distributed rainfall information. The spatial resolution of radar rainfall data is basically determined by the hardware and physics. The radial resolution (or range resolution) is a function of the pulse length (In principle the range resolution is equal to half the pulse length, Battan, 1973) and can thus be very small for all radar bandwidths. However, for operational radars the radial resolution is often an indirect

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function of the maximum unambiguous radar range due to storage and data transmission restrictions. Thus, each radar scanline is subdivided into a fixed/selected number of range bins, which eventually determines the range resolution of the data. For pulsed radars, the number of range bins is determined by the ratio of the maximum unambiguous range and the range resolution (i.e. half the pulse length). X-band radars with shorter range than C- and S-band radars, are therefore typically operated with a finer radial resolution, e.g. down to a minimum of 500 m. Radial resolution between 3 and 100 m have been documented by e.g. Leijnse et al. (2010), van de Beek et al. (2010), Lengfeld et al. (2014), and Mishra et al. (2016).

The spatial resolution also depend on the azimuthal (or angular) horizontal resolution, which is a function of the beam width determined by the size and design of the antenna. In contrast to the radial resolution, the azimuthal resolution decreases as a function of the radial distance from the radar. Most operational weather radars use parabolic dich antennas with a beam width of approx. 1 degree, thus functioning with an azimuthal horizontal resolution close to 1 degree (http://www.eumetnet.eu/opera). As an example, a distance of 100 km from the radar will thus lead to a width of the beam of ~1750 m. Small local X-band radars with (non-parabolic), horizontal fan beam antennas typically have larger opening angles between 2 and 3 degrees, but also a smaller maximum range compared to meteorological radars due to integration of rainfall over a large vertical distance (Pedersen et al., 2010a, 2010b; Nielsen et al., 2012; Thorndahl and Rasmussen, 2012; Goormans and Willems, 2013; Nielsen et al., 2013; Borup et al., 2016).

Typical values for spatial resolutions and maximum ranges for operational radars are provided in Table 2. Generally, operational X-band radars function with both higher spatial and temporal resolution than C- and S-band radars. This is typically because X-band radars require smaller antennas than C- and S-band radars to achieve the same angular resolution. There are, however, examples of configurations of C- and S-band radars where high resolution data are derived. Such *super-resolution* can be achieved by shortening the pulse lengths to obtain higher range resolutions (e.g. Seo and Krajewski; 2010, Sharif and Ogden, 2014; Ochoa Rodriguez et al., 2015) or applying adaptive scanning strategies to capture the most intensive part of a storm with a high degree of detail (e.g. Dolan and Rutledge 2010).

Examples of radar reflectivity with four different spatial resolutions covering an area (~12 km x 12 km) over the city of Aalborg, Denmark, are shown in Figure 2. The example illustrates the importance of high spatial resolution data in order to capture the spatial variability of rainfall over an urban area.

2.1.3 Projection of data

Many applications of radar data in urban hydrology favor projected cartesian (gridded) over polar data with decreasing resolution as a function of range. The limit for generating high resolution cartesian data is mainly related to the azimuthal resolution and thus range. Two common methods of data projection are: 1) the Constant Altitude Plan Position Indicator (CAPPI) in which scans at different elevation angles (comprising one volume scan) are merged in order to generate a radar product with altitude independent of range (however with an inhomogeneous zone where changing from one elevation to the

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next one), and 2) the Plan Position Indicator (PPI) that applies one scan elevation only, thus has an increasing altitude as a function of range.

Due to the curvature of the earth, the refraction of the radar beam through the atmosphere, and wind drift of the raindrops, assigning a radar measurement to a specific point on the surface can be quite challenging. This should also be considered when working with high spatial resolution radar data, since it is not certain that the rain can be allocated with the same accuracy at ground level as in a specific elevation.

2.1.4 Advection interpolation (temporal downscaling)

In order to increase the temporal resolution of operational meteorological radar data, especially for urban hydrological applications, some authors have developed methods to interpolate between radar images (Fabry et al., 1994; Atencia et al., 2011; Jasper-Tönnies and Jessen, 2014; Nielsen et al., 2014a; Thorndahl et al., 2014b; Wang et al., 2015a). The governing principle in these downscaling methods is to apply the advection field of the rain, and by resampling in space, convert the spatial resolution into temporal resolution. The methods have been proven to give better local peak estimates of rainfall intensities as well as more accurate accumulated quantitative precipitation estimates in comparison with point ground observations. Jasper-Tönnies and Jessen (2014), Nielsen et al. (2014a); Seo and Krajewski (2015), and Wang et al. (2015a) have successfully converted data with a 5 or 10 minute resolution into a product with 1 minute resolution for use in urban hydrological modelling. The concept of advection interpolation works if the raw radar data are instantaneous. If radar data are averaged (by multiple scans) over a time period, advection interpolation will not be favorable and temporal resolution cannot be increased. In relation to urban hydrological modelling, where very fine temporal resolution indeed is needed for some applications (e.g. down to 1 min), the radar data based on instantaneous sampling are therefore preferable.

Considering the advective nature of rain, it is also clear that advection interpolation yields a better estimate of the area precipitation. Accumulation of instantaneous radar data with e.g. 10 minute sampling rate might result in a "fishbone" pattern consisting of periodical variability in rainfall accumulations. This is a result of the advection of rainfall between consecutive radar scans.

Commercial radar rainfall products (see section 2.2.3) often provide data that are temporally accumulated or averaged; hence, a coarser temporal resolution of data can be found in these products.

2.1.5 Impacts of temporal and spatial resolution of radar data in hydrological modelling

In the literature, the impact of spatial and temporal radar data resolution on hydrological model responses has been studied intensively (Quirmbach and Schultz, 2002; Berne et al., 2004; Villarini et al., 2010; Emmanuel et al., 2012b; Gires et al., 2012; Liguori et al., 2012; Nielsen et al., 2012; Schellart et al., 2012b; Vieux and Imgarten, 2012; Gires et al., 2013; Lobligeois et al., 2014; Bruni et al., 2015; Gires et al., 2015; Ochoa-Rodriguez et al., 2015; Rafieeinasab et al., 2015; Wang et al., 2015a; Thorndahl et al., 2016). Other than different spatial and temporal resolutions of radar rainfall input data, these studies represent a vast variety of different types, severity and number of events, radar types, catchment sizes, shapes and

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slopes, catchment imperviousness, models, model scales and resolutions (fully distributed, semi distributed or lumped), model outputs (e.g. peak flows, water levels, volumes, combined sewer overflow (CSO) discharges, volumes, frequencies, inundation levels, etc.), objective functions for evaluating and comparing results, etc. For these reasons, it is hard to formulate general conclusions on the impacts of the spatial and temporal data resolution, since they largely depend on the studied setup. However, three significant findings could be identified related to the requirements for spatial and temporal resolution in runoff response modelling:

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1. *For increasing catchment sizes, the demand for high spatial and temporal resolution radar rainfall data decreases.* Schilling (1991) and Einfalt et al. (2004) recommended a minimum temporal resolution of 1-5 min and a minimum spatial resolution of 1 km for the application of radar data in urban hydrology in general. Berne et al. (2004) detailed this to ~1 min/2 km for 10 ha catchments, ~3 min/3 km for 100 ha catchments and ~6 min/4 km for 1000 ha catchments. For even smaller catchments with an area of 1 ha or less, recent studies by Ochoa-Rodriguez et al. (2015) suggest a minimum resolution of 1 min/100 m.
2. *Catchment characteristics and modelled runoff response play an important role in defining the required temporal and spatial radar data resolution*
   The concentration time of the urban catchment or to a point of interest in the system are of importance and affected by many factors. According to the rational method (Kuichling, 1889), increasing concentration times will lead to greater critical rainfall aggregation levels (in this case coarser temporal resolution). Due to the dependence between temporal and spatial resolutions described above, increasing concentration times will reduce the demands for high spatial resolution. Thus, high space-time resolution is required for the simulation of peak runoff responses (surcharge, local flooding, etc.) upstream in an urban system. However, for the simulation of total catchment runoff or basin storage, the requirements on resolution may be reduced (Berne et al., 2004; Bruni et al., 2015; Rafieeinasab et al., 2015).
3. *Storm characteristics (size, movement, shape, lifespan, intensity, etc.) can be important when choosing the spatial and temporal resolution.*
   The ability to resolve rainfall adequately in time and space for urban hydrological applications depends on the velocity of rainfall fields. By studies of variograms at different temporal aggregation levels and analysing runoff responses, Ochoa-Rodriguez et al. (2015) found a strong interaction between the temporal and spatial resolutions and the impacts on urban runoff response. Berne et al. (2004) suggested a relation between the temporal (t in min.) and spatial (r in km) resolution of: $r = 1.5t^{0.5}$ for Mediterranean rainfall conditions and van de Beek et al. (2012) extrapolated this to $r = 5\ t^{0.3}$ for summer conditions in the Netherlands.
   The type and severity of a storm might also set requirements to the space-time resolution. A high-intensity convective thunderstorm with small spatial extent will need a higher resolution in both space and time to be resolved in contrast to a stratiform long-duration storm. This is again related to the runoff response of the system in question. Germann and Joss (2001), Berne et al. (2004), Bruni et al. (2015), and Ochoa-Rodriguez et al. (2015)

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suggested to apply climatological variograms to characterize the spatial structure of rainfall fields, and to investigate the spatial resolution requirements (given a specific temporal resolution) in order to resolve the spatial structure of rainfall fields in a sufficient way for urban hydrological applications.

2.2 Rainfall estimation, radar data adjustment and quality

The use of radar data implies that the data are of good quality. There are numerous items such as radar hardware calibration, clutter removal, overshooting/vertical profile correction, etc. (Michelson et al., 2004; Villarini and Krajewski, 2010), which may play a role before radar reflectivity data can be converted into reliable rainfall intensities. A thorough quality check and potential correction are therefore required. Disturbances for a good radar measurement may be undesired reflections off mountains or high towers, air planes, ships, wind turbines, attenuation by heavy rain or hail, snow or melting snow instead of rainfall, anomalous propagation conditions and others. Methods to test for these problems exist, and they are partly reduced by dual-polarization information from new generation radars. The preprocessing of radar data by meteorological services usually only covers a part of the above points.

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Observed radar reflectivity can be converted into rain rates (intensities), but in order to produce valid *quantitative precipitation estimates (QPE)* comparison and adjustment with against ground observations is required. This is most often referred to as radar rainfall adjustment or radar-rain gauge merging and is presented in the following section. Rain gauges for adjustment also need to be of high quality. Frequently observed shortcomings of rain gauge data are missing data, time shifts (or differently set clocks), clogging of the gauge, data transmission drop outs, gauge calibration errors, local wind effects around gauges leading to measurement errors, or gauge sampling errors (e.g. Ciach, 2003; Villarini et al., 2008b; Gires et al., 2014). In order to avoid random or systematic errors, such effects need to be eliminated before rain gauge data are used to adjust radar rainfall.

2.2.1 Reflectivity-rain rate conversion

Radar reflectivity, Z (mm^6/m^3) depends on the *drop size distribution (DSD)* of the target precipitation. Conversion into rain rate, R *(mm/h)* therefore depends on the size of the individual drops. As documented by numerous authors (e.g. Marshall and Palmer, 1945; Uijlenhoet, 2001) the most typical conversion for single polarization radars is to apply a *two-parameter* power-law relationship to describe the relation between rain rate and reflectivity (*Z-R* relationship): $Z=aR^b$. Since the power-law parameters will vary with the *DSD shape*, i.e. the type of rain, they will not be constant in time. One solution is to adjust the *Z-R* relationship continuously by use of ground observations. It is however more common to apply a fixed *Z-R* relationship and perform a posteriori bias adjustment (see next section). Whereas traditional *Z-R* conversion has been documented in numerous applications of radar, there are recent advances in the application of dual-polarized radars which enable accurate *QPE* assessment using polarimetric parameters (e.g. Scarchilli et al., 1993; Bringi and Chandrasekar, 2001; Anagnostou et al., 2004; Anagnostou and Anagnostou, 2008; Bringi et al., 2011; Mishra et al., 2016). Polarization of a radar signal characterizes the orientation of the electric field (both transmitted and received). Dual-polarimetric radars transmit a

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radar signal alternately in *horizontal (H)* and *vertical (V)* polarization. Depending on the shape of the rain drops, two different signals will be received: reflectivities Z_{HH} and Z_{VV}. Additionally, the phase of the horizontally and vertically polarised return signals, f_{HH} and f_{VV}, are measured (Illingworth, 2004). Four parameters can be defined based on the polarimetric measurements: differential reflectivity Z_{dr}, linear depolarization ratio L_{dr}, co-polar correlation coefficient r_{co} and the specific differential phase K_{dp} (Illingworth, 2004). It has been shown that K_{dp} is proportional to the product of rainwater content and the mass-weighted mean diameter (Bringi and Chandrasekar, 2001) and thus can be used to estimate rainfall rates. The advantage of using K_{dp} for rainfall rate estimation is that it is more sensitive to the raindrop shape, thus rainfall rate can be estimated from K_{dp} in the case of rain/hail mixture. As soon as the hydrometeors are spherical or quasi-spherical, K_{dp} is about 0°/km (hail, light rain). The advantage of using K_{dp} is also that it is independent of radar calibration and not sensitive to attenuation, an issue of particular importance at X-band frequency. K_{dp} can only be estimated for medium to high rainfall rates (Otto and Russchenberg, 2011).

2.2.2 Bias adjustment against ground observations

Many different methods have emerged in the last decade for adjusting rain rates estimated from reflectivities and several profound review papers on different adjustment/merging techniques related to hydrological applications exist (e.g. Goudenhoofdt and Delobbe, 2009; Wang et al., 2013; McKee and Binns, 2016). For specific details we refer to these. Below, we present some of the most widely applied methods.

One of the simplest methods of adjusting radar rainfall data has been proposed by Smith and Krajewski (1991) who introduced the concept of *Mean Field Bias (MFB)* adjustment. The concept is to estimate the ratio between accumulated rainfall in a number of ground observation points (rain gauges) and accumulated radar rainfall in the corresponding points (or grid cells if the radar data is projected onto a cartesian grid). Under the assumption that the radar field has a homogeneous *DSD* and that no systematic range effects in the radar rainfall retrievals are present, the whole radar field is multiplied by the *MFB* factor. The *MFB* factor should be based on a temporal integration of data over a period of time in which the *DSD* does not change significantly. If the integration period is too short (e.g. in the range of the temporal resolution of radar data), the bias assessment becomes vulnerable to random errors. On the other hand if the integration period is too long, the adjusted radar rainfall might be inaccurate due to temporal changes in the *DSD* (Krajewski and Smith, 2002). Within urban hydrology most commonly hourly (e.g. Borga et al., 2002; Thorndahl et al., 2014b; Rico-Ramirez et al., 2015; Wang et al., 2015b) or daily (e.g. Seo and Breidenbach, 2002; Wright et al., 2012; Thorndahl et al., 2014a) *MFB* adjustment is applied.

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The optimal temporal integration period or spatial aggregation level is to a large extent dependent on the representativeness of the gauges (gauge network density) to capture the temporal and spatial variability of the rain (e.g. Gires et al., 2014). It is difficult to recommend specific gauge network densities for radar rainfall adjustment since the optimal value will depend on storm type, homogeneity of the rain gauge network, orographic features of the rain, adjustment methods, etc. Generally you will need a rain gauge network with a higher density for smaller aggregation levels or in other words, the density of the rain

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gauge network will determine the temporal aggregation level of the radar rain gauge adjustment. McKee and Binns (2016) suggest conducting a sensitivity analysis in order to identify the effect of gauge density on rainfall estimation.

For annual precipitation measurements WMO (2008) recommends 1 per 5750 km^2 for plains and 1 per 2500 km^2 for mountainous areas. Furthermore, for application in design and management of stormwater systems WMO (2008) recommends 1 rain gauge per 10-20 km^2 for urban areas. For radar rainfall adjustment such density it is not necessary since the radar data will provide information on the spatial and temporal variability of the rainfall. As an example Goudenhoofdt and Delobbe (2016) found no remarkable improvement in the *MFB* assessment of daily rainfall for gauge densities between 1 per 500 and 1 per 135 km^2. Wright et al. (2014b) also examined the role of gauge density in *MFB* estimation, concluding that 1 gauge per 100 km^2 provided a robust bias adjustment on a daily scale.

MFB adjustment has an implicit range adjustment feature, in that, at least for storms that do not cover a large portion of the radar coverage, the gauges reporting positive rain will be within a close distance to each other and at similar distance from the radar, and thus the computed *MFB* will be in some sense compensate for range dependent bias.

As an extension of the *MFB* adjustment, the concept of *conditional MFB* adjustment was proposed by Ciach et al. (2000), Ciach et al. (2007), and Villarini et al. (2008a). The *conditional MFB* adjustment introduces a range (distance) dependent bias in order to account for rain rate dependent biases especially for convective rainfall with rapidly changing *DSD*. Wright et al. (2014b) demonstrate that especially estimation of large rain rates can be improved significantly by introducing *conditional MFB* adjustment, whereas Thorndahl et al. (2014b) conclude an insignificant effect of *conditional MFB* adjustment for advection interpolated radar data.

Spatial variability adjustment approaches and geostatistical merging of radar and rain gauge data are developed to account for range dependence issues as well as heterogeneous DSD's. They represent another range of methods which are widely applied for *QPE*. The concept here is to merge the spatial variability of the radar rainfall fields into the interpolated rain gauge precipitation fields in order to increase the spatial resolution of this product. The interpolation can be performed by many different spatial interpolation methods e.g. variations of kriging (Krajewski, 1987; Todini, 2001; Sinclair and Pegram, 2005; Haberlandt, 2007; Goudenhoofdt and Delobbe, 2009; Velasco-Forero et al., 2009; He et al., 2011; Berndt et al., 2014; Rabiei and Haberlandt, 2015) or by *inverse distance weighting* or *Thiessen polygon weighting* (Johnson et al., 1999; Haberlandt, 2007). The kriging based methods rely on variograms for describing the spatial dependence in rainfall fields and are in general more computationally demanding than weighting methods. The latter are therefore often used in real-time operation.

Other methods such as the singularity approach (Wang et al., 2015b) have been proposed in order to overcome problems with spatial smoothing as a results of the variograms in the Kriging based methods. Geostatistical merging and spatially distributed bias adjustment is mostly applied for radar composites or in mountainous areas with orographic rainfall effects (e.g. Germann et al., 2006; Sideris et al., 2014). Merged rainfall products are described in section 2.2.3.

Another alternative to the optimization and sensitivity approaches of radar-gauge adjustment described above, is to model errors and thereby acknowledge uncertainties in rainfall estimates (e.g. Ciach et al., 2007; Gires et al., 2012; Pegram et al.,

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2011; Villarini et al., 2014; Rico-Ramirez et al., 2015). It is expected that these uncertainty based methods and development of rainfall ensembles for hydrological applications will gain more impact in future applications, concurrently with development in probabilistic/ensemble models for urban hydrology.

2.2.3 Operational radar rainfall products

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Today, most national meteorological services produce radar rainfall products consisting of radar composites from national radar networks. They provide state of the art corrected *CAPPI* or *PPI* products which have been adjusted or merged with rain gauge network data in order to provide users with the best possible rainfall estimates for historical records or in real-time. The majority of operational products are based on rather simple range and *MFB* approaches as described in 2.2.2 (e.g. Gjertsen et al., 2004). Examples of products are in Germany: *RADOLAN*, in the UK: *NIMROD* and in the USA: *NEXRAD*. These *QPE* products are often provided in a fixed cartesian grid with data summarized over a fixed time period. In some cases only historical data in hourly or daily precipitation maps but in other cases also fine temporal resolution data are available.

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Generating radar composites merging data from two or more radars might be subject to inconsistencies in radar data due to merging of data from different elevations, with different scanning strategies, and using different merging techniques. In application of commercial *QPE* products, it is important to be aware of these inconsistencies.

2.2.4 Dynamic adjustment in real-time

Operational real-time continuous adjustment of radar rainfall against rain gauges constitutes a challenge in comparison to event based or discontinuous adjustment based on historical data (off-line mode). Nonetheless, for real-time operation of urban hydrological systems, it is crucial to be able to produce valid rainfall estimates in an on-line mode. The real-time adjustment is especially difficult in the beginning of rainfall events with no prior rain gauge data recordings or in situations with large spatial rainfall variability. In these cases where rain gauge observations might be sparse and thus subject to domain sampling errors, bias adjustment might be dominated by random factors and can easily result in a erroneous adjustment (Seo et al., 1999; Krajewski and Smith, 2002; Nielsen et al., 2014a). The accuracy of a real-time bias adjustment is thus dependent on the temporal aggregation scale at which the adjustment is performed. The shorter the aggregation scale (e.g hourly or sub-hourly) the larger the risk of erroneous adjustment due to sampling errors and the larger the aggregation scale (e.g. daily or super-daily) the larger the risk of errors due to changes in *DSD* and bias over the aggregation interval. Several authors apply *MFB* adjustment rather than area-based adjustment in real-time operation due to the fact that the latter is more vulnerable to rain gauge sampling errors (Seo et al., 1999; Borga et al., 2000). In order to avoid abrupt changes in bias several authors have suggested to apply algorithms to smooth the bias in time, e.g. using Kalman filtering (Chumchean et al., 2006) or exponential smoothing (Seo and Breidenbach, 2002).

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2.2.5 Choosing adjustment procedures for hydrological modelling

It is evident, that for hydrological modelling, accurate rainfall estimates at ground level are desired. Different adjustment methods and their impacts have been investigated in recent studies, e.g. Quirmbach and Schultz (2002), Tilford et al., (2002), Vieux and Bedient, (2004a), Emmanuel et al. (2012a), Gires et al. (2012), Goormans and Willems (2013), Wang et al. (2013), Leonhardt et al. (2014), and Rico-Ramirez et al. (2015). It is difficult to recommend one method of adjustment over another, since it to a large extent depends on the application considered. Instead we have identified some of the key issues related to the requirements of radar rainfall adjustment or radar-rain gauge merging for runoff response modelling in urban areas:

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1. *Catchment characteristics are important for the choice of the radar rainfall adjustment method.*

   The choice of the adjustment method depends on the required accuracy of the spatially distributed rainfall in the application and the radar rainfall product available. For catchments and spatially homogeneous rainfall events, an adjustment using rain gauges in or outside the catchment and a fixed *MFB* adjustment might be sufficient to represent rainfall variability. For a large catchment potentially covered by multiple radars, geostatistical merging techniques are required to represent the variability in *DSD* within the study domain and thus more sophisticated techniques might be preferred (see e.g. Wang et al., 2013, 2015b).

2. *Overall model uncertainty might have a significant impact on the urban hydrological model outputs leaving accurate radar rainfall adjustment less crucial.*

   Urban hydrological model outputs are subject to uncertainties associated with rainfall inputs as well as representation of hydrological and hydraulic processes, expressed in parameter and model structure uncertainties (e.g. Freni et al., 2008; Thorndahl and Willems, 2008; Thorndahl et al., 2008; Willems, 2008; Dotto et al., 2012). In cases where parameter uncertainty estimation of such processes dominates runoff response, the rainfall input to urban hydrological model may become less important. Instead of adjusting the radar rainfall individually, some authors have therefore calibrated or optimized hydrological models directly to match runoff response observations without specific adjustment of the rainfall input (Krämer et al., 2005; Ahm et al., 2013; Thorndahl and Rasmussen, 2013; Löwe et al., 2014). However, this is recommended only if parameter or model uncertainties are high and/or radar rainfall data adjustment is not possible, because it may lead to error compensation with undesired consequences for prediction.

3. *In real-time applications, change in storm characteristics might influence the radar rainfall inputs to hydrological models.*

   It is of utmost importance that real-time adjustment of radar data reflects the potential changes in *DSD*. In case of rapid changes e.g. between convective and stratiform precipitation a bias shift might occur. The aggregation time on which a bias (either mean field of spatially varying) adjustment is performed should therefore be able to reflect these changes. This will to a large degree also depend on the density of rain gauges available for adjustment.

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Required gauge density for an unambiguous adjustment will thus depend on the aggregation level on which the adjustment is performed as well as the storm extent and homogeneity of the storm.

2.3 Nowcasting of radar rainfall

Next to the interpolation for urban design, control or scenario simulation applications, temporal extrapolation of radar rainfall fields forms the basis of real-time forecasting and control (e.g. Austin and Bellon, 1974; Einfalt et al., 1990; Sharif et al., 2006; Smith et al., 2007; Javier et al., 2007; Achleitner et al., 2009; Einfalt et al., 2009; Liguori et al., 2012; Schellart et al., 2012a; Wang et al., 2012; Thorndahl et al., 2013; Ntegeka et al., 2015). Due to the short response time of the urban drainage system, the short life time and small spatial size of convective rain cells, urban rainfall forecasts are only reliable for very short lead times (Achleitner et al., 2009; Foresti et al., 2016). Short-term forecasts are called nowcasts and provide input for real-time warning and/or control of urban floods or CSO pollution.

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Several generic methods have been developed to nowcast radar data, based on deterministic approaches:, e.g. TREC (Rinehart and Garvey, 1978), CO-TREC (Li et al., 1995), SCIT (Johnson et al., 1998; Mecklenburg et al., 2000), SCOUT (Einfalt et al., 1990) or stochastic approaches: e.g. MAPLE (Turner et al., 2004), SBMcast (Berenguer et al., 2005, 2011), STEPS (Bowler et al., 2006). We refer to the individual papers for detailed descriptions of the methods and focus instead on the application of nowcasts within urban hydrological applications here. We have identified three issues which constitute the current major challenges:

1. *Extrapolation of observed radar rainfall has a limited lead time.*

   Despite development of the aforementioned methods, rainfall nowcasting for urban drainage applications is still in its infancy. Albeit rain cells can be extrapolated by radar image extrapolation (e.g. Thorndahl et al., 2013; Löwe et al., 2014) or applying cell tracking (e.g. Sharif et al., 2006; Einfalt et al., 2009; Muñoz et al., 2015), this is often of limited value given the limited duration of rain cells, especially during convective conditions. The quality of an extrapolation-based nowcast depends on the radar range, possible merging of radar networks, resolution, climate zone, and rainfall type. For a standard deterministic nowcast, the lead time varies between less than 30 minutes (small convective cells) to more than two hours (large scale slow moving systems). As a rule of thumb, extrapolation is more difficult with small rainfall cells and for small target areas, and less difficult with large rain fields and large target areas.

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2. *For reliable nowcasting, stochastic uncertainty should be included.*

   The most promising alternative to simple extrapolation of radar rainfall data is to perturb the deterministic radar extrapolation with stochastic noise to account for the unpredictable rainfall growth and decay processes (Bowler et al., 2006; Germann et al., 2009; Liguori and Rico-Ramirez, 2013). The stochastic noise model aims to describe the nowcast error together with its spatial and temporal correlations. In the Short-Term Ensemble Prediction System (STEPS), this is done by adding stochastic perturbations to the deterministic Lagrangian extrapolation of radar images (Liguori and Rico-Ramirez, 2013). The perturbations moreover aim to reproduce the dynamic scaling of

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precipitation fields, i.e., the observation that large-scale rainfall structures are more persistent and predictable than small-scale convective cells. STEPS was originally co-developed by the UK Met Office and Australian Bureau of Meteorology, and is currently further customised for urban applications, e.g. in the UK (Liguori et al., 2012; Liguori and Rico-Ramirez, 2012), STEPS-BE for the Belgian version (Foresti et al., 2016). It provides probabilistic ensemble nowcasts. So far, however, these nowcasting systems rely on radar data that is too coarse for urban applications (e.g. 1 km resolution C-band radar data for STEPS-BE).

3. *There is a challenge in combining high resolution radar observations with nowcasts.*

Future developments will likely involve the use of higher resolution X-band radar data. These are currently only available at experimental sites (e.g. http://www.casa.umass.edu/) without large spatial coverage and with short ranges that hamper extrapolation. A future research challenge will be to combine the coarser resolution radar data, which are available at large scale, with the higher-resolution but more local rainfall estimates (Nielsen et al., 2014c). The coarser but larger scale radar data allow estimation of velocity fields and the advection of radar composites, whereas the local, higher resolution estimates allow near-real-time spatial interpolation and dynamic calibration of the stochastic noise model parameters. Additional blending or assimilation with numerical weather prediction models increases the lead time (Liguori and Rico-Ramirez, 2012, 2013; Jensen et al., 2015; Korsholm et al., 2015)

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3 The value of radar rainfall for urban hydrology

The field of urban hydrology has over the last decade expanded the focus from analysis, design and operation of urban stormwater systems and wastewater treatment plants. Today, the key drivers of research include urban city resilience to hydrological extremes, water and resource recovery, climate change impacts and adaption as well as integration with other city planning and management disciplines, including urban development. This has led to a need for new and more diverse precipitation inputs, both to address the challenges mentioned above, and also because urban hydrology is becoming more complex with implementation of sustainable stormwater management infrastructure. This increased complexity often implies that the spatial distribution of precipitation becomes even more important in both planning and operation of urban systems, and therefore urban hydrology will require better resolved rainfall products in the future. The current main application fields for radar rainfall in urban hydrology are shown in Table 3. As shown in the table, several new application fields have emerged over the last decade. Radar measurements can provide important contributions to these new fields. The improvements discussed in the previous section have also enhanced the possibility to use radar data in the existing application fields.

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3.1 General statistical and hydrometeorological characterization of precipitation at urban scales

Long-term analysis of precipitation using single or multiple rain gauges has been applied for several decades. They provide valuable information to decision-making within design and analysis of urban water infrastructure, both for quantifying uncertainty and for studying non-stationary behaviour (e.g. Ntegeka and Willems, 2008; Madsen et al., 2009; Willems, 2013a, 2013b; Gregersen et al., 2014). When using single site rain gauges for large catchments simple Areal Reduction Factors (*ARF*) can be applied to account for the spatial distribution of extremes (e.g. Sivapalan and Blöschl, 1998; Vaes et al., 2005; and Wright et al., 2014a). While this is sufficient within a given catchment it is not adequate to validate spatial rainfall as modelled by *Regional Climate Models (RCM)* when describing anticipated future climatic changes over a range of scales. Rather, this verification should be based on spatial datasets using historical data with the same spatial resolution as the *RCMs* in order to test the model performance on current climate as a measure of its accuracy of predicting future changes. These datasets are typically still based on point measurements, but there are known shortcomings of this approach, especially in areas with low density of measurement stations (e.g. Haylock et al., 2008; Lenderink, 2010). Radar rainfall data is expected to be able to provide better estimates of precipitation for these gridded datasets. An example of such an application is Kendon et al. (2014), where a high resolution model (1.5 x 1.5 km grid size) covering part of the UK is validated against a 9-year series of radar rainfall data, because a suitable gridded dataset cannot be constructed based on point measurements. Similar datasets are being constructed for other regions (Overeem et al., 2009a; Thorndahl et al., 2014b; Wright et al. (2014b); Berg et al., 2015; Goudenhoofdt and Delobbe, 2016). Climate change models with this high resolution can provide much better physical description of the climatic changes of sub-daily extreme precipitation in high spatial resolution (Tabari et al., 2016) and hence such uses are clearly an emerging field for radar applications in urban hydrology.

As radar data quality improves, it can also be directly used to estimate precipitation extremes, for example in the form of traditional *intensity-duration-frequency* curves (e.g. Overeem et al., 2009b, 2010; Marra and Morin, 2015; Paixao et al., 2015). For small-scale urban applications this requires an understanding of the spatial rainfall variability at the radar subpixel scale. Recent advances in stochastic space-time rainfall modelling allow the quantification of this subpixel variability explicitly and the generation of ensembles of *IDF* curves at radar subpixel scale which remove the bias in radar *IDF* curves (Peleg et al., 2016). This can be of major importance for very local estimates of rainfall extremes from radar data.

3.2 Re-analysis of damaging extreme events

Re-analysis of extreme events was mentioned in Einfalt et al. (2004) as an important field of application of radar rainfall and a field where good approaches had been developed. The continued development of radars have enabled very accurate re-analyses of historical events (Jessen et al., 2005; Smith et al., 2013; Yang et al., 2013; Thorndahl et al., 2014a, 2014b; Wright et al., 2014a, 2014b).

Slettet: The long-term analysis of single- or multi-site rain gauges continues to receive substantial hattention in the design and analysis of urban water infrastructure, both for quantifying uncertainty and for studying non-stationary behavior (e.g. Ntegeka and Willems, 2008; Madsen et al., 2009; Willems, 2013a, 2013b; Gregersen et al., 2014). However, the field of assessing future precipitation extremes due to anthropogenic climatic changes is heavily dependent on spatially distributed information on precipitation quantities. Previously, Areal Reduction Factors were appliedproved to be sufficient to account for describe the spatial distribution of extremes (e.g. Sivapalan and Blöschl, 1998 and Vaes et al., 2005), but the *Global Circulation Models (GCM)* used to describe anticipated future climatic changes require spatially distributed precipitation estimates for verification purposes. Such datasets are therefore set up with historical data with the same spatial resolution as the *GCMs* in order to test the model performance on current climate as a measure of its accuracy of predicting future changes. These datasets are typically still based on point measurements, but there are known shortcomings of this approach, especially in areas with low density of measurement stations (e.g. Haylock et al., 2008; Lenderink, 2010). Radar rainfall data is expected to be able to provide better estimates of precipitation for these gridded datasets. An example of such an application is Kendon et al. (2014), where a high resolution model (1.5 by 1.5 km grid size) covering part of the UK is validated against a 9- year series of radar rainfall data, because a suitable gridded dataset cannot be constructed based on point measurements. Similar datasets are being constructed for other regions (Overeem et al., 2009; Thorndahl et al., 2014b; Wright et al., 2014; Berg et al., 2015; Goudenhoofdt and Delobbe, 2016). Climate change models with this high resolution can provide much better physical description of the climatic changes of sub-daily extreme precipitation in high spatial resolution (Tabari et al., 2016) and hence such uses are clearly an emerging field for radar applications in urban hydrology.¶
As radar data quality improves, it can also be directly used to estimate precipitation extremes, for example in the form of traditional *intensity-duration-frequency* curves (e.g. Overeem et al., 2009b, 2010; Marra and Morin, 2015;¶ ...

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The field of distributed 1D-2D hydraulic/hydrological models for urban flood simulations have matured and standard methods have been developed (e.g. Zhou et al., 2012, Henonin et al., 2013). The state of the art described in these papers use point rainfall statistics as opposed to spatial rainfall inputs. Since, there is a large uncertainty of estimating volume estimates for high return periods it is argued that the error not including spatial variability of rainfall within the catchment is minor. However, recent studies have also partitioned the contribution of spatial and temporal variability in rainfall to urban flow quantiles, and shown that spatial rainfall variability does matter, especially for high return periods (e.g. Peleg et al., 2016a).

3.3 Urban water management

The paradigm of using point rainfall data from rain gauges at very high temporal resolution, assuming it to be representative of an entire urban catchment is challenged by several factors. First, rainfall data from high resolution radar have shown high spatial variability at the intra-urban scale. Moreover, many cities experience substantial development in the form of urban sprawl. This leads to very large cities, where uniform precipitation cannot be assumed, because the catchment size is larger than the spatial representativeness of point precipitation. Hence, there is a far more complex hydrological response from large urban and peri-urban areas compared to smaller urban areas.

Another driver is the climate change adaptation needs of larger cities. Many countries and regions explicitly mention Nature Based Solutions or Sustainable Urban Drainage Systems, as a very important component in this adaptation, including countries and regions such as China, EU, and Australia. These wetlands, rain gardens, soakaways etc. are making the hydrological response of cities more complex. Hence, there is a need for generating spatially distributed rainfall series in high resolution in space and time. As mentioned in Section 3.1, such series are becoming available in a few places based on radar measurements. Means to develop artificial series based on stochastic properties are being investigated (e.g. Raut et al., 2012 and Sørup et al., 2015), but there is a long way to go before standard procedures have been identified. Over time, these procedures will most certainly be based on spatially distributed rainfall observations such as radar rainfall observations.

3.4 Nowcasting and operational warning

With a higher risk of damage due to heavy rainfall in urban areas as a consequence of climate change and increased urbanization, there is a motivation to develop reliable warning systems, which have a higher level of detail regarding urban hydrology than traditional numerical weather prediction model forecasts of heavy rainfall, cloud bursts, hurricanes, etc. The evolution in computational power and models enables operational weather models to provide finer resolutions than just a few years ago. However, neither temporal resolution nor spatial resolution are currently fine enough to resolve rainfall sufficiently for many urban hydrological applications (e.g. Thorndahl et al., 2016). Furthermore, numerical weather prediction models may still have offsets of tens of kilometers in terms of predicting the exact location of a rain cell. This constitutes a significant problem in applying weather model data for urban hydrological systems, where the location of heavy rainfall is key. For short lead times this problem can to some extent be solved by assimilating radar nowcasts into numerical weather prediction models in order to improve initial conditions of the latter (e.g. Stephan et al., 2008; Dixon et al., 2009;

Slettet: The state of the art described in these papers use point rainfall statistics, mainly because the uncertainty of estimating volume estimates for very high return periods supersedes the uncertainty related to the internal dynamics of how to distribute this rainfall estimate within the catchment.

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Jensen et al., 2015). Operational systems with assimilation of radar data are rare, so in order to issue valid urban hydrological warnings, it can be beneficial to have 1) on-line rainfall estimates at high temporal and spatial resolution from radars and potentially also nowcasted data, as well as 2) on-line information on the current state of the hydrological system, e.g. baseflow, soil saturation, residual storage capacity, etc.

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Examples of operational warnings systems based on radar data are: local flood warning systems, systems for emergency planning in case of flooding, warning systems for capacity of receiving waters, etc. Operational warning systems based on radar observations have potential in rainfall warnings if radar rainfall estimates exceed a specified threshold (e.g. Einfalt and Luers, 2015) or as hydrological warnings where radar observations (or nowcasts of radar data) are applied as input to an on-line hydrological model as described above. With regards to the latter there are still rather few applications of operational on-line distributed 2D or 1D-2D flood warning models, since they tend to be too computationally expensive to run in real-time. Instead simplified lumped models or 1D-models are often applied (Bell and Moore, 1998; Sharif et al., 2006; Javier et al., 2007; Smith et al., 2007; Fang et al., 2008; Einfalt et al., 2009; Duncan et al., 2013; Wolfs and Willems, 2017).

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In the literature, there are various examples of real-time operation of urban drainage models, which are applied to warn if flow, water level, CSO volume, storage filling, etc. exceeds certain thresholds, e.g. Yuan et al. (1999), Vieux and Bedient (2004a, 2004b), Vieux et al. (2008), Achleitner et al. (2009), Liguori et al. (2012), Liguori and Rico-Ramirez (2012), Schellart et al. (2012a), Dirckx (2013), Thorndahl et al. (2013), Thorndahl and Rasmussen (2013), Löwe et al. (2014), Schellart et al. (2014), and Löwe et al. (2016). Several of these are pre-operational and have studied the potentials of applying radar data (with or without nowcasting) in real-time prediction of sewer system states.

Slettet: combined sewer overflow

Simulation of the probabilistic urban rainfall nowcasts in urban drainage models allows probabilistic nowcasts to be obtained of the inundation hazards and risks in urban areas. Ntegeka et al. (2015) have shown how probabilistic urban inundation risk maps can be obtained by combining STEPS-based rainfall nowcasts with a nested 1D-2D sewer hydraulic and surface inundation model, and a model to assess the damages and social consequences of the urban inundations (Van Ootegem et al., 2016). Such a system, however, only becomes useful for operational management when the uncertainties in the inundation risks can be communicated in a compact and clear way, and when these are informative and manageable by decision makers or the wider public.

Slettet: (Van Ootegem et al., 2017).

An example of a runoff forecasting system is provided in figure 3. The figure illustrates differences between runoff simulation with radar observations, a deterministic radar nowcast as well as a probabilistic nowcast with 300 ensemble members for forecast lead times of 10, 30 and 60 minutes.

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3.5 Operational real-time control

Model based real-time control of urban drainage systems has evolved significantly during the past decade. Many model based real-time control methods were developed for applications with on-line in-sewer instrumentation or rain gauges for local systems (e.g. Schütze et al., 2004). With advances in estimating spatially distributed rainfall with radars, it is possible to implement real-time control on a much larger scale, e.g. a whole city. By exploiting the spatial variability of rain and

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successive unequal local loading of the hydrological systems, novel developed methods aim at utilizing spare capacity systems in order to reduce spills, overflows, flooding, etc. (e.g. Faure and Auchet, 1999; Pfister and Cassar, 1999; Mounce et al., 2014).

Other real-time control applications have been used to estimate the loads on waste water treatment plants in order to reduce spills of untreated waste and stormwater and to optimize treatment processes during rain (Quirmbach and Schultz, 1999; Fuchs and Beeneken, 2005; Thorndahl et al., 2013; Vezzaro and Grum, 2014a; Kroll et al., 2016). With large linked hydrological systems, centralization of treatment plants in urban areas, advances in model predictions and data, there seems to be a large potential for global predictive control of hydrological systems in cities, which is not yet fully exploited.

4 Summary and recommendations

This paper summarized literature findings from the last decade in three key research areas: *temporal and spatial radar rainfall resolution in relation to their use in urban hydrology*, *radar rainfall data adjustment and quality*, and *use of radar data for rainfall nowcasting and on-line applications*.

In the following, we summarise emerging developments and applications of radar rainfall in urban hydrology that were identified in this review and provide recommendations for future research as well as practical recommendations for the application of radar rainfall in urban hydrology:

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1. *Radar resolution*

   A recent and promising development is the installation of X-band polarimetric radars in urban areas, providing high resolution rainfall estimates, typically at or below 1 minute and 100 meters, but with a shorter range than C- and S-band radars. While X-band radar is sensitive to attenuation due to its frequency band, the use of polarimetric signals provides additional parameters insensitive to attenuation, thus solving an important problem associated with X-band radars. While dual polarimetric radars are capable of providing an independent rainfall product, single polarimetric X-band radars on the other hand, require extensive post-processing incorporating data from additional sensors to obtain reliable, high resolution rainfall estimates. In S- and C-band radar networks, high resolution products are starting to be developed, based on for instance compressed pulse lengths. This reveals a transition from use of primarily research radars with high resolution to more operational products from meteorological services focusing also on high resolution for urban hydrological application.

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   Where high resolution radar rainfall products are not available, spatial and temporal downscaling (advection interpolation) is applied to obtain higher resolution rainfall estimates, starting from coarse resolution radar products. Downscaling can be based on physical processes or on stochastic principles, the latter being more flexible for including uncertainty, and being less computationally intensive, but also having more difficulty in reproducing the natural, physical structure of storms.

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2. *Radar data adjustment and rainfall data quality*

Radar rainfall estimates suffer from uncertainties associated with variability in drop size distribution, partial beam filling, overshooting, and signal attenuation. One way to reduce these uncertainties is by using polarimetric signals, another way is by reducing distance to the radar, by increasing the density of the radar network. Both require significant investments and in many situations are not foreseen in the near future. This implies that radar data adjustment based on a network of rain gauges will still be required to reduce radar rainfall uncertainty. The quality of radar data adjustment in turn depends on the density and quality of the rain gauge network. The optimal temporal integration period or spatial aggregation level for radar adjustment is directly related to the ability of the rain gauge network to capture the temporal and spatial rainfall variability. It is difficult to recommend specific gauge network densities for radar rainfall adjustment since the optimal value will depend on storm type, homogeneity of the rain gauge network, orographic features, adjustment methods, etc. as well as the specifications of the urban hydrological application. In many studies simple mean field bias adjustment between radar and rain gauges has proven sufficient and robust which is probably also the reason that this method is applied in many operational systems. At present, the more advanced geostatistical approached to bias adjustment are mostly applied within the research community.

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3. *Nowcasting of rainfall and on-line applications*

Whereas numerical weather forecast models have too coarse a spatial and temporal resolution for reliable forecasts in urban hydrological applications, the use of short-term forecasting (nowcasting) of radar rainfall shows potential in many on-line urban hydrological applications with warning systems or real-time control of urban hydrological systems. Currently, there are some drawbacks with pure radar extrapolation methods in terms of predicting convective rainfall with rapidly evolving storm structure evolution. In order to overcome these problems stochastic blending of radar rainfall observations/extrapolations with numerical weather prediction models ensembles shows potential for fast hydrological response systems. Given the high nowcasting uncertainties, the explicit consideration of these uncertainties, e.g. by means of stochastic modelling approaches, is important.

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Pluvial flood warning for small urban catchments based on critical rainfall thresholds or pluvial flood warning based on real-time urban hydrological modelling are expected to be developed significantly in forthcoming years in order to adapt to climate changes and increased urbanization.

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For urban hydrological applications in general, higher resolution and higher accuracy rainfall estimates are beneficial for a better understanding of the hydrological response. Higher accuracy comes with required investments in equipment (X-band radar, polarimetric capability or dense rain gauge network for adjustment) that need to be justifiable either from a research or a societal perspective (higher efficiency of operational control, more accurate early warning). Some general recommendations can be derived from the recent literature as to requirements for radar rainfall resolution: studies have shown that the sensitivity of hydrological response and thus added value of higher resolution rainfall data input increases for smaller catchment size, larger catchment spatial variability, smaller storm size, larger storm variability and higher storm

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movement velocity. An important consideration here is that accuracy of rainfall estimates generally decreases for higher resolution: accuracy of storm total rainfall is typically much higher than for 5-15 minute rainfall estimates, the same applies for spatial aggregation levels. Conversely, higher rainfall measurement resolution results in higher accuracy of rainfall estimates than if rainfall estimates are derived from coarse resolutions. In applications, a balance will always be needed between the benefit of higher accuracy and the required investment obtaining such accuracy. In a nowcasting and near real-time context, challenges are even higher, because data correction and adjustment windows are typically short, while false early warnings can have large societal impacts.

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Whereas the initial word of the title of the Einfalt et. al. 2004 paper (*Towards a roadmap for use of radar rainfall data in urban drainage*) suggested a progression, this paper has demonstrated that radar rainfall data presently is applied in many operational systems and that radar has become an invaluable source of data along with other types of observations applied in urban hydrology. This said, there is still research to be conducted in order to improve radar rainfall estimates, e.g. especially with regard to dual-polarimetry, uncertainty assessment and generation of realistic ensemble forecasts, combined radar and weather model rainfall products, and real-time applications.

5 Author contributions

S. Thorndahl coordinated the joint collaboration and developed the greater part of the manuscript with partial contributions from other co-authors on: radar uncertainties and data quality (T. Einfalt); nowcasting, real-time applications and uncertainties (P. Willems); spatial and temporal resolution (J.E. Nielsen); X-band polarimetry, summary and recommendations (M.-C.t Veldhuis); off-line applications and future outlooks (K. Arnbjerg-Nielsen); technical radar specifications (M. R. Rasmussen); and radar rainfall extremes and proofreading (P. Molnar).

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Tables

Table 1. Most cited papers within radar and urban drainage

	Paper title	Citations Scopus[1]	Citations Web of Science[1]
Einfalt et al. (2004)	Towards a roadmap for use of radar rainfall data in urban drainage	94	81
Smith et al. (2002)	The Regional Hydrology of Extreme Floods in an Urbanizing Drainage Basin	85	76
Schilling (1991)	Rainfall data for urban hydrology: what do we need?	81	76
[1] per 01 February 2017			

Slettet: 88

Slettet: 75

Slettet: 84

Slettet: 76

Slettet: 71

Slettet: October

Slettet: 2016

Table 2. Typical operating resolutions and maximum ranges for different types of weather radars used in hydrological applications.

	X-band	C-band	S-band
Spatial resolution	100-1000 m	250-2000 m	1000-4000 m
Temporal resolution	1-5 min	5-10 min	10-15 min
Maximum quantitative range	30-60 km	100-130 km	100-200 km

Table 3. Application fields for radar rainfall in urban hydrology. Applications that have emerged significantly since Einfalt et al. (2004) are marked with bold. Numbers in parenthesis indicate which sub-section discusses the particular application.

Off-line applications	On-line applications
- General statistical and hydrometeorological characterization of precipitation at urban scale (4.1) - Present climate - **Extremes** - **Future climate** - Re-analysis of damaging extreme events (4.2) - Insurance claims - **Hydrological re-analysis of flood events** - **Distributed hydrological modelling for flood risk assessment** - Urban water management (4.3) - Design of basins and pipes - **Resilience and livability measures**	- **Nowcasting and operational warning (4.4)** - Severe rainfall warning - **Flow/flood warning based on on-line hydrological models** - **Operational real-time control of hydrological systems (4.5)** - Nowcasting - Real-time hydrological models with data assimilation - **Scenario/ensemble modelling for on-line evaluation of control strategies**

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Figures

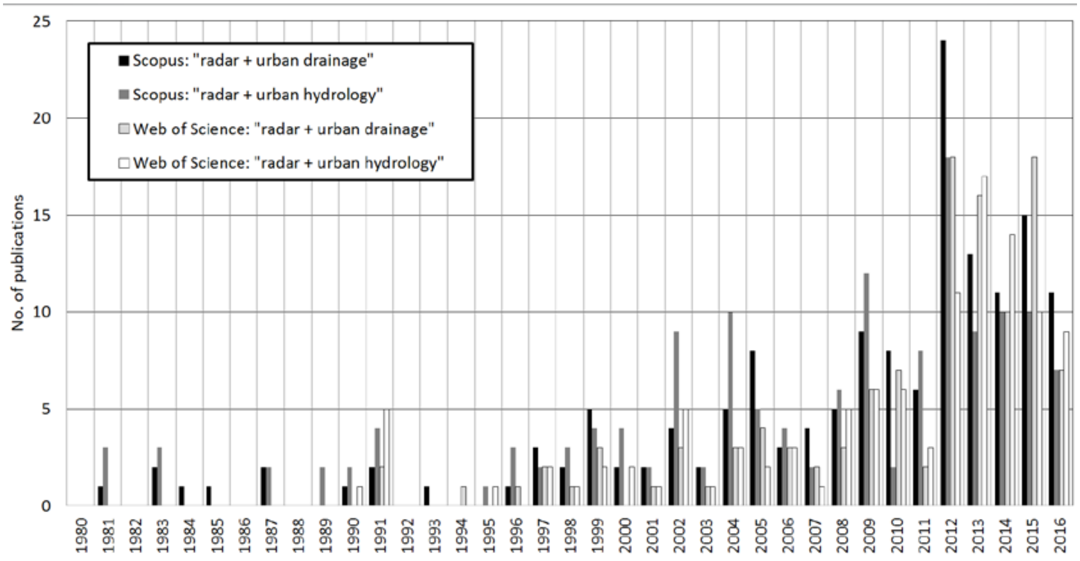
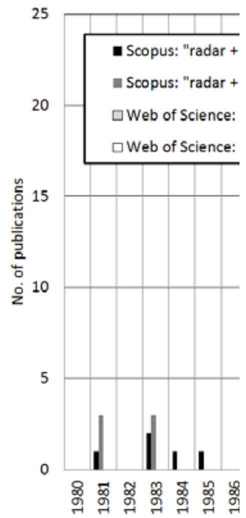


Figure 1: Scopus and Web of Science documents under search strings "*radar + urban drainage*" and "*radar + urban hydrology*".



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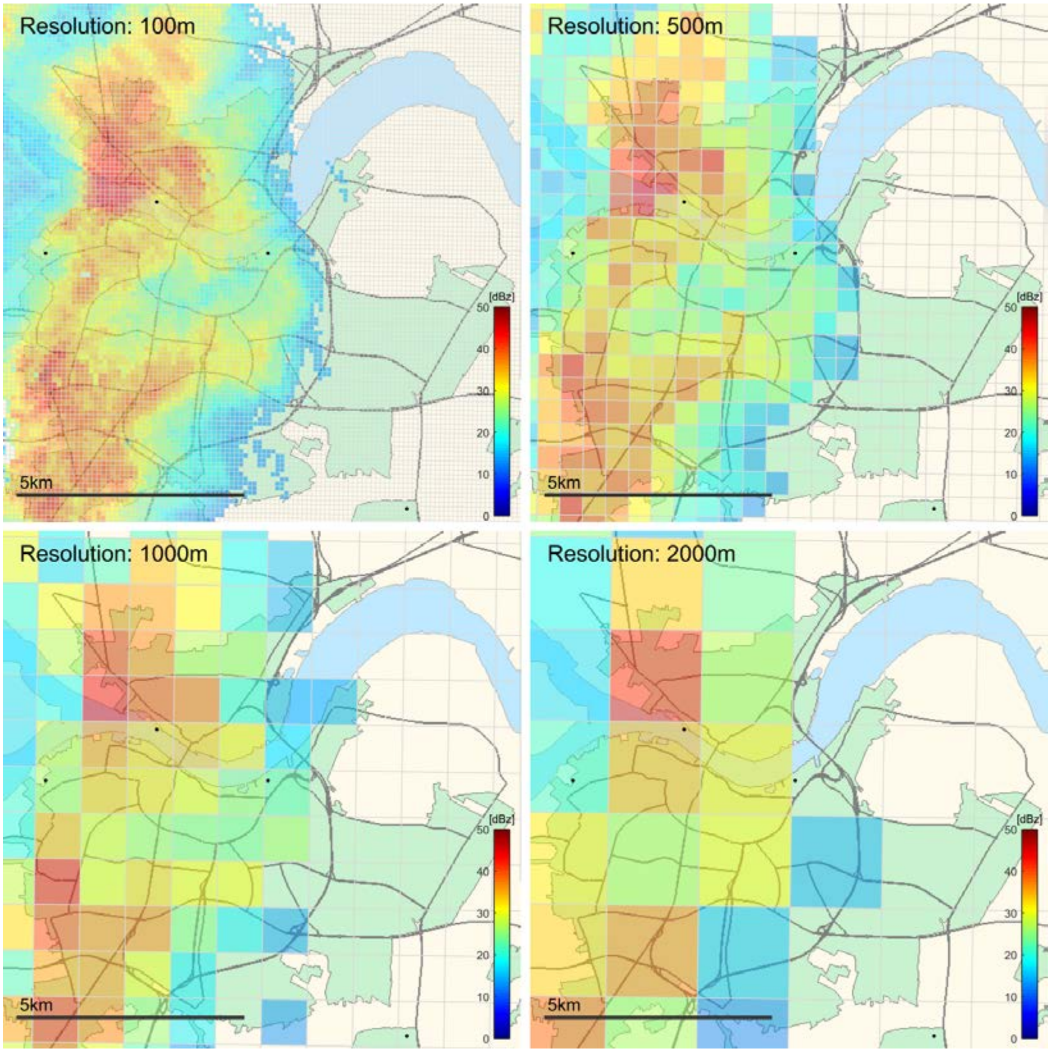

Figure 2: Example of radar reflectivity in four different cartesian spatial resolutions over Aalborg, Denmark (Lat: 57.05, Lon: 9.92). The radar data is acquired with a Furuno WR-2100 dual-polarimetric X-band radar (Nielsen et al., 2015) in 1 min. temporal resolution at 16:20:00 UTC on July 25, 2016. Black circles are rain gauges of the Danish Water Pollution Committee network.

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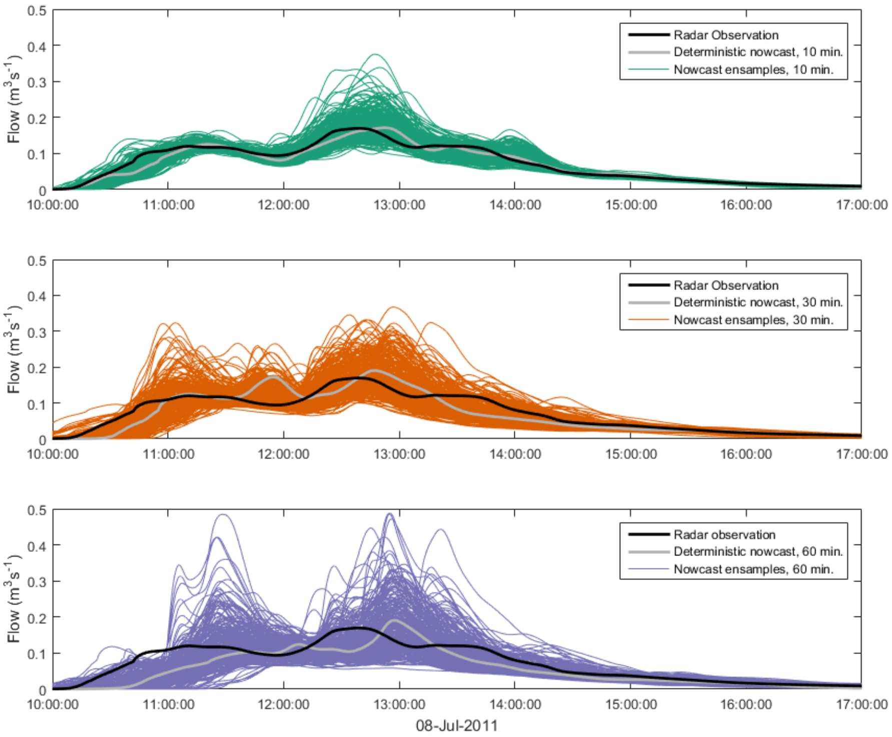

Figure 3: Examples of runoff forecast prediction in an urban drainage system in Frejlev, Denmark using a radar ensemble nowcast algorithm (Jensen et al., n.d.) An ensemble of 300 nowcasts, a deterministic nowcast, and observed radar data are applied as inputs to an urban drainage model (Thorndahl et al., 2006, Thorndahl and Rasmussen 2013) covering an area of 0.8 km2 with an impervious area of approx. 40 %. Six radar pixels with a 2x2 km2 resolution cover the area. The radar is operated by the Danish Meteorological Institute. Maximum observed rainfall intensities are 6 mm/h and the observed accumulated rainfall is 11.2 mm. It is evident that there is a significant increase in the ensemble spread as a function of the different shown forecast lead times of 10, 30 and 60 minutes, respectively.

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