Comments: Reply to Reviewer #1

General

The manuscript entitled "Spatial and temporal variability of rainfall and their effects on hydrological response in urban areas - a review" by Cristiano et al. provides a literature review of the current understanding of hydrological processes in urban environments with a focus on spatial and temporal variability and scales. It is well written and understandable and would fit well into the scope of HESS special issue on rainfall and urban hydrology. I found no major issues or concerns to be addressed while reading the manuscript, but I have some suggestions of expending the content discussed in part of the sections. Please find my comments, corrections and suggestions below.

Specific comments [Page; Lines]

Thank you for catching the typo mistakes. They have been corrected

[1; 19-20] For that you can also add the relatively new use of high-quality imagery from unmanned aerial vehicles (UAVs). See the paper by Tokarczyk et al. (2015).

Tokarczyk, P., Leitao, J. P., Rieckermann, J., Schindler, K., and Blumensaat, F.: High-quality observation of surface imperviousness for urban runoff modelling using UAV imagery, Hydrol. Earth Syst. Sci., 19, 4215-4228, doi:10.5194/hess-19-4215-2015, 2015.

Thank you for the suggestion. The reference has been added.

[2; 5] "many aspects" – such as?

The ambiguous sentence was rephrased as follows: "Despite these efforts, many aspects of hydrological processes in urban areas remain poorly understood, especially concerning the interaction between rainfall and runoff".

[2; 13-14] "Section 7, main knowledge gaps are identified for the with respect to accurate

prediction" – please revise.

The sentence was corrected: "In Section 7, main knowledge gaps are identified with respect to …"

[3; 3] The title is not completely accurate as you specifically refer to downscaling and upscaling of climate variable to be used as input into hydrological models.

Thank you for the suggestion. The title was changed as suggested:" Downscaling and upscaling of climate variables used as input for hydrological models"

[3; 9] "meteohydrology" – I believe that the term "hydrometeorology" is more common.

Thank you. The term "hydrometeorology" is now used

[3; 13] "Muthusamy et al., 2016" – this paper discusses upscaling rather than downscaling. I suggested changing the beginning of the sentence to "Statistical downscaling and upscaling approaches … ".

Thank you for the correction. The cited reference is indeed referring to upscaling. The sentence was rephrased as suggested.

[3; 14] In addition to the paper by Wilby and Wigley (1997) I would also suggest the authors to add the review paper of Wilks and Wilby from 1999 and the (relatively newer) paper by Fowler et al (2007). After all, this is a review paper that should cover the benchmarked papers in the field.

Fowler, H. J., Blenkinsop, S., and Tebaldi, C.: Linking climate change modelling to impacts studies: recent advances in downscaling techniques for hydrological modelling, International Journal of Climatology, 27, 1547–1578, doi:10.1002/joc.1556, 2007.

Wilks, D. S. and Wilby, R. L.: The weather generation game: a review of stochastic weather models, Progress in Physical Geography, 23, 329–357, 1999.

Thank you for the good suggestions. The references have been added.

[3; 18-19] I believe that some progress has been made in the AR methods that are being used to generate distributed rainfall since the papers of Ferraris (2003) and Schertzer and Lovejoy (2011). I would suggest the authors to modify the sentence in lines 18-19 to account for some of the relatively new publications in the field. Maybe something like: "Autoregressive methods, also refer to nowadays as "rainfall generator models", are used to generate multidimensional random fields while preserving the rainfall spatial autocorrelation (e.g. Paschalis et al., 2013; Peleg and Morin, 2014; Niemi et al., 2016)".

The three references represent the state of the art high resolution rainfall generator that are now available: STREAP (Paschalis), HiReS-WG (Peleg) and STEPS (Niemi). To that you can probably add the paper by McRobie et al. (2013) in which they extended the earlier Willems model to generate spatially distributed Gaussian rainfall cells (alternatively, this can go to the last model type you are suggesting in this paragraph).

Paschalis, A., Molnar, P., Fatichi, S., and Burlando, P.: A stochastic model for high resolution space-time precipitation simulation, Water Resources Research, 49, 8400– 8417, doi:10.1002/2013WR014437, http://dx.doi.org/10.1002/2013WR014437, 2013.

Peleg, N. and Morin, E.: Stochastic convective rain-field simulation using a high-resolution synoptically conditioned weather generator (HiReS-WG),Water Resources Research, 50, 2124–2139, doi:10.1002/2013WR014836, http://dx.doi.org/10.1002/2013WR014836, 2014.

McRobie, F. H., Wang, L.-P., Onof, C., and Kenney, S.: A spatial-temporal rainfall generator for urban drainage design, Water Science and Technology, 68, 240–249, doi:10.2166/wst.2013.241, 2013.

Niemi, T. J., Guillaume, J. H. A., Kokkonen, T., 5 Hoang, T. M. T., and Seed, A. W.: Role of spatial anisotropy in design storm generation: Experiment and interpretation, Water Resources Research, 52, 69–89, doi:10.1002/2015WR017521, http://dx.doi.org/10.1002/2015WR017521, 2016.

Thank you for the useful suggestion. The first sentence has been rephrased as suggested: "Autoregressive methods, nowadays often referred to as "rainfall generator models" are used to generate multidimensional random fields while preserving the rainfall spatial autocorrelation (Paschalis et al., 2013; Peleg and Morin, 2014; Sørup et al., 2015; Niemi et al., 2016).", and the paper by McRobie et al. (2013) was added as reference to the last model type.

[4; 8-10] There is a repetition with the previous sentence.

The sentence was indeed repetitive and has been removed

[4; 30-31] "… as, for example the approximation presented by Gericke and Smithers (2014), for which tlag = 0.6tc" – consider deleting this sentence, I don't see how this example can contribute to the reader.

We agree with the reviewer that the sentence was not adding value and removed it.

[5; 9] "… the behaviour of four Israelian catchments" – instead: "… the behaviour of four rural catchments in Israel".

Thank you for the correction. The sentence was corrected as suggested

[6; 3] You are referring to five papers as an example to "urban catchments" while not referring at all to studies on "natural watershed", although there are plenty of papers to choose from. I would suggest adding 2-3 references to benchmark papers discussing the use of weather radar in rural catchments as well. If already mentioning papers that are related to radar and urban hydrology, there is also the paper by Thorndahl et al (2016) which is part of the special issue and I think should also be mention in this review paper.

Thorndahl, S., Einfalt, T., Willems, P., Nielsen, J. E., ten Veldhuis, M.-C., Arnbjerg-Nielsen, K., Rasmussen, M. R., and Molnar, P.: Weather radar rainfall data in urban hydrology, Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-517, in review, 2016.

Thank you for this suggestion. The suggested reference was added, but we preferred not to add references related to natural basins, in order to keep the focus on urban areas.

[6; 8-9] Consider also to add to this references the paper by Fencl et al. (2016), which is going to be published as part of this special issue.

Fencl, M., Dohnal, M., Rieckermann, J., and Bareš, V.: Gauge-Adjusted Rainfall Estimates from Commercial Microwave Links, Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess- 2016-397, in review, 2016.

Thank you for suggesting the reference. It has been added.

[6; 20-21] "To solve the problem of spatial representation, interpolation techniques are used to obtain distributed rainfall fields…" – good. But sometimes you wish to do the opposite, go from a data obtained by a dense rain—gauge network to the areal rainfall that represents the catchment. This is the upscaling paper by Muthusamy et al. (2016) that was mentioned on [3; 13].

Thank you for the comment. The sentence was revised taking into account the suggested reference.

[6; 25-26] "A second problem is introduced by hard surfaces, that may cause water splashing into the gauges" – I thought that the recommendation of the WMO are to mount the gauges at an elevation of 1.2 m above ground. If this is the case, I don't think water splashing is an issue.

The sentence was rephrased as follows: "..water splashing into the gauges, if it is not placed at an elevation of at least 1.2m."

[7; 6-7] Consider presenting the comparison between the different band widths in a table. Maybe add price estimation for each radar type?

Thank you for the suggestion. A table summarizing the properties of radars has been added. Prices vary wildly due to many factors and would not be included.

[7; 14] Limitations of rain—gauges are not discussed in this section. Please remove "abd rain gauges" from the section title.

The title has been changed as suggested

[7; 19-20] "…and to define the uncertainty related to radar-rainfall estimation (Mandapaka et al., 2009; Overeem et al., 2009a)" – I suggest the authors to remove the reference to Overeem from this sentence (but to keep this reference when it cited next in the paragraph) and to replace it with other studies that were more focusing on rainfall radar uncertainties, such as: Ciach and Krajewski (1999), Villarini et al. (2008) and Peleg et al. (2013).

Ciach, G. J. and Krajewski, W. F.: On the estimation of radar rainfall error variance, Adv. Water Resour., 22, 585–595, doi:10.1016/s0309-1708(98)00043-8, 1999.

Villarini, G., Mandapaka, P. V., Krajewski, W. F., and Moore, R. J.: Rainfall and sampling uncertainties: A rain gauge perspective, J. Geophys. Res.-Atmos., 113, D11102, doi:10.1029/2007jd009214, 2008.

Peleg, N., Ben-Asher, M., and Morin, E.: Radar subpixel-scale rainfall variability and uncertainty: lessons learned from observations of a dense rain-gauge network, Hydrology and Earth System Sciences, 17, 2195–2208, doi:10.5194/hess-17-2195-2013, 2013.

Thank you for the good comment. The suggested references are indeed interesting for the study of rainfall radar uncertainties. They have been added as suggested.

[7; 32-33] A repetitive sentence. Consider deleting.

The sentence was deleted as suggested.

[8; 7-8] I think that an operative rainfall forecast based on weather radar has been activated in Belgium (using STEP model). Please check the following paper: Foresti, L., M. Reyniers, A. Seed, and L. Delobbe. "Development and verification of a realtime stochastic precipitation nowcasting system for urban hydrology in Belgium." Hydrology and Earth System Sciences 20 (2016): 505-527.

Thank you for suggesting this reference. It was added and the sentence was rephrased as follows:" Radar data can provide an accurate short term forecast and recent studies have presented nowcasting systems able to reduce errors in rainfall estimation (e. g. Foresti et al. 2016)."

[8; 10-12] Pollution due to urbanization also affects rainfall. Check for example the paper mention below. I would also suggest add to modify the sentence in line 11 accordingly: "Increase in heat and pollution produced by human activities …".

Givati, A., & Rosenfeld, D. (2004). Quantifying precipitation suppression due to air pollution. Journal of Applied meteorology, 43(7), 1038-1056.

Thank you for suggesting this reference. It has been added. Following the suggestion of reviewer #2 paragraph "Influence of urban areas on rainfall" has been removed and summarised at the beginning of section 3. "Urban areas affect the local hydrological system, not only by increasing the imperviousness degree of the soil, but also by changing rainfall generation and intensity patterns. Several studies show that increase in heat and pollution produced by human activities and changes in surface roughness influence rainfall and wind generation (Huff:1973, Shepherd:2002, Givati:2004, Shepherd:2006, Smith:2012, Daniels:2015, Salvadore:2015). This phenomenon is not deeply investigated in this paper, but it is an important aspect to consider."

[9; 6-23] This read to me as a separate subsection, entitled as "rainfall variability at the urban scale", or alike.

Thank you for the suggestion. The 2 sections have been separated as suggested

[9; 16-17] Not necessarily, the setup needed for deployment of a dense rain-gauge network at the urban scale that can well represent the rainfall spatial variability can be calculated using the variance reduction factor. See papers by Villarini et al. (2008) and Peleg et al. (2013) that were suggested above.

Thank you for the constructive comment. The paragraph has been revised; the following text was added taking into account the suggested references: "An alternative solution is to consider the variance reduction factor method, a numerical method to represent the uncertainty from averaging a number of rain gauges per pixel, taking into account their spatial distribution and the correlation between them. The variance reduction factor method was introduced for the first time by Rodriguez-Iturbe and Mejıa (1974) and lately applied in various studies (Krajewski et al., 2000; Villarini et al., 2008; Peleg et al., 2013)."

[9; 23] Please also have a look at the recent paper by Peleg et al., whom examined the spatial distribution of extreme rainfall intensity for the same scale and using similar methods (but with different rainfall model) as Gires et al. mentioned here. They found that the spatial distribution of extreme rainfall over small domains (1 x 1 km2) can be very high.

Peleg, N., Marra, F., Fatichi, S., Paschalis, A., Molnar, P., and Burlando, P.: Spatial variability of extreme rainfall at radar subpixel scale, Journal of Hydrology, doi:doi:10.1016/j.jhydrol.2016.05.033, 2016.

This reference has been added and discussed as follows: "Similar results are confirmed by Peleg et al. (2016), who studied the spatial variability of extreme rainfall at radar subpixel scale. Comparing a radar pixel of 1kmx1km with high resolution rainfall data, obtained by applying the stochastic rainfall generator STREAP (Peleg et al., 2013) to simulate rain fields, this study highlights that subpixel variability is high and increases with increasing of return period and with shorter duration."

[9; 27] What do you mean by common? C-band radars?

The word common was replaced with operational.

[10; 27-28] Please delete. It repeats what is already mention.

The sentence was deleted, as suggested.

[10; 29] Consider changing the title to: "Groundwater recharge and subsurface processes in urban areas". Infiltration is already discussed in the previous paragraph.

The title has been changed as suggested.

[11; 10-12] Please revise this sentence.

The sentence was rephrased as follows:" Several types of pervious pavements are used in urban areas. They can generally be separated in monolithic and modular structures. Monolithic structures consist of a combination of impermeable blocks of concrete and open joints or apertures that allow water to infiltrate. In the modular structures, gaps between two blocks are not filled with sand, as with conventional pavements,…."

[13; 20] A reference is needed here.

The requested reference was added.

[13; 21] Delete "Recent", a study from 1991 cannot be consider as recent…

The word "recent" was replaced by "some"

[13; 30] Why the catchments need not to be placed on concrete or asphalt?

The sentence has been removed.

[15; 2-7] Please give references and examples to the two types of models used in urban studies.

The sentence has been removed as suggested by reviewer # 2, because it is considered ambiguous and not clear.

[16; 14-18] Please indicate full names for UDTM and EPA SWMM models. A reference for the SWMM model should also be added.

The full name of the 2 models and the reference for the SWMM model have been added.

[16; 2-24] It can be useful to add a table with the most common hydrodynamic models that are been used in urban studies (including full name, abbreviation, reference and the model type).

Thank you for this suggestion. A similar and exhaustive table was already presented in Salvadore et al. (2015). We decided to refer to this paper, instead of inserting a similar table in our manuscript: "A good summary of the most used urban hydrological models is presented by Salvatore et al. (2015), where a table containing 43 numerical studies highlights the model characteristics."

[17; 12] There is another relevant paper that is a part of this special issue (see below). It deals with the effect of spatially distributed rainfall on the flow total variability in an urban catchment.

Peleg, N., Blumensaat, F., Molnar, P., Fatichi, S., and Burlando, P.: Partitioning spatial and temporal rainfall variability in urban drainage modelling, Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-530, in review, 2016.

The reference has been added with a few sentences that describe the paper: "To investigate the effects of spatial and temporal variability on urban hydrological response, Peleg et al. (2016 in review) used a stochastic rainfall generator to obtain high resolution spatially variable rainfall as input for a calibrated hydrodynamic model. They compared the contributions of climatological rainfall variability and spatial rainfall variability on peak flow variability, over a period of 30 years. They found that peak flow variability is mainly influenced by climatological rainfall, while the effects of spatial rainfall variability increase for longer return periods."

Figure 2 – Consider changing the pixel to a point for the point value (or add a point within the pixel).

Thank you for the suggestion. The figure has been changed and a point is added within the pixel.

Comments: Reply to Reviewer #2

General comments: This manuscript is a scientific review on the variability of rainfall in urban hydrology. Several review papers have recently been published on urban hydrology in the main journals. An additional one could be interesting if it proposes an original point of view. As far as I know, it seems to be the case for this manuscript. Nevertheless, I consider that the manuscript requires a significant revision before its publication in HESS can be considered. - The manuscript covers a wide range of topics, sometimes from a very general point of view (for instance disaggregation, but not only), and sometimes already very well documented in text books (for instance hydrological processes). It is not consistent with a review paper which should present the state of the art of research on the addressed subject. The authors are recommended to focus on the most original part of the manuscript, for which a review presents an added value. - I have in mind several papers, which address the subject of the manuscript, and which have been omitted. I recommend that the authors provide a more comprehensive and exhaustive state of the art, representative of the recent studies. In addition, the references to studies of urban basins (instead of, or in addition to, natural ones) would be welcome in a manuscript covering urban areas.

Specific comments

p1. 15-18: This sentence is questionable. Hydrologists have been working on rainfall radar measurement for a very long time, and have significantly contributed to this subject, including in urban hydrology (Einfalt et al., 2004 for a review). The cited references are recent and don't reflect this long term research effort which has known a renewed interest with the emergence of polarimetric X-band radars which allow to solve some problems met with classic low-cost radars.

Thank you for the suggestion. We reconsidered the sentences and we agree that the paragraph was not reflecting the long term research effort. We highlighted the emphasis on the long term effort and on the fact that it is not only a recent or future development. The suggested reference (Einfalt et al. 2004) has been added, as well as the recent and interesting paper by Thorndahl et al 2016. The sentence was rephrased as follows: "These developments have been applied in urban hydrology research (for a review Einfalt et al. (2004); Thorndahl et al. (2016)), where the hydrological response is….."

p2. 1-3: I am not sure that it is more complicated, I would say different.

Thank you for pointing out this unclear sentence, the word "complicated" could indeed be ambiguous. The sentence has been changed to: "detention and control facilities, such as reservoirs, pumps and weirs, are additional elements…"

 p3.1-2 : I don't well understand this sentence

The sentence has been rephrased as follows: " Under the best scenario, process and observation scale should coincides, but this is not always the case, and transformations based on downscaling and upscaling techniques (Fig. 2) might be necessary to obtain the required observation scale."

p3. 3-21: Downscaling and upscaling in hydrology: This paragraph is a very brief and general introduction of downscaling methods. It is not very useful for the reader because the authors don't refer to the applications of these methods in urban hydrology, which is the subject of the manuscript.

The paragraph was lacking of specific references. It has been modified, adding the references suggested by reviewer #1(Paschalis et al., 2013; Peleg and Morin, 2014; and McRobie et al. (2013)) and Niemi et al., 2016).

p3. 27-30: the paper by Julien and Moglen (1990) doesn't address the particular case of urban catchments.

The authors agree with this comment. We mentioned the paper by Julien and Moglen (1990) as an example of spatial scale definition, while indicating that it was developed for natural catchments, yet there is no reason it could not be applied to urban catchments. We have revised this section and references to spatial scale definitions used in studies of urban catchments. A new paragraph was added: "In urban catchments, the concept of catchment length, defined as the squared root of the (sub)catchment or runoff area, has been used (Bruni et al. 2015, Ochoa-Rodriguez et al., 2015}. Additionally, Bruni et al. (2015) introduced the sewer length or inter-pipes sewer distance, as the ratio between the catchment area and the total length of the sewer, to characterize the spatial scale of sewer networks."

4. 6-11: I have read the paper by Gericke and Smithers (2014). Their review of the existing methods doesn't address the urban basins.

Thank you for the suggestion. We modified this paragraph, shortened the part dedicated to Gericke and Smithers (2014) and made clear that we mentioned this reference to highlight the difference with urban areas.

p4. 13-14: The production function is very different in natural areas and urban areas. Initial losses don't exceed 1 or 2 mm, and most of the impervious surfaces are directly connected to the hydrographic (or sewer) network. This statement is not valid for urban basins.

The statement was rephrased as follows: "In urban areas, where most of the surface is directly connected to the drainage system, concentration time is given by the time the rainfall needs to enter the sewer system and the time spent in the sewer."

p4. 24: The term response time is also often used; this term may be similar to the response time (Musy, 2011).

We assume the reviewer suggested to consider the response time proposed by Musy and Higy (2010). This reference has been added to the paper.

p4. 32-33: To the best of my knowledge, the paper by Morin et al. (2001) doesn't address urban basins

The work done by Morin et al. (2001) is indeed referring to natural catchments. This paragraph was shortened and the specification that it refers to natural catchments was added. We believe it is important to keep this reference as it has potential for application in urban areas.

paragraph 2.3.2: "time scale characteristics". It is interesting to highlight these terms which characterize the basin dynamics are less used nowadays (see the topic called synthetic hydrology which addresses this subject). In my opinion, there are more or less equivalent, and too many words are used to name very close concepts, which can be confusing. It could be the opportunity to propose one or two terms. I think that most of the papers that are cited (not very recent) don't concern urban basins, which is a problem concerning the subject of this manuscript. I know that similar relations have been proposed (at the same period) in urban hydrology to relate the response (or lag) time of urban basins to the characteristics of basins : surface, imperviousness, slope, roughness . . . I recommend to add references on time scale characteristics that address urban basins.

Thank you for this suggestion. Paragraph 2.3.2 was revised and references related to urban catchments were added, as follows:" In this section, we present a brief overview of time scales reported in the literature and discuss approaches to estimate characteristic time scales that have been specifically developed for urban areas. A summary of time scale characteristics if presented in Table 1. The first method to investigate the hydrological response is the rational method, presented more than a century ago by (Kuichling, 1889) for urban areas. This method was later adapted for rural areas. The rational method requires the estimation of the time of concentration in order to define the runoff volume. Time of concentration tc is one of the most common hydrological characteristic time scales and it is defined as the time that a drop that falls on the most remote part of the basin needs to reach the basin outlet (Singh, 1997; Musy and Higy, 2010). Several equations to estimate this parameter are available in the literature for natural (Gericke and Smithers, 2014) and urban (McCuen et al., 1984) catchments. The time of concentration is difficult to measure, because it assumes that initial losses are already satisfied and the rainfall event intensity is constant for a period at least as long as the time of concentration. Different theoretical definitions have been developed in order to estimate the time of concentration as function of basin length, slope and other characteristics (see for some examples Singh (1976); Morin et al. (2001); USDA (2010); Gericke and Smithers (2014)).

Due to difficulties related to the estimation of time of concentration, Larson (1965) introduced the time of virtual equilibrium t_{ve}, defined as the time until response is 97% of runoff supply. When a given rainfall rate persists on a region for enough time to reach the equilibrium, this time is called time to equilibrium t_e (Ogden et al., 1995; Ogden and Dawdy, 2003; van de Giesen et al., 2005). Time of equilibrium for a turbulent flow on a rectangular runoff plane given rainfall intensity i, with given roughness n, length L_p and slope S can be written as (Ogden et al., 1995):

$$te = [nLp/(S^{1/2}i^{2/3})]^{3/5}$$

Another commonly used hydrological characteristic time scale or response time is the lag time t_{lag}. It represents the delay between rainfall and runoff generation. t_{lag} is defined as the distance between the hyetograph and hydrograph center of mass of (Berne et al., 2004), or between the time of rainfall peak and time of flow peak (Marchi et al., 2010; Yao et al., 2016). t_{lag} can be considered characteristic of a basin, and is dependent on drainage area, imperviousness and slope (Morin et al., 2001; Berne et al., 2004; Yao et al., 2016). Berne et al. (2004), including the results of Schaake and Knapp (1967) and Morin et al. (2001), defined a relation between the dimension of the catchment area S (in ha) and the lag time t_{lag} (in mm): $t_{lag} = 3S^{0.3}$ for urban areas. Empirical relations between t_{lag} and t_c are presented in the literature (USDA, 2010; Gericke and Smithers, 2014).

Another characteristic time scale is the 'response time scale' T_s, presented for the first time by Morin et al. (2001). It is defined as the time scale at which the pattern of the time averaged and basin

averaged radar rainfall hyetograph is most similar to the pattern of the measured hydrograph at the outlet of the basin. This definition was updated by Morin et al. (2002), that used an objective and automatic algorithm to analyse the smoothness of the hyetograph and hydrograph instead of the general behaviour, and by Shamir et al. (2005), who related the number of peaks with the total duration of the rising and declining limbs of hyetographs a and hydrographs.
In urban areas, where most of the surface is directly connected to the drainage system, concentration time is given by the time the rainfall needs to enter the sewer system and the travel time through the sewer system."

p6. 15-20: I suggest to refer to Lanza and Stagi (2009) and or to Lanza and Vuerich (2009) for a recent evaluation lab. and field evaluation and comparison of rain gauges.

Thank you, the suggested references were added.

p6. 18-19: the rain gauge data is punctual, but as rainfall field displays a spatial organization, this data is representative of rainfall in its neighborhood, in a surface area which depends on time step and decorrelation distance, itself related to the rainfall type. P6. 21: It exists in the scientific literature many papers, including review papers, dealing with the interpolation of rain gauges data for mapping rainfall fields by various methods, and I don't understand why the authors refer to Shaghaghian and Abedini (2013) not published in an international journal.

The paragraph was rephrased as follows: " The main disadvantage of rain gauges is that the obtained data are point measurements and, due to the high spatial variability of rainfall events, measurements from a single rain gauges are often not representative of a larger area. Rainfall fields, however, present a spatial organization and, by interpolating data from a rain gauge networks, it is possible to obtain distributed rainfall fields (Villarini et. Al., 2008; Muthusamy et al., 2016)."

p7. 10-14: The added value of polarimetric data is mainly: i) for ground clutter detection removal, and for X-band (and C-band also) radars for attenuation correction. X-band are strongly affected by attenuation of the signal by rainfall, and the correction of this problem is very unstable. Polarimetric data allow to efficiently correct this problem.

The sentence has been rephrased as follows:" A specific strength of polarimetric radars is the use of differential phase K_{dp}, which allows to correct signal attenuation thus solving an important problem generally associated with X-band radars (Otto et al., 2011; Ochoa-Rodriguez et al., 2015; Thorndahl et al., 2016 in review).

p7. 15-25 : I don't agree with this paragraph for two reasons. The authors refer to a few studies dealing with the calibration of radar data by rain gauges, or the combination of radar and rain gauges data (which is a much more recent approach of this question). I think that these studies are not representative of the state of knowledge on that subject. In addition, based on a very limited number of studies, they conclude to the underestimation of rainfall by radar. I consider that this conclusion is erroneous and not justified

Thank you for the constructive comment. The paragraph was revised and several references were added, as suggested by reviewer #1 (Ciach and Krajewski, 1999; Villarini et al., 2008; Mandapaka et al., 2009; Peleg et al., 2013). Those references confirm that, generally, radar measurements underestimate rainfall when compared to rain gauges. It is however a general conclusion, and "in

p7. 28: Be more precise, please! The radar equation relates the backscattered power to the radar reflectivity factor, usually called reflectivity. This radar equation doesn't depend on the drop size distribution.

Thank you for the constructive comment. The sentence was rephrased as follows: "Moreover, radar measurements need to be combined with a rain drop size distribution to obtain an accurate rainfall estimation."

p8 : paragraph 3.2 "Influence of urban areas on rainfall". This paragraph provides a brief, and general overview of this subject. What is its interaction with the subject of the manuscript? Is this paragraph useful ? I am not convinced.

We agree that this paragraph was not relevant considering the main goal of the paper. P The paragraph was reduced to a brief summary at the beginning of section 3: "Urban areas affect the local hydrological system, not only by increasing the imperviousness degree of the soil, but also by changing rainfall generation and intensity patterns. Several studies show that increase in heat and pollution produced by human activities and changes in surface roughness influence rainfall and wind generation (Huff:1973, Shepherd:2002, Givati:2004, Shepherd:2006, Smith:2012, Daniels:2015, Salvadore:2015). This phenomenon is not deeply investigated in this paper, but it is an important aspect to consider in rainfall analysis in urban areas."

p8-9. Paragraph 3.3. It seems that the weather is a very convenient device to analyze the spatial and temporal scales of rain fields for urban hydrology.

Thank you for the comment. The paragraph was rephrased as follows: "Characterizations and classifications of intense rainfall events have been proposed by various authors, combining rain gauges and radar rainfall data. In particular, weather radars are used as main tools to analyse rainfall spatial and temporal scale in urban areas."

p9 to p14: section 4 Hydrological processes. This very long paragraph summarizes the main hydrological processes and the main approaches used to represent them, in natural and urban areas as well. It regroups the basic knowledge in hydrology, addressed in text books, and not suited to a review manuscript. This section must be removed.

Thank you for the useful suggestion. This section has been thoroughly revised, textbook information was removed and the discussion now focus only on the aspects relevant for urban areas.

p15. 1-6: I don't understand these sentences. Are stochastic models used in urban hydrology? What type of models for what application? I don't see its usefulness in this manuscript. It could be confusing for the reader. Please, remove it!

We agree with the reviewer that this paragraph was confusing and we removed it from the manuscript.

p15. 11-14: As I understand this criterion, it concerns only the influence of the spatial variability of rainfall. There are many other factors involved in the choice of an hydrological model, depending on the applications of this model.

Thank you for this useful comment. The criterion proposed was only an example, and to highlight this the paragraph was rephrased as follows: "For example Berne et al. (2004) suggested a guideline for choosing between lumped and distributed modelling considering the representative surface associated to a single rain gauge S_r [L^2]."

p15. 24-31. The notion of physically-based or conceptual is valid at a given scale (in my opinion). The computational power is no more a problem, but I agree that the parameterization of a model, and the values to assign to these parameters remains a key issue.

Thank you, we agree with the reviewer's comment.

p16. 2-3 : it is an important element for all models at all scales

Thank you for the comment. The sentence "especially at small scale" was removed, to avoid the misunderstanding.

p16. 14-25: Meselhe et al. (2008) : I have not found this article in WRR. This example is certainly interesting. Unfortunately, it doesn't deal with urban hydrology. In a review manuscript addressing the hydrological response of urban basins, it is highly recommended to refer to papers which address the subject of the manuscript.

We agree that this article is not relevant in relation with the focus of the paper and removed the reference.

p17. 1-12: I would say that this subject is yet an open research subject, and the influence of spatial variability of rainfall on the basin response at its outlet is not yet well understood. A basin is a very powerful filter in time and space which smooths significantly an input impulse. Some studies, mostly dealing with flash floods, have been performed to determine the characteristics of rainfall which explain the variations of hydrographs at the basin outlet and reach different conclusions.

Thank you for this suggestion, we rephrased this to bring out this point more clearly, as follows: "These studies have shown how catchments act as filters in space and time for hydrological response to rainfall, delaying peaks and smoothing the intensity. However, the influence of spatial variability of rainfall on catchment response in urban areas is complex and remains an open research subject."

p17. 13-16: It is interesting to keep in mind that a basin is a geographic system, not only characterized by its outlet. A distributed model allows to determine the flow at any location within the basin, if the rainfall is measured at corresponding scales.

Thank you for this comment. We added the following text to section 5.1 to include this interesting consideration: "The flow can be estimated at any location within the basin and not only at the catchment outlet. This is, however possible only if the rainfall is provided at an appropriate scale."

p17. 18.32 (paragraph 6.1.1): this reasoning applies to calculate the flow at the basin outlet, and it is no more valid if to get the flow at locations within the basin.

Agreed. The process is applicable to a specific range of basins, or sub-basins within the main basin, with a surface area that varies between 10ha and 100000ha, as indicated in the text..

p17. 25-26: I would suggest be very careful with these relations, which remain only indicative, and subject to a large mean error. For instance, it is very different from the equation 2. I would suggest to keep a critical and consistent approach along the manuscript.

Thank you for notice this error. There was a typing mistake in this formula, and for this reason the two equation were looking so different. However, the relations referred to specific study cases and are obtained fitting the empirical data.

p17-18 (paragraph 6.1.2): I suggest to regroup it with 6.1.1. both deal the influence of rainfall variability according to the basin features : surface, length, response time . . ..

Thank you, we followed this suggestion and merged the two paragraphs into section 6.2, changing the title as follows: "Influence of spatial and temporal rainfall variability in relation to catchment dimensions"

p17-18. The subject of these two paragraphs (to be regrouped) - influence of spatial and temporal rainfall variability in relation with basin characteristics – is very important, and has been addressed by a large number of papers. The authors present in detail a limited number of studies (five or six). I suggest that they enrich their bibliography on that subject in order to provide a more comprehensive state of the art on that subject.

Thank you for the interesting suggestion. We have done another search to find additional literature, and added new references (Wright et al., 2013 and Peleg et al. 2016). We also added a brief discussion on studies by Smith et al (2002, 2005), who studied relationships between rainfall scale and catchment scale, based on rainfall spatial coverage.

Text added: "To investigate the effects of spatial and temporal variability on hydrological response in urban drainage modelling Peleg et al. (2016 in review) used a stochastic rainfall generator to obtain high resolution spatially variable rainfall as input for a calibrated hydrodynamic model. They compared the contributions of climatological rainfall variability and spatial rainfall variability on peak flow variability, over a period of 30 years. They found that peak flow variability is mainly influenced by climatological rainfall, while the effects of spatial rainfall variability increase for longer return periods."

Lanza LG, Stagi L., 2009. High resolution performance of catching type rain gauges from the laboratory phase of the WMO Field Intercomparison of Rain Intensity Gauges. Atmos Res., 94, 555-563. Lanza L.G., Vuerich E., 2009. The WMO Field Intercomparison of Rain Intensity Gauges. Atmos. Res., 94,4, 534-543.

Spatial and temporal variability of rainfall and their effects on hydrological response in urban areas - a review

Elena Cristiano[1], Marie-claire ten Veldhuis[1], and Nick van de Giesen[1]

[1]Department of Water Management, Delft University of Technology, Postbox 5048, 2600 GA, Delft, The Netherlands

Correspondence to: Elena Cristiano (E.Cristiano@tudelft.nl)

Abstract. In urban areas, hydrological processes are characterised by high variability in space and time, making them sensitive to small-scale temporal and spatial rainfall variability. In the last decades new instruments, techniques and methods have been developed to capture rainfall and hydrological processes at high resolution. Weather radars have been introduced to estimate high spatial and temporal rainfall variability. At the same time, new models have been proposed to reproduce hydrological response, based on small-scale representation of urban catchment spatial variability. Despite these efforts, interaction between input variability and model resolution remains poorly understood, and further investigations are needed. This paper presents a review of our current understanding of hydrological processes in urban environments as reported in the literature, focusing on their spatial and temporal variability. We review recent findings on the effects of rainfall variability on hydrological response and identify gaps where knowledge need to be further developed to improve our understanding of and capability to predict urban hydrological response.

1 Introduction

The lack of sufficient information about spatial distribution of short-term rainfall ~~can be considered as~~ has always been one of the most important sources of errors in urban runoff estimation (Niemczynowicz, 1988). In the last ~~years~~ decades considerable advances in quantitative estimation of distributed rainfall ~~data~~ have been made, thanks to new technologies, in particular weather radars (Leijnse et al., 2007; van de Beek et al., 2010; Otto and Russchenberg, 2011). ~~This is a promising development, especially for urban hydrology research, where the~~ These developments have been applied in urban hydrology researches, see Einfalt et al. (2004); Thorndahl et al. (2016))for a review. The hydrological response is sensitive to small-scale rainfall variability in both space and time (Faures et al., 1995; Emmanuel et al., 2012; Smith et al., 2012; Ochoa-Rodriguez et al., 2015b), due to a typically high degree of imperviousness and to a high spatial variability of urban land use.

Progress in rainfall estimation is accompanied by increasing availability of high resolution topographical data, especially digital terrain models and land-use distribution maps ~~derived (Mayer, 1999; Fonstad et al., 2013)~~ (Mayer, 1999; Fonstad et al., 2013; Tokarczyk et al., 2015). High resolution topographical datasets have promoted development of more detailed and more complex numerical models for predicting flows (Gironás et al., 2010; Smith et al., 2013). However, model complexity and resolution need to be balanced with the availability and quality of rainfall input data and datasets for catchment representation (Morin et al., 2001; Rafieeinasab et al., 2015; Rico-Ramirez et al., 2015; Rafieeinasab

et al., 2015; Pina et al., 2016). This is particularly critical in ~~urban hydrology~~small catchments, where flows are sensitive to variations at small space and time scales as a result of the fast hydrological response and the high catchment variability (Fabry et al., 1994; Singh, 1997). ~~In urban areas, alterations~~ Alterations of natural flows introduced by human interventions, especially artificial drainage networks, sewer pipe networks, detention ~~facilities~~ and control facilities~~(such as~~, such as reservoirs, pumps and weirs ~~) complicate prediction of flows~~are additional elements to take into account for flow predictions. Recently, various authors investigated the sensitivity of spatial and temporal rainfall variability on the hydrological response for urban areas (Bruni et al., 2015; Ochoa-Rodriguez et al., 2015b; Rafieeinasab et al., 2015). Despite these efforts, many aspects of hydrological processes in urban areas remain poorly understood, especially in the interaction between rainfall and runoff.

It is timely to review recent progress in understanding of interactions between rainfall spatial and temporal resolution, variability of catchment properties and their representation in hydrological models. Section 2 of this paper is dedicated to definitions of spatial and temporal scales and catchments in hydrology and methods to characterise these. Section 3 focuses on rainfall, analysing the most used rainfall measurement techniques, their capability to accurately measure small-scale spatial and temporal variability, with particular attention to applications in urban areas. Hydrological processes are described in Section 4, highlighting their variability and characteristics in urban areas. Thereafter, the state of the art of hydrological models, as well as their strengths and limitations to account for spatial and temporal variability, are discussed. Section 6 presents recent approaches to understand the effect of rainfall variability in space and time on hydrological response. In Section 7, main knowledge gaps are identified ~~for the~~ with respect to accurate prediction of urban hydrological response in relation to spatial and temporal variability of rainfall and catchment properties in urban areas.

2   Scales in urban hydrology

2.1   Spatial and temporal scale definitions

Hydrological processes occur over a wide range of scales in space and time, varying from 1 mm to 10000 km in space and from seconds up to 100 years in time. A scale is defined here as the characteristic region in space or period in time at which processes take place or the resolution in space or time at which processes are best measured (Salvadore et al., 2015).

Several authors have classified hydrological process scales and variability, focusing in particular on the interaction between rainfall and the other hydrological processes (Blöschl and Sivapalan, 1995; Bergstrom and Graham, 1998). Blöschl and Sivapalan (1995) ~~:~~presented a graphical representation of spatial and temporal variability of the main hydrological processes on a logarithmic plane. The plot has been updated by other authors, each focusing on specific aspects. For example, Salvadore et al. (2015) analysed phenomena related to urban processes, focusing small spatial scale, while Van Loon (2015), added scales of some hydrological problems, such as flood and drought. Figure 1 presents an updated version of the plot that integrates the information contribyted by Berndtsson and Niemczynowicz (1986), Blöschl and Sivapalan (1995), Stahl and Hisdal (2004) and Salvadore et al. (2015). Figure 1 shows that in urban hydrology attention is mainly focused on small scales. Characteristic processes, such as storm drainage, infiltration and evaporation vary at a small temporal and spatial scale, from seconds to hours and from centimetres to hundreds of meters. Many processes are driven by rainfall, that varies over a wide range of scales.

Blöschl and Sivapalan (1995) highlighted the importance of making a distinction between two types of scales: the "process scale", i.e. the proper scale of the considered phenomenon, and the "observation scale", related to the measurement and depending on techniques and instruments ~~being used. In~~ used. Under the best scenario, process and observation scale should ~~coincide~~match, but this is not always the case. ~~In order to match observation with process scale, it is often necessary to scale~~

5 ~~the measurements. These transformations are~~ , and transformations based on downscaling and upscaling techniques (Fig. 2) ~~,~~ ~~as~~ might be necessary to obtain the required observation scale. These techniques are discussed in section 2.2.

2.2 Downscaling ~~and upscaling in hydrology~~of climate variables used as input for hydrological models

The term downscaling usually refers to methods used to take information known at large scale and make predictions at small scale. There are two main downscaling approaches: dynamic or physically based and statistical methods (Xu, 1999). Dynamic

10 downscaling approaches solve the process-based physics dynamics of the system. In statistical downscaling, a statistical relationship is defined between local variables and large scale prediction and this relationship is applied to simulate local variables (Xu, 1999). Dynamical downscaling is widely used in climate modelling and numerical weather prediction, while statistical models are often used in ~~meteohydrology~~hydrometeorology, for example rainfall downscaling. Dynamic downscaling models have the advantage ~~to be~~ of being physically-based, but they require a lot of computational power compared to statistical

15 downscaling models. Statistical approaches require historical data and knowledge of local ~~condition~~conditions.

~~Statistical downscaling approaches are reported in the literature for a wide variety of variables (Rummukainen, 1997; Deidda, 2000; Ferraris et al., 2003; Gires et al., 2012; Wang et al., 2015b; Muthusamy et al., 2016) and techniques such as regression methods , weather pattern-based approaches and stochastic weather generators (see Wilby and Wigley (1997) for a review).~~ The use of downscaling methods in a study of climate change impacts on hydrological

20 models was presented by Fowler et al. (2007). They investigated what can be learnt from downscaling method comparison studies, what new methods can be used together with downscaling to assess uncertainties in hydrological response and how downscaling methods can be better utilized within the hydrological community. They highlighted that the importance given to the applied research is still too little, and manager and stakeholders should be more aware of uncertainties within the modelling system.

25 Ferraris et al. (2003) presented a review of three common stochastic downscaling models, mainly used for spatial rainfall downscaling: multifractal cascades, autoregressive processes and point process models based on the presence of individual cells. The first were introduced in the 1970s and are widely used to reproduce the spatial and temporal variability (see Schertzer and Lovejoy (2011) for a review). Autoregressive ~~processes are mainly~~ methods, also nowadays often referred to as "rainfall generator models", are used to generate multidimensional random fields ~~and they take into account~~

30 ~~the spatial autocorrelation of the rainfall field. The last model is~~ while preserving the rainfall spatial autocorrelation, for natural (Paschalis et al., 2013; Peleg and Morin, 2014; Niemi et al., 2016) and urban (Sørup et al., 2015) areas. Point-process models are used when the spatial structure of intense rainfall ~~field~~ is defined by convective cells (see McRobie et al. (2013) for an example). It incorporates local information and requires a more detailed storm cell identification.

Statistical downscaling and upscaling approaches are reported in the literature for a wide variety of variables (Rummukainen, 1997; Deidda, 2000; Ferraris et al., 2003; Gires et al., 2012; Wang et al., 2015b; Muthusamy et al., 2016) and techniques such as regression methods, weather pattern-based approaches and stochastic weather generators (see Wilby and Wigley (1997); Wilks and Wilby (1999) for a review). Some recent studies about downscaling and upscaling focus

5 mainly on urban areas (Gires et al., 2012; Wang et al., 2015b, a; Muthusamy et al., 2016): Wang et al. (2015a), for example, presented a gauge-based radar rainfall adjustment methods sensitive to singularities, characteristic of small scale.

2.3 Methods to characterize hydrological process scales

2.3.1 Spatial variability of basin characteristics

Slope, degree of imperviousness, soil properties and many other catchment characteristics are variable in space and time
10 and this variability affects the hydrological response (Singh, 1997). This is especially the case of urban areas, where spatial variability and temporal changes in land-use are typically high.

Julien and Moglen (1990) gave a first definition of the catchment length scale L_s as part of a theoretical framework applied to a natural catchment, where they analysed 8400 dimensionless hydrographs obtained from one-dimensional finite element models under spatially varied input. Length scale was presented as function of rainfall duration t_c, spatially averaged rainfall
15 intensity i, average slope s_0 and average roughness n:

$$L_s = \frac{t_c^{\frac{5}{6}} s_0^{\frac{1}{2}} i^{\frac{2}{3}}}{n} \tag{1}$$

~~The length scale is derived starting from the Manning equation, assuming rainfall duration t_c equal to the time of equilibrium~~ ~~t_e, and it depends on both catchment and storm characteristics. For a field with runoff lengthshorter than L_s,~~

In urban catchments, the ~~spatial variability has a small influence on the runoff generation, while for runoff length longer~~
20 ~~than L_s, the runoff discharge is strongly affected. The length scale can be useful to determine critical hydrological model~~ ~~grid size: a long duration and low intensity rainfall event, for example, can be analysed using coarse resolution models~~ ~~(Julien and Moglen, 1990)~~concept of catchment length, defined as the squared root of the (sub)catchment or runoff area, has been used (Bruni et al., 2015; Ochoa-Rodriguez et al., 2015a). Additionally, Bruni et al. (2015) introduced the sewer length or inter-pipes sewer distance, as the ratio between the catchment area and the total length of the sewer, to characterize the spatial
25 scale of sewer networks. Ogden et al. (2011) used the width function, defined as the number of channel segments at a specific distance from the outlet, to represent the spatial variability of the drainage network. This parameter describes the network geomorphology by counting all stream links located at the same distance from the outlet, but it does not give an accurate description of the spatial variability of hydrodynamic parameters.

2.3.2 Time scale characteristics

30 ~~Hydrological response time parameters have a high influence on the spatial and temporal distribution of runoff and are~~ ~~necessary to estimate the risk hazard (Gericke and Smithers, 2014). A detailed review of several methods to estimate hydrological~~

4

~~response time was proposed by Gericke and Smithers (2014), with the aim to analyse the impact that time scale catchment parameters have on peak discharge~~In this section, we present a brief overview of time scales reported in the literature and discuss approaches to estimate characteristic time scales that have been specifically developed for urban areas. A summary of time scale characteristics is presented in Table 1.

5 The first method to investigate the hydrological response is the rational method, presented more than a century ago by (Kuichling, 1889) for urban areas. This method was later adapted for rural areas. The rational method requires the estimation of the time of concentration in order to define the runoff volume.

 ~~The time~~ Time of concentration t_c is one of the most common hydrological characteristic time scales ~~(Gericke and Smithers, 2014)~~ and it is defined as the time that a drop that falls on the most remote part of the ~~drainage~~ basin needs to reach the basin outlet

10 ~~(Singh, 1997).~~ (Singh, 1997; Musy and Higy, 2010). Several equations to estimate this parameter are available in the literature for natural (Gericke and Smithers, 2014) and urban (McCuen et al., 1984) catchments. The time of concentration is difficult to measure, because it assumes that initial losses are already satisfied and the rainfall event intensity is constant for a period at least as long as the time of concentration. Different theoretical definitions have been developed in order to estimate the time of concentration as function of basin length, slope and other characteristics (see for some examples

15 ~~(Singh, 1976; Morin et al., 2001; USDA, 2010; Gericke and Smithers, 2014)~~

Singh (1976); Morin et al. (2001); USDA (2010); Gericke and Smithers (2014)).

 Due to difficulties related to the estimation of time of concentration, Larson (1965) introduced the time of virtual equilibrium t_{ve}, defined as the time until response is 97% of runoff supply.

 When a given rainfall rate persists on a region for enough time to reach the equilibrium, this time is called time to equilibrium

20 t_e (Ogden et al., 1995; Ogden and Dawdy, 2003; van de Giesen et al., 2005). Time of equilibrium for a turbulent flow on a rectangular runoff plane given rainfall intensity i, with given roughness n, length L_p and slope S can be written as (Ogden et al., 1995):

$$t_e = [\frac{nL_p}{S^{1/2}i^{2/3}}]^{3/5} \tag{2}$$

 Another commonly used hydrological characteristic time scale or response time is the lag time t_{lag}. It represents the delay

25 between rainfall and runoff generation. t_{lag} is defined as the distance between the hyetograph and hydrograph center of mass of (Berne et al., 2004), or between the time of rainfall peak and time of flow peak (Marchi et al., 2010; Yao et al., 2016). t_{lag} can be considered characteristic of a basin, and is dependent on drainage area, imperviousness and slope (Morin et al., 2001; Berne et al., 2004; Yao et al., 2016). Berne et al. (2004), including the results of Schaake and Knapp (1967) and Morin et al. (2001), defined a relation between the dimension of the catchment area S (in ha) and the lag time t_{lag} (in mm): $t_{lag} = 3S^{0.3}$

30 for urban areas. Empirical relations between t_{lag} and t_c are presented in the literature (USDA, 2010; Gericke and Smithers, 2014)~~,as, for example the approximation presented by Gericke and Smithers (2014), for which $t_{lag} = 0.6t_c$~~.

 Another characteristic time scale is the 'response time scale' T_s, presented for the first time by Morin et al. (2001). It is defined as the time scale at which the pattern of the time averaged and basin averaged radar rainfall hyetograph is most similar to the pattern of the measured hydrograph at the outlet of the basin. This definition was updated by Morin et al. (2002)~~.~~

Here, the response time was estimated using ~~,~~ that used an objective and automatic algorithm ~~, that analyses~~ to analyse the smoothness of the hyetograph and hydrograph instead of the general behaviour~~. The smoothness is represented by the peak density PD, which is the ratio between the~~ , and by Shamir et al. (2005), who related the number of peaks PN ~~and total rising limbs duration T_r:~~

$$PD = \frac{PN}{T_r}$$

~~The peak density was estimated for the measured hyetograph and for the hydrographs, generated for rainfall measured with a C-band weather radar at a temporal resolution of 5 min, aggregate to a range of lower temporal resolutions. The response time scale was defined as the time scale corresponding to the aggregated temporal resolution, at which peak density of hydrograph and hyetograph matched closely. These works analysed the behaviour of four Israeli catchments. Results show that urban basins have a smaller T_s, about $10 - 15$ min, compared to semiarid rural regions, where T_s was found between $125 - 130$ min. Morin et al. (2003) investigated also the effects of catchment characteristics, such as length and roughness of hillslope and channels, on the response time scale. For this study, a distributed model was used. They found that for small contributing areas T_s is more affected by hillslope routing processes, while for larger areas, T_s depends strongly on the channel flow length.~~ with the total duration of the rising and declining limbs of hyetographs a and hydrographs.

~~A similar definition of peak density was given by Shamir et al. (2005), who presented the rising limb density RLD and declining limb density DLD, as ratio between peak number PN and total duration of the rising T_r and declining T_d limbs of the hyetograph respectively:~~

$$RLD = \frac{PN}{T_r}$$

$$DLD = \frac{PN}{T_d}$$

In urban areas, where most of the surface is directly connected to the drainage system, concentration time is given by the time the rainfall needs to enter the sewer system and the travel time through the sewer system.

~~A summary of time scale characteristics is presented in Tab. 1.~~

3 Rainfall measurement and variability in urban regions

Rainfall is an important driver for many hydrological processes and represents one of the main sources of uncertainty in studying hydrological response ~~(Niemczynowicz, 1988; Rico-Ramirez et al., 2015)~~

(Niemczynowicz, 1988; Einfalt et al., 2004; Thorndahl et al., 2016; Rico-Ramirez et al., 2015).

Urban areas affect the local hydrological system, not only by increasing the imperviousness degree of the soil, but also by changing rainfall generation and intensity patterns. Several studies show that increase in heat and pollution produced by human activities and changes in surface roughness influence rainfall and wind generation

(Huff and Changno, 1973; Shepherd et al., 2002; Givati and Rosenfeld, 2004; Shepherd, 2006; Smith et al., 2012; Daniels et al., 2015; Sal
This phenomenon is not deeply investigated in this paper, but it is an important aspect to consider.

In this section instruments and technologies for rainfall measurement are described, pointing out their opportunities and ~~and~~ limitations for measuring spatial and temporal variability in urban environments. Subsequently, methods to characterise rainfall events according to their space and time variability are described.

3.1 Rainfall estimation

Rain gauges were the first instrument used to measure rainfall and are still commonly used, because they are relatively low in cost and easy to install (WMO, 2008).

Afterwards, weather radars were introduced to estimate the rainfall spatial distribution. These instruments allow to get measurements of rainfall spatially distributed over the area, instead of a point measurement as in the case of rain gauges. Rainfall data obtained from weather radars are used to study the hydrological response in natural watersheds and urban catchments ~~(Einfalt et al., 2004; Berne et al., 2004; Sangati et al., 2009; Smith et al., 2013; Ochoa-Rodriguez et al., 2015b)~~ (Einfalt et al., 2004; Berne et al., 2004; Sangati et al., 2009; Smith et al., 2013; Ochoa-Rodriguez et al., 2015b; Thorndahl et al., 2016) often combined with rainfall measurement from rain gauge networks (Winchell et al., 1998; Smith et al., 2005; Segond et al., 2007; Smith et al., 2012), as well as to improve short-term weather forecasting and nowcasting ~~(Montanari and Grossi, 2008; Liguori and Rico-Ramirez, 2013; Dai et al., 2015)~~ (Montanari and Grossi, 2008; Liguori and Rico-Ramirez, 2013; Dai et al., 2015; Foresti et al., 2016).

More recently, commercial microwave links have been used to estimate the spatial and temporal rainfall variability ~~(Fencl et al., 2015; Leijnse et al., 2007)~~ (Leijnse et al., 2007; Fencl et al., 2015, 2016). Rainfall estimates are obtained from the attenuation of the signal caused by rain along microwave link paths. This approach can be particularly useful in cities that are not well equipped with rain gauges or radars, but where the commercial cellular communication network is typically dense (Leijnse et al., 2007).

3.1.1 Rain gauges networks

Several types of rain gauges have been developed, such as weighing gauges, tipping bucket gauges and pluviographs (Lanza and Stagi, 2009; Lanza and Vuerich, 2009). They are able to constantly register accumulation of rainfall volume over time, thus providing a measurement of temporal variability of rainfall intensity. Rain gauge measurements are sensitive to wind exposure and the error caused by wind field above the rain gauge is $2-10\%$ for rainfall and up to 50% for solid precipitations (WMO, 2008). Other errors can be due to tipping bucket losses during the rotation, to wetting losses on the internal walls of the collector, to evaporation (especially in hot climates) or water splashing into and out of the collector (WMO, 2008). The main disadvantage of rain gauges is that ~~they measure rainfall in one specific location, and~~ the obtained data are point measurements and, due to the high spatial variability of rainfall events, ~~the measurement is~~ measurements from a single rain gauges are often not representative of a larger area. ~~To solve the problem of spatial representation, interpolation techniques are used~~ Rainfall fields, however, present a spatial organization and, by interpolating data from a rain gauge networks, it is

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possible to obtain distributed rainfall fields ~~(Shaghaghian and Abedini, 2013)~~(Villarini et al., 2008; Muthusamy et al., 2016). Uncertainty induced by interpolation strongly depends on the density of the rain gauge network and on homogeneity of the rainfall field (Wang et al., 2015b).

5   In urban areas, rainfall measurements with rain gauges present specific challenges associated with microclimatic effects introduced by the building envelope. WMO (2008) recommended minimum distances between rain gauges and obstacles of one to two times the height of the nearest obstacle, a condition that is hard to fulfil in densely built areas. A second problem is introduced by hard surfaces, that may cause water splashing into the gauges, if it is not placed at an elevation of at least 1.2 m. Rain gauges in cities are often mounted on roofs for reasons of space availability and safety from vandalism. This means they

10 are affected by the wind envelope of the building, unless they are elevated to a sufficient height above the building.

Rain gauge measurement error can be 30% or more depending on the type of instrument used for the measurement and local conditions (van de Ven, 1990; WMO, 2008).

3.1.2   Weather radars

In the last decades, weather radars have been increasingly used to measure rainfall

15 ~~(Berne and Krajewski, 2013; Krajewski and Smith, 2005; Niemczynowicz, 1999; Otto and Russchenberg, 2011)~~ (Niemczynowicz, 1999; Krajewski and Smith, 2005; Otto and Russchenberg, 2011; Berne and Krajewski, 2013)). Radars transmit pulses of microwave signals and measure the power of the signal reflected back by raindrops, snowflakes and hailstones (backscatter). Rainfall rate R [L T^{-1}] is estimated using the reflectivity Z [L^6 L^{-3}] measured from the radar through a power law:

20 $$R = aZ^b \tag{3}$$

where a and b depend on type of precipitation, climate characteristics and spatial and temporal scales considered (van de Beek et al., 2010; Smith et al., 2013). Weather radars ~~of three~~ present different wavelengths λ, frequencies ν and sizes of the antenna l~~, are commonly used : S-band ($\lambda = 8 - 15$ cm, $\nu = 2 - 4$ GHz, $l = 6 - 10$ m), C-band ($\lambda = 4 - 8$ cm, $\nu = 4 - 8$ GHz, $l = 3 - 5$ m) and X-band ($\lambda = 2.5 - 4$ cm, $\nu = 8 - 12$ GHz, $l = 1 - 2$ m)~~. Characteristics of commonly used weather radars

25 are reported in Table 2. X-band radars can be beneficial for urban areas: they are low cost and they can be mounted on existing buildings and measure rainfall closer to ground at higher resolution than national weather radar networks (Einfalt et al., 2004). Polarimetric weather radars transmit signals polarised in different directions (Otto and Russchenberg, 2011), enabling it to distinguish between horizontal and vertical dimension, thus between rain drops and snowflakes as well as between smaller or larger more oblate rain drops.

30 A specific strength of polarimetric radars is the use of differential phase K_{dp}~~, which is not affected by attenuation, and is immune to radar calibration errors (Otto and Russchenberg, 2011; Ochoa-Rodriguez et al., 2015b).~~ K_{dp}, which allows to correct signal attenuation thus solving an important problem generally associated with X-band radars (Otto and Russchenberg, 2011; Ochoa-Rodriguez et al., 2015b; Thorndahl et al., 2016).

3.1.3 Opportunities and limitations of weather radars~~and rain gauges~~

Berne and Krajewski (2013) presented a comprehensive analysis of the advantages, limitations and challenges in rainfall estimation using weather radars. One of the main problems is that ~~the radar uses~~ an indirect relation is used (Eq. (3)) to estimate rainfall~~and has~~. Rainfall measurements have to be adjusted based on rain gauges and disdrometers. Various techniques have been studied to calibrate radars (Wood et al., 2000), to combine radar rainfall measurements with rain gauge data for ground truthing

~~(Cole and Moore, 2008; Smith et al., 2012; Wang et al., 2013; Gires et al., 2014; Wang et al., 2015b)~~

(Cole and Moore, 2008; Smith et al., 2012; Wang et al., 2013; Gires et al., 2014; Nielsen et al., 2014; Wang et al., 2015b) and to define the uncertainty related to radar-rainfall estimation ~~(Mandapaka et al., 2009; Overeem et al., 2009a)~~
(Ciach and Krajewski, 1999; Quirmbach and Schultz, 2016; Villarini et al., 2008; Mandapaka et al., 2009; Peleg et al., 2013; Villarini et a
These studies show that in most of the cases, radar measurements underestimate the rainfall compared to rain gauge measurements (Smith et al., 2012; Overeem et al., 2009a; Overeem and Buishand, 2009b; van de Beek et al., 2010). ~~For instance, Overeem et al. (2009a) compared rainfall measurements from two C-Band radars, located in the Netherlands, with two rain gauge networks, one with 326 manual rain gauges and another with 33 automatic rain gauges. They found that radar measurements underestimate rainfall by more than 30%, for 24h rainfall accumulations. They tested various techniques to reduce bias and standard deviation and found that hourly mean bias adjustment allowed to obtain zero bias error for some combinations of radar and rain gauge.~~

Another downsides of radars is their installation at high locations to have a clear view without obstacles, while rainfall intensities can change before reaching the ground (Smith et al., 2012).Moreover, ~~the radar equation can not account for variations in~~ radar measurements need to be combined with a rain drop size distribution to obtain an accurate rainfall estimation. Berne and Krajewski (2013) pointed out additional aspects that have to be taken into account like, e.g., management and storage of the high quantity of data that are measured, possibility to use the weather radars to estimate snowfall and the uncertainty related to it, and problems related to rainfall measurement in mountain areas.

~~High resolution rainfall data are particularly important for hydrological studies in urban areas, where dimensions of catchments are typically small and hydrological response is fast (Einfalt et al., 2004; Bruni et al., 2015).~~ Rain gauge measurements in urban areas tend to be prone to errors due to microclimatic effects introduced by the building envelope. In this context, the use of weather radar could represent a big improvement to obtain a more accurate rainfall information for studying hydrological response.

A promising application of radar is their combination with nowcasting models to obtain short-term rainfall forecasts. Liguori and Rico-Ramirez (2013) presented a review of different nowcasting models, that benefit from radar data. This work focused in particular on a hybrid model, able to merge the benefits of radar nowcasting and numerical weather prediction models. Radar data can provide an accurate short term forecast ~~, but rainfall estimation is still affected by errors, and these limit the high-potential for the use in hydrological forecasting studies .~~

3.2 ~~Influence of urban areas on rainfall~~

~~Several studies tried to estimate effects of increasing urbanization and changing land cover on rainfall~~

~~(Huff and Changno, 1973; Shepherd et al., 2002; Shepherd, 2006). Increase in heat produced by human activities and changes in surface roughness, influencing rainfall and wind (Salvadore et al., 2015).~~

~~Shepherd et al. (2002) studied on 5 large metropolitan areas located in the United States, using data from the Tropical Rainfall Measuring Mission satellite's precipitation radar for the warm season (1998-2000). They found an average increase of about 28% in monthly rainfall rates within $30-60km$ downwind of a metropolis, with a modest increase of 5.6% over the metropolis. The maximum value was generally found at an average distance of 39km from the edge of the urban centre.~~

~~Smith et al. (2012) studied a 9 year radar rainfall data set, measured with resolution of $1x1$ km^2~~ and ~~15 min respectively, for a 17000 km^2 metropolitan area located in the Baltimora region(U.S.). They studied the effect of urbanisation on rainfall by comparing rainfall patterns upwind and downwind and found heavy precipitation above 25 mm daily accumulation to be four times more likely in the area downwind of the city compared to the area upwind.~~ recent studies have presented nowcasting systems able to reduce errors in rainfall estimation (e. g. Foresti et al. (2016)).

~~Similar results were found by Daniels et al. (2015), at an at an extended urban region along the Dutch west coast. They used rainfall observations for the period 1951-2010 and found annual precipitation increase of about 7% downwind of urban areas. This increase in rainfall was similar throughout the entire distribution of precipitation intensities, in extreme precipitation as well as the mean.~~

~~These studies show that areas seem to affect the local hydrological system, not only by increasing the imperviousness degree of the soil, but also by changing rainfall generation and intensity patterns.~~

3.2 Characterising rainfall events according to their spatial and temporal scale

Characterizations and classifications of intense rainfall events have been proposed by various authors~~.~~, combining rain gauges and radar rainfall data. In particular, weather radars are used as main tools to analyse rainfall spatial and temporal scale in urban areas. An example of characterisation of rainfall structure was given by Smith et al. (1994), who presented an empirical analysis of four extreme rainstorms in the Southern Plains (U.S.), using data from two networks of more than 200 rain gauges and from a weather radar. They defined *major rainfall event* as storms for which 25 mm of rain covered an area larger than 12500 km^2. Thorndahl et al. (2014) presented a storm catalog of heavy rainfall, over a study area of 73500 km^2 in southern Wisconsin, and key elements of storm evolution that control the scale. The catalog contains the 50 largest rainfall events recorded during a 16 year period by WSR-88D radar with spatial and temporal resolution of 1x1 km^2 and 15 min respectively. Over the 50 events, there is 0.60 probability that rainfall exceeds 25 mm of daily accumulation in a 1 km^2 pixel and 0.14 probability of exceeding 100 mm. Results showed that there is a clear relation between the characteristic length and time scale of the events. The length scale increased with time scale: a length scale of 35 ± 20 km was found for a time step of 15 minutes, up to 160 ± 25 km for a 12 hour aggregation time.

3.3 Rainfall variability at the urban scale

Studying rainfall variability at the urban scale, Emmanuel et al. (2012) classified 24 rain periods, recorded by the weather radar located in Treillieres (France), with a spatial and temporal resolution of $250X250$ m^2 and 5 min respectively. They classified the events into four groups, based on variogram analysis: light rain period, shower periods, storms organized into rain bands and unorganized storms. The first group, characterized by light rainfall events, presented very high decorrelation distance and time (17 km and 15 min) compared to the second group, with a decorrelation distance and time of 5 km and a decorrelation time of 5 min. The last two groups presented a double structure, where small and intense clusters, with low decorrelation distance and time (less than 5 km and 5 min) are located, in a random or organized way, inside areas with a lower variability (decorrelation of 15 km and 15 min).

Jensen and Pedersen (2005) presented a study about variability in accumulated rainfall within a single radar pixel of 500x500 m^2, comparing it with 9 rain gauges located in the same area. The results showed a variation of up to 100% at a maximum distance of about 150 m, due to the rainfall spatial variability. This study suggested that a huge quantity of rain gauges is needed to have a powerful rain gauge network capable of representing small scale variability. An alternative solution is to consider the variance reduction factor method, a numerical method to represent the uncertainty from averaging a number of rain gauges per pixel, taking into account their spatial distribution and the correlation between them. The variance reduction factor method was introduced for the first time by Rodriguez-Iturbe and Mejıa (1974) and lately applied in various studies (Krajewski et al., 2000; Villarini et al., 2008; Peleg et al., 2013).

Gires et al. (2014) focused on the gap between rain gauges and radar spatial scale, considering that a rain gauge usually collects rainfall over 20 cm of surface and the spatial resolution of most used radars is of 1x1 km^2. They evaluate the impact of small scale rainfall variability using a Universal Multifractal downscaling method. The downscaling process was validated with a dense rain gauge and disdrometer network, with 16 instruments located in 1x1 km^2. They showed two effects of small scale rainfall variability that are often not taken into account: high rainfall variability occurred below 1 km^2 spatial scale and the random position of the point measurement within a pixel influenced measured rainfall events. Similar results are confirmed by Peleg et al. (2016), who studied the spatial variability of extreme rainfall at radar subpixel scale. Comparing a radar pixel of 1kmx1km with high resolution rainfall data, obtained by applying the stochastic rainfall generator STREAP (Peleg et al., 2013) to simulate rain fields, this study highlights that subpixel variability is high and increases with increasing of return period and with shorter duration.

In ~~Tab.~~ Table 3 four types of rainfall events are presented with their characterization and typical spatial and temporal decorrelation lengths, based on van de Beek et al. (2010); Emmanuel et al. (2012); Smith et al. (1994). Considering that the minimal rainfall measurement resolution required for urban hydrological modelling is 0.4 the decorrelation length (Julien and Moglen, 1990; Berne et al., 2004; Ochoa-Rodriguez et al., 2015b), ~~common~~ operational radars are not able to satisfy this requirement.

4 Hydrological processes

In this section, general characteristics and parametrisations of hydrological processes are presented, highlighting their spatial
and temporal variability and characteristics specific to urban environments.

4.1 Precipitation losses

4.1.1 Infiltration, interception and storage

The term infiltration is usually used to describe the physical processes by which rain enters the soil (Horton, 1933). Different
equations and models have been proposed to describe infiltration. The most commonly used is Richards equation (Richards,
1931)describes infiltration , which represents this phenomenon using a partial differential equation with nonlinear coefficients.
The Richards equation combines Darcy's law, continuity equation and the definition of the total head:

$$\frac{\partial \theta}{\partial t} = -\frac{\partial q}{\partial z} = \frac{\partial}{\partial z}(D\frac{\partial \theta}{\partial z} + K)$$

where θ L^3 $L^{-3}$is water content, t Tis time, q L $T^{-1}$is infiltration flow, z Lis depth, D L $T^{-1}$is diffusivity and K L $T^{-1}$is
hydraulic conductivity. Several models and equations have been proposed to solve the Richards equation in order to estimate
infiltration rate. The two terms Philip's equation (Philip, 1957), for example, assumes that hydraulic conductivity K and
diffusivity D are functions of water content θ, and they do not depend on z. With these assumptions, Eq. (??) becomes:

$$I(t) = St^{-\frac{1}{2}} + K$$

where t is time, S L $T^{-1}$is sorptivity and K is hydraulic conductivity. The sorptivity S is defined as capacity of soil to absorb
water by capillarity.

Another possibility to estimate the infiltration capacity is given by the empirical equation presented by Horton (1933)Horton (1939).
In Horton's equation hydraulic conductivity K and diffusivity D are constants, and diffusivity are constant and do not depend
on water content θ or on depth$z$. The infiltration capacity f_t decreases exponentially with t, following the relation:

$$f_t = f_e + (f_b - f_e)e^{-k_a t}$$

where f_b L $T^{-1}$and f_e L $T^{-1}$are the maximum and minimum infiltration capacity respectively, and k_a $T^{-1}$is the time factor
for decreasing infiltration capacity (Horton, 1939). .

If water cannot infiltrate, as is the case in impervious areas, it can be stored in local depressions, where it does not contribute
to runoff flow. This is the case of local depressions on streets or flat roofs, where water accumulates until the storage capacity
is reached. Before reaching the ground, rainfall can be intercepted by vegetation cover or buildings. Interception can constitute
up to 20% of rainfall at the start of a rainfall event (Mansell, 2003), and decreases quickly to zero, once surfaces are wetted.

Spatial scale of precipitation losses is strongly influenced by land cover variation. In urban areas, land cover variability
typically occurs at a spatial scale of 100 m to 1000 m. Time scale is associated with local storage accumulation volume,
sorptivity and hydraulic conductivity, which in turn depend on soil type and soil compaction.

~~In impervious areas, water can not infiltrate, but can be stored in local depressions, where it does not contribute to runoff flow. This is the case of local depression on street or flat roofs, where water accumulates till the storing capacity is reached.~~

4.1.2 ~~Infiltration~~ Groundwater recharge and subsurface processes in urban areas

Groundwater recharge mechanisms change due to human activities and urbanization, both in terms of volume and quality of the water. The increase of imperviousness of land cover leads to a decrease in infiltration of rainfall into soil, reducing direct recharge ~~of~~ to groundwater. The presence of leakage from drinking water and sewer networks can increase infiltration to groundwater and amount of contaminants that is spread from the sewer system into the soil (Salvadore et al., 2015).

Although it is well known that not all ~~the~~ rainfall turns into runoff (Boogaard et al., 2013; Lucke et al., 2014), it is common to consider the losses from impervious areas so small that they can be assumed negligible compared to the total runoff volume (Ragab et al., 2003; Ramier et al., 2011). ~~Some studies~~ Ragab et al. (2003) tried to emphasise the importance of accounting for ~~the~~ infiltration in the ~~study of the~~ urban water balance, ~~considering~~ and found that infiltration through the road surface can constitute between 6 and 9% of annual rainfall ~~(Ragab et al., 2003)~~. Due to high spatial variability of infiltration, representative measurements are difficult to obtain and require a large amount of point-scale measurements (Boogaard et al., 2013; Lucke et al., 2014).

Several types of pervious pavements are used in urban areas. They can generally be divided into monolithic and modular structures. Monolithic structures consist of a combination of impermeable blocks of concrete and open joints or apertures ~~,~~ that allow water to infiltrate. ~~Modular~~ In modular structures, gaps between two blocks are not filled with sand, as with conventional pavements, but with $2-5$ mm of bedding aggregate, that facilitate infiltration (Boogaard et al., 2013). Following European standards, minimum infiltration capacity for permeable pavements is $270\,\mathrm{l\,s^{-1}\,ha^{-1}}$, equal to $97.2\,\mathrm{mm\,h^{-1}}$ (OCW, 2008). ~~The effects of age on the efficiency of permeable pavements was analysed by Boogaard et al. (2013), who studied 55 permeable pavements with ages between 1 and 12 years, located in the Netherlands and in Australia. They showed that the performance of clogged permeable pavement system was higher than the required rate in more than 90% of the cases.~~

Pervious areas in cities can effectively act as $\mathrm{semi-impervious}$ areas, because within the soil column there is a shallow layer that presents a low hydraulic conductivity at saturation, caused by soil compaction during the building process. ~~(Smith et al., 2015)~~ Smith et al. (2015) studied the influence of this phenomenon on peak runoff flow by applying 21 storm events on a physically based, minimally calibrated model of the Dead Run urban area (U.S.) with and without the compacted soil layer. Results showed that the compacted soil layer reduced infiltration by $70-90\%$ and increased peak discharge by 6.8%

4.2 Surface runoff

When rainfall intensity exceeds infiltration capacity of the soil, water starts to accumulate on the surface and flows following the slope of the ground. This process is generally called Hortonian runoff (Horton, 1933) or infiltration capacity excess flow. It is usually contrasted with saturation excess flow, or Dunne flow (Dunne, 1978), that occurs when the soil is saturated and rainfall can no longer be stored (van de Giesen et al., 2011). ~~Different numerical models were built to describe overland flow generated during rainfall events (Ajayi et al., 2008; van de Giesen et al., 2011). These models are mainly based on the de Saint Venant~~

~~equations (Eq. (**??**) and Eq. (**??**)), which are the monodimensional expression of the Navier-Stokes equations for shallow flow, where vertical flow is much smaller than horizontal flow and can be neglected.~~

In urban areas, runoff is generated when the surface is impervious and water can not infiltrate, or when infiltration capacity is exceeded by rainfall intensity. Water flows over the surface and can reach natural drainage channels or be intercepted by the drainage network through gullies and manholes. If the drainage network capacity is exceeded, the system become pressurized, and water starts to flow out from gullies, increasing runoff on the street (Ochoa-Rodriguez et al., 2015a).

It is important to pay attention to some elements that characterize the runoff in urban environments: sharp corners or obstacles can, for example, deviate the flow and introduce additional hydraulic losses. Interactions between surface flow and subsurface sewer systems through sewer inlets and gully pots are hydraulically complex and their influence on overland and in-sewer flows remains poorly understood. Runoff flows are often characterised by very small water depths that are often alternated with dry surfaces, especially when rainfall intensities vary strongly in space and time.

4.2.1 ~~Approximation of the de Saint Venant equations~~

~~The de Saint Venant equations are expressed by a conservation mass equation and a momentum conservation or dynamic equation. They can be written as:~~

$$\frac{\partial h}{\partial t} + u\frac{\partial h}{\partial x} + h\frac{\partial u}{\partial x} - q = 0$$

$$\frac{\partial u}{\partial t} + \frac{\partial u}{\partial x} + g\cos\beta\frac{\partial h}{\partial x} - g(S_0 - S_f) - \frac{q_u}{h} = 0$$

~~where x L is the direction of the one dimensional flow, t T is the time, h L is the depth, u L T^{-1} is the average velocity at (x,t) and q L T^{-1} is the lateral inflow per unit area per unit time, g L T^{-2} is the gravity acceleration, β the constant angle of the slope, and S_f the friction slope (Daluz Veira, 1983).~~

~~Daluz Veira (1983) defined the conditions to approximate the de Saint Venant equations for shallow surface water, considering different values of the Froude number Fr, and the kinematic wave number k. The Froude number F_r is a dimensionless quantity expressed by $F_r = \frac{v}{\sqrt{gy}}$ where v L T^{-1} is the velocity of the flow, g L T^{-2} is gravity acceleration and y L is a characteristic length. The kinematic wave number k is defined by $k = L S_0 / F_0^2 y_0$, where L L is the length of overland-flow plane or channel segment, S_0 is the bed slope, F_0 is the Froude number for normal flow and y_0 L is normal depth. For values of k higher than 50, it is possible to simplify the momentum equation, and obtain the kinematic wave approximation, that does not account for the advective acceleration. For high values of k and $Fr < 0.1$, the diffusion wave approximation, that neglects inertial acceleration, is obtained, while the gravity wave approximation is defined for small values of k. For example, for smooth urban slopes, the values of k is usually between 5 and 20: the kinematic or diffusion wave approximation may be used, depending on the value of Fr.~~

4.2.1 ~~Impact of land cover on overland flow in urban areas~~

4.3 Impact of land cover on overland flow in urban areas

Ragab et al. (2003) presented an experimental study of water fluxes in a residential area, in which they estimated infiltration and evaporation in urban areas, showing that the assumption that all rainfall becomes runoff is not correct and that it leads to an overestimation of runoff. Ramier et al. (2011) studied the hydrological behaviour of urban streets over a 38-month period to estimate runoff losses and to better define rainfall runoff transformations. They estimated losses due to evaporation and infiltration inside the road structure between 30 and 40% of the total rainfall.

The impact of increase of imperviousness on hydrological response was studied by Cheng (2002), who analysed the effects of urban development in Wu-Tu (Taiwan's catchment) considering 28 rainfall events (1966-1997). Results showed that response peak increased by 27% and the time to peak decreased from 9.8 to 5.9 hours, due to an increase of imperviousness from 4.78% to 11.03%.

In a similar study, Smith et al. (2002) analysed the effects of imperviousness on flood peak in the Charlotte metropolitan region (U.S.), analysing a 74 year discharge record. Results showed that different land covers were associated with large differences in timing and magnitude of flood peak, while there were not significant differences in the total runoff volume. Hortonian runoff was the dominant runoff mechanism. Antecedent soil moisture ~~is playing~~ played an important role in this watershed, even in the most urbanized catchment~~, where the effects are generally less evident~~.

The influence of antecedent soil moisture is, however, not always so evident. Smith et al. (2013) showed that in nine watersheds, located in the Baltimore metropolitan area, the antecedent soil moisture, defined as 5 day antecedent rainfall, seemed not to affect the hydrological response. Introduction of stormwater management infrastructure played an important role in reducing flood peaks and increasing runoff ratios. Results showed that rainfall variability may have important effects on spatial and temporal variation in flood hazard in this area.

Analysing the effects of a moderate extreme and an extreme rainstorm on the same area presented by Smith et al. (2013), Ogden et al. (2011) highlighted the importance of changes in imperviousness on flood peaks. ~~For~~ They found that for extreme rainfall event, imperviousness ~~has~~ had a small impact on runoff volume and runoff generation efficiency.

4.4 Evaporation

Evaporation plays an important role in the hydrological cycle: in forested catchment around $60 - 95\%$ of total annual rainfall evaporates or is absorbed by the vegetation (Fletcher et al., 2013). In an urban catchment, ~~effects of the evaporation are~~ evaporation is drastically reduced (Oke, 2006; Fletcher et al., 2013; Salvadore et al., 2015). Evaporation is often neglected in analysis of fast and intense rainfall events (Cui and Li, 2006): the order of magnitude of evaporation is very small compared to the total amount of rainfall. ~~Recent~~ Some studies have shown that evaporation is not always negligible in urban areas and can constitute up to 40% of the annual total losses (Grimmond and Oke, 1991; Salvadore et al., 2015). In their experimental study, Ragab et al. (2003) showed that evaporation represents ~~,~~ $21 - 24\%$ of annual rainfall, with more evaporation taking place during summer than winter. It is particularly important to have measurements with high resolution because a coarse spatial

description can hide heterogeneous land covers and consequently, heterogeneous evaporation losses (Salvadore et al., 2015). Different techniques and approaches have been developed to measure the impact of evaporation, from the standard lysimeter to the use of remote sensing (Nouri et al., 2013).

Evaporation measurements in urban areas are one of the weak points of the water balance (van de Ven, 1990) and they present many problems and challenges (Oke, 2006). It is quite hard in fact to find a site, representative of the area, ~~that is~~ far enough from obstacles ~~, not placed on concrete or asphalt~~ and not unduly shaded. Errors in estimation of annual evaporation in urban areas may still be higher than 20% (van de Ven, 1990).

4.5 Flow in sewer systems

In urban areas, part of the surface runoff enters in the sewer system through gully inlets, depending on the capacity of these elements, on their maintenance (Leitão et al., 2016) and the sewer system itself.

Stormwater flow in sewer systems is highly non-uniform and unsteady, it can be considered as one dimensional, assuming that depth and velocity vary only in the longitudinal direction of the channel. Flow in sewer pipes is usually free-surface, but during intense rainfall events the system can become full and temporarily behave as a pressurised system, a phenomenon called surcharge. In particular conditions, as for example in flat catchments, inversion of the flow direction in pipes can occur during filling and emptying of the system. The most common form to model flow in sewer pipes is based on a one-dimensional form of the de Sain-Venant ~~(Eq. (??) and Eq. (??)).~~ equations.

Sewer system density influences runoff generation (Ogden et al., 2011; Yang et al., 2016): a dense pipe network can, in fact, reduce the runoff generation, increasing the storage capacity of the system (Yang et al., 2016). Ogden et al. (2011)presented a study about the importance of drainage density on flood runoff in urban catchments. Defining the drainage density as channel length per total catchment area, they studied the hydrological response of the same basin modelled with drainage density that varied from 0.4 km km^{-2} and 3.9 km km^{-2}. Results showed a significant increase in peak discharge and runoff volume for drainage density between 0.4 km km^{-2} and 0.9 km km^{-2}, while for values higher than 0.9 km km^{-2}, effects were negligible. When the storage and transport capacity of a system is not sufficient to prevent flooding, detention basins are effective tools to reduce peak flows, and they can reduce the superficial runoff up to 11% (Smith et al., 2015).

Similarly, green roofs can significantly decrease and slow peak discharge and reduce runoff volume. Versini et al. (2014) presented a study on the impact of green roofs at urban scale using a distributed rainfall model. They showed that green roofs can reduce runoff generation in terms of peak discharge, up to 80% depending on the rainfall event and initial conditions.

5 Urban hydrological models

Urban hydrological models were developed since the 1970s to better understand the behaviour of the components of the water cycle in urban areas (Zoppou, 2000). Since then, many models, with different characteristics, principles and complexity have been built. These models are used for several purposes, such as to study and predict the effects of urbanization increase on

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the hydrological cycle, to support flood risk management, to ensure clean and fresh drinking water for the population, and to support improvement of waste water networks and treatments.

5   Hydrological models have shown to be useful to compensate partially for the lack of measurements (Salvadore et al., 2015), but all models present errors and uncertainties of different nature and magnitude (Rafieeinasab et al., 2015). In this chapter, different classifications and characterizations of hydrological models are presented.

5.1   Urban hydrological model characterization

~~A first distinction that can be made is between deterministic and stochastic models. They differ in the use of random variables~~
10   ~~to solve mathematical relationships that describe system behaviour. Stochastic models use random values from a chosen probability distribution for one or more model parameters or input variables. Deterministic models do not consider any randomly chosen values and will always produce the same identical results for a given configuration of variables. For given inputs, stochastic models account for the uncertainty in input variables and model parameters, by incorporating selected probability distributions.~~

15   ~~Models can also be classified~~ Hydrological models can be characterized and classified in different ways. A first distinction can be made according to the representation of spatial variability of the catchment. A lumped model does not consider spatial variability of the input, and uses spatial averaging to represent catchment behaviour. In contrast, distributed models describe spatial variability, usually using a node-link structure to describe subcatchment components (Zoppou, 2000; Fletcher et al., 2013). ~~A general criterion to choose~~ The choice of a suitable model depends on many factors and it is generally related to
20   the applications and final objective. For example Berne et al. (2004) suggested a guideline for choosing between lumped and distributed ~~models was presented by Berne et al. (2004). The~~ modelling considering the representative surface associated to a single rain gauge S_r [L^2]. This characteristic, defined in relation to the rainfall spatial resolution r as $S_r = \pi[r/2]^2$, ~~was~~ is compared with the surface area of a catchment S [L^2]. If $S_r > S$ or $S_r \sim S$ a lumped modelling approach ~~was~~ is suggested, while for $S_r < S$, ~~they recommended using~~ a distributed model is recommended, as well as collecting measurements at the
25   subcatchment scale. Different sub-categories are presented to characterize model spatial variability. Distributed models can be divided into fully distributed and semi-distributed models. Fully distributed models present a detailed discretization of the surface, using a grid or a mesh of regular or irregular elements, and apply the rainfall input to each grid element, generating grid-point runoff. The flow can be estimated at any location within the basin and not only at the catchment outlet. This is, however possible only if the rainfall is provided at an appropriate scale. Semi-distributed models are based on subcatchment
30   units, through which rainfall is applied. Each subcatchment is modelled in a lumped way, with uniform characteristics and a unique discharge point (Pina et al., 2014). Salvadore et al. (2015) proposed a model classification based on spatial variability with 5 categories: lumped, semi-distributed, Hydrological Response Unit based (semi-distributed with a specific way to define the subcatchment area), grid based spatially distributed and Urban Hydrological Element based (mainly focused on the urban fluxes).

    Another distinction is between conceptual and physically based (or process based) models, depending on whether the model is based on physical laws or not. Recently, Fatichi et al. (2016) presented an overview of the advantages and limitations of

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physically based models in hydrology. They defined a physically based hydrological model as "a set of process descriptions that are defined depending on the objectives". The downsides of using a physically based model are related to over−complexity and over−parametrization: conceptual models are much easier to manage and they are usually less affected by numerical instability. Physically based models usually require high computational power and time and a large number of parameters, but there are situations in which it is important to keep the complexity to better understand ~~the~~ system mechanisms. They are also necessary to deal with ~~the~~ system variability and ~~they~~ allow to include a stochastic component to represent ~~the~~ uncertainty in parameter and input values (Del Giudice et al., 2015).

A good summary of the most used urban hydrological models is presented by Salvadore et al. (2015), where a table containing 43 numerical studies highlights the model characteristics.

5.2 Spatial and temporal variability in urban hydrological models

Depending on their characteristics, models can be very sensitive to spatial and temporal rainfall variability or not be able to correctly reproduce effects of this variability. Spatial variability of land cover and soil characteristics is an important element in hydrological models~~, especially at the small urban scale~~. Choosing between a lumped, semi-distributed or fully distributed hydrological model leads to different representation of catchment characteristics and, consequently, to a different output (Meselhe et al., 2009; Salvadore et al., 2015; Pina et al., 2016).

A comparison between semi-distributed and fully-distributed urban stormwater models was made by Pina et al. (2016). Two small urban catchments, Cranbrook (London, UK) and the centre of Coimbra (Portugal), were modelled with a semi- and a fully-distributed model. Flow and depth in the sewer system of the different models were compared with observations and, in general, semi-distributed models predicted sewer flow patterns and peak flows more accurately, while fully distributed models had a tendency to underestimate flows. This was mainly due to the presence small−scale surface depressions, building singularities or lack of representation of private connections. Although fully-distributed models are more realistic and able to better represent spatial variability of the land cover, they need a higher resolution and accuracy to define module connections. Calibration of detailed, distributed models remains a complex issue that is not yet well resolved. The authors suggested to use a semi-distributed model approach in cases of low data resolution and accuracy.

To study the hydrological response Aronica and Canarozzo (2000) presented the ~~UDTM~~Urban Drainage Topological Model (UDTM), a model that represents sub-catchments of a semi−distributed model with two conceptual linear elements: a reservior and a channel. In a more recent study (Aronica et al., 2005), this model was compared to the Storm Water Management Model(EPA SWMM model, (Rossman, 2010)), that allows the user to choose different conceptual models to simulate runoff and sewer flow. Results showed that model structure and sensitivity to parameters influence the sensitivity to the rainfall input resolution.

~~Depending on their characteristics, models can be very sensitive to spatial and temporal rainfall variability or not be able to correctly reproduce their effects. In the literature, different comparisons between models and their sensitivity to spatial and temporal rainfall resolution have been presented. An example is given by Meselhe et al. (2009), who investigated the impact of temporal and spatial sampling of rainfall on runoff predictions using a physically based System Hydrologique European~~

~~(MIKE SHE)and conceptual hydrologic modelling system (HMS)hydrologic models. Their study showed that the physically based model was more sensitive to both spatial and temporal rainfall samplings than the conceptual model.~~

6 Interaction of spatial and temporal rainfall variability with hydrological response in urban basins

Storm structure and motion play an important role in the ~~variabilty~~ variability of the hydrological response (Smith et al., 1994; Bacchi and Kottegoda, 1995; Ogden et al., 1995; Singh, 1997; Emmanuel et al., 2012; Nikolopoulos et al., 2014; Emmanuel et al., 2015), especially for small catchments (Faures et al., 1995; Fabry et al., 1994). The characterization and the influence of spatial and temporal rainfall variability on runoff response is still not well understood (Emmanuel et al., 2015).

Recent studies address the impact of rainfall variability, focusing on urban catchments (Berne et al., 2004; Ochoa-Rodriguez et al., 2015b; Rafieeinasab et al., 2015; Yang et al., 2016). The main results and conclusions are presented in the following sections. It is discussed how basin characteristics impact the sensitivity of hydrological response to rainfall variability and how the interaction between spatial and temporal rainfall variability influences hydrological response.

6.1 Interaction between rainfall resolution and urban hydrological processes

Many studies highlight the importance of high resolution rainfall data (Notaro et al., 2013; Emmanuel et al., 2012; Bruni et al., 2015) and how their use could improve runoff estimation, especially in an urban scenario, where drainage areas are small and spatial variability is high (Schilling, 1991; Schellart et al., 2011; Smith et al., 2013). These studies have shown how catchments act as filters in space and time for hydrological response to rainfall, delaying peaks and smoothing the intensity. However, the influence of spatial variability of rainfall on catchment response in urban areas is complex and remains an open research subject.

A theoretical study, conducted by Schilling (1991), emphasised the necessity to use rainfall data with a higher resolution for urban catchments compared to rural areas, and suggested to choose a minimum temporal resolution of $1 - 5$ min and a spatial resolution of 1 km. The effects of temporal and spatial rainfall variability below 5 min and 1 km scale were subsequently studied by Gires et al. (2012). They investigated the urban catchment of Cranbrook (London, UK), with the aim of quantifying uncertainty in urban runoff estimation associated with unmeasured small scale rainfall variability. Rainfall data were obtained from the national C-band radar with a resolution of 1 km^2 and 5 min and were downscaled with a multifractal process, to obtain a resolution $9-8$ times higher in space and $4-1$ in time. Uncertainty in simulated peak flow associated with small-scale rainfall variability was found to be significant, reaching 25% and 40% respectively for frontal and convective events.

To investigate the effects of spatial and temporal variability on urban hydrological response, Peleg et al. (2016) used a stochastic rainfall generator to obtain high resolution spatially variable rainfall as input for a calibrated hydrodynamic model. They compared the contributions of climatological rainfall variability and spatial rainfall variability on peak flow variability, over a period of 30 years. They found that peak flow variability is mainly influenced by climatological rainfall, while the effects of spatial rainfall variability increase for longer return periods.

Required rainfall resolution for urban hydrological modelling strongly depends on the characteristics of the catchment. Several researchers have studied the sensitivity of urban hydrological response to different rainfall resolutions, highlighting correlations between rainfall resolution and catchment dimensions, such as drained area (Berne et al., 2004; Ochoa-Rodriguez et al., 2015b) or catchment scale length (Ogden and Julien, 1994; Chirico et al., 2001; Bruni et al., 2015).

6.1.1   ~~Influence of spatial and temporal rainfall variability in relation with drained area~~

6.2   Influence of spatial and temporal rainfall variability in relation to catchment dimensions

Drainage area dimensions influence hydrological response and their sensitivities to spatial and temporal rainfall resolution have recently been investigated.

Wright et al. (2014) presented a flood frequency analysis, based on stochastic storm transposition SST (Wright et al., 2013) coupled with high resolution radar rainfall measurements, with the aim to examine the effects of rainfall time and length scale on the flood response. Rainfall data were used as input for a physics-based hydrological model representative of 4 urbanized subcatchemnts. This study showed that there is an interaction between rainfall and basin characteristics, such as drainage area and drainage system location, that strongly affects the runoff.

Berne et al. (2004) studied the hydrological response of six urban catchments located in the south-east of the French Mediterranean coast. Rainfall data and runoff measurements were collected using two X-band weather radars, one vertically pointing radar and one radar performing vertical plane cuts of the atmosphere, with a spatial resolution of 7.5 m and 250 m and a temporal resolution of 4s and 1min respectively. The minimum temporal resolution required Δt [T] was defined as $\Delta t = \frac{t_c}{4}$, where t_c [T] is the characteristic time of a system and the value 4 depends on catchment properties (Schilling, 1991). By considering lag time t_{lag} equal to the characteristic time t_c, it was possible to write the minimum required temporal resolution as a function of surface area S, based on the relationship $\sim\sim\sim t_{lag} = S^{0.3} \sim\sim\sim t_{lag} = 3S^{0.3}$: $\Delta t = 0.75\,S^{0.3}$. Spatial resolution was studied considering rainfall data collected from the X-band weather radar performing vertical plane cuts of the atmosphere, combined with measurements of rain gauges. Two spatial climatological variograms were built with a time resolution of 1 min (from radar) and 6 min (from a network of 25 rain gauges). Based on variogram analysis, it was possible to define the relation between range r and time resolution Δ_t as: $(r = 4.5\sqrt{\Delta t})$. The minimum required spatial resolution Δs [L^2] was defined by the ~~author~~ authors as $\Delta s = \frac{r}{3}$, and it can also be expressed as a function of Δt:

$$\Delta s = 1.5\Delta t. \tag{4}$$

In this way, both spatial and temporal resolution requirements were defined as a function of surface dimensions of a catchment. Required resolutions for urban catchments of 100 ha are 3 min and 2 km, but common operational rain gauge networks are usually less dense, while radars seldom provide data at this temporal resolution. Results presented are valid for catchments with characteristics similar to the catchments studied, such as surface area (from 10 ha to 10000 ha), slope (1% to 10%), imperviousness degree (10% to 60%), and exposed to climatic conditions similar to those of Mediterranean area.

Ochoa-Rodriguez et al. (2015b) analysed the impact of spatial and temporal rainfall resolution on hydrological response in seven urban catchments, located in areas with different geomorphological characteristics. Using rainfall data measured by a

dual polarimetric X-band weather radar with spatial resolution of 100x100 m^2 and temporal resolution of 1min, they investigated the effects of combinations of different resolutions, with the aim to identify critical rainfall resolutions. A strong relation between drainage area and critical rainfall resolution and between spatial and temporal resolutions was found. Sensitivity to different rainfall resolutions decreased when the size of the subcatchment considered increased, especially for catchment size above 1 km^2. This study highlighted the importance of high resolution rainfall data as input. Spatial resolution of 3x3 km^2 is not adequate for urban catchments and temporal resolution should be lower than 5 min. Most operational radars present a temporal resolution of 5 min, not sufficient to correctly represent the effects of temporal rainfall variability.

The sensitivity to rainfall variability on 5 urban catchments of different sizes, located in the City of Arlington and Grand Prairie (U.S.), was studied with a distributed hydrological model (HLRDHM, Hydrology Laboratory Research Distributed Hydrological Model) by Rafieeinasab et al. (2015). Rainfall data were provided by the Collaborative Adaptive Sensing Atmosphere (CASA) X-band radar with spatial resolution of 250x250 m^2 and temporal resolution of 1 minute and upscaled in various steps to 2x2 km^2 and 1 hour. Results showed peak intensity and time to peak error to be sensitive to spatial rainfall variability. The model was able to represent observed variability for all catchments except the smallest (3.4 km^2) at a temporal resolution of 15 minutes or lower, combined with spatial variability of 250x250 m^2 and capture variability in streamflow.

Rainfall required resolutions is higher for small basins, as in the case of urban catchments. The influence of slope, imperviousness degree or soil type were not separately investigated, but the relationships between catchment area and rainfall resolution are expected to depend on these characteristics as well.

6.2.1 **Influence of spatial and temporal rainfall variability in relation with length scale**

Sensitivity of hydrological response to different spatial and temporal rainfall resolutions have been investigated with dimensionless parameters to represent the length scales of storm events, catchments and of sewer networks.

Ogden and Julien (1994) identified dimensionless parameters to analyse correlations between catchment and storm characteristics and to study sensitivity of runoff models to radar rainfall resolution. Rainfall data of a convective storm event, measured by a polarimetric radar with a spatial resolution of 1x1 km^2, were applied on two basins. The storm smearing was defined as the ratio between rainfall data grid size and rainfall decorrelation length. Storm smearing occurs when rainfall data length is equal or longer than the rainfall decorrelation length. The watershed smearing was described as the ratio between rainfall data grid size and basin length scale. When infiltration is negligible, watershed smearing is an important source of hydrological modelling errors, if the watershed ratio (rainfall measurement length/basin length) is higher than 0.4.

A similar approach, with dimensionless parameters, was recently applied by Bruni et al. (2015) to urban catchments. Rainfall data from a X-band dual polarimetric weather radar were applied to an hydrodynamic model, to investigate sensitivity of urban model outputs to different rainfall resolutions. Runoff sampling number was defined as ratio between rainfall length and runoff area length. Results confirm what was found by Ogden and Julien (1994). A third dimensionless parameter, called runoff sampling number, was identified. Small-scale rainfall variability at the 100x100 m^2 affects hydrological response and the effect of spatial resolution coarsening on rainfall values strongly depends on the movement of storm cells relative to the catchment.

Using dimensionless parameters is a productive approach to study sensitivity of hydrological response to spatial and temporal rainfall variability. Effects of other catchment characteristics, such as slope or imperviousness, were so far neglected, but they

5   need a deeper investigation.

6.3   Spatial vs temporal resolution

As it was already discussed in previous sections, there is a dependency between spatial and temporal rainfall required resolution and they affect in a different way the hydrological response (Marsan et al., 1996; Singh, 1997; Berne et al., 2004; Gires et al., 2011; Ochoa-Rodriguez et al., 2015b).

10   A first interaction between spatial and temporal rainfall scale was defined ~~assuming~~ based on the assumption that atmospheric properties are valid also for rainfall. Following this assumption, Kolgomorov's theory (Kolgomorov, 1962) was combined with the ~~scale invariance property of~~ scaling properties of the Navier-Stokes equation, in order to define ~~the anisotropy coefficient H_t~~ ~~(Marsan et al., 1996; Deidda, 2000; Gires et al., 2011). Temporal and spatial scale changing law (t_λ and s_{lambda}) are defined~~ ~~using scaling factors (λ_t~~ a relation between space and time variability. For large Reynolds numbers, in fact, Navier-Stokes

15   equation is invariant under scale transformations (Marsan et al., 1996; Deidda, 2000; Gires et al., 2011), and in this way temporal and spatial "scale changing" operator can be defined by dividing space and time (s and t) by scaling factors λ_s and ~~λ_s), related~~ ~~by the~~ λ_t relatively: $s \mapsto s/\lambda_s$ and $t \mapsto t/\lambda_t$, where the scaling factors represent the the degree . For scaling processes, there is a relation between scaling factors in time and space to take into account, that is represented the anisotropy coefficient H_t:

$$t_\lambda \mapsto t_\lambda/\lambda^{1-H_t}$$

20    $$s_\lambda \mapsto s_\lambda/\lambda$$

$$\lambda_t = \lambda_s^{1-H_t}$$

$\lambda_t = \lambda_s^{(}1-H_t)$. H_t is a priori unknown for rainfall, but it can be assumed equal to $1/3$, a value that characterise atmospheric turbulence (Marsan et al., 1996; Gires et al., 2011, 2012). Lovejoy and Schertzer (1991) estimated $H_t = 0.5 \pm 0.3$ for raindrops. An example of application of this theory in a downscaling process is given by Gires et al. (2012): here, the rainfall is measured

25   with a certain spatial resolution s and temporal resolution t. They hypothesised to downscale the pixels, dividing the length by a scaling factor $\lambda_s = 3$, to obtain 9 pixels out of one. In this case, the duration of the time step has to be divided by a scaling factor $\lambda_t = \lambda_s^{1-1/3} = 2^{2/3} \simeq 2$.

Studying the hydrological response of the south-east French Mediterranean coast, Berne et al. (2004) proposed another relationship between spatial Δ_s and temporal Δ_t resolution used to measure rainfall, as : $\Delta s = 1.5\sqrt{\Delta t}$ (see section 6.1.1 for

30   the formula derivation).

Ochoa-Rodriguez et al. (2015b) derived the theoretically required spatial rainfall resolution for urban hydrological modelling starting from a climatological variogram, that characterised average spatial structure of rainfall fields over the peak storm period, fitted with an exponential variogram model. They defined characteristic length scale r_c [L] of a storm event as

$r_c = (\frac{\sqrt{2\pi}}{3})r$, where r [L] is the variogram range. The minimum required spatial resolution for adequate modelling of urban hydrological response was defined as half characteristic length scale of the storm:

$$\Delta s = \frac{r_c}{2} \cong 0.418r. \tag{5}$$

The theoretically required temporal resolution Δt, was defined based on the time needed for a storm to move over distance equal to the characteristic length scale of the storm event r_c. It can be written as:

$$\Delta t = \frac{r_c}{v}, \tag{6}$$

where v [L t^{-1}] is the magnitude of the mean storm velocity, obtained from average of the velocity vectors (magnitude and direction) estimated at each time step. Authors investigated the impact of 16 combinations of 4 different spatial resolutions (100x100 m, 500x500 m, 1000x1000 m, and 3000x3000 m) combined with 4 different temporal resolutions (1, 3, 5 and 10 min). Resolution combinations were chosen considering different aspects, such as the operational resolution of radar and rain gauges networks, characteristics temporal and spatial scale already discussed in the literature (Berne et al., 2004), and according to Kolgomorov's scaling theory (Kolgomorov, 1962). Results showed that hydrodynamic models are more sensitive to the coarsening of temporal resolution of rainfall inputs than to the coarsening of spatial resolution, especially for fast moving storms. Critical rainfall resolutions were identified, considering the drainage area (~~Tab.~~ Table 4). For small catchments, with area smaller than 1 ha, was found to be equal to 100x100 m and 1 min, while for areas between 1 ha and 100 ha, a spatial resolution of 500x500 m can be sufficient to estimate the hydrological response. The critical spatial resolution found is lower than 5 min, for catchment size from about 250 to 900 ha. Results were confirmed by Yang et al. (2016), that presented an analysis of flash flooding in two small urban subcatchments of Harry's Brook (Princeton, New Jersey, US), focusing on the influence of rainfall variability of storm events on hydrological response.

Moreover, spatial variability seemed to influence timing of runoff hydrograph, while temporal variability mainly influences peak value Singh (1997).

These studies highlighted the relatively more important role of temporal variability compared to spatial variability, for extreme rainfall events. The impact of the spatial variability, seemed to decrease with increase of total rainfall accumulation.

7 Discussion

In this article, the state of the art of spatial and temporal variability impact of rainfall and catchment characteristics on hydrological response in urban areas has been presented.

A first aspect that has been analysed is the high variability in space and time of hydrological processes and phenomena, highlighting how difficult it is to define spatial and temporal scale parameters, that are able to characterize catchments in an effective way. Several definitions to classify time scale characteristics are available in the literature, such as time of concentration, lag time, time of equilibrium and response time scale. However, measurement or estimation of those parameters is often difficult, which implies a high level of uncertainty. For this reason, thus far, no common agreement has emerged on a unique set of parameters able to characterize the variability of a catchment.

A similar problem can be observed for rainfall analysis, where there is not an unique way to classify rainfall events and to consider the spatial and temporal variability. In the last decades, new technologies have been developed in order to reduce the uncertainty connected to measurements of rainfall and to capture its variability. Weather radars are a good example of recently developed instruments, able to estimate rainfall spatial variability and to reduce uncertainty, especially when combined with rain gauge networks. High resolution rainfall data are necessary to estimate the hydrological response, especially in urban areas, where rainfall effects are combined with a high variability of catchment characteristics and hydrological processes, such as infiltration, evaporation and surface runoff. An important role in urban areas is played by drainage infrastructures that highly affect the hydrological response, while in some cases the effects of these structures are not perfectly understood.

When radar data are used in a distributed model, the highest available rainfall time resolution does not always provide the best estimation of peak flow (Atencia et al., 2011). Under the assumption of a perfect hydrological model with a perfect rainfall input, the accuracy of model output should increase with increase of resolution of both model and rainfall input. In reality, there are some limitations, due to uncertainty and errors related to rainfall measurements and model characteristics (Rafieeinasab et al., 2015).

Many studies present hydrological models, with different characteristics and different representations of the catchment spatial variability. These models have become more and more detailed, reaching high levels of spatial resolution. If there are no high resolution rainfall data, high model resolution is not the best choice. Rainfall measurement and hydrological modelling resolutions need to be in agreement. Increasing availability of higher resolution rainfall data from rainfall radars will enable deeper investigation of this relationship.

Improved rainfall measurements have also allowed to investigate the relations between temporal and spatial rainfall scale. Relations have been presented, mostly adapting the Kolgomorov's theory to rainfall, to define the interaction between spatial and temporal scale in atmosphere. A unique relationship has not been find yet, and further investigations are necessary in this direction.

8 Conclusions

The relevance of the spatial and temporal variability of rainfall, hydrological processes and catchment characteristics and the impact that they have on the hydrological response have been discussed in this paper. The main key points and conclusion of this study are the following.

– Hydrological phenomena and processes have different spatial and temporal variability, and sometimes instruments are not able to measure the considered process at the relevant scale. It is important to study hydrological problems at a spatial and temporal scale that is in agreement with the variability of the processes involved.

– Uncertainty associated with rainfall spatial and temporal variability is one of the main sources of error in the estimation of hydrological response in urban areas. New technologies have been developed to measure rainfall spatial and temporal variability more accurately and at higher resolution. While rain gauges remain the most common used rainfall

measurement instruments, weather radars are increasingly used to measure rainfall distributed in space. Especially in urban areas, rain gauges present many limitations due to strong microclimatic variability, complicating identification of suitable locations for representative rainfall measurements. Additionally, rain gauges provide a poor representation of spatial variability because they measure rainfall only at a specific point.

– Infiltration, local storage, interception and evaporation are quite difficult to measure, especially in urban areas, because of the strong heterogeneity of urban land-use.

– Different types of hydrological models have been developed in order to represent the spatial variability of catchment properties, such as land cover and imperviousness degree. Models can be classified based on their ability to represent the spatial variability of the catchment into lumped, semi-distributed and fully distributed models. Fully distributed models represent catchments in a more detailed way, but this also requires a higher resolution of the rainfall used as input for the higher model resolution to be beneficial.

– The impact of spatial and temporal rainfall variability on the hydrological response in urban areas and the role of drainage infrastructure and man-made control structures herein still remains poorly understood. It was found that sensitivity of hydrological response to spatial and temporal rainfall variability varies with catchment size, catchment shape, storm scale and storm velocity. So far, findings are mainly based on sensitivity studies using theoretical model scenarios. A wider range of conditions and scenarios based on observational datasets for urban hydrological basins need to be analysed in order to characterize better the hydrological response and its sensitivity to different spatial and temporal rainfall resolutions.

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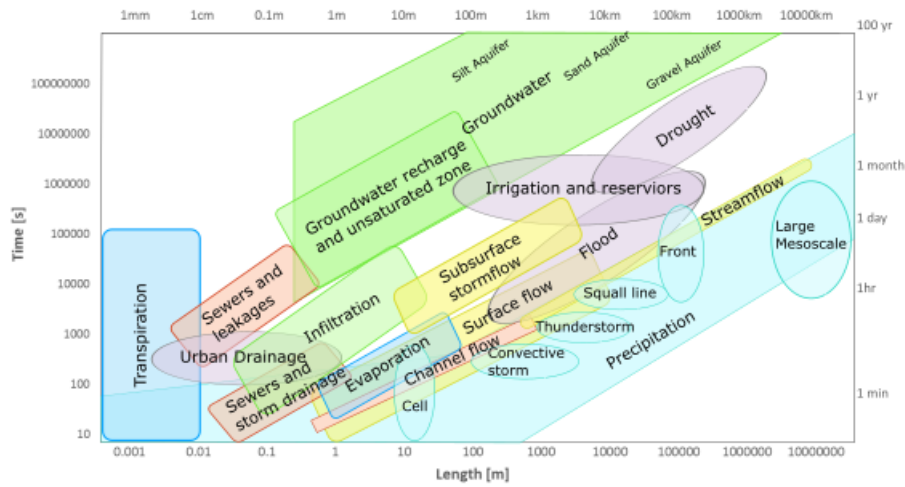Zoppou, C.: Review of urban storm water models, Environ. Model. Softw, 16, 195–231, 2000.

Figure 1. Spatial and temporal scale varibility of hydrological processes, adapted from Berndtsson and Niemczynowicz (1986), Blöschl and Sivapalan (1995), Stahl and Hisdal (2004) and Salvadore et al. (2015). Colours represent different groups of physical processes: blue for processes related to the atmosphere, yellow for surface processes, green for underground processes, red highlights typical urban processes and grey indicates problems hydrological processes can pose to society.
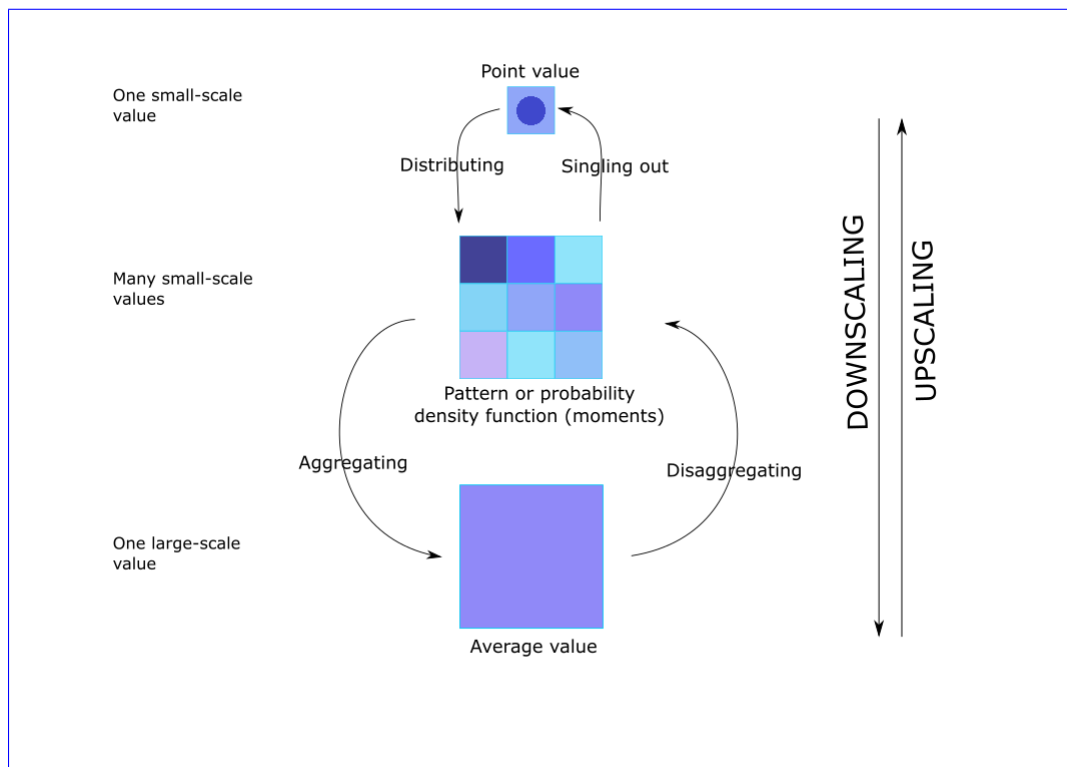
Figure 2. Downscaling and upscaling processes (modified from Blöschl and Sivapalan (1995))

Table 1. Time scale parameters

Characteristic	Reference	Description
Time of concentration t_c	Singh (1997) Gericke and Smithers (2014)	The time that a drop that falls on the most remote part of the drainage basin needs to reach the basin outlet
Time of equilibrium t_e	Ogden et al. (1995) Ogden and Dawdy (2003) van de Giesen et al. (2005)	Minimum time needed for a given stationary uniform rainfall to persist until equilibrium runoff flow is reached
Lag time t_{lag}	Berne et al. (2004) Marchi et al. (2010) Gericke and Smithers (2014)	The time difference between the gravity center of the hyetograph of catchment mean rainfall and the gravity center of the generated hydrograph
Response time scale T_s	Morin et al. (2001) Morin et al. (2002) Morin et al. (2003) Shamir et al. (2005)	The time scale at which the pattern of time averaged radar hyetograph is most similar to the pattern of the measured hydrograph at the outlet of the basin

Table 2. Weather radar characteristics

	λ	ν	l
	cm	GHz	m
S-band	8-15	2-4	6-10
C-band	4-8	4-8	3-5
X-band	2.5-4	8-12	1-2

Table 3. Characterization of rainfall events, spatial and temporal scales and rainfall estimation uncertainty. From van de Beek et al. (2010); Smith et al. (1994) and Emmanuel et al. (2012)

	Characterization and Intensity	Spatial Range	Temporal Range	Radar Estimation
Light rainfall	$1mmh^{-1}$	$17km$	$15min$	Underestimation rainfall values often below the threshold ($0.17mmh^{-1}$)
Convective Cells	short and intense from $25mm$	$5km$	$5min$	Overestimation
Organized Stratiform	up to $17mmh^{-1}$	$< 5km$	$< 5min$	General underestimation, good representation of the hyetograph behaviour
Unorganized Stratiform	intense peak inside intensity rainfall lower	$15km$	$15min$	Underestimation of the peaks, good representation of the hyetograph behaviour

Table 4. Critical Resolutions in relation with the drainage area

Drainage Area DA (ha)	Critical spatial resolution (m x m)	Critical temporal resolution (min)
DA<1	100	1
1<DA<100	500	1
250<DA<900	1000	<5