**Anonymous referee #2**
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**General**
This paper suggest a method to upscale rainfall intensity from point scale to catchment scale. The authors suggest a Kriging-based stochastic method for this upscaling; a method that allows an uncertainty estimation of the areal rainfall. I found the method suggested by the authors very interesting. I think that it will be of interest mainly for the hydro-meteorologist community (dealing with weather radar estimations) rather than for the urban hydrologist community. Main problem in the paper is the short period of observation (two seasons) that is expressed in a low confidence in the presented results.
I found that some key papers dealing with dense rain-gauge networks and rainfall variability in the past were not mentioned and that some trivial aspects discussed in the past are repeated in here. I would suggest the authors to thoroughly revise the paper as follow: make the upscaling method as the main focus of the paper, explain it with much further details and with a much clearer language. Use the data you have from the dense rain-gauge network as a case study to demonstrate how you can upscale rainfall for the catchment / weather radar scale and show the advantages of estimating uncertainties with the method you are suggesting. Please find below my specific comments, following by some general comments.

<u>Authors:</u> *We thank the reviewer for the professional and thorough revision of our paper. We have attempted to address all comments listed below.*

…Main problem in the paper is the short period of observation (two seasons) that is expressed in a low confidence in the presented results…

<u>Reply:</u> *Please refer to our detailed response to the reviewer's specific comment on data used in the study [3:19-20]*

…I found that some key papers dealing with dense rain-gauge networks and rainfall variability in the past were not mentioned

<u>Reply:</u> *Please refer to our detailed response to reviewer's specific comment on literature used in the study [2:19-21]*

….and that some trivial aspects discussed in the past are repeated in here.

<u>Reply:</u> *We attempt to deal with the concerns stated by the reviewer. Few sentences will be removed and some will be rewritten in the revised manuscript to try and reduce the level of trivial results. They are listed below*

*[5: 11] "As expected, with increasing temporal averaging the number of time instants t reduces." will be corrected as "Number of time instants t reduces with increasing temporal averaging intervals due to the aggregation process."*

*[5: 12-13] "Figure 5 also shows that the higher the intensity, the smaller the t. There is a large difference between t for lower and higher intensity ranges which shows the dominance of lower intensity (0.1-5.0 mm/h) rainfall over the recording periods" will be corrected as "The natural characteristic of rainfall data results in the dominance of lower intensity rainfall (0.1-5.0 mm/h) over the recording period."*

*[10: 16] "It is expected that with increasing temporal averaging interval the local minima and maxima of AARI get smoothed out. Here it can be noted that in this event this effect decreases the event peak AARI from around 50 mm/h to around 20 mm/h as the temporal averaging interval*

*increases from 2 min to 30 min." will be corrected as "It is obvious that with increasing temporal averaging interval the local minima and maxima of AARI get smoothed out. As a result the event peak gets reduced from around 50 mm/h to around 20 mm/h as the temporal averaging interval increases from 2 min to 30 min"*

… I would suggest the authors to thoroughly revise the paper as follow: make the upscaling method as the main focus of the paper, explain it with much further details and with a much clearer language. Use the data you have from the dense rain-gauge network as a case study to demonstrate how you can upscale rainfall for the catchment / weather radar scale and show the advantages of estimating uncertainties with the method you are suggesting.

*Reply: Thank you for the suggestion. With all due respect to the reviewer's suggestion, we think that the manuscript is already heavily focused on methodology with a dedicated section which covers around 35% of the manuscript (page wise). Further, to enable the reader to follow the methodology more easily, we explained it with a step by step procedure for a general case of estimating uncertainty in upscaling of point rainfall data. We tried to keep the methodology as general as possible while also providing enough detail on how each step is applied in the case of the Bradford case study.. Furthermore, we believe that introducing the data before the methodology enables the reader to follow the methodology more easily as some of the steps require a pre-introduction to the data to explain why such step is needed. Hence we feel that the structure of the manuscript follows a logical work flow. Changing the structure to follow the reviewer's advice will lead to repetition.*

*Nevertheless we accept that some part of the manuscript needs more explanation, especially the spatial stochastic simulation methodology. We also agree that the language could be clearer throughout the manuscript. Hence we are planning to modify several sections/ parts of sections including the following based on reviewer's specific comments:*

*Quality control of rainfall data using paired gauge set up: please refer to our response to reviewer's specific comment [4:1-5]*

*Spatial stochastic simulation: please refer to our response to reviewer's specific comment [7:13-22]*

**Specific comments**

**[Page:Lines]**

[2:4-6] Please support this statement with a reference.

*Reply: The following references will be added in the revised manuscript:*
*(Seo and Krajewski, 2010; Villarini et al., 2008)*

[2:19-21] Since you are dealing with rainfall uncertainty for small domains, taking into consideration the rainfall spatial and temporal variability, I am strongly recommend you to check also the following papers that were published in the recent years, which I think you will find them all relevant to your study:

Peleg N, Ben-Asher M, Morin E. Radar subpixel-scale rainfall variability and uncertainty: lessons learned from observations of a dense rain-gauge network. Hydrol. Earth Syst. Sci. 2013 Jun 14;17(6):2195-208.

Krajewski, W. F., Kruger, A., and Nespor, V.: Experimental and numerical studies of small-scale rainfall measurements and variability, Water Sci. Technol., 37, 131–138, doi: 10.1016/s0273-1223(98)00325-4, 1998.

Pedersen, L., Jensen, N. E., Christensen, L. E., and Madsen, H.: Quantification of the spatial variability of rainfall based on a dense network of rain gauges, Atmos. Res., 95, 441–454, doi:10.1016/j.atmosres.2009.11.007, 2010.

Fiener, P. and Auerswald, K.: Spatial variability of rainfall on a sub-kilometre scale, Earth Surf. roc. Land., 34, 848–859, doi:10.1002/esp.1779, 2009.

Seo, B. C. and Krajewski, W. F.: Investigation of the scale dependent variability of radar-rainfall and rain gauge error covariance, Adv. Water Resour., 34, 152–163, doi:10.1016/j.advwatres.2010.10.006, 2011.

Gebremichael, M. and Krajewski, W. F.: Assessment of the statistical characterization of small-scale rainfall variability from radar: Analysis of TRMM ground validation datasets, J. Appl. Meteorol., 43, 1180–1199, doi:10.1175/1520-0450(2004)043<1180:aotsco>2.0.co;2, 2004.

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.

<u>*Reply:*</u> *Thank you for suggesting the above papers. We wanted to keep our introduction mainly focused on the methodology that we adapted for this study. Hence we followed the below order in our introduction*

- *Lumped hydrological models need spatial average rainfall over catchments*
- *Focus is on rainfall observations at points*
- *Thus point observations need to be scaled up*
- *Review of existing methods that can do this*
- *Disadvantages of these methods*
- *Solution that does not have these disadvantages is to take geostatistical approach*
- *The main challenges with geostatistical approach and how these can be dealt with*

*We quoted the most relevant studies wherever necessary. We accept that there are many other studies like the ones mentioned by the reviewer which can be relevant because of the similar spatial extent of the rainfall data. But most of these publications are based or partly based on radar data (areal rainfall data) and outside the main scope of our study, which is upscaling of point rainfall data and estimating associated uncertainty. Discussion of the literature where both radar data and point rainfall are used together to compare and/or analyse spatial correlation is slightly out of the context and might lead to a very lengthy Introduction and might also confuse the readers even if the spatial extend of interest is same. Therefore to keep the Introduction to the point and precise on what we wanted to introduce (upscaling of point rainfall data and associated uncertainty) we have not included literature which are completely/partly based on radar data.*

*However from the reviewer's suggestion we found the following papers directly relevant to our study. We thank the reviewer for suggesting these papers. We will discuss these papers in appropriate sections of the revised manuscript. We summarised how these papers are related to our study below.*

*Pedersen, L., Jensen, N. E., Christensen, L. E., and Madsen, H.: Quantification of the spatial variability of rainfall based on a dense network of rain gauges, Atmos. Res., 95, 441–454, doi:10.1016/j.atmosres.2009.11.007, 2010.*

*The aim of this paper is to quantify the uncertainties of using a single rain gauge to represent the rainfall over a 500 × 500 m area. A field experiment placing nine rain gauges within an area of 500 × 500 m, each representing one-ninth of the area, was used to address the issue. The variability of rainfall is studied and uncertainty in areal rainfall is estimated for different time scales. Although a* *simpler approach is used in this study to estimate the uncertainty, results are still comparable to our study.*

*Fiener, P. and Auerswald, K.: Spatial variability of rainfall on a sub-kilometre scale, Earth Surf. roc. Land., 34, 848–859, doi:10.1002/esp.1779, 2009*

*In this study, a network of 13 tipping-bucket rain gauges was operated on a 1·4 km2 test site in southern Germany for four years to quantify spatial trends in rainfall depth, intensity, erosivity, and predicted runoff. Their data is comparable to ours as they also used summer half-year data for their analyses. Although they did not calculate any uncertainty in areal rainfall estimation, their analyses on spatial trend against temporal averaging interval could be of interest to our study. One of their conclusions suggests that in the longer term there is no difference in rainfall depth within the test site, but in short-time periods or for single events the assumption of spatially uniform rainfall is invalid on the sub-kilometre scale, This complements one of the findings from our study.*

[2:27] Reference typo.

*Reply: The following references will be added in the revised manuscript.*
*(Ly et al., 2013; Mair and Fares, 2011)*

[2:32] I would even claim that it is rare to find locations where the rainfall is normally distributed.

*Reply: Thank you for pointing this error out. This will be corrected in the revised manuscript.*

[3:3] word "often" can be deleted.

*Reply: Thank you for pointing this error out. This will be corrected in the revised manuscript.*

[3:19-20] This is a very short period of observation, and winter rainfall is not represented at all. How does it affect your results? Moreover, in [4:7-12] you mention the large difference between the two years of observation. This imply that the climatology was different between the two years and therefore I would expect that it will somehow influence on the rainfall spatial correlation. With only two years, the variability expected for the spatial rainfall structure cannot be represented and this should be discussed.

*Reply: We acknowledge that the data cover only 10 months, i.e. two summer periods in 2012 and 2013. However, for such a dense network this is often the case (Eg: 15 months - Ciach and Krajewski, 2006; 16 months - Jaffrain and Berne, 2012) due to practical difficulties and funding issues to maintain such networks for longer periods. The characteristics of our data are comparable with those studied in Ciach and Krajewski (2006) and Fiener and Auerswald (2008) as they also used rainfall data only from warm months to investigate spatial correlation structure of rainfall data.*

*We would also like to point out that the entire ten months of rainfall data, from 8 locations were used for the development of the geostatistical model in the form of variograms. Webster and Oliver (2007) suggested around 100 samples to reliably estimate a variogram model. Even in the case of 30 min temporal averaging interval and > 10 mm/hr (where we had the least observations) we had 196 sampling to calculate the variogram which is sufficiently larger than 100. Hence all our variogram models (based on which further results are derived) are stable and reliable.*

*Furthermore, to test the stability of variogram estimation we carried out the following experiment. We randomly selected 80% of the data from each intensity class and produced the variograms again to compare these with the variograms presented in Figure 7 of the manuscript. The variograms computed from 80% of the data are presented below in Figure C1.*

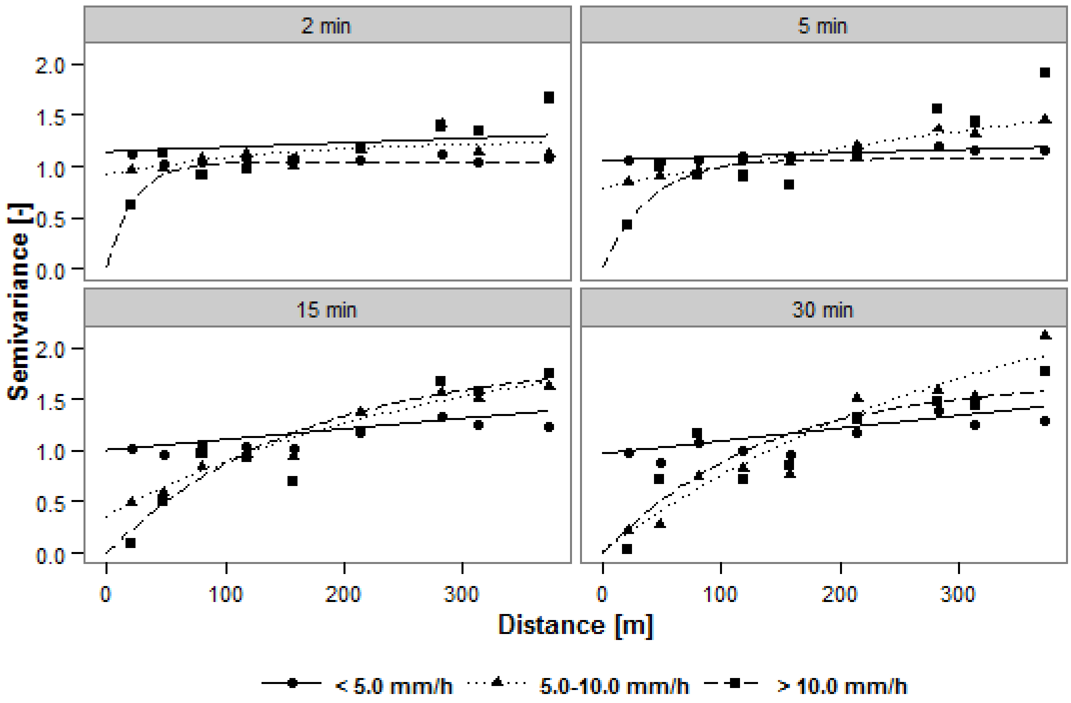


**Figure C1: Calculated variograms for each temporal averaging interval and for each range of intensity within a temporal averaging interval using randomly selected 80% of the data from each subclasses**

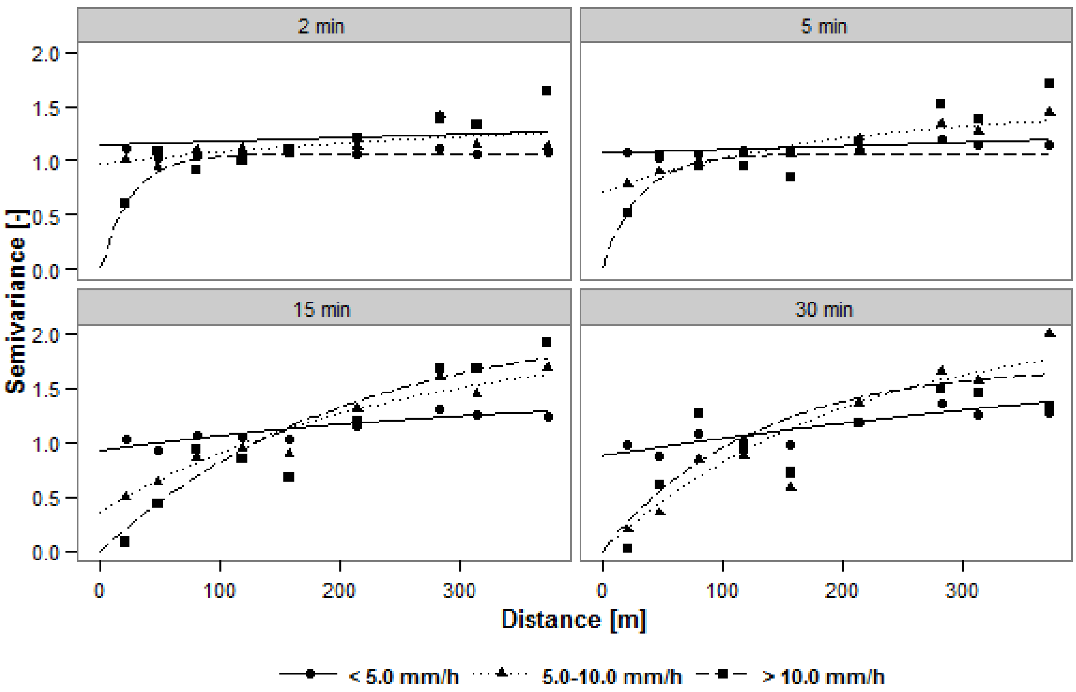


**Figure 1: Calculated variograms for each temporal averaging interval and for each range of intensity within a temporal averaging interval**

*Comparison of Figure C1 with Figure 7 shows that these are very similar. This analysis supports our claim that the variograms shown in Figure 7 are stable and an adequate representation of the rainfall spatial variation for each intensity class and temporal averaging interval.*

*Nevertheless we agree that different climatology of two years might influence the results and we will discuss this in the revised manuscript.*

[Fig. 1] The recommendation is to mount rain-gauges elevated at 1.2 m above ground, where here the gauges seem to be placed directly on ground level (roof top). I wonder how this affects rainfall intensity estimations.

<u>Reply:</u> *We understand that different guidelines suggest different elevations when it comes to height of a rain gauge from the surrounding ground level. In our case we followed the standard UK practice (http://www.metoffice.gov.uk/guide/weather/observations-guide/how-we-measure-rainfall) which suggests the rim of the tipping bucket to be around 0.5 m above the surrounding ground level. This clarification will be added to the manuscript.*

[3:29] what about time drift? Did you reset the loggers every 4-5 weeks to avoid this problem?

<u>Reply:</u> *Thank you for pointing this out. The data loggers were reset every 4-5 weeks during data collection to avoid any significant time drift. We will include this information in the revised manuscript.*

[4:1-5] This is not clear to me. If I got it right, you are comparing paired gauges for each rain event by accumulating the rainfall over the gauges and comparing them and if the difference exceed the 4%

Peleg, N., Marra, F., Fatichi, S., Paschalis, A., Molnar, P. and Burlando, P., 2016. Spatial variability of extreme rainfall at radar subpixel scale.
Journal of Hydrology.

<u>Reply:</u> *This section will be modified in the revised manuscript as given below to give more precise information on how the quality control was carried out using paired setup.*

*Quality control procedures were performed prior to statistical analysis, taking advantage of the paired gauge setup. The paired gauge design provides efficient quality control of the rain gauge data records as it helps to identify the instances when one of the gauges fails, and to flag the periods of missing or incorrect data (Ciach and Krajewski, 2006). During the dynamic calibration of all rain gauges in the laboratory before the deployment, it was identified that the highest and lowest values of the calibration factors for the tipping bucket size are 0.196mm and 0.204mm, respectively, resulting in a maximum potential error of ± 4 % due to the observed variation per tip for any two of the rain gauges used in this study. It was therefore decided that this is the maximum acceptable difference in cumulative rainfall that could be accepted between any pair of gauges. Sets of cumulative rainfall data corresponding to specific events from the paired gauges were checked against each other and if the (absolute) difference in cumulative rainfall was greater than 4 %, that complete set was identified as unreliable (e.g. due to partial clogging caused by debris) and the data from both gauges were removed from further analysis.*

[5:10] three rainfall intensity classes were SUBJECTIVELY selected? What was the criterion?

<u>Reply:</u> *The maximum threshold value was limited to 10mm/hr to have enough time instants for the highest range (i.e. > 10 mm/hr) to produce stable variograms even at 30 min temporal averaging interval. We then decided to divide 0 – 10 mm/hr in to two equal subclasses (i.e. < 5mm/hr and 5-10 mm/hr). This gave us three subclasses which we thought a reasonable number given the length of the data, work load and computational demand.*

*Furthermore, we performed the following test to see if these three classes represent the entire intensity range. We produced variogram models for narrower intensity classes ranging from 0 to 14 mm/hr for the 5 min averaging interval. The highest intensity class is limited to ≥12 - <14 mm/hr as for further narrower ranges (i.e ≥14 - <16 mm/hr and so on) there are not enough sample points to produce a meaningful variogram. Looking at these variogram at figure C2, we believe the variograms in figure 7 are good representations of the average conditions for corresponding intensity classes.*

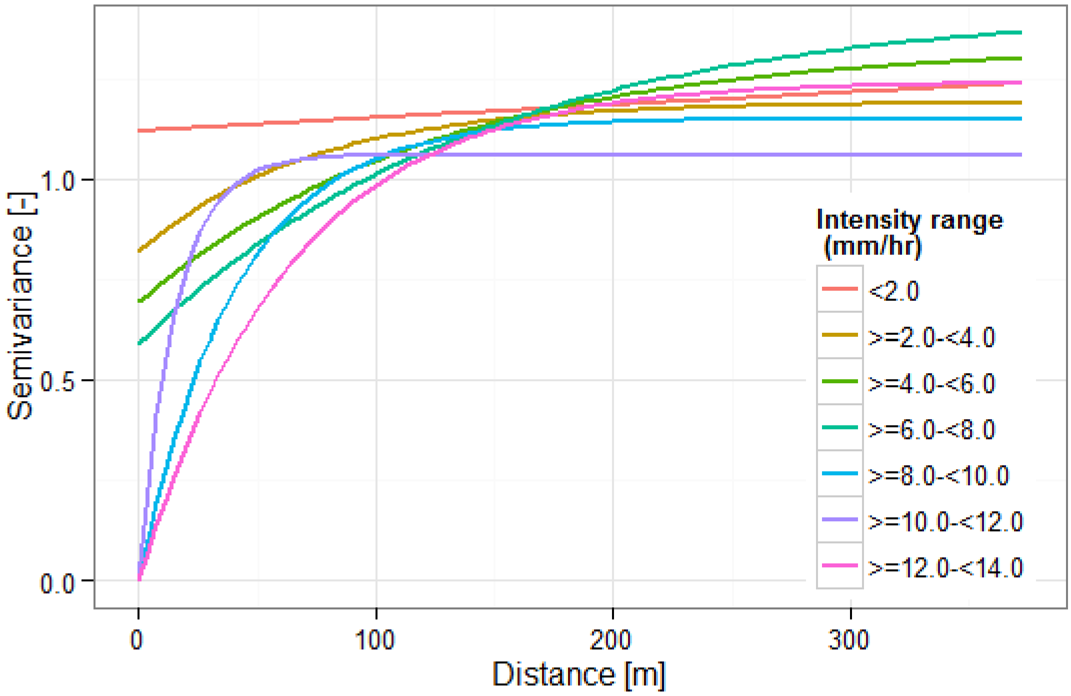


**Figure C2: Calculated variograms for 5 min averaging interval and for a narrower range of intensity**

[6:8] n.d.?

*<u>Reply:</u> Thank you for pointing out this. It should be Van der Waerden (1953). We will correct this in the revised manuscript*

[6:26] "It is negligibly small in the case of rainfall intensity data". Not necessarily, Peleg et al. (2013) reported a 0.92 nugget for 1-min time resolution. I am not sure that this can be neglected.

*<u>Reply:</u> We wanted to argue that any physical micro-scale spatial variation between rain gauges, which theoretically may be one of the causes of the nugget effect, is negligibly small for this case. We did not mean to claim that the nugget itself is negligibly small. We accept that the particular sentence was poorly constructed. We also think that this sentence can be removed as the nugget effect is discussed in detail at a later stage in the manuscript.*

[7:13-22] spatial stochastic simulation – Please provide more information about how the actual stochastic engine works. How was the variogram reproduced?

*Reply: We accept that this section requires more detail. We will modify this section in the revised manuscript as given below.*

*The output from spatial stochastic simulation is a set of alternative realisations ('possible realities') of rainfall at user-defined grid points. The differences among these realisations are used as a measure of uncertainty. Hence it involves the following two steps*

*1. Definition of grid cells (25m × 25m in this case)*

*2. Production of substantial number of possible realisations (500 in this case) for each time instant using stochastic simulation based on the corresponding geo statistical model (variograms in this case).*

*We used the stochastic simulation conditioned on the available rainfall data at measured stations. The grid size and number of simulations were selected considering the spatial resolution of available measurements and computational demand. It was observed that neither a finer grid nor more simulations improves the results much. Increasing the resolution to 10 m × 10 m only improves the standard deviation of the prediction by less than 5% in most cases while almost doubles the computational time.*

[7:22] I would except that a finer grid would improve your predictions. Especially when very high rainfall intensity is recorded over the domain, as a rapid (exponential) decrease in rainfall intensity from the centre away is expected (for convective rainfall at least).

*Reply: We agree that convective rainfall would vary rapidly and therefore having a higher resolution grid might improve the results. But we had only 8 measurement points over the area of 200m × 400m which gives a measurement resolution of 10000 $m^2$/measurement point. Hence estimation at every 25 m× 25 m (625 $m^2$) is fine enough for the estimation of areal rainfall for even convective rainfall. We noticed that increasing the resolution to 10 m × 10 m only improves the standard deviation of the prediction by less than 5% in most cases while almost doubles the computational time.*

[Equation 6 and 7] Equation 6 – doesn't it also need to be divided by m? I think the readers are aware to the statistics of mean and standard deviation thus you can probably delete these equations.

*Reply: Thank you for pointing out this error in Equation 6. It will be corrected in the revised manuscript. Although these equations are well-known in general, given the context of the application, we think it would help the reader to understand the step 8 clearly.*

[8:17] "nugget effect . . . at zero lag distance due to measurement error" – are you sure it is just because of a measurement error? Rainfall variability exists between pair gauges, even for a 1 m distance, at least for temporal resolution of 1-5 min. Please check over the paper I have mentioned at comment [2:19-21] above. Your statement is repeated several times again during the text. I would at least discuss the possibility of having the nugget effect as more than a simple representation of rain-gauges measurement error.

<u>*Reply:*</u> *We accept that the nugget effect could be due to a combination of micro-scale spatial variability and measurement error. Since we cannot quantify the nugget effect caused by measurement error we cannot prove quantitatively that the nugget is only due to the measurement error.*

*But with regarding the clear increasing trend of nugget against (a) decreasing temporal averaging interval and (b) increasing intensity range, we believe this trend is as a result of similar trend in sampling related error of tipping bucket (TB error). If it is due to spatial variability of rainfall then such trends expected to be consistent at greater distance too. But the variograms show no consistent trend against intensity range at greater distance. In a previous similar study (Ciach and Krajewski, 2006), where the behaviour of spatial correlation against rainfall intensity was analysed, they also could not find a consistent trend and concluded that such trends are not consistent.*

*In summary,*

1. *Nuggets corresponds to each variogram could be a combined effect of measurement error and spatial variability. We cannot comment on individual contribution as we cannot quantify them.*
2. *The trends in the nugget against a. rainfall intensity and b. temporal averaging interval correspond well with TB error. Hence these trends in the nugget can be attributed to the TB error.*

*We will include the above discussion in the revised manuscript.*

[9:18-21] I would argue that reason why "the behaviour of spatial correlation against rainfall intensity class is not very distinctive" in your study is due to the short period of data you have used.

Reply: *As stated in our response to comment [3:19-20], we had enough data points to develop meaningful and stable variograms based on which the above statement ("the behaviour of spatial correlation against rainfall intensity class is not very distinctive") is made. Webster and Oliver (2007) suggested around 100 samples to reliably estimate a variogram model. Even in the case of 30 min temporal averaging interval and > 10 mm/hr (where we had the least observations) we had 196 sampling to calculate the variogram which is sufficiently larger than 100. Hence, we do not think that the absence of a clear trend in the behaviour of spatial correlation against rainfall intensity class is due to lack of data. Moreover, as stated in our response to comment [8:17], in a previous similar study (Ciach and Krajewski, 2006), where the behaviour of spatial correlation against rainfall intensity was analysed, they also could not find a consistent trend and concluded that such trends are not consistent.*

[Equation 8] CV equation is also commonly known, I suggest you to delete this equation as well.

Reply: *Thank you for your suggestion. But no other reviewer has made this request so we will retain this equation.*

[12:23] X-band radar can reach 250 m and 3 min resolution. I think it is good enough for small urban catchments.

Reply: *We agree with the reviewer. What we wanted to argue was that the resolution of most commonly available radar data (1000 m) is not enough for an urban catchment of this spatial extent (< 1000m). In addition the level of uncertainty in radar measurements would be much higher than that of point measurements, especially at a fine averaging interval (< 5 min) which is often of interest in urban hydrology (Seo and Krajewski, 2010; Villarini et al., 2008). We will modify this sentence in the revised manuscript.*

[12:29-31] for a similar climate.

Reply: *Thank you for pointing out this. We will include this in out revised manuscript.*

[General comment 1] I think your method suggested for rainfall upscaling is really interesting and can be very useful to some of the reader. However I, as a reader, would like to have more information, such as: What is the minimum number of rain-gauges required for a given catchment is order to apply your suggested upscaling (e.g. are 3 gauges over 1 km2 are enough?)? What should be the spatial configuration of these rain-gauges over the domain? Another question- if you would leave one of the gauges out of your analysis, how it would affect the results (what is the sensitivity of the network design?)?

Reply: *Thank you for the suggestion. We agree that this additional information would be useful to some readers, but to answer some of these questions we would need a more extensive analyses on the* *sampling design which we think is a research topic in its own right. Please find below our detailed response:*

What is the minimum number of rain-gauges required for a given catchment is order to apply your suggested upscaling (e.g. are 3 gauges over 1 km2 are enough?)? What should be the spatial configuration of these rain-gauges over the domain?

*We think such a hard and fast rule on number of data points cannot be derived for this methodology. Because, like any other geostatistical interpolation method, the efficiency of this method also heavily depends on reliable estimation of the geostatistical model (variogram). Hence it basically comes down to the question of whether a given rain gauge network can produce a meaningful variogram? As we mentioned in the manuscript, Webster and Oliver (2007) suggested around 100 measurement points to calculate a geostatistical model. But there is no hard and fast rule to define minimum number of bins and the number of samples for each bin to produce a reliable variogram. Further, since pooling of repeated measurements would produce a multiplication of spatial lags, the length of the available data would also play a role in deciding the number of measurement locations.*

Another question- if you would leave one of the gauges out of your analysis, how it would affect the results (what is the sensitivity of the network design?)?

*Leaving one station out would affect the results. First it will reduce the accuracy of the estimation of the variograms as the number of spatial lags per time instant would reduce to 21 from 28. But the further effect of leaving one station out needs to be analysed in detail to see how it affects the uncertainty in the estimation of areal average rainfall intensity. In the manuscript we have not included such sensitivity analysis considering the direct relevance to the main scope of this study and the work load required to perform such analysis.*

[General comment 2] You stated that the stochastic model require some “computational demands”. Can you give some details? How much time is needed to run the stochastic model per time step? What kind of machine do you need to use? It can be given as supplementary information but some readers might be interested to know.

<u>*Reply:*</u> *Thank you for this comment. We will provide this information as supplementary material together with revised manuscript.*

[General comment 3] The paper is oriented for the urban hydrology community, but if fact who will benefits the most from your method are hydro-meteorologists that are often looking for different methods to upscale rainfall observation from point scale to weather radar scale. Consider changing the title and addressing this as well. I think that due to the lack of sufficient length of observation, you should focus more on the method and who can benefit from it and less on your results.

<u>*Reply:*</u> *Thank you for the suggestion. We think the spatial extent (0 – 400 m) and the temporal averaging intervals (2 min -30 min) considered in this study are in interest of urban hydrology. Also we think the uncertainty estimation in areal rainfall would be more useful for the hydrology community working on the uncertainty. These are the main reasons why the paper was oriented towards the urban hydrology community.*

*Regarding the comment on lack of data and focusing more on the methodology, we request the reviewer to refer to our responses to the general comment and specific comment [3:19-20],*

**Reference**

Ciach, G. J. and Krajewski, W. F.: Analysis and modeling of spatial correlation structure in small-scale rainfall in Central Oklahoma, Adv. Water Resour., 29, 1450–1463, doi:10.1016/j.advwatres.2005.11.003, 2006.

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