Reply RC3(Referee: Dr. Søren Thorndahl) on October 20th 2016

Urban sewershed overflow analysis using super-resolution weather radar rainfall
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Authors: Jin-Young Hyun, Thomas D. Rockaway and Mark N. French

This document provided detailed response to referee comments (RC3) from Dr. Søren Thorndahl. The authors recognize and thank this reviewer for the effort and suggestions to improve this manuscript.

NO	Questions/Suggestions and Addresses
1	Q. Despite both subjects of the paper being very interesting, I don't see the point of joining them in one paper. Reading the paper there are in my opinion little that justifies the use of radar rainfall. Same analysis of overflows could have been conducted with rain gauge data with similar or same results. I would suggest dividing the paper in two. One on the optimization of Z-R relationships and rainfall estimates, and one on the analysis of rainfall-overflow relationships. The objective of each paper would be much clear in this way. A. Yes, the manuscript contains two distinguished section; the initial submission was more limited in content regarding radar-rainfall and more on the CSO topic. In the earlier version, the authors provided a summary section for radar-rainfall estimation and it was more focused on the CSO and rainfall induced overflow analysis. Prior to the 'Interactive Discussion' period, the 'Editor Initial Decision' requested details to be included regarding the 'rainfall estimation' in order to provide explicit evidence of the innovative merit. Therefore, the significant sections on radar and rainfall and optimization supplement the first part of this paper. The authors agree to either continue this paper(s) in 'as-is' form or to develop two separate papers according to your suggestion. The authors accept either decision from the editor at the final stage of this discussion. The only concern is that if partitioned into two papers the review and publication schedule may be lengthen the publication period by another review process starting from

	the beginning.
2	Q. You use a spatial resolution of 220m of radar data, but a temporal resolution of 15 minutes. I would expect that a coarser spatial resolution fairly sufficient, when you are using a temporal resolution of 15 minutes or you should increase the temporal resolution in order to benefit from the fine spatial resolution. Since the radar data consists of instantaneous values every 15 minutes, an individual rain cell can move a large distance (and much more than the spatial resolution) within the time step of 15 minutes. Your estimation of the total precipitation over 15 minutes is thus probably not very accurate. See e.g. paper from this HESS special Issue on "Rainfall and urban hydrology": Thorndahl et al. (2016) and references herein on the relationship between spatial and temporal resolution of radar rainfall data. In this paper there are also given references for advection interpolation (or downscaling) methods, which can convert the spatial resolution into temporal resolution, creating better volumetric rainfall estimates (e.g. Nielsen et al., 2014). Furthermore, I am missing the reason for looking at the adjacent 8 pixels. Why not just use one? A. The Super-Resolution (0.5°, 250 m) National Weather Service (NWS) weather radar is used to retrieve the level II radar reflectivity (instantaneous base scan). The coordinate system was converted to Cartesian (220m by 220m) using Weather and Climate Toolkit which provided from National Oceanic Atmospheric Administration (NOAA). Yes, the authors absolutely agree to your statements. At the single radar pixel spatial scale, a temporal resolution less than 15-minute is better suited to limit storm advection variations. Fifteen minutes may allow advection across the distance of the radar pixel and the rain cell dynamics may change within the pixel boundary regardless of wind translation. This study does not consider a sub-pixel scale (pixel by pixel) approach to match rainfall values between the measured locations in the air and on the ground. In this microscopic view point, many other error sources may hinder synchronization such as falling time (even using base scan), and vertical wind variation. Current operational weather radar equipment at this location is sufficiently free of spatial limitations and constraints at the urban hydrologic sewershed addressed by this case study. A study of the spatiotemporal variation of the rainfall, Hyun et al. (2016) provides objective

	measures evaluated to determine the validity of the spatiotemporal extent of the resolutions utilized. For this specific location, for the selected study period, at 15-minute temporal resolution, a high correlation is observed across a few kilometers of range. The authors used ground-based gauge data to evaluate this relationship, and the nearest-neighbor inter-gauge distance is 4.9 km. Even though this assumption is based on an extrapolation of correlation structure (attached figure in AC1 in the discussion), it supports with confidence the conclusion that rainfall for these events tends toward an isotropic condition across several adjacent pixels in any direction. The study area sewershed is 29 acres (11 hectares), and thus the isotropic condition is expected based on the spatiotemporal structure of rainfall for these events. In Thorndahl et al. (2016), temporal and spatial resolution of rainfall data were utilized for types of hydrologic applications somewhat different from this work. This study was not as concerned with the broad topic of urban rainfall observation network optimization, but only with the optimization of available data records to identify rainfall characteristics at a specific site. Meaning, if a rain gauge(s) were located directly in the sewershed it could have served as a primary source for volume estimation, and radar-derived rainfall taken less of prominent role. To meet this requested modification, the authors suggest the sentence may be rephrased as '…a 15-minute resolution used for the overflow analysis portion of this work since this is an event-based approach and regional rainfall structure details indicate a degree of homogeneity within the spatiotemporal rainfall structure (Hyun et al. 2016)". In summary, the authors thank the reviewer for this comment and note the recommendation of considering a 10-minute temporal resolution to minimize influences of rainfall advection. The reviewers research (Thorndahl et al. 2016) addresses a spectrum of fascinating topics of urban hydrologic research and the authors would like to add citation of this reference to note the considerations of these effects in the urban application of the radar-rainfall products. In summary for this study, only 0.068 % of the observation periods required utilization of a neighboring radar data when the target pixels covering the sewershed were not available. In other words, most of the data were derived from the values of the radar reflectivity directly over the sewershed.

3	Q. In the evaluation of Z-R relationships you discard rainfall intensities less than 5mm/15min. This is still a significant rainfall intensity, and I think this is problematic in terms of estimating lower rainfall intensities later on the paper and especially since you have CSO spills generated with less rain than 5mm. The large variability of the small intensities in figure 1 bottom right is probably related to the point above, that your intensity is not a sum over 15 minutes but a random instantaneous intensity within the 15 minute window – and that the coincident rain gauge observation has a much better volumetric estimate of the rainfall over 15 minutes. A. Again, the authors thank you for your comments on this topic. Yes, a 5 mm depth can be a significant amount of the rainfall. The figure 1 does not discard any rainfall observations. The figure 1 (lower-right) is a scatter plot using NWS Z-R conversion (least RMSE error), and all the retrieved scan reflectivity. The discarding of rainfall values less than 5 mm over a 15 minute interval was performed only for calibration or identification of the optimal Z-R relationship in order focus on extreme rainfall events and in order to minimize underestimation issues at this temporal scale. Yes. The rain gauge network is operated by the local sewer agency, Metropolitan Sewer District (MSD), and the nearest gauge is deployed about 700 m away from the study region. Based on the spatiotemporal correlation structure identified by Hyun et al. (2016), the gauge is suitable for use as a volumetric data source. However, also fortunate in this case is that this gauge is located within a kilometer range since the average intra-gauge-network distance is near 11 km, implying that a single gauge data provides rainfall coverage for more than a 5km range. At a 15 minute of temporal scale, the spatiotemporal characterization definition by a single rain gauge is expected to be low. Meaning, at the fine temporal resolution required for most urban hydrologic runoff related studies, there remains many sewersheds not covered by ground-based rainfall (gauge) locations, even though gauge networks are considered densely deployed. Broadly, this study countered the negative effect of gauge location and temporal downscaling through application of locally calibrated radar-rainfall products at a scale appropriate for the urban watershed.
4	Q. I am surprised that you don't consider traditional bias adjustment (e.g. Mean field

	bias) of radar rainfall data against rain gauges rather than adjusting Z-R relationship. There is substantial research conducted on this, applying different methods. I think you could get equally good estimates using a simple bias adjustment, without having to divide in different rainfall types, e.g. as presented in Figure 2. A. Yes. The use of traditional methods was considered during this research. One intriguing aspect of this study was optimization of radar-rainfall for the localized urban area (sewershed). The mean-field-bias is a typically a single correction (up or down) and may not account for rain gauge locations in the vicinity of a specific site, such as this single sewershed, since adjustment is uniform across the region. There are more advanced and detailed MFB methods (Thorndahl et al. 2016) but again, additional complexity of analysis is required. This study acknowledges the existence of rainfall spatial variation across the areal extent associated with the meso-scale city region, and this is why the authors adopted a site specific type of radar optimization process rather than a single overall radar calibration. The NWS/NOAA incorporates four fixed empirical Z-R relationship across the entire US nation. Furthermore these traditional relationships do not necessarily recognize more recent types of rainfall patterns and possible influences of climate change on rain cloud characteristics. This study focus on the suitability of the Z-R relationship into the localized area at a fine temporal resolution. As results indicate, it is beyond the capacity of a few operational Z-R relationships to adequately represent extreme storms (tropical storm region). For this reason, an investigation was completed to develop additional relationships for extreme storm types. As shown in figure 4 (tropical storm scatter plots), a single correction for the otherwise underestimated rainfall produces an overestimation problem. For this reason, a partitioned approach, as a sort of mean micro-field bias (MFB) adjustment, was developed specifically for the projects purpose. Since the data resources and capability exists to show this concept and illustrate its application, this is the reason to overstep the traditional single MFB method. The authors recognize that for larger regions, such as when the entire radar site (150-230km radius) or large watershed are considered, it may be more suitable to use traditional calibration methods such as MFB. Thank you very much again for this discussion point.

5	Q. Section 3: How is the overflow estimated? Is it measured? In that case I would be relevant to describe how and with some specifications of equipment. – Or is it modelled? Also it would be interesting to know how you defile the overflow depth. I guess the overflow volume, per event divided by the contributing catchment area, e.g. the impervious area. Is this the case? Please clarify. It could be relevant to discuss the time-scale/time-step of the CSO estimates. A. Yes. The overflow was measured at the downstream point in the pipe at the diversion chamber overflow weir (and the amount includes only the measured overflow amount directed into the surface stream – this is due to the requirement by the Federal Government agency, EPA (Environmental Protection Agency) to have a report on the overflow volume amount). The overflow water volume is measured from a gauge mounted at the discharge pipe. These data records are obtained from the local sewer agency (MSD mentioned earlier) and measurement devices were not deployed specifically for this study. As with the rain gauge network and the weather radar records, the specific type of gauges, manufacturer, data logger and data transmission specifications are not readily available to the authors, but were requested from the MSD agency. It is expected that the equipment is representative of standard types used around the USA (or globally) for sewer pipe flow. Typically these are weir-type gauges with a pressure sensor to detect water depth, which is then converted to flowrate. The flowrate integrated over time provides the overflow volume. The “overflow depth in mm” means the volume of water that is not captured by the sewer pipe and transmitted to the waste water treatment plant, and the volume is expressed as a depth (relative to the sewershed area size – dividing volume by the sewershed size). The coupled data of rainfall and overflow were integrated into a single “coupled event” through the terminology “rainfall event” as defined by US Environmental Protection Agency (USEPA) and the hydrologic lag-time is not a directly significant in this study due to the small size of the sewershed.
6	Q. I am missing the point of using radar rainfall estimates to compare to the overflow depths. In figure 6, it is evident that the 15 minute radar estimates have some spatial variability, but since the catchment you analyze is very small. I would not expect any

	significant spatial variability of rainfall within the catchment. In that case you could just use the rain gauge. – or do you think that the areal estimates are better provided by the radar? A. Thank you for your comment. The authors will address the point more clearly and make a modification in the manuscript statements to do so. The study area of catchment CSO130 is small, but also isolated from all other sewer networks. Therefore, it is possible to investigate the relationship of rainfall and overflow directly. This also allowed consideration of this small sewershed region as isolated from surroundings instead of a typical case with a larger catchment where rainfall variability might be a factor (or sewersheds connected to one another and therefore a need to consider upstream inflow amounts). Therefore, it also allowed illustration of the benefit of radar-rainfall in the urban setting by describing some of the limitations of one-dimensional rainfall measurement equipment, rain gauges. Of course, since the rain gauge records rainfall volume near the surface, in many instances, when co-located, it is advantageous to use rain gauge records. However, as the distance between the gauge location and the catchment area of interest increases, consideration of the critical spatial variation distance, in conjunction with the temporal scale of interest must be weighed. In this work the temporal scale is 15 minutes, and the nearest gauge distance for a research study must be not more than a kilometer. It means that the urban setting needs an extremely dense network of the rain gauges in order to provide high quality rainfall definition. Realistically, these conditions are unlikely due to several issues including obtaining permission for access to deployment locations and maintenance issues. Fortunately, this catchment has well-maintained rain gauge 700 m from the study area, however, even due to this distance, this gauge data were only used for referencing the radar data calibration. Additionally, the second closest rain gauge, TR12 (lower-left plot in figure 6) was compared. Based on that, the two-dimensional radar-rainfall estimation was indicated as more suitable for this downscaled/microscopic urban hydrologic study.
7	Q. I like the idea to try to characterize the rain producing overflow. I did similar analysis, based on modelling, e.g. trying to identify the impact of duration in CSO-volumes (Thorndahl, 2009). This might be relevant to compare to, even though the

	catchment characteristics and the upstream storage volume plays important roles. It could be relevant to mention the design criteria, if any, for CSO structures in terms of frequency of overflow, overflow volumes, etc? A. The authors really appreciate for your encouragement. Currently, US EPA regulate the prohibition of CSO events by indicating simply a frequency (return period) basis of the rainfall events causing overflows. However, this regulation is too simplified an approach and does not consider magnitude of the overflow volume. Due to the spatial variation of rainfall, duration of rainfall, and size of the surface stream impacted by the overflow volume, a single overflow event may cause serious degradation of the aquatic environment due to a high concentration of harmful constituents in the combined sewer water. The volumetric approach is necessary for environmental hydrologic mitigation of overflows as well as for design/modeling. This study provides a more specific characterization for the CSO overflow rain event, for example: "Occurrence of a 20-mm rainfall over a 6-hour period or a rainfall with intensity greater than 6-mm/15-min (24-mm/hr) will induce a significant combined sewer overflow event for the CSO-130 sewershed." This wording could be included in the revised manuscript conclusions. The authors appreciate the reviewer for these comments and information.