Reply RC1(Anonymous Referee #1) on September 30th 2016

Urban sewershed overflow analysis using super-resolution weather radar rainfall
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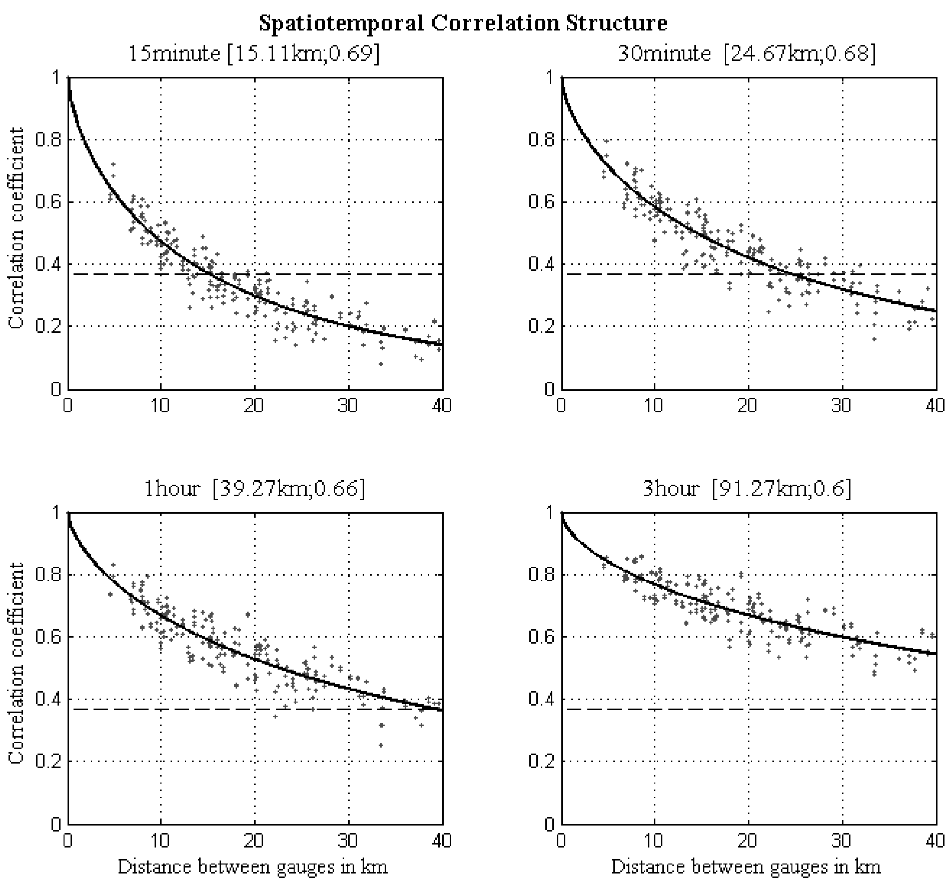
This document provided detailed response to referee comments (RC1) from Anonymous Referee #1. The authors recognize and thank this reviewer for the effort and suggestions to improve this manuscript.

NO	Referee #1 Questions/Suggestions and Addresses
1	Q. Line 66: Mailhot 2015, not Mailhot 2016 (unless there is a missing reference) A. This is a typo and the cited paper was published in 2015 as referenced. The sentence in lines 66-68 was corrected “Mailhot et al. (2015) developed a relationship between annual duration of overflow occurrence and rainfall threshold category derived from rain gauge data, and described the value of rainfall data in terms of spatial co-location and temporal coincidence….”
2	Q. Line 98: “The focus of this study is the application…” Line 104: “… with (or by) weather radar…”, Line 125: “phenomena” (if plural is what is intended) A. Line 98: One of the main purposes of this study illustrates application of local weather radar for CSO investigation in an urban watershed. The rain gauge data are used for the quality comparison or reference for the weather radar data. Therefore, the sentence of Line 98-99 is modified as “The focus of this study is application of weather radar in a small-scale sewershed allowing consideration of spatial variation.” Line 104: The correction has been made. “Hydrometeorologic rainfall monitoring and measurement technology by weather radar has ...” Line 125: Yes. The intent is plural (multiple factors), wording modified to ‘phenomena’.
3	Q. Line 141: Please specify more clearly what the correlation is here – do you mean the spatial correlation?

	A: Yes, implicit intention addresses spatial correlations. The temporal correlation temporal interval is defined as quarter-hourly (15 minutes) corresponding to the radar scan temporal resolution. The radar data available are radar volume scans (multiple rotations of the radar antenna at each scan angle) and this is transmitted each 4 to 6 minutes. The available shortest temporal resolution contains 3 to 4 instantaneous radar scans (including the base scan reflectivity). The results indicate a spatial correlation at 15-minute temporal resolution of near 0.6 at 5-km distance. The sentence was rephrased by "a spatial correlation near 0.6 at 5-km distance for …."
4	Q. Line 144: What is the inter-gauge distance? A. Previously, the spatial structure of rainfall was evaluated using the rain gauge network over the same region by Hyun et al. (2016) as a case study. The local sewer agency, Metropolitan Sewer District (MSD), operates this rain gauge network. The inter-gauge distance represents the distance between neighboring gauges in the network. The overall average distance between neighboring gauges is about 11-km. The un-gauged site, indicated by rainfall (spatial) correlation less than 0.6, is 5-km away from the nearest gauge even in this relatively dense gauge network (15 well-maintained gauges are in operation for the study period of 2010-2014). Due to economic and practical reasons, many urban government entities such as sewer agencies face challenges in deploying and maintaining rain gauges in urban areas. The result is that the spatial value or useful limit boundary for single-gauge coverage is shorter than the necessary sub-hourly temporal resolution for this fine temporal resolution application. This leads the conclusion that appropriate use of fine-resolution radar rainfall estimates is necessary in such applications.
5	Q. Line 174: Could you justify this step a little further. If the central cell (of the 9) is smoothed to the average, is this not likely to remove what might be heavier rainfall? Alternatively this step could increase low rainfall values. Could you say how often this smoothing took place and how it may have affected the results? Could this be related to the underestimation you see, especially for tropical rainfall? A. The size of the 9-pixel radar region is about 100 acres. In the study by Hyun et al.

	(2016), correlation is above 0.9 within the 1-km distance range for quarter-hourly temporal resolution (figure below shows the rainfall structure). This indicates the rainfall structure generally has limited variation within the 9 pixel region and smoothing influences are likewise expected to be minor. The main purpose of this data pre-processing step is to evaluate neighboring radar pixel values and account for discontinuous rainfall, if any, within the isotropic rainfall area. For all radar-rainfall data, the portion requiring adjustment (indicating more than 50% difference in neighboring pixels) to the raw value is only 0.068% across the range of 20-dBZ or higher reflectivity for the entire study period. In other words, the original data pixel value is available and used more than 99.9%. Based on this clarification, there is no expectation for underestimation in tropical type rainfall group. 
6	Q. Line 178: Could you explain how the rainfall type is identified? Was this provided to you as part of the original dataset and the classification made by the providers of the

	data? Or is this what you mean by optimization. (As I have read further, I see on line 436 that this is discussed. Could you explain this earlier in the paper please?) A. Yes, the National Weather Service (NWS) selects the rainfall type from among these pre-defined types and assigns the type to a single radar site. The practical range of the radar is 150-km radius, and the entire coverage area is considered one rainfall type and this follows in conversion of reflectivity to rainfall using a single Z-R relationship. For this reason, this work is initiated with Level-II NEXRAD data from NWS rather than the higher level rainfall product which has been converted and smoothed using the pre-specified Z-R relation. Since any single storm may be dynamic with significant spatial variation, the pixel region corresponding to the catchment area or rain gauge site was individually identified by storm type for the 15-min temporal encapsulation period. The method of root-mean-square error (RMSE) with the rain gauge value was used to define the rainfall type each quarter-hour. The NWS or other agency does not act as a data provider to define rainfall type. In order to clarify this issue, a modification to the explanation of the decision making process for identification of rainfall type is added to line 178. "The KLVX radar data management system applies a Z-R relationship according to four storm types… with root-mean-square error (RMSE) every 15 minute individually."
7	Q. Line 189: Why is this equation in the appendix? A. All equations are now moved to appear within the text of the manuscript; and only notations remain in the appendix section.
8	Q. Line 205: Could you clarify what is meant by optimization here? Is it the selection of one of four Z-R relationships, or the modification of the parameters of the Z-R relationship? A. Basically, optimization in this work begins with the spatiotemporal downscaling for application of the rainfall type decision process. This is an important starting point for data quality evaluation and optimization. The tendency for rainfall underestimation is observed in the original tropical rainfall group and is an undesirable result for

	hydrological applications. In order to reduce underestimation, the SVC process is a second or supplementary optimization and eventually leads to identification of two alternate tropical Z-R relationships. These two optimizations are complementary and both are necessary for the most optimal application of uncalibrated local radar data.
9	Q. Line 316: you talk quite early on in the paper about continuity, but it is not until line 432 where you define it. Could it be defined earlier? A. As you recognize, the paper describes two primary tasks – generation of radar rainfall and its application to investigation of combined sewer overflow. The first continuity concept addresses the identification of rainy periods into independent events; these then forms the series of "rain events" necessary for use in the CSO overflow evaluation. Later in the manuscript, use of the term "continuity" in Line 432, a more focused view considers each rain event individually. In this case, the uninterrupted occurrence in time or inter-connection of rainfall pattern for a single rainfall event is described as one factor influencing small-scale sewershed overflow occurrence. These two concepts are briefly described in the abstract and introduction sections. The authors are willing to make additional modifications to the text if recommended - Thank you for the comment.
10	Q. Line 319: Here you say super-resolution data is important to the estimation of CSO, but with your smoothing operation (already discussed), you may be losing the high resolution data that is important. If I understand correctly, the pixel resolution is 5 ha. If you use the smoothed result from 9 pixels, you are using the rainfall from an area of 45 ha. Is this correct? A. Yes, you are right. The radar is fundamentally use the polar coordinate system. The super-resolution radar resolution is 250-m and 0.5-degree (previously 1-km, 1-degree), and the radar site (KLVX) is 40-km from the study area. As in response no.6 to reviewer comment, rainfall variation is known to be limited across the 1-km range and each radar pixel is evaluated. However, there is a limited range effect along with distance from radar location. The radar range is up to 230-km and at more distance locations the pixel size is influenced by smoothing and partial beam filling. The NEXRAD network is a two dimensional radar observation system and covering most of the entire the USA

	continent at a relatively fine radar resolution. As stated earlier, for this particular location, the use of any smoothing with surrounding pixels was limited in 0.068%. The NWS or National Oceanic Atmospheric Admistration (NOAA) provide conversion tools (NOAA Weather and Climate Tookit) to tranform the polar coordinate data into the Cartesian coordination system. The actual pixel size is 0.0020132 lat/lon degree (about 220m, the size of the pixel is about 12 acres). This implies that a single data value can be assigned to about a 200 acres area of the earth's surface at a quarter-hourly time interval. Although the spatial variation of rainfall depends on rainfall type, it was found to have limited to no influence for the study period.
11	Q. Line 370: I'm not sure I follow the analysis of acceptable and unacceptable overflow events. Where there is an overflow and the overflow ratio is less than 0.6, is anything known about the volume of overflow that reaches the receiving body? What is an acceptable overflow? If I proceed to line 400, we read that for values greater than 0.4, there is a likelihood of significant pollution. Why then is 0.6 chosen as the threshold for acceptable overflow volumes? It is clear from Figure 11 that the unacceptable events are those events with greater volumes, but I would appreciate a better understanding of how you derive at this from the index. A. The coupling of the previously defined rainfall event and its corresponding overflow event is the most challengeable point in this study. The chosen CSO (CSO130) is isolated from neighboring sewersheds, and the flow data are only for the overflow discharge into the surface stream (Beargrass Creek, Louisville, KY). The flow data are provided by the local sewer agency and the flow records are known to contain overflow periods where there is no overflow – this is due to flow gauge error associated with debris or other disruption of the flow sensor. In order to select only overflow events with higher quality flow records, the flow data from the beginning of a rainfall event to the 6 hours after the end of rainfall were coupled as shown in Figure 7 (most significant nine overflow producing rainfall-overflow events). Based on the EPA rainfall event definition, there must be no runoff producing rainfall for 6 hours following the end of a previous event. In this sewershed, the volume of dry-weather sewer flow alone is not influential for inducing an overflow and only the combination of sewer water and storm

runoff together cause overflows. After identification of the rainfall-overflow events (coupling), we recognized existence of a limited number of excessive and non-rain event overflow records as shown in figure 8 (left). The partitioning or extraction of valid coupled rainfall-overflow data is necessary when selecting and using field data. In this case, a region in Figure 8 left-side, the range of ovwerflow ratio from about 0.6 to 0.9 shows ‘no dots’ (no events). This indicates that a threshold or runoff index may exist for this catchment with a value somewhere in this range (0.6 to 0.9). Additionally implying that higher runoff ratio values (above 0.9 and even exceeding 1.0) are likely due to flow gauge error sources. Therefore only coupled events which fall within the (0 to 0.6 (bolded-solid-quarter circle in figure 8) are included in the study. Following this index screening process, there remains 52 coupled rainfall-overflow events or “acceptable”, and another 47 events were discarded as “non-acceptable”.

Regulatory requirements from EPA prohibit municipalities from allowing CSO with frequency more than twice per year. This study formulates a systematic methodology to define the relation between rainfall spatiotemporal characteristics and CSO overflow. The methodology allows one to define a numerical rainfall volume associated with occurrence of overflow in a specific sewershed. Every sewershed would likely respond differently to the same type of rainfall depending on the size/land use/shape of the sewershed. This identification of overflow inducing rainfall characteristics in terms of volume, intensity, and temporal pattern for a specific sewershed allows development of strategies to mitigate overflow occurrence. For example, in this sewershed, the rain depth can be related to overflow as shown in Figure 9 (left). Additionally, discriminant analysis can divide overflow producing rainfall events into two groups – significant and non-significant. In figure 11, an index threshold line divides the 52 coupled events into two groups for discriminant analysis. The significant and noticeable group differences are quantified by volume and duration of rainfall in Table 1. The traditional rainfall design methods, using IDF curves for example, are convenient but suffer from limitations when implemented to identify or characterize CSO occurrence. In short, this study allows 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."
12	Q. Line 389: Could you say something about the relationship between rain gauge and radar for the CSO causing events? Are they in anyway different from the other rainfall events? A. The rain gauge data are from a gauge 700-m away from the sewershed, CSO 130. All gauge data was used as reference data for quality control, quality assurance and evaluation of the reflectivity-rainfall relationship. It is fortunate to have gauge data available close to the study site. In the period of 2010-2014, there are 15 quality-checked gauges is in operation across the city of the Louisville, Kentucky. According to Hyun et al. (2016), even though this is a relatively dense gauge network, applications in rainfall-runoff evaluation for a relatively small ungauged site still require radar-rainfall details due to the space-time variability of rainfall. For example, flash floods are recognized as an emerging disaster type due to local extreme storms in this climate changing era. In order to study the impact of the incremental changes in rainfall at the urban catchment scale, sub-hourly rainfall is essential. Therefore, the application and improvement of radar-rainfall estimation is an urgent need. The NOAA/NWS provide improved Level-III products such as dual-polarized instantaneous rainfall rate, but the product is not specified or optimized for local use. The future research plans must consider investigating use of operational dual-polarized rainfall products. Again, in this work, the rain gauge resource serves only as a reference in the evaluation of radar-rainfall; rainfall for the CSO event evaluation follows from the radar-rainfall estimation work.
13	Q. Conclusions: Could you discuss any differences you may have seen between the two types of tropical storms? Can the information in your research be used to identify in real-time which Z-R relationship to use, and whether it can be used to improve the prediction of CSOs? The conclusions section could be improved. You say early on that "Categorization of the severe rainfall events including CSO occurrence can provide insights for hydrologic and hydraulic design guidelines to reduce sewer overflows from

	combined sewer systems in an urban area". Can you say a little more about how this might be done? Could you also say more about the number of false negatives in Table2? Out of 52 events listed, you predict 11 out of 52 incorrectly? What is different about these events. If you look at Table1, the major differences seem to be rainfall intensity and total depth (the other differences aren't great. This is what you would expect. When do you make a false prediction? A. In the figure 5, the two newly created tropical Z-R relationships are plotted. Through use of the Support Vector Classification with Kernel threshold of the 46 dBZ, the two groups were divided by the linear hyperplane (lower-left in figure 4). Let's back to the figure 5 (lower-right), and the tropical 2 (red-dotted) power curve takes care the underestimated group. Therefore, the matching rainfall intensity to observed reflectivity is necessary to prevent the underestimation problem. Fundamentally, a single tropical type of Z-R relationship cannot cover storm variability in extreme convective. Addressing a shift in the fit of the Drop-Size-Distribution, in this case for the tropical storm due to the reflectivity threshold of 46 dBZ, resulted in an evenly distributed set of two groups. Yes, clearly it is possible to apply these methods in near real-time weather prediction. However, processing speed is a key in practical radar operation. An efficient and well-designed multi-processor algorithm would make it possible to identify and assign rainfall type on a 'pixel-by-pixel' scale for the entire detection boundary and with a very short time window. However, the limits of current hardware and communications systems might hinder the operational usefulness. Nevertheless, details of storm dynamics are becoming more detectable by local weather observation and measurement networks and government agencies must continuously pursue the development of improved operations for understanding hydrologic processes in order to maintain public safety. Furthermore, a dense rain gauge will always be required to validate radar-rainfall for hydrologic applications. Recently more rain gauges (about doubled) has been deployed over the study area for the purpose of improving the "2 hour in advance weather forecasting" (MSD report 2016) for the city. In my opinion, only the densely

	populated areas need this "short-temporal rainfall-type assignment system" when considering the socio-economic effect. Improved accurate emergency weather forecasting may possible for a sub-section of the city or even smaller areas such as CSO sewersheds. The conclusion section is modified as detailed below. These sections will be merged into the existing conclusions during the revision of the manuscript process. In the Figure 7, the top 9 overflow events are plotted. Overall, rainfall volume governs the overflow, but the intensity (for example, CSO events 5, 6, and 7) and rainfall continuity (uninterrupted rainfall or event duration) (for example, CSO events 3, 4 and 8) also have a role. Rainfall volume, intensity, duration (uninterrupted rainfall) are historically important factors influencing hydrologic response. In a related study, a detailed study proposing a classification is being prepared for defining the classification of rainfall events under these guidelines. Results of that work indicate three different rainfall groups – high intensity group, high depth (volume) group and light rainfall groups. The groups were objectively partitioned through a k-means clustering method in the 2-dimensional intensity-volume rainfall field. The clustered groups are validated using an objective clustering performance measure. That work is currently in "review" status with the Journal of Hydrometeorology, American Meteorological Society [title: Rainfall event characterization with cluster and variogram analysis as an expedited contribution, Hyun et al.]. Discriminant analysis (DA) partitions the 52 coupled events into two groups according to the significance of the volumetric overflow. First, the discriminant analysis is used for the categorical analysis, thus, the threshold of the 1.5 mm initially assigns the events evenly into one of two groups, significant or non-significant overflow. Based on the assigned factors: rainfall total volume, duration, rain peak, rain type, and rain continuity, DA predicts the events again. There are no false events in the DA analysis, but a relocation of group according to the assigned factors. Yes, each factor provides a part of the contribution to identify the discriminant among the group. The governing

	factor is volume, but this result does not mean volume is the only factor of significance in overflow occurrence. The EPA regulations on CSO overflow currently focus on a frequency based decision or rainfall event characteristic. However, this work hints that the volumetric approach may be more effective to identify the types of rainfall inducing a CSO. For these reasons, the DA algorithm is applied to distinguish significant overflows and identify the characteristics of the overflow inducing rainfall event.

The authors thank the referee for detailed comments which have provided guidance for an improved manuscript. The re-evaluation of the significance and presentation of the core findings has allowed this work to improve its conclusions in the context of weather radar optimization and applications to urban sewersheds. Thank you very much again.