Spatial uncertainty of extreme rainfall using the gauge network at urban catchment

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ABSTRACT

Using the gauge network with 180 rain gauges over an area of 4,900 km² and high temporal resolution (e.g. 5 min) rainfall in Shanghai, China, this paper assessed the spatial uncertainty in capturing extreme rainfall events based on the gauge observations. Our results showed that the spatial rainfall structure was nonstationary and anisotropic in time and space. The uncertainty in areal rainfall depth and spatial rainfall structure had a pronounced dependence on the gauge numbers and timescales. At least 10 ~ 20 gauges (0.002 ~ 0.004 gauges per km²) are needed for rainfall-related research in Shanghai.

KEY WORDS: extreme rainfall; gauge; urban; spatial correlation, uncertainty

INTRODUCTION

Rainfall is arguably the most essential piece of information for understanding and modeling the water cycle in environmental, and hydro-meteorological applications as climate change intensify (Hänsler and Weiler, 2022; Kidd and Huffman, 2011; Sun et al., 2018; Yu et al., 2020; Zhang et al., 2018; Zhao et al., 2022). The frequency and complexity of flash floods, for instance, have been proven to be highly sensitive to the spatiotemporal variability of extreme rainfall (Cristiano et al., 2019; Nikolopoulos et al., 2014; Smith et al., 2005; Yang et al., 2016). Especially in urban catchments, both rainfall and hydrologic response even display small-scale variability (Berne et al., 2004; Paschalis et al., 2014; Zhou et al., 2021; Zhan et al., 2020; Zhuang et al., 2022), which makes its measurement difficult. Hence, available and assessment of more accurate rainfall in such a procedure are growing attention (Krajewski et al., 2010).

Despite advances in remote sensing technology, rain-gauge networks remain the most reliable source of rainfall data — regarded as “ground truth” (Lopez et al., 2015; Zeng et al., 2018). However, observations at the sparse point scale or an un-uniform pattern can still bring uncertainties in gauge-based rainfall estimations (O and Foelsche, 2019; Peleg et al., 2013; Villarini et al., 2008). Many studies have found that high-density gauges lead to better performance in areal rainfall interpolation (Chen et al., 2010; Ly et al., 2011), hydrological response identification (Michel et al., 2021), and remote sensing bias correction (Mapiam et al., 2022), due to their unique value at critical and partial areas (Balme et al., 2006). O and Foelsche (2019) suggested that regularly distributed gauges also significantly contribute to delivering accurate areal rainfall estimates. Dong et al. (2005) and Xu et al. (2013), by contrast, reported a certain threshold existed in the benefit of gauge density. Since the widespread difficulty in achieving adequate densities of rain gauges, quantification of gauge-based uncertainty and identification of the need-for-fit (or minimum) rain gauge density are increasing at various catchment scales.

Spatial sampling error (SSE) is one of the major sources of uncertainty from point-scale observation-based studies (Villarini et al., 2008), leading to a difference in areal rainfall estimation and rainfall spatiotemporal structure identification. For areal rainfall estimates, the SSE could be as large as 150% of the areal-mean rainfall (Kitchen and Blackall, 1992), with even up to 90% rainfall variation among gauges within 0.25 square kilometers (Jensen and Pedersen, 2005). For the spatial structure, Pearson’s correlation coefficient (Israelsson et al., 2020; Moron et al., 2007; O and Foelsche, 2019; Peleg et al., 2013; Tokay and Ozturk, 2012; Villarini et al., 2008), variogram (Garetz et al., 2014; Song et al., 2018), and Moran’s I (Kumari et al., 2019; Moron, 1950) were used to estimate the rainfall spatial correlation (or autocorrelation) in the previous studies. The rainfall spatial correlation was recently considered a useful tool to quantify the spatial variability of rainfall fields, which summarized the relationships between the point-scale observations and it is mostly expressed using a correlogram to link inter-gauge correlations and inter-site distances (Cristiano et al., 2017; Marra and Morin, 2018; Pedersen et al., 2010; Zhuang et al., 2020).

In the previous work, SSE was found to be scale-dependent and varies depending on rainfall intensity, regional climate, and domain terrain (Ciach, 2003; Jensen and Pedersen, 2005; Steiner et al., 2003), complicating the understanding of local-specific rainfall processes. Furthermore, 1) the role of SSE in the identification of spatial rainfall structure is still unclear gauge-based studies and their uncertainty on the sub-daily scale or even minute scale is still ill-informed. Such questions need more worthy attention.