Mapping of precipitation in extreme rainfall events in Zhuhai, China

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Abstract. Floods caused by extreme rainfall events have been a predominant water-related issue to coastal cities in Pearl River Delta (PRD), China. In 2017 and 2018, Typhoon Hato and Mangkhut hit the area consecutively, caused severe damages in Zhuhai as well as in other adjacent cities. To combat the inverse impact of these extreme events, adequate emergency response, infrastructure upgrade, and appropriate urban planning are necessary to against the potential extreme rainfalls in future, but all depending on the standards of urban flood protection and storm-water drainages. Precipitation amounts responding to given return-periods are essential parameters for computing the required standards; however, due to the lack of long-term historical observational precipitation records in Zhuhai, it is difficult to precisely predict the value, then a rough prediction was applied in the whole city without considering the spatial variation of extreme precipitation. To specify the spatial distribution of precipitations for given return-periods in Zhuhai, ground-based rainfall observation were analyzed with combined of generalized extreme value (GEV) model and spatial interpolation techniques to compute the precipitation responding to varied given return-periods. The spatial distributions of precipitation in given return-periods offer a more accurate and spatial varied prediction. The information provides reasonable support for Zhuhai’s city manager to conduct proper strategies for emergency response, infrastructure upgrade, and future urban planning to against extreme rainfall events.

1. Introduction

Pearl River Delta (PRD) region, sited in southern Guangdong province with a land area of 7,500 square km, is ranked as a top economic development zone of China. Zhuhai is one of the central cities in PRD. It locates in the southern coastal area of Pearl River estuary, 20°48’~20°27’N and 113°03’~114°19’E, co-bordered with Macao and Shenzhen. Originated from a fish village, Zhuhai was appointed as one of the first special economic development zones in 1980 associated with China’s open and reform policy, then rapidly developed into a sizable industrial city [1]. Now, Zhuhai is a prefecture-level city of Guangdong province with a terrestrial area of 1,711 square km, consists of Hengqin New Area, Xiangzhou District, Doumen District and Jinwan District (figure 1). In 2018, Zhuhai reached a population of 1.68 million and GDP over 291 billion RMB.

Global Climate Change has been promoting extreme rainfall events in the PRD region [2]. In the last three years, two consecutive typhoons (Hato in 2017 and Mangkhut in 2018) have hit Zhuhai
resulted in several deaths/body injuries and exceeded 10.7 billion RMB property damages [3]. The flood caused by the massive storm has been categorized as a primary natural threat to the coastal PRD cities, in particular to Zhuhai and Macao. To against the disasters, it is crucial to perform proper urban planning, infrastructures update, and modern storm-water management following a reasonable urban flood protection and storm drainages criteria, which is limited by the precise predicting of precipitation responding to various return-periods.

Figure 1. Zhuhai’s administrative map.

Indeed, precipitation is not evenly distributed in whole city areas but with substantial spatial differences [4,5], especially in extreme rainfall events like typhoons. Lack considering the spatial difference may result in the bias-estimation of the urban flood protection and storm drainages standards in a different region. However, it is challengeable to precisely estimate region-specified precipitation in Zhuhai with conventional approaches due to insufficient site-specific historical rainfall records available.

The work aimed to map the one hour and daily period precipitation in Zhuhai city according to various return-periods. The generalized extreme value (GEV) distribution and spatial interpolation were applied to analyze the precipitation data.

2. Data and methodology

2.1. Dataset
Zhuhai’s weather monitoring network consists of two national level ground stations and 56 regional level ground stations. National level ground stations have worked since 1980, and primary weather parameters, e.g., temperature, precipitation, wind speed and direction, and surface pressure have been observed. Monthly summary of precipitation between 1980-2018 at both national stations was obtained from Zhuhai Meteorological Bureau. Local level ground stations had been gradually built to monitor the hourly weather condition, including temperature, precipitation, wind speed and direction and surface pressure since 2000 (the latest local ground station built in 2013), and available hourly precipitation data was also obtained from Zhuhai Meteorological Bureau.

2.2. Methodology
- Generalized Extreme Value (GEV) Model
  Extreme value theory (EVT) is a unique statistical approach to describe the unusual events. It originated for the need to keep or reject extreme high or low values from a dataset [6]. The extreme
value distributions were modeled with Gumbel Distribution [7], Fréchet Distribution [8], and Weibull Distribution [9]. EVT analysis has been widely applied in many fields, such as structural engineering, material science, economics, and finance. Gilli applied EVT to compute stock market financial risks [10], and Marimoutou et al performed EVT to estimate the risk of oil market [11]. Extreme events prediction related to climate change is another relevant field in which EVT analysis are extensively performed [12,13].

The Generalized Extreme Value (GEV) distribution combines the three type EVT distributions as a three-parameter distribution [6], which is defined by the location parameter $\mu$, the scale parameter $\sigma$, and the shape parameter $\xi$. For a GEV distribution, $\sigma$ and $1 + \xi \frac{x - \mu}{\sigma}$ must be greater than zero.

The cumulative distribution function (CDF) of GEV is formulated by equation (1),

$$F(x; \mu, \sigma, \xi) = \begin{cases} \exp\left[\frac{1}{\xi} \left(1 + \xi \left(\frac{x - \mu}{\sigma}\right)^{\frac{1}{\xi}}\right)^{-\frac{1}{\xi}} \right] & \xi \neq 0 \\ \exp\left[-\exp\left(\frac{x - \mu}{\sigma}\right)\right] & \xi = 0 \end{cases}$$

and the probability density function (PDF) of GEV is formulated by equation (2),

$$f(x; \mu, \sigma, \xi) = \begin{cases} \left(\frac{1}{\sigma}\right) \exp\left[-1 + \xi \left(\frac{x - \mu}{\sigma}\right)^{\frac{1}{\xi}}\right] \left[1 + \xi \left(\frac{x - \mu}{\sigma}\right)^{\frac{1}{1+\xi}}\right] & \xi \neq 0 \\ \left(\frac{1}{\sigma}\right) \exp\left[-\exp\left(-\frac{x - \mu}{\sigma}\right) + \left(\frac{x - \mu}{\sigma}\right)\right] & \xi = 0 \end{cases}$$

A particular case can be categorized into one of the three followed distributions defined by the shape parameters: (1) the Gumbel Distribution with $\xi = 0$, referred to EVD Type I distribution, is used to describe exponential tailed distributions like exponential, normal, log-normal and gamma type distributions; (2) the Fréchet Distribution with $\xi > 0$, referred to EVD Type II distribution, is used to describe fat-tailed distributions like Cauchy and Pareto type distributions; and (3) the Weibull Distribution with $\xi < 0$, referred to EVD Type III distribution, is used to describe short-tailed distributions like uniform and beta type distributions.

Several statistic methods have been applied for the GEV parameter estimation, such as the maximum likelihood method, the weighted moments method and the Bayesian method [14]. Among these methods, the maximum likelihood method is the most popular method and broadly used for extreme climate events analysis. In this paper, the maximum likelihood method was used to determine the parameters. Estimating of the GEV parameters ($\mu$, $\sigma$, and $\xi$) was conducted using R software with ismev package (http://www.kai.ucar.edu/~ericg/softextreme.php). Return-period related one-hour and daily precipitation was estimated by equation (3),

$$P_r(T; \mu, \sigma, \xi) = \begin{cases} \mu + (\frac{\mu}{\sigma}) \left[-1 + \left[-\ln\left(1 - \frac{1}{T}\right)\right]^{-\frac{\xi}{\xi}}\right] & \xi \neq 0 \\ \mu + \sigma \left[-\ln\left(1 - \frac{1}{T}\right)\right] & \xi = 0 \end{cases}$$

where $P_r$ (mm) refers to precipitation according to a specific return-period $T$ (year).

- Spatial Interpolation Analysis

Different statistic methods can be used to predict the spatial distribution of variables. In this case, a spatial interpolation approach was applied to expand the spatial precipitation from at-site station modeled information to the region. The Kriging method, using z-scores to generate an estimated surface model from the spatial description of a scattered set of data points, is a popular type of regression that gives a least square estimate of data [15]. In this study, the Kriging method was conducted to interpolate at-site precipitation spatially to whole space of Zhuhai. The spatial
interpolation analysis was performed on ArcGIS10.5 with the spatial analysis toolbox.

3. Results and discussion

3.1. Annual and monthly rainfall variation
As shown in figure 2, total annual precipitation was monitored as 2278±445 mm (mean ± SD) with a median of 2310 mm and 2063±425 mm (mean ± SD) with a median of 2065 mm at Station1 and Station2, respectively. The value in Zhuhai is rough 3~4 times larger than in Beijing and two times larger than in Shanghai. During 1980-2018, total annual precipitation shows no significant difference ($p > 0.2$, t-test) at both stations, referring that global climate change may not significantly alternate the total precipitation in this region in the past three decades.

![Figure 2. Annual precipitation at two national ground stations in Zhuhai.](image)

Zhuhai is categorized in the subtropical zone in which precipitation is primarily controlled by subtropical monsoon climate. As shown in figure 3, monthly precipitation is less than 200 mm in winter and early spring seasons in which the weather is dominated by dry-cold air mass originated from Euro-Asia continent. However, enhanced monthly precipitation starts from April and continues to September caused by the seasonal reverse of zonal land-sea thermal contrast, with a significant increase of the frequency and precipitation intensity of rainfall events. The maximum monthly rainfall of 1138 mm was monitored in June 2008.

![Figure 3. Monthly variation of precipitation in Zhuhai during 1980-2018.](image)

3.2. Spatial distribution of one-hour precipitation responding to specific return-periods
One-hour precipitations were interpolated then mapped in whole-city space according to specific return-periods of 2-, 5-, 10-, and 20-year. As shown in figure 4, one-hour precipitations present
significant spatial differences in various regions, for example, Doumen and Jinwan districts are dominated by enhanced precipitation, while rainfalls with specified return-periods in Xiangzhou district and Hengqin New Area are slight weak. With more extended return-periods, peak precipitation increases from 32.8 mm (2-year of return-period) to 115.8 mm (20-year of return-period).

**Figure 4.** Spatial distribution of one-hour precipitation according to specific return-periods.

The spatial distribution of one-hour precipitation is an essential foundation for urban planning, emergency response, and construction development. Large impervious surface in urban area will result in enhanced surface runoff generated in a short-term, intensive rainfall in a very shallow time-window (usually less than one hour) potentially leads to the huge surface runoff volume and peak flow which resulted to a significant flooding risk, threatening those low elevation areas. Figure 3 demonstrates that Doumen and Jinwan areas may receive larger precipitation at given return-period and more vulnerable to extreme rainfall events. City planners and managers of Zhuhai should carefully verify the current standard of urban flood protection and storm drainages in those areas to combat the extreme rainfall events. Currently, whole-in-one precipitation values of various given return-period events are insufficient to apply in the whole city area. It is important to have a concern on the spatial variation of precipitation events in city management.

3.3. **Spatial distribution of daily precipitation responding to specific return-periods**

The spatial distributions of daily precipitation in Zhuhai regarding 2-, 5-, 10-, and 20-year return-period were mapped in figure 5. Daily precipitation distribution exhibits less spatial difference compared to one-hour values. As shown, highest precipitation in extreme rainfall events often occurs
in the south coastal area of Jinwan District, with rainfall declining from the south to north of Zhuhai. As discussed in section 3.1, Zhuhai is controlled by the subtropical monsoon climate. The extreme rainfall events primarily occur in the summer season and are dominated by low-pressure tropic cyclones, especially typhoon events generated in the South China Sea. During the movement and landing of cyclones onto Zhuhai land, coastal areas usually receive more severe rainfall.

![Spatial distribution of daily precipitation responding to given return-periods.](image)

**Figure 5.** Spatial distribution of daily precipitation responding to given return-periods.

4. **Conclusion**

On the basis of historical ground-based precipitation observation, we analyzed the spatial distribution of precipitation regarding specific return-periods using the GEV modeling and spatial interpolation approach. The maps of precipitation in whole Zhuhai areas present a significant spatial distribution, which illustrates the previous prediction approach of precipitation for extreme events is insufficient to apply in the whole city area. The prediction of extreme precipitation with a spatial distribution is crucial to precisely estimate the standard of urban flood protection and storm drainages. Precise spatial prediction of extreme precipitation provides scientific support for improving the flood protection and storm drainages standard and the urban storm-water management.

Extended return-period prediction requires much longer historical observation data to acquire a confident prediction. Currently, due to the lack of an available precipitation dataset for a more extended period, the prediction of precipitation for extreme events were only conducted for 2-, 5-, 10-, and 20-year return-period. In the future, the prediction should be re-conducted and updated with a longer ground precipitation record available.

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