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What are the best covariates for developing non-stationary rainfall Intensity-Duration-Frequency relationship?

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ABSTRACT

Present infrastructure design is primarily based on rainfall Intensity-Duration-Frequency (IDF) curves with so-called stationary assumption. However, in recent years, the extreme precipitation events are increasing due to global climate change and creating non-stationarity in the series. Based on recent theoretical developments in the Extreme Value Theory (EVT), recent studies proposed a methodology for developing non-stationary rainfall IDF curve by incorporating trend in the parameters of the Generalized Extreme Value (GEV) distribution using Time covariate. But, the covariate Time may not be the best covariate and it is important to analyze all possible covariates and find the best covariate to model non-stationarity. In this study, five physical processes, namely, urbanization, local temperature changes, global warming, El Niño-Southern Oscillation (ENSO) cycle and Indian Ocean Dipole (IOD) are used as covariates. Based on these five covariates and their possible combinations, sixty-two non-stationary GEV models are constructed. In addition, two non-stationary GEV models based on Time covariate and one stationary GEV model are also constructed. The best model for each duration rainfall series is chosen based on the corrected Akaike Information Criterion (AICc). From the findings of this study, it is observed that the local processes (i.e., Urbanization, local temperature changes) are the best covariate for short duration rainfall and global processes (i.e., Global warming, ENSO cycle and IOD) are the best covariate for the long duration rainfall of the Hyderabad city, India. Furthermore, the covariate Time is never qualified as the best covariate. In addition, the identified best covariates are further used to develop non-stationary rainfall IDF curves of the Hyderabad city. The proposed methodology can be applied to other situations to develop the non-stationary IDF curves based on the best covariate.

1. Introduction

There is a long tradition of the use of methods based on the statistical theory of extreme values in hydrology (Katz, 2013) and these methods are based on the assumption of temporal stationarity (i.e. the occurrence probability of extreme precipitation event is not expected to change significantly over time) (Jakob, 2013). But, recent studies reported that the extreme precipitation events are intensifying due to global climate change (Allen and Ingram, 2002; Emori and Brown, 2005; Trenberth et al., 2003; Xu et al., 2015; Cavanaugh et al., 2015). In particular, there is an increase in global temperature due to human activities in the past century (Min et al., 2011). This additional temperature increases the atmospheric moisture content and it may increase the probable maximum precipitation (Kunkel et al., 2013). By the middle of 2009, the population living in urban areas reached more than half of the world's population (DESA, 2010) and by 2030, towns and cities will be home to almost 5 billion people and it will be around 80% of the world's population (UNFPA, 2007). At the same time, during the last decade, the possible changes in precipitation due to urbanization are identified (Shepherd et al., 2001; Shepherd and Burian, 2003; Burian and Shepherd, 2005; Lei et al., 2008; Zhang et al., 2014; Yang et al., 2015; Villarini, 2016). Especially, the recent studies reported the influence of urbanization on extreme rainfall events (Lei et al., 2008; Miao et al., 2011). Ajayamohan and Rao, (2008) demonstrated the effect of Indian Ocean Dipole (IOD) on the extreme rainfall events over India. In addition, it is worth to note that the frequency of extreme Indian Ocean Dipole event is increasing due to greenhouse warming (Cai et al., 2014). In specific to India, Mondal and Mujumdar (2015) showed the non-stationarity in the extreme rainfall over India due to different physical processes, namely, El Niño-Southern Oscillation (ENSO) cycle, global warming and local temperature changes.

In addition, Gouri and Srinivas (2015) assessed the reliability of Bengaluru city, India storm water drain network and they found that the reliability of Bengaluru city storm water drainage network

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is low and authors suggested to redesign to improve the drain network reliability. Further, Moglen and Vidal (2014) reported that the storm water drainage network of Washington, DC is inadequate due to climate change.

Developing rainfall Intensity-Duration-Frequency (IDF) relationship is one of the main application of extreme value theory in hydrology. The IDF curves are widely used in storm water management and other engineering design applications across the world (Endreny and Imbeah, 2009). The IDF curves are developed based on historical rainfall time series data by fitting a theoretical probability distribution of annual maximum extreme rainfall series or partial duration series. Current IDF curves are based on the concept of stationary extreme value theory. However, the various physical processes (discussed in the above paragraph) are expected to alter the intensity, duration and frequency of rainfall extremes over time. Thus, the time series will have a non-stationary component in it.

Based on recent theoretical advancements in the Extreme Value Theory (EVT), Cheng and AghaKouchak (2014) developed a non-stationary rainfall IDF curves by incorporating linear trend in the location parameter of Generalized Extreme Value (GEV) distribution using Time covariate. Yilmaz and Perera (2014) investigated the non-stationarity in the IDF curves of Melbourne, Australia by incorporating linear trend in location and shape parameters of the GEV distribution using Time covariate. The previous studies on the non-stationary IDF curves have used only Time as a covariate. However, the covariate Time may not be the best covariate. Without analyzing all possible covariates, straightforwardly utilizing Time as a covariate to develop non-stationary IDF curves may affect the analysis results. Therefore, to model non-stationarity, it is important to find the best covariate(s) for each duration extreme rainfall series.

This study aims to find the best covariates to develop the non-stationary IDF curves. Thus, towards identifying the best covariate, five physical processes, namely, urbanization, local temperature changes, global warming, ENSO cycle and IOD are used as covariates and based on these five covariates and their combinations, sixty-two non-stationary GEV models are constructed. In addition, two non-stationary models based on Time covariate and one stationary model are also constructed. The best model for each duration extreme rainfall series is chosen based on the corrected Akaike Information Criterion (AICc) value and the covariate(s) of the best GEV model is/are the best covariate(s) for developing non-stationary rainfall IDF relationship for the corresponding duration. In addition, based on the best non-stationary models, the non-stationary rainfall IDF relationship is developed for the Hyderabad city, India.

2. Study area

The Hyderabad city is the fourth biggest city in India and it is the capital of the southern Indian state of Telangana. Fig. 1 shows the location map of the Hyderabad city. The Hyderabad city lies between the latitude of 17.25 °N and 17.60 °N and longitude of 78.20 °E and 78.75 °E and situated at a height of about 500 m above the mean sea level. The significant urbanization of Hyderabad city occurred after 1990. During1972 to 1990, the average precipitation of Hyderabad city was 796 mm/year. But, it has increased to 840 mm/year amid 1991 to 2013. The wettest month of the city is August and the normal precipitation of this month is 163 mm. The Hyderabad city is grouped under semi-arid region and the Köppen–Geiger classification is BSh (Peel et al., 2007). Recently, Agilan and Umamahesh (2015) detected and attributed non-stationarity present in the Hyderabad city, India extreme rainfall intensity and frequency, and they reported that the stationary model is not even qualified as a considerable model when compared with the best non-stationary model for modeling extreme rainfall of Hyderabad city, India.

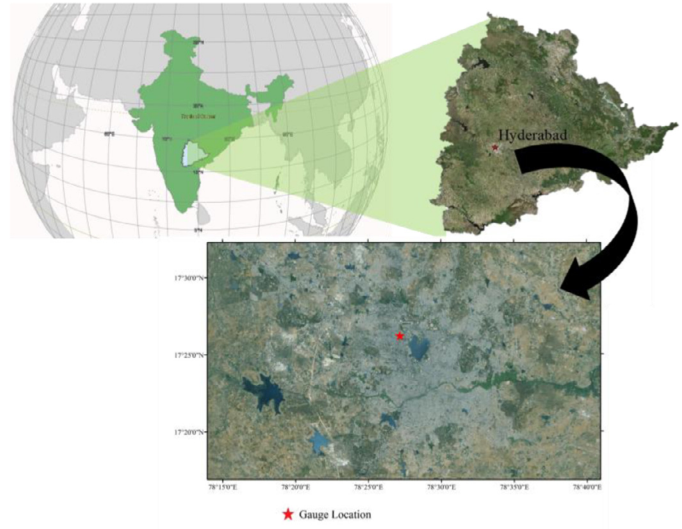

Fig. 1. Study area.

3. Data

3.1. Rainfall data

For this study, the hourly observed rainfall data for Hyderabad city is procured from the India Meteorological Department (IMD) for the period of 01-01-1972 to 31-12-2013 (42 years). This data is gauge observation and it is observed at the center of the Hyderabad city i.e. 78.46 °E and 17.45 °N. The location of this gauge is given in Fig. 1 (star mark). From the hourly observations, the 2 h, 3 h, 6 h, 12 h, 18 h, 24 h, 36 h and 48 h duration rainfall are calculated. Then the annual maximum series is extracted from each duration (i.e., 1h to 48h) rainfall and it is shown in Fig. 2.

From Fig. 2, it is noted that the linear best fits of all duration are having an increasing trend. Except 1 h duration linear best fit, all other linear best fits are statistically significant at 5% level of significance.

3.2. Covariates

Towards identifying the best covariate for developing non-stationarity IDF curves, the five physical processes, namely, urbanization, local temperature changes, global warming, ENSO cycle and IOD and their possible combinations are considered. As the previous studies are used Time as a covariate, this study also considers the time as one of the possible covariates. The data used to represent the five physical processes and justification to use them is given in this section.

3.2.1. Urbanization

In an urban area, natural land surfaces are replaced with artificial surfaces that have different thermal properties (e.g., heat capacity and thermal inertia). Such surfaces are typically more capable of storing solar energy and converting it to sensible heat. As sensible heat is transferred to the air, the temperature of the air in urban areas tends to be 2°–10 °C higher than surrounding non-urban areas (Shepherd et al., 2001). Thus, urban areas modify boundary layer processes through the creation of an Urban Heat Island (UHI) and the UHI can have a significant influence on mesoscale circulations and resulting convection