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Research papers

Is the covariate based non-stationary rainfall IDF curve capable of encompassing future rainfall changes?

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ABSTRACT

Storm water management and other engineering design applications are primarily based on rainfall Intensity-Duration-Frequency (IDF) curves and the existing IDF curves are based on the concept of stationary Extreme Value Theory (EVT). However, during the last few decades, global climate change is intensifying the extreme precipitation events and creating a non-stationary component in the extreme rainfall time series. Subsequently, in recent years, advancements in the EVT helped the researchers to propose a method for developing non-stationary rainfall IDF curve by modelling trend present in the observed extreme rainfall series using covariate. But, is it capable of encompassing future rainfall changes? Towards answering this question, the Hyderabad city, India non-stationary rainfall IDF curves are compared with the IDF curves of two future time periods (2015–2056 and 2057–2098). Using 24 Global Climate Models' (GCMs') simulations and 'K' Nearest Neighbor (KNN) weather generator based downscaling method, the IDF curves are developed for two future time periods and they are compared with covariate based non-stationary rainfall IDF curves of the Hyderabad city. The results of this study indicate that the return of period of an extreme rainfall of the Hyderabad city is reducing. In addition, it is noted that the non-stationary IDF curve developed by modelling trend in the observed extreme rainfall with covariate is an appropriate choice for designing the Hyderabad city infrastructure under climate change.

1. Introduction

The rainfall Intensity-Duration-Frequency (IDF) curves are generally used in storm water management and other engineering design applications (Endreny and Imbeah, 2009; Cheng and AghaKouchak, 2014) and these curves are constructed using observed rainfall time series data by fitting a appropriate theoretical probability distribution to partial duration series or annual maximum rainfall series (Cheng and AghaKouchak, 2014). The concept of stationary extreme value theory (i.e. exceedance probability of extreme rainfall event is not expected to change significantly over time (Jakob, 2013)) was used to develop the existing IDF curves. However, it is now widely recognized that the global climate change is intensifying the extreme rainfall events and creating a non-stationary component in the extreme rainfall time series (Allen and Ingram, 2002; Trenberth et al., 2003; Emori and Brown, 2005; Tramblay et al., 2012; Cavanaugh et al., 2015; Xu et al., 2015; Milly et al., 2008; Wasko and Sharma, 2014). In particular, during the last century, the global temperature is increased due to human activities (Min et al., 2011; IPCC, 2013) and this additional temperature increases the air's water holding capacity by around 7% for every 1 °C warming, in this manner straightforwardly influencing rainfall (Trenberth, 2011). In addition, the recent studies prove that more intense rainfall events may occur due to the high atmospheric water vapor (Berg et al., 2013; Kunkel et al., 2013; Wasko and Sharma, 2015; Lenderink and van Meijgaard, 2008). Moreover, the probable maximum precipitation or the expected extreme precipitation may increase due to rising temperatures and subsequent increases in atmospheric moisture content (Trenberth et al., 2003; Kunkel et al., 2013).

In addition, greenhouse warming is also increasing the frequency of extreme Indian Ocean Dipole (IOD) events (Cai et al., 2014) and this IOD has a significant influence on extreme rainfall of India (Ajayamohan and Rao, 2008). Furthermore, the recent studies demonstrate the effect of El Niño-Southern Oscillation (ENSO) cycle on extreme rainfall at regional and local scale (Kenyon and Hegerl, 2010; Zhang et al., 2010; Villafuerte and Matsumoto, 2015; Franks and Kuczera, 2002; Kiem et al., 2003; Pui et al., 2012) and the frequency of El Niño events (part of ENSO

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cycle) will increase, if the concentration of future greenhouse-gas is more (Timmermann et al., 1999).

In addition to global warming, IOD and ENSO effects on extreme rainfall, there is another process which also affects the extreme rainfall of urban area i.e. urbanization. In specific, in urban areas, artificial surfaces that have different thermal properties (e.g., thermal inertia and heat capacity) are replacing the natural land surfaces. Typically, such surfaces are capable of storing solar energy and transforming it into sensible heat. The temperature of the air in urban areas tends to be 2–10 °C higher than neighboring non-urban areas because the sensible heat is transferred to the air (Shepherd et al., 2001). Therefore, through the creation of an Urban Heat Island (UHI), urban areas alter boundary layer processes. Consequently, the mesoscale circulations and resulting convection are significantly influenced by UHI (Shepherd et al., 2001). During the previous decade, the possible changes in rainfall due to urbanization are identified (Shepherd et al., 2001; Shepherd and Burian, 2003; Burian and Shepherd, 2005; Lei et al., 2008; XiQuan et al., 2009; Zhang et al., 2014; Yang et al., 2015). Particularly, the recent studies show that the extreme rainfall events are significantly influenced by urbanization (Lei et al., 2008; Kishtawal et al., 2009; Miao et al., 2011; Agilan and Umamahesh, 2015).

Hence, it is clear that the intensity, duration and frequency of rainfall extremes are expected to change over time due to various physical processes (discussed in the above paragraphs). Therefore, the time series will have a non-stationary component in it and the stationary extreme value theory based rainfall IDF curves may underestimate the extreme event. In other words, the frequency of future extreme rainfall events that exceed the capacity of current drainage networks will increase if the drainage is designed based on the concept of stationary extreme value theory (Langeveld and Schilperoort, 2013; Willems, 2013; Zahmatkesh et al., 2015).

To cope with climate change, researchers have developed future rainfall IDF curves with the help of Regional Climate Models' (RCMs) or Global Climate Models' (GCMs) future rainfall simulations (Mailhot et al., 2007; Prodanovic and Simonovic, 2007; Willems, 2013; Rodriguez et al., 2014; Rupa et al., 2015; Hassanzadeh et al., 2014). In detail, Prodanovic and Simonovic (2007) developed IDF curves of London for the future wet scenario using 'K' Nearest Neighbor (KNN) based weather generator and they reported 30% increase in the intensity of future return level. Rodriguez et al. (2014) constructed IDF curves of Barcelona, Spain for different scenarios and reported that the daily rainfall with a return period longer than 20 years will increase at least 4%. All these studies compared rainfall IDF curves constructed with observed rainfall under stationary assumption and IDF curves constructed with simulated future rainfall.

On the other hand, to design infrastructure in a changing climate, researchers have developed a non-stationary rainfall IDF curves by modelling trend present in the observed extreme rainfall. In particular, Cheng and AghaKouchak (2014) constructed a non-stationary rainfall IDF curves by introducing linear trend in the Generalized Extreme Value (GEV) distribution's location parameter. Yilmaz and Perera (2014) investigated the non-stationarity in the IDF curves of Melbourne, Australia by introducing linear trend in the GEV distribution's location and shape parameter. However, till date, it is not clear that the non-stationary rainfall IDF curves developed by modelling trend present in the extreme rainfall series are capable of encompassing future rainfall changes or not. Therefore, in this study, the Hyderabad city, India future IDF curves are developed using 24 GCM outputs and KNN weather generator based downscaling method. Further, these IDF curves are compared with the covariate based non-stationary IDF curves of the Hyderabad city.

2. Study area and data

Recently Agilan and Umamahesh (2015) detected and attributed non-stationarity existing in the Hyderabad city extreme rainfall frequency and intensity, and they reported that the stationary statistical model is not even qualified as an adequate model when compared to non-stationary statistical model for modelling extreme rainfall of the city. Therefore, Hyderabad city is chosen as a study area to compare covariate based non-stationary IDF curve with climate model based future IDF curve. The Hyderabad city is the fourth biggest city in India. 796 mm/year was the average precipitation of Hyderabad city during 1972–1990, and it is 840 mm/year amid 1991–2013.

The hourly rainfall observed at the centre of the Hyderabad city by the India Meteorological Department is procured for the period of 01-January-1972 to 31-December-2013. 24 GCM (Table 1) precipitation flux outputs for historical and future time periods are downloaded from CMIP5 website http://www.ipcc-data.org/sim/gcm_monthly/AR5/Reference-Archive.html (accessed during September and October 2015). In addition, for developing non-stationarity IDF curves, five physical processes, namely, ENSO cycle, urbanization, global warming, local temperature changes and IOD are considered as covariates.

In order to represent global warming, with respect to the 1961–1990 mean, the HadCRUT4 yearly Global Temperature Anomaly (GTA) is used. The GTA is directly downloaded from http://www.metoffice.gov.uk/hadobs/hadcrut4/ (Accessed on 15-July-2015) and it is based on average surface air temperature observations. Similarly, based on India Meteorological Department observed hourly temperature of the Hyderabad city, yearly Local Temperature Anomaly (LTA) with respect to the 1972–2013 mean is used to represent local temperature changes. Southern Oscillation Index (SOI), Multivariate ENSO Index (MEI) and Sea Surface Temperature (SST) are the indices which are used to represent the ENSO cycle. To model the non-stationarity, different ENSO indices are used by different studies, i.e. SOI (Katz et al., 2002), SST (Mondal and Mujumdar, 2015). Mondal and Mujumdar (2015) used SST index averaged over the winter season (November to March) as a covariate for modelling the non-stationarity in intensity, duration and frequency of daily extreme rainfall over India. In this study, the approach of Mondal and Mujumdar (2015) is considered due to their local relevance. The monthly sea surface temperature anomaly over NINO 3.4 (17°E-120°W, 5°S-5°N) region with respect to 1981–2010 mean is the more common SST index and it is downloaded from http://www.cpc.ncep.noaa.gov/data/indices/sstoi.indices (Accessed on 19-July-2015). Then the average November to March NINO 3.4 SST anomalies is used as a covariate representing the ENSO cycle in a yearly basis. Indian Ocean Dipole (IOD) is quantified with Dipole Mode Index (DMI) (Saji et al., 1999). Monthly DMI derived from HadISST dataset is downloaded from http://www.jamstec.go.jp/frcgc/research/d1/iod/DATA/dmi.monthly.txt (Accessed on 15-June-2015) and yearly (i.e. averaged from June to November) DMI is calculated and used as a covariate which represents IOD. For this study, the urbanization of Hyderabad city modelled by Agilan and Umamahesh (2015) is used. In order to know the urbanization pattern, Agilan and Umamahesh (2015) used high-resolution remote sensing data to model the urban growth of the Hyderabad city. In particular, they studied the growth in urban built-up land using remote sensing data and supervised image classification algorithm. For more information on preparing urbanization data set, the interested reader is referred to Agilan and Umamahesh (2015).