Effect of Catchment Wetness on Flood Generation of a Medium-sized Catchment with Tropical Pluvial Regime

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Abstract: Floods causes serious devastations to millions of people around the globe annually. India is highly prone to floods affecting about 7.5 million hectares of area every year. In this study, we attempted to understand the role of antecedent precipitation as a proxy of catchment wetness in the flood generating mechanism. A case study for Basantpur catchment in the Mahanadi River basin is presented. We analyzed the correlation between antecedent precipitations lagged from the day of flooding to the seventh day using a non-linear measure of dependence. Floods were characterized as peak over threshold events over the 99th percentile discharge. Antecedent precipitation with n^{th} day lag having the highest correlation with flood events were considered for the study. Considering precipitation and discharge as random variables, marginal distributions were fitted using L-moments. Bivariate flood frequency analysis was analysed using Gumbel-Hougaard, Joe and Rotated Clayton copulas. Copula-based conditional return periods were obtained for two extreme flooding events (95th and 99th percentile). The results indicate higher flood hazard of the 95th percentile extreme event (with lesser return periods) as compared to the 99th percentile extreme for all the scenarios. This study aids the understanding of the effect of antecedent precipitation in the flood generating mechanism of the catchment. It can provide an insight to the planners and decision makers in design of structural flood control measures.

Keywords: Antecedent precipitation; peak over threshold; catchment wetness; flood hazard

1. Introduction

Global population across one-third of the surface of the earth are subjected to flood vulnerability (Aksoy *et al*., 2016). According to the Intergovernmental Panel on Climate Change (IPCC), the volume and temporal distribution of streamflow are likely to change over the Asian continent as an impact of the intensification of global hydrological cycle. However, an increase in the severity and frequency of floods over the Indian peninsula is projected as a reflex of the warming climate (Hirabayashi *et al*., 2013; Apurva *et al*., 2015). Studies to assess the impact of changing climate on the streamflow and flood regimes play an important role for the planners and decision makers towards implementing an adaptation strategy. Several studies recently used hydrological models like VIC (Das *et al*., 2013; Wu *et al*., 2014), HBV-D (Lü-Liu *et al*., 2012), SWAT (Mishra and Lilhare, 2016; Mohammed *et al*., 2017), SWIM (Aich *et al*., 2014; Aich *et al*., 2016) and CaMa-Flood (Hirabayashi *et al*., 2013), and rainfall-runoff models like HEC-HMS (Rafei Emam *et al*., 2016) and NAM (Supharatid *et al*., 2016) to simulate river flows using the outputs of different Global Climate Models (GCMs) for small to large river basins all over the world. Relatively smaller subset of studies opted for hydrodynamic models like FLO-2D (Mishra *et al*., 2017), SOBEK (Budiyono *et al*., 2016) and MIKE 11 (Mirza, 2002). Fewer research analyzed the applicability of grid-based distributed models such as Mac-PDM.09 (Arnell and Gosling, 2016), PCR-GLOBWB (Gain *et al*., 2013) and DHSVM (Zhao and Gao, 2016) for climate change impact studies on floods at a large scale. However, an ensemble of hydrological models is applied on a global (Dankers *et al*., 2014; Krysanova *et al*., 2017) scale. Despite increases in precipitation extremes, a flood magnitude in many regions does not show an increasing trend. Reasons could be the decrease

in the extent of storm, snowmelt and antecedent soil moisture condition prevailing (Nied *et al*., 2017; Sharma *et al*., 2018). In light of this, few studies evaluated the effect of antecedent precipitation on the flood generating mechanism (Tramblay *et al*., 2012; Froidevaux *et al*., 2015; Fang and Pomeroy, 2016; Bischiniotis *et al*., 2018). Apart from this, several other studies analyzed the effect of changing climate on streamflow and floods in future (Apurv *et al*., 2015; Wang *et al*., 2015; Zhang *et al*., 2016; Maurer *et al*., 2018) with a few of them targeting the Mahanadi river basin in India (Asokan *et al*., 2008; Ghosh *et al*., 2010).
Among all, majority of the studies taken into account hydrological models where only the vertical flow is considered. Very few researches was found to use data-driven complex hydrological models capturing the lateral flow effect along with different storages of the infiltered water. Studies on the effect of antecedent precipitation condition on the occurrence and severity of flash flood events in large river basins is also very limited (Jena et al., 2014; Santos and Fragoso, 2016). As such, occurrence of extreme floods due to intensification of the global hydrological cycle as a result of global warming poses a serious threat to life and property in large river basins of developing countries.
As an effort to overcome the above-mentioned research gaps, the present study contributes towards understanding the behavior of flash floods as a reflex of the underlying precipitation accumulated over Basantpur, a medium-sized catchment (about 59,000 km^2) in a rapidly warming climate. Delusive of the decreasing trend in precipitation shown over the past years in the upper region of the Mahanadi River basin, it would be interesting to assess the role of antecedent precipitation as a proxy of catchment wetness in streamflow generation. Analyzing the effect of accumulated precipitation as the generating mechanism of floods in the historical period and in a future planning horizon makes this study one of its kind and helpful for decision makers to implement a climate change adaptation strategy.

2. Materials and Methodology

Study Area

The area selected for the present study is the Basantpur catchment (Fig. 1) in the upper region of the Mahanadi River basin located between 80°28´ and 82°71´E longitudes and 19°98´ and 23°32´ N latitudes. It has a total geographical area of 59,175 km^2. It has an average annual rainfall of about 1200-1400 mm, most of which is received during the monsoon season (June-October). The Basantpur gauging station is located in the Mahanadi River in the state of Chhattisgarh.

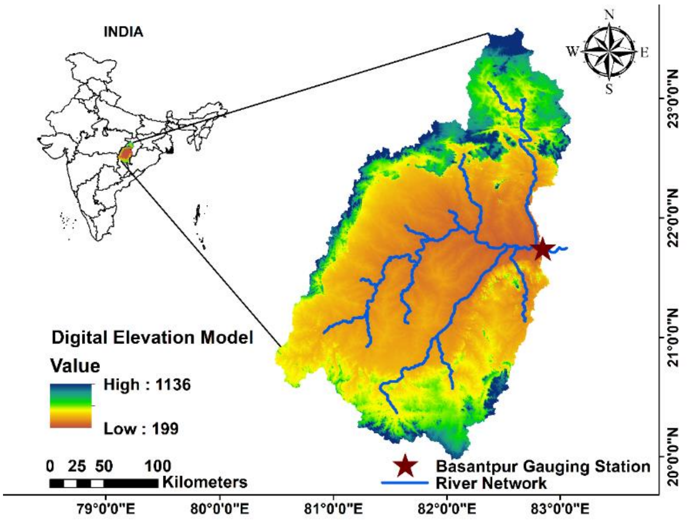

Fig. 1 Location map of the study area

Data used

Details of the hydro-meteorological and geospatial datasets used in the present study are shown in Table 1. Minimum and maximum temperature, precipitation data for the historical (1980-2005) and future (2010-2039) period under Representative Concentration Pathways (RCP4.5 and RCP8.5) of the Global Climate Model (GCM) BCC-CSM1.1(m) are downloaded from Earth System Grid Federation.

Table 1 Details of the hydro-meteorological and geospatial data

Sl. No.	Data	Spatial resolution	Data interval	Data period (Year)	Source
1	Rainfall	0.25° × 0.25°	Daily	1980-2005	IMD, Pune
2	Temperature				IMD, Pune
3	Stage/discharge of Basantpur gauging station	Station	Daily	1980-2005	India-WRIS (www.india-wris.nrsc.gov.in/)
4	SRTM 90m DEM	90 m × 90 m	--	--	https://earthexplorer.usgs.gov/
5	SRTM 30m DEM	30 m × 30 m	--	--	https://earthexplorer.usgs.gov/

Methods

Correlation between catchment wetness and discharges

For this study, at first the peak over threshold discharges at the Basantpur gauging station above the 99th percentile were selected. The corresponding precipitation accumulated over a period of 0 to 7 days prior to the selected discharge event were considered as a proxy of catchment wetness. The correlation between the Peak over Threshold (POT) discharges and the lagged accumulated precipitations were computed using a non-linear measure of dependence, Kendall's Tau (Helsel and Hirsch, 2002). Discharges and corresponding nth day lagged accumulated precipitation with highest correlation was considered for the study.

Hydrological modeling

MIKE11 NAM, a conceptual hydrological model, was calibrated and validated to simulate the daily streamflows for the historical and future period. Calibration and validation was done for 26 years (1980-2005) and 6 years (2006-2011), respectively. Two performance evaluation measures, namely Nash-Sutcliffe Efficiency (NSE) and coefficient of determination (R^2) were used to evaluate the model performance during calibration and validation. NSE and R^2 were calculated as shown in equations (1) and (2), respectively.

$$NSE = 1 - \frac{\sum(O-S)^2}{\sum(O-\bar{O})^2} \quad (1)$$

$$R^2 = \frac{\sum[(O-\bar{O})(S-\bar{S})]^2}{\sum(O-\bar{O})^2(S-\bar{S})^2} \quad (2)$$

where, O and S are observed and simulated discharges and $\bar{O}$ and $\bar{S}$ are mean of observed and simulated discharges, respectively.

Historical and future streamflow simulation

After the hydrological model was set up, the bias-corrected data of BCC-CSM1.1(m) GCM for the historical period (1980-2005) and a future period (2010-2039) under RCP4.5 and RCP8.5 was used to simulate the daily streamflow at the Basantpur gauging site. Ability of the selected GCM to represent the climate scenario during the historical period was evaluated by comparing the observed and simulated daily discharges using Taylor Skill Score. Details about Taylor Skill Score can be found in Ganguli and Coulibaly (2019). POT discharges and the corresponding n^{th} day lagged accumulated precipitation were then computed for the future period.

Copula-based return period analysis

To obtain the copula-based flood hazard, at first four marginal distributions (Generalized Extreme Value distribution, Generalized Pareto distribution, Gamma distribution and Lognormal distribution) were fitted to the data and the best-fit distribution was selected on the basis of MSE i.e., Mean Square Error, AIC i.e., Akaike Information Criteria and KS (Kolmogorov-Smirnov) test statistic. Three copulas namely, Joe, Gumbel-Hougaard (GH) and Rotated Clayton were used to test (using Cramer-von Mises (CvM) test statistic) and obtain the conditional return periods of the 95^{th} and 99^{th} percentile discharge events of the POT series and the corresponding accumulated precipitation. Theoretical aspects of the copulas can be obtained from Reddy and Ganguli (2012) and Sraj *et al.* (2015).

3. Results and Discussion

Correlation Analysis

The value of Kendall's Tau for the POT discharges and the corresponding precipitation accumulated from 0^{th} to the 7^{th} day prior to the discharge events are presented in Table 2. From this table, it is clear that the maximum correlation (0.3913) was found for the 4^{th} day lagged accumulated precipitation. This pair of discharge and precipitation was considered for carrying out the further study.

Table 2 Correlation between POT discharges and accumulated precipitation

Lagged day(s)	0	1	2	3	4	5	6	7
Kendall's Tau	0.0783	0.3564	0.3885	0.3564	0.3913	0.3774	0.3354	0.3159

Hydrological model setup and simulation of streamflows

The MIKE11 NAM model was calibrated and validated for 26 years (1980-2005) and 6 years (2006-2011), respectively. Values of NSE and R^2 during calibration were found to be 0.76 and 0.79 and during validation 0.79 and 0.83, respectively. A graphical representation of the model performance in both the periods is shown in the form of line plots (Fig. 2a-b). Overall, performance of the model was found to be satisfactory. Bias-corrected data of BCC-CSM1.1(m) GCM for the historical period (1980-2005) was fed into the developed MIKE11 NAM model to obtain the simulated streamflows. Taylor Skill Score, used as a performance evaluation statistic of the GCM to represent the current climate scenario was found to be 0.67, which is satisfactory (Ganguli and Coulibaly, 2019). Data of this model was then taken to simulate future streamflows at the Basantpur gauging station for the period 2010-2039 under RCP4.5 and RCP8.5.

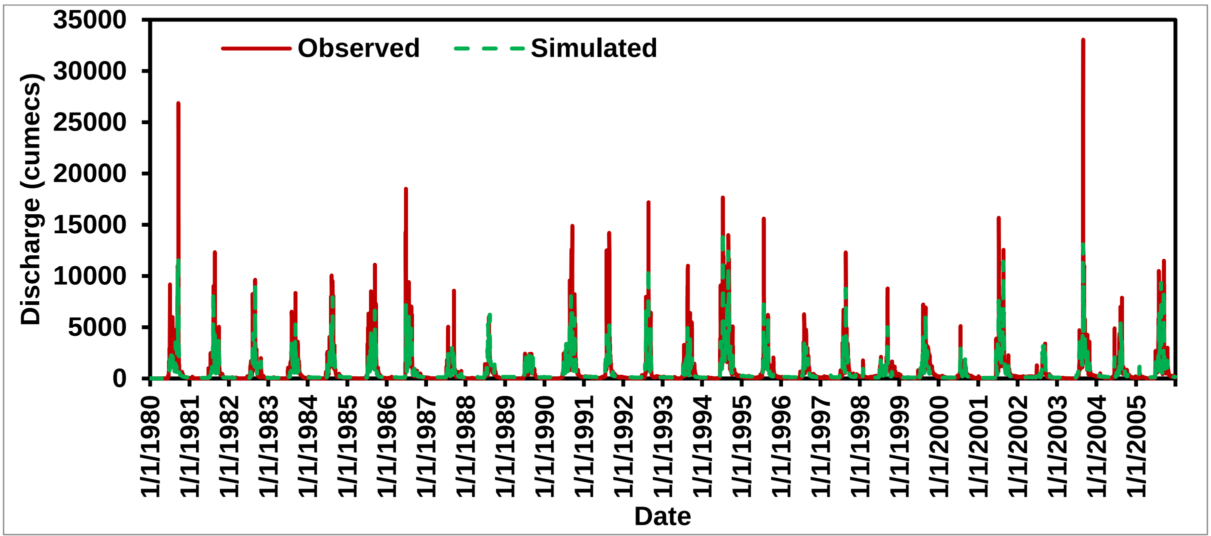

Fig. 2(a) Observed and simulated discharges during calibration (1980-2005)

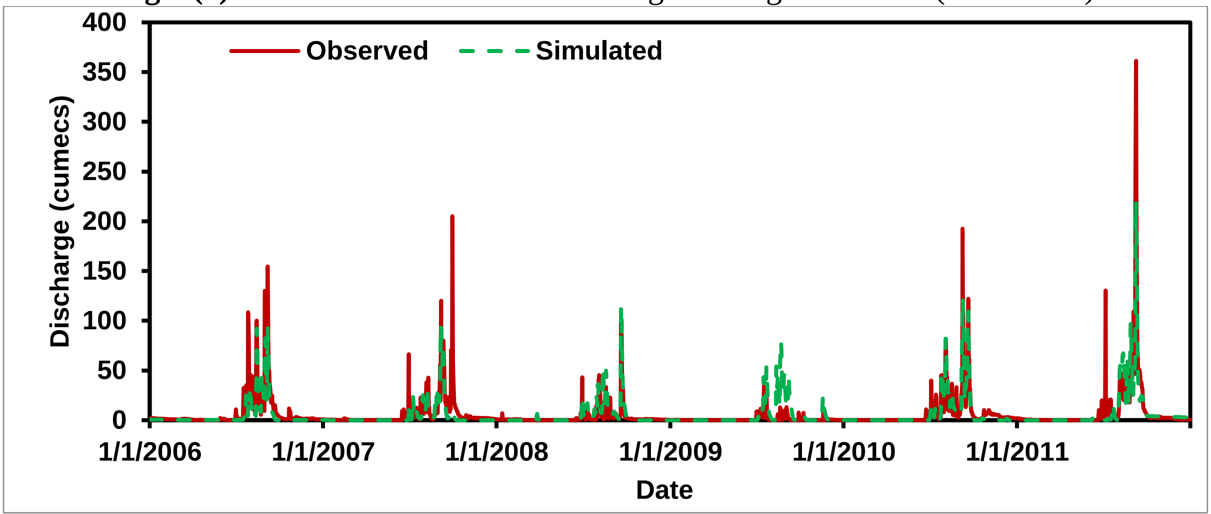

Fig. 2(b) Observed and simulated discharges during validation (2006-2011)

Bivariate return periods

Considering the best-fit marginal distribution out of the four (Generalized Extreme Value distribution, Generalized Pareto distribution, Gamma distribution and Lognormal distribution), three copulas were tested to obtain the conditional return periods for both the historical and future periods. Rotated Clayton, Rotated Clayton and Joe copula were found to be the best fitting to the observed and two (RCP4.5 and RCP8.5) future period data. The conditional return periods obtained using the best-fit copulas are shown in Fig. 3. From this figure, it can be inferred that the less extreme events (95th percentile events) are more hazardous with lesser return periods as compared to the highly extreme events (99th percentile events). Comparing among the scenarios, flood hazard was found to decrease in the future period under both RCPs. However, floods under RCP8.5 were found be more hazardous than that under RCP4.5.

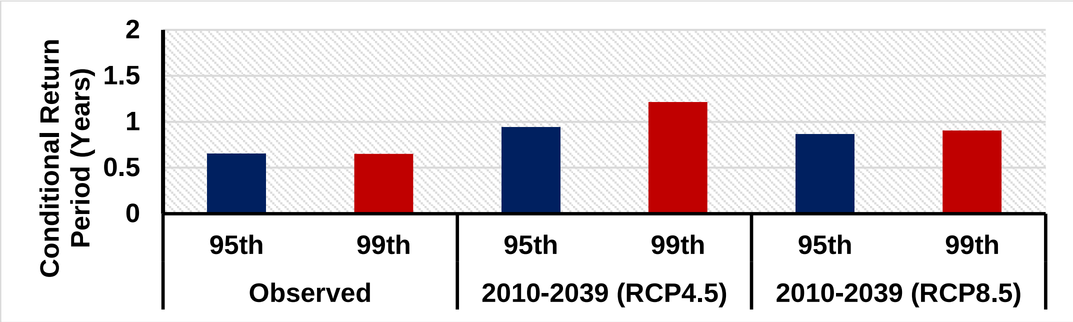

Fig. 3 Conditional return periods of the 95th and 99th percentile flood events under observed and future periods

4. Conclusions

The present study focussed on obtaining the conditional return period of two extreme flood events using a copula-based approach. Climate data of one GCM BCC-CSM1.1(m) for the historical period and a future period under two RCPs (4.5 and 8.5) were considered for the study. The results indicated higher flood hazard of the 95th percentile extreme event (with lesser return periods) as compared to the 99th percentile extremes for all the scenarios. Also, return period of both the events were found to increase in the future period under RCP4.5 and decrease under the RCP8.5. However, under both RCPs, the return periods were higher than that of the observed return periods indicating decreased flood hazard in the Basantpur sub-catchment in the upper region of Mahanadi River basin in near future.

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