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Received 23 April 2021; revised accepted 9 February 2022

doi: 10.18520/cs/v122/i9/1081-1085

Increasing and decreasing trends in extreme annual streamflow in the Godavari catchment, India

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In this study, we present the changing trends in extreme annual streamflow at 38 gauging stations in the Godavari catchment, India, during the period 1966–2015. We have applied Mann–Kendall trend test to the time series of at least 20 years of continuous data. The results indicate an increasing trend in the peak streamflow in the northern stations located within the Wainganga, Wardha and Indravati sub-catchments. We observed a critical declining trend at the upstream, central and downstream of the Godavari main catchment. Increasing trends in annual peak streamflow may cause severe higher magnitude floods in the Godavari catchment in the near future that may affect the lives of millions of population.

Keywords: Flood, gauging stations, peak streamflow, river catchment, trend analysis.

AT the beginning of the 21st century, due to global warming and anthropogenic activities, the increase in flood risks in various parts of the world has been reported[1,2]. India has witnessed several devastating flood events in the past few years that caused colossal damage to the infrastructure, economy and, most importantly, loss of life. Most of the time, floods in the Himalayan foreland and plains are related to heavy precipitation and glacial lake outburst[3,4]. Although severe floods in Peninsular India are primarily triggered by extreme precipitations, the severity and damage depend on both natural and anthropogenic factors[5,6].

The most recent devastating flood event in India was the Rishiganga–Dhauliganga flash flood in Garhwal Himalaya due to rock mass failure that resulted in an avalanche[7]. In 2018, nearly 500 people died and 150 went missing during the Kerala flood due to heavy precipitation and poor management of impoundments[8]. In 2005, Mumbai experienced unprecedented flooding due to heavy precipitation, causing more than 500 fatalities[9].

The Godavari basin is the largest catchment in Peninsular India, comprising an area of ca. 0.3 million km^2 (Supplementary Figure 1). The major geological units of the Godavari are Archean granites, Deccan basalts, Gondwana sedimentary rocks and Quaternary alluvium[10]. Topographically, the Godavari catchment shows great diversity.

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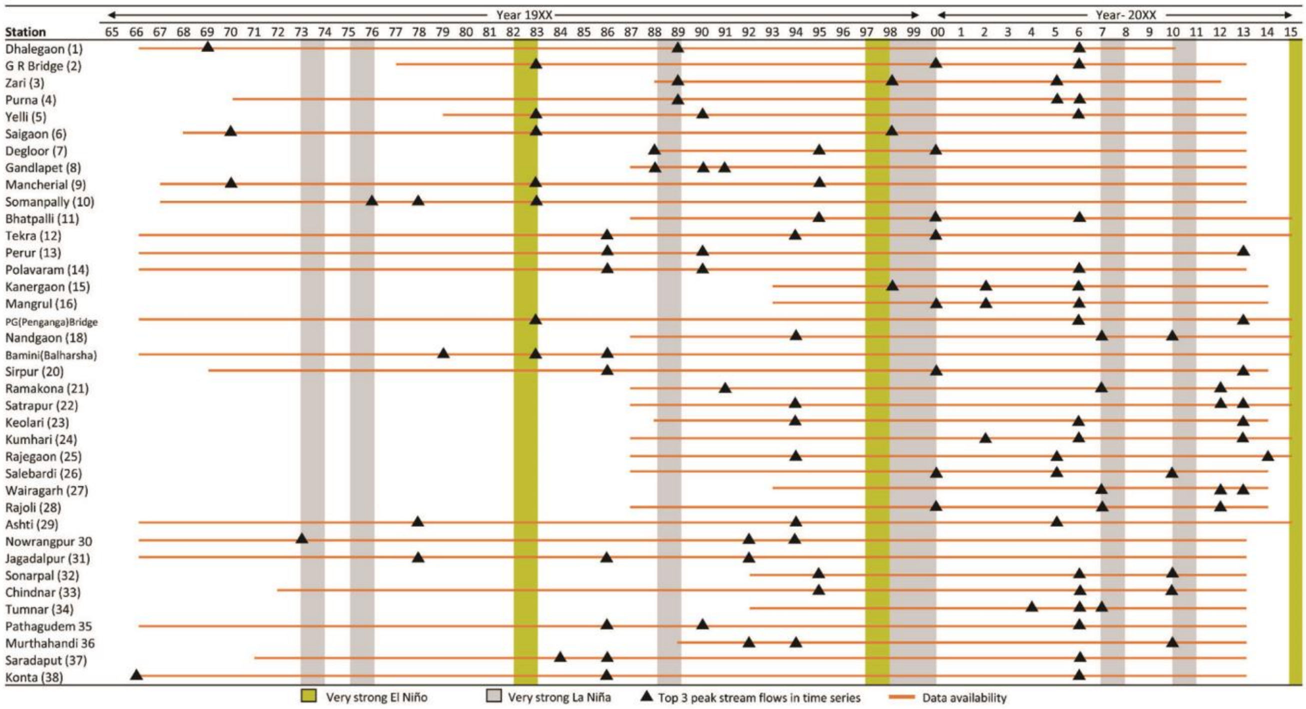

Figure 1. Station-wise data range. The top three peak streamflow years have been plotted for each station to determine the most severe flood years (e.g. the 2006 flood had led to extreme discharge in almost the entire catchment). Very strong El Niño and La Niña years have been determined based on NOAA data (https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php).

In the west, topography is highly rugged and shows high to moderate relief (Deccan Trap area). However, the eastern zone exhibits low relief topography, except for the Eastern Ghats region. Furthermore, the Godavari has developed a vast delta before debouching into the Bay of Bengal (BoB). The major land uses in the Godavari are agriculture, natural vegetation, settlement, numerous water bodies, barren land and shrubland[11]. On an average, the river drains about 87×10^9 m^3 water and 99×10^6 tonnes sediment into the BoB annually[11]. More than 600 dams and reservoirs were constructed within this catchment between 1970 and 2015 (ref. 12). The hydrology of the Godavari and its tributaries is controlled by the Indian summer monsoon (ISM) which occurs from June to September. In the past several decades, the Godavari experienced several large flood events. The most severe flood in Peninsular India during the past half-a-century occurred in 1986, with a record peak discharge of more than 55,000 m^3 s^{-1} at Polavaram. The discharge exceeded 50,000 m^3 s^{-1} during the 1990 and 2006 flood events as well.

Under warming climatic conditions, the frequency of extreme precipitation and flood is increasing in Peninsular India[13]. Although floods in Peninsular India are not frequent as seen in the Himalayan regions, in terms of severity, Peninsular Indian floods cause massive infrastructural damage. Recently, Garg and Mishra[14] assessed the role of extreme precipitation in flood occurrence in the Godavari basin, considering four gauging stations. Choosing a limited number of stations in such studies mostly over-generalizes the catchment-scale interpretations as the hydro-meteorological variables can broadly vary from place to place. Therefore, for a comprehensive understanding, it is necessary to consider the maximum possible stations in large catchments. Studies on peak streamflow trends and projections in the Godavari at the catchment scale considering maximum possible gauging stations are still lacking. Therefore, the main objective of this study was to present the long-term trends in peak discharge considering about half-a-century of continuous data for 38 gauging stations, spatially well distributed within the Godavari catchment.

The Central Water Commission (CWC), New Delhi is the Government organization that collects and records the streamflow and sediment concentration in Indian rivers. The streamflow data are available for download for the unclassified Peninsular Indian rivers in the portal of the Water Resources Information System (WRIS), India (http://www.india-wris.nrsc.gov.in/; presently this website has moved to a new domain – https://indiawris.gov.in/). In the Godavari catchment, more than 50 gauging stations have been established to record streamflow. A large difference in the recorded timing spans was noticed in the data at different stations. Several stations that used to record data previously are now closed. Therefore, we selected 38 gaging stations that have at least 20 years of continuous data (Figure 1). From the daily data, we identified the peak discharge of each year for statistical analysis.

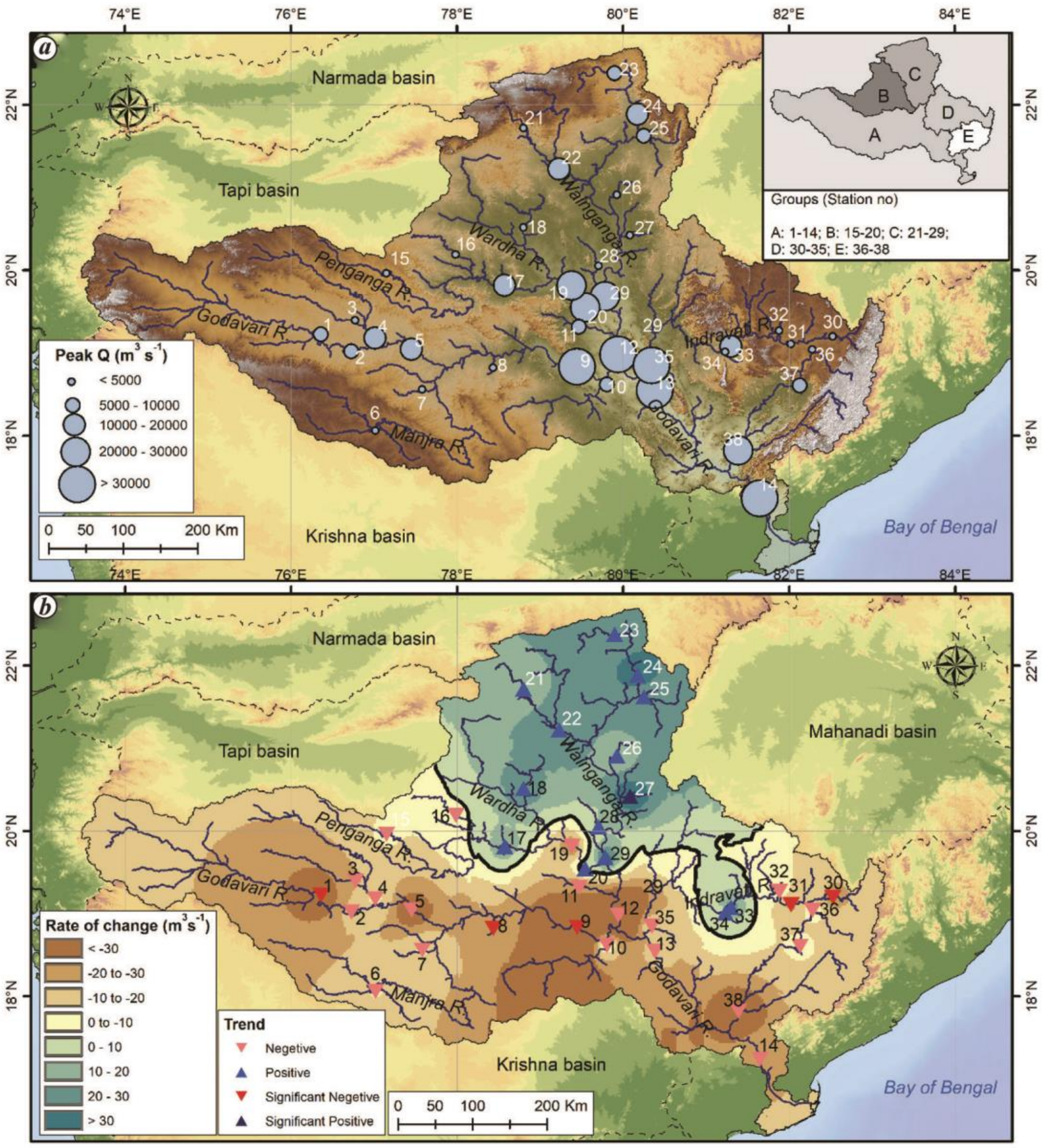

Figure 2. Peak flood discharge character in the Godavari catchment. ***a***, Location of the gauging stations considered in this study and historical peak discharge records at these locations. (Inset) Map showing five major divisions of the Godavari catchment that have been considered for an easier explanation of the data. See Figure 1 for station names. ***b***, Spatial distribution of trends and rate of change in the annual extreme discharge. Note that despite peak stream flows are confined within the streams and spatial interpolation can lead to misinformation, we prepared this map for easier visualization and interpretation using inverse distance weighted method in ArcGIS.

Non-parametric Mann–Kendall[15,16] and Sen's[17] slope tests are widely applied in identifying the changes in hydroclimatic data. Therefore, we applied these two methods in order to compute trends and determine the rate of changes in the peak flow in the Godavari basin. The hypothesis of Mann–Kendall test is that the data is independent and randomly ordered. However, hydro-meteorological time series generally show autocorrelation. To avoid this problem, we used the modified Mann–Kendall trend test of Hamed and Rao[18] for the autocorrelated datasets. Among 38 datasets, lag-1 autocorrelation was detected in two sets of data (Supplementary Figure 2). We applied standard Mann–Kendall test for the non-autocorrelated data. All the statistics was computed at a significance level of $\alpha = 0.05$ in the XLSTAT software package (https://www.xlstat.com/). We categorized the entire Godavari catchment into five different sections for easy description of the data as: (A) Godavari main, (B) Penganga and Wardha, (C) Wainganga, (D) Indravati and (E) Sabari sub-catchments (Figure 2 *a*).

The Godavari and its tributaries are fed by the southwest monsoon rainfall and therefore, all the peak streamflows at all stations are recorded between June and September. The annual peak discharge events in the Godavari are

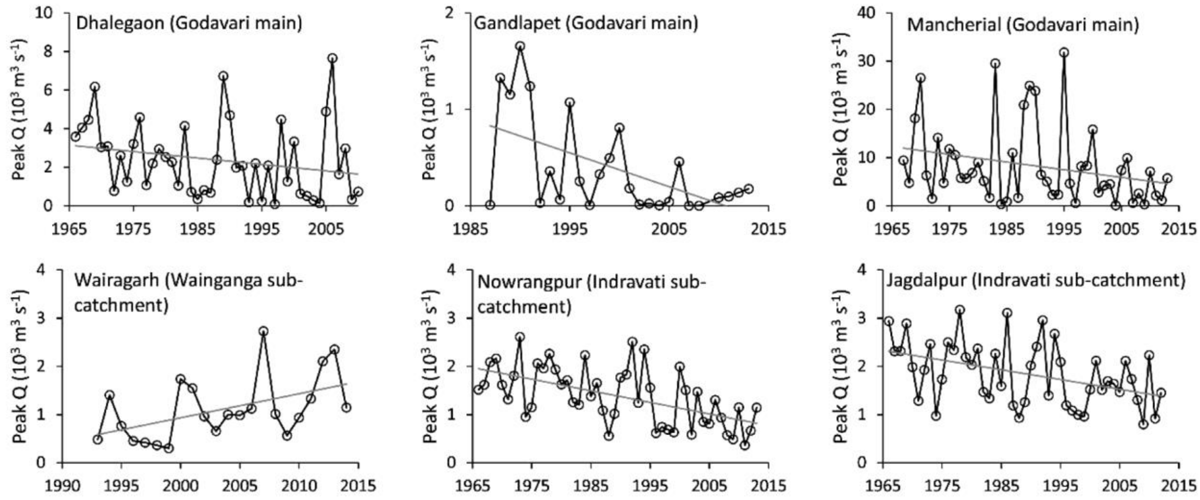

Figure 3. Temporal variation in the annual peak discharge at stations where statistics is significant at $\alpha = 0.05$.

generally up to 10–15 times higher than the average monsoon discharge. A great variation in the peak streamflow is found in all stations due to the unpredictable arrival time and intensity of the monsoon. Between 1966 and 2013, the Godavari recorded an exceptionally high peak discharge at Perur (62,889 $m^3 s^{-1}$) and Polavaram (61,657 $m^3 s^{-1}$) in 1986 and 1990 respectively. While Polavaram is the terminal gauging station, Perur is located where all the major tributaries (Wardha, Wainganga and Indravati) join the trunk channel, and this might be the reason (discharge from major tributaries leads to a sudden increase in discharge in the trunk stream) for the historical record of exceptionally high discharge.

The results exhibit both increasing and decreasing trends in peak streamflow at different locations in the Godavari (Figure 3). Among 14 gauging stations in the Godavari main section, three stations show a significant ($\alpha = 0.05$) decreasing trend, while the other 11 show weak decreasing trend (Supplementary Figures 3–7 for individual historical peak discharge graphs). The maximum rate of decline was recorded at Mancherial (Sen's slope = –124.54 $m^3 s^{-1}$) (Supplementary Table 1). Dhalegaon station, located upstream of the Godavari, indicated a significant decline in peak discharge at a rate of 47.76 $m^3 s^{-1} yr^{-1}$. However, the terminal gauging station (Polavaram) showed a weak declining trend at 21.04 $m^3 s^{-1} yr^{-1}$.

In the Penganga–Wardha sub-catchment, three gauging stations indicated an insignificant decreasing trend, while three others showed an insignificant positive trend. Sirpur, the final gauging station in Wardha River before it joins the Godavari, showed an increasing trend at 5.78 $m^3 s^{-1} yr^{-1}$.

All nine gauging stations in the Wainganga sub-catchment recorded an increasing trend. At Wairagarh, the peak discharge showed a significantly increasing trend at 41.63 $m^3 s^{-1}$ annually, which is the maximum rate observed in the entire Godavari catchment.

Similar to the Penganga and Wardha sub-catchment, Indravati showed a complex scenario. Four stations recorded a negative trend, among which two were statistically significant. The other two stations indicated a weak positive trend. Peak streamflow at Nowrangpur and Jagadalpur showed a decreasing trend at the rate of 24.34 and 22.19 $m^3 s^{-1}$ annually. All gauging stations located within the Sabari sub-catchment showed an insignificant negative peak discharge trend.

The results indicated an interesting spatial pattern of trends in the Godavari catchment when the rate of change is presented on a map (Figure 2 *b*). Nearly all stations in the northern section show a remarkably increasing trend in peak discharge and the rates decrease towards the south. Most of the areas in the north show an increasing rate of about 10–30 $m^3 s^{-1} yr^{-1}$. The upstream, central and downstream sections of the Godavari indicate an acute decrease (>30 $m^3 s^{-1} yr^{-1}$) in annual peak discharge.

Peak streamflow at any point of the river depends on not only the amount of precipitation but also numerous topographic and anthropogenic factors[19,20]. It is often found that extreme rainfall has little or no influence on peak annual streamflow[21,22], and it is difficult to identify the factor(s) responsible for peak streamflow at a specific location. Roxy *et al.*[13], based on long-term (1950–2015) precipitation data, reported about 10% decline in the mean monsoon rainfall in central India and about 75% increase in the number of extreme events. Although our data indicate a decline in extreme streamflow in large parts of the Godavari catchment; the northern section shows increasing peak streamflow, where mean monsoon rainfall indicates a declining trend[13]. This suggests an altered spatial pattern of the monsoon rainfall as well as anthropogenic conditions and other factors to greatly influence the peak streamflow in the upper Godavari catchment. Furthermore, based on data analyses of four stations, Garg and Mishra[14] reported that about 50–70% of extreme precipitation events cause extreme streamflow in the Godavari, while the rest depends on other factors.

One notable observation made in the present study is that several extreme peak streamflows correspond to strong La *Niña* years. This requires further studies to establish the connection of ENSO events with the sensitivity of peak streamflow not only in the Godavari, but also other Peninsular Indian catchments. While our primary aim was limited to determining the trends in peak streamflow, this study revealed possibly a greater role of mesoscale changes in climatic conditions, topographic response, and anthropogenic factors that may significantly influence the erratic peak streamflow behaviour in the Godavari basin. Moreover, as the high magnitude flooding events in Peninsular India are related to extreme annual streamflows, the increasing trends in the northern stations (Indravati sub-catchment) indicate the alarming potential of increasing flood intensity that may affect larger populations and infrastructures in those regions in the future.

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ACKNOWLEDGEMENTS. S.D. thanks UGC-India for financial support. We thank the Heads, Department of Geography and Department of Geology, Savitribai Phule Pune University, for providing necessary facilities to carry out this study. We also thanks Prof. Rajiv Sinha (Subject Editor) and an anonymous reviewer for their insightful comments and suggestions that helped improve the manuscript.

Received 17 January 2022; accepted 12 March 2022

doi: 10.18520/cs/v122/i9/1085-1089

Numerical analysis of heat dissipation through granite and clay in the multi-barrier system of a geological disposal facility

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High-level heat-emitting long-lived vitrified radioactive waste produced during recycling of the spent nuclear fuel is under consideration for permanent disposal in deep geological formations with appropriate thermomechanical, hydrogeological and geochemical properties. The capability of these rock formations ensuring long-term confinement and isolation of such waste from the environment is significantly controlled

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