SUPPLEMENTARY MATERIALS FOR

Co-incidence Analysis of Changes in Flood Magnitude and Shifts in Flood Timing in a Large Tropical Pluvial River Basin

*Poulomi Ganguli[*1], Yamini Rama Nandamuri[1], Chandranath Chatterjee[1]*

[1]Department of Agricultural and Food Engineering, Indian Institute of Technology Kharagpur, West Bengal 721 302, India

**Correspondence to*: Dr. Poulomi Ganguli (pganguli@agfe.iitkgp.ac.in)

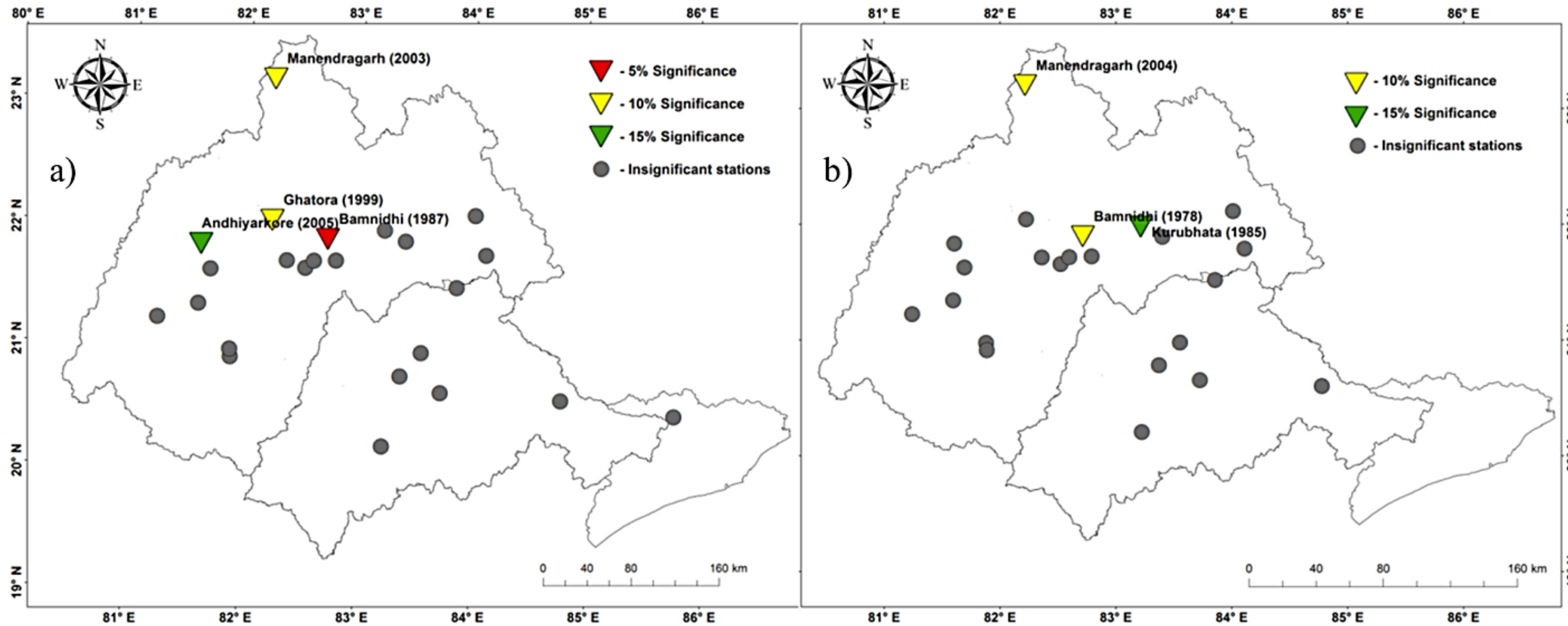

Figure S1. Change point analysis (Pettitt test) of (a) MMF events and (b) POTF events for gauge stations at a significance level of 5, 10 and 15%, respectively. While the single change point analysis is performed by the Pettitt test, differences in mean stream flow after and before the detected change points are shown using the triangle. The downward orientation of the triangle indicates a decrease in mean stream flow after change point years at respective gauge locations.

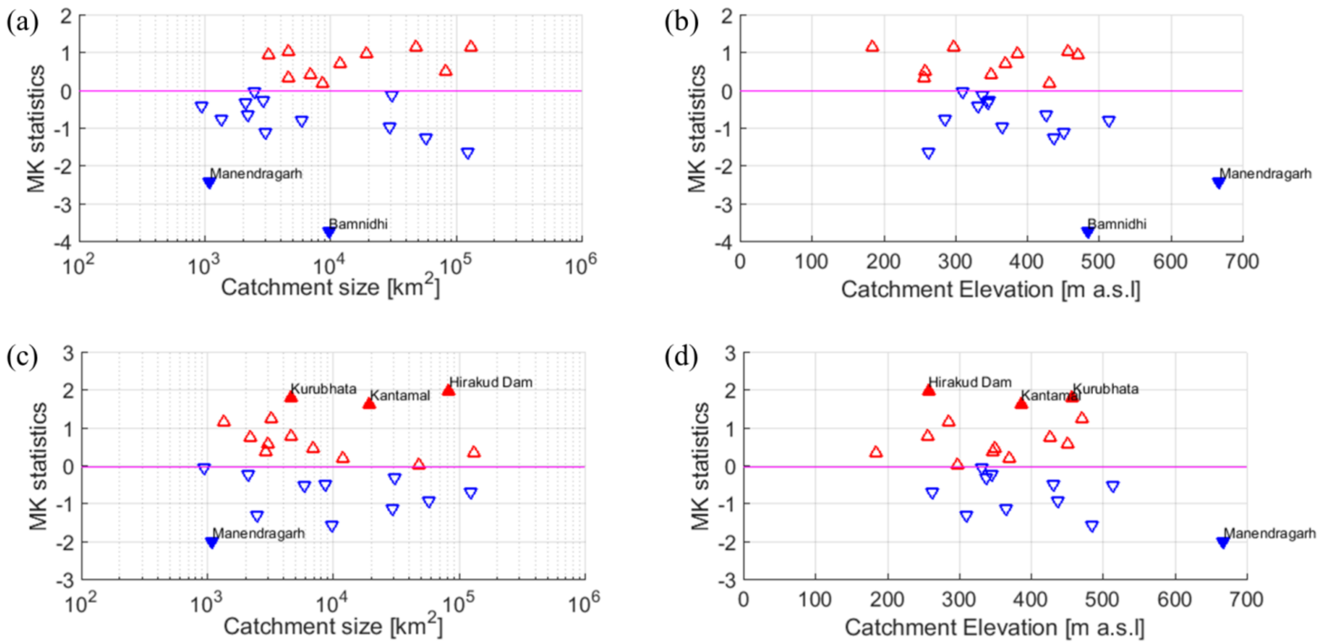

Figure S2. Mann-Kendall trend statistics are plotted as a function of the basin area (in km^2) and mean basin elevation (m above sea level) for MMF events (a, b) and POTF events (c, d). The up (/downward) triangles indicate increasing (decreasing) trend in flood magnitude. The filled triangles indicate detected trends in flood magnitude are significant (at α = 10% significance level).

Table S1. Summary of some past relevant studies and their key insights

	Study	Region	Approach & Dataset Information	Key findings
Trend analysis	*Petrow and Merz (2009)*	Throughout Germany	(i) Sites: 145 discharge gauges across Germany (ii) Period of analyses: 52 years (1951–2002) (iii) Data: Annual maximum series and peak over threshold discharge series (iv) Approach: Non-parametric Mann–Kendall test for trends in flood magnitude and frequency	(1) Most of the stations showed significant increasing flood trends (at a 10% significance level). (2) Very few stations exhibited decreasing trends and were not field-significant. (3) Stations with significant trends were spatially clustered over the region.
	Tian et al. (2011)	Poyang Lake Basin, China	(i) Sites: 10 hydrological stations were considered across Poyang Lake Basin (ii) Period of analyses: nearly 50 years of observed records (1957–2003) (iii) Data: Annual maximum and minimum flow, annual peak-over-threshold flows (iv) Approach: Mann-Kendall trend test and the linear regression method	(1) Both methods showed good agreement with each other in detecting flood trends. (2) Most annual maximum flows occurred between April to July, owing to southeast monsoon. (3) No significant upward/downward trends in flood magnitude are noted. (4) In contrast, a significant increasing trend was observed for low flow events.
	Panda et al. (2013)	Mahanadi River Basin, India	(i) Sites: 19 gauging stations spread across the basin (ii) Period of analyses: 1972–2007 (iii) Data: Seasonal and sub-seasonal streamflow and rainfall variables were analyzed (iv) Approach: Mann–Kendall trend test after removing the serial auto-correlation	(1) The streamflow was primarily controlled by the rainfall over the basin. (2) Increasing trends in flood magnitude in June while decreasing trends in August (3) Increased trends in both pre- and post-monsoon season streamflow and rainfall time series.

	Bawden et al. (2014)	Athabasca River Basin, Canada	(i) Sites: 19 gauge stations of Athabasca River Basin (ii) Period of analyses: Varying record length between 1952 and 2010 (iii) Data: Twenty flood indicators like annual and monthly mean flows, mean flow for the warm season, annual maximum and minimum daily flow were used (iv) Approach: Mann–Kendall trend test	(1) Strong decreasing trends in the annual warm season (March – October) and summer stream flows (2) Trends in streamflow were more strongly linked to precipitation than to air temperature
	Jena et al. (2014)	Mahanadi River Basin, India	(i) Sites: Two gauge stations at upper and middle reaches of the basin (ii) Period of analyses: 1957-2011 for streamflow record and 1957-2007 for rainfall data (iii) Data: Annual peak streamflow releases and $1^o \times 1^o$ Gridded daily rainfall data. (iv) Approach: Mann–Kendall trend test	(1) The upper region of the basin showed no (significant) trend in rainfall while the middle region showed an increasing trend in rainfall. (2) The middle reach showed a significant increasing trend due to an upward trend in extreme rainfall in the middle reaches of the basin.
Seasonality analysis	*Bloschl et al. (2017)*	Entire Europe	(i) Sites: 4262 hydrometric stations from 38 European countries (ii) Period of analyses: 1960-2010 (iii) Data: Dates of occurrence of annual flood peaks (iv) Approach: Circular statistics, Theil-Sen slope estimator in a 10-year moving wimdow	(1) Earlier spring snowmelt floods throughout northeastern Europe (2) Late winter floods around the North Sea and some sectors of the Mediterranean coast (3) Earlier winter floods in Western Europe.
	Cunderlik and Ouarda (2009)	Canada	(i) Sites: 162 streamflow records from relatively pristine and stable land-use conditioned watersheds	(1) The snowmelt floods shifted toward the earlier times of the year.

			(i) Period of analyses: 1974 to 2003 (ii) Data: Dominant Seasonal floods were analyzed (iii) Approach: The Mann–Kendall test in conjunction with the method of pre-whitening was used in the trend analysis and Directional statistics was used for seasonality analysis	(2) No significant trends were found in the timing of the rainfall dominated flood events. (3) The magnitude of the floods has been decreasing over the last three decades.
Both trend and seasonality analysis	*Burn et al. (2010)*	Canada	(i) Sites: 68 streamflow gauging stations in Canada (ii) Period of analyses: A record length of at least 50 years (1957–2006) (iii) Data: Extreme hydrological events (both high and low flows) drawn from annual and spring events (iv) Approach: Trends were analyzed using the Mann–Kendall test. A bootstrap resamplings-based field significance test was used to determine the *regional* trend. Seasonality measures that characterize the timing and persistence of extreme hydrologic events were examined using directional statistics	(1) High flow events showed decreasing trends whereas low flow events showed both decreasing and increasing trends in flow magnitude. (2) Nival sites showed an earlier high flow occurrence and an earlier low flow occurrence. (3) Pluvial sites tend to experience a later annual maximum flow in the more recent part of the record.
	Burn et al. (2016)	Canada	(i) Sites: 132 gauging stations spread over Canada (ii) Period of analyses: Four periods ranging from 50 to 80 years (iii) Data: Peak over threshold flood (POTF) events (iv) Approach: Trend and Seasonality analysis were examined using the Mann–Kendall trend test and directional statistics respectively.	(1) There was an increased number of over threshold events. (2) There was increased importance of both rain on snow events and rainfall events and decreased importance of snowmelt events.

			(3) A transition of mixed flood regime to a more pluvial regime whereas nival catchments transition towards a more mixed response was observed.
Matti et al. (2017)	Scandinavia	(i) Sites: 59 catchments across Scandinavia (ii) Period of analyses: A record length of 54-122 years (1892–2014) (iii) Data: Seasonal maximum daily flows in a hydrological year (iv) Approach: Circular or directional statistics were used to assess flood seasonality and modified Mann–Kendall trend test was used for trend analysis	(1) Summer maximum daily flows showed a decreasing trend while winter and spring maximum daily flows showed an increasing trend (2) Snowmelt-dominated regime is shifting towards rainfall-dominated with consistent changes towards earlier flood peaks
Burn and Whitfield (2018)	Canada and the northern United States	(i) Sites: Hydrometric reference streamflow gauging stations at 27 natural watersheds (ii) Period of analyses: Past 100 years record span from 1916 to 2015 (iii) Data: Only POTF time series (iv) Approach: Circular statistics were used to explore changes in the nature of the flood regime, Mann-Kendall trend test was used for change detection, and block bootstrap resamplings was used to correct for serial correlation in the data	(1) All flood regime show an increased number of threshold exceeding events. (2) A shift in the nival flood regime to a mixed regime and mixed flood regime to a pluvial regime is noted.

Change Point Analysis	*Villarini et al. (2009)*	The continental United States	(i) Sites: 50 stream gauging stations (ii) Period of analyses: Varying length for different stations with at least 100 years record starting from 1838 (iii) Data: Annual maximum peak discharge. (iv) Approach: A nonparametric Pettitt test was performed to detect abrupt changes in mean and variance of peak flows	(1) 18 and 6 out of 50 stations exhibited a significant abrupt change in the mean and variance respectively. (2) Land use and land cover changes and gauge height variations have led to change points.
	Nka et al. (2015)	West Africa	(i) Sites: 11 catchments across West Africa (ii) Period of analyses: 1950-2010 (iii) Data: Annual maximum and POTF series (iv) Approach: The Pettitt test was used to identify change points in the data	(1) Most of the change points lie between 1950 and 2000 (2) Land use changes are the primary contributing factor for the change in flood magnitude.
In our study*	*This study*	Mahanadi River Basin, India	(i) Number of sites: 24 gauge stations (ii) Analyses period: varies between 1971 and 2016 (iii) Flood Event Samplings: Both Monsoon maximum flood (MMF) and POTF series (iv) Approach: (a) Trend Detection: revised Mann-Kendall trend statistics to analyze monotonic trends and Pettitt change-point statistics to identify abrupt shifts in the peak discharge time series. A field significance test was conducted to investigate the nature of the regional trend.	(1) POTF events showed increasing trend while MMF events showed a mixture of increasing and decreasing trends in the middle reach (2) Mean date of peak discharge for all the sites was found during August (3) Delayed floods at lower reaches of the Mahanadi River Basin

	(b) Seasonality analyses: using directional statistics. (c) Changes in flood timing: Adjusted Theil-Sen slope estimator with correction for circular data.	

*Contributions of the current paper is added for the completeness

Table S2. Percentages of gauges showing increasing (decreasing) trends; bold numbers indicate field significance at 10% significance level across MRB

Methods of Flood Sampling	**Region I**	**Region II**
MMF	33.3 **(66.7*)**	66.7 (33.3)
POTF	44.4 (55.6)	80 (20)

*For stations showing a downward trend in flood magnitude, we find $p_{fdr} = 0.016$ and $N = 1$, where p_{fdr} indicates p-value threshold that controls the FDR at $\alpha = 0.10$ significance level, and N denotes the number of sites with p-value < p_{fdr}. $N \geq 1$ indicates a regional trend is field significant.

Table S3. Details of dams at Region I in MRB

Name of dams	Nearest stream gauge	Year of construction	Type of dam	Length of the dam (m)	Maximum height above foundation (m)	Total volume content of dam (TCM)	Spillway capacity (cumec)
Lai	Manendragarh	2004	Earthen	518	16.5	374	35
Jagatpur	Manendragarh	2004	Earthen	180	18.9	191	34
Amakhokhra	Bamnidhi	1985	Earthen	744	10.8	57	34
Gobari	Bamnidhi	1976	Earthen	430	16.2	155	151