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# Dynamics of Vegetation Response to Seasonal Rainfall in the Gomati River Basin (India) using Earth Observation Data Sets

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***Abstract:*** **Present study evaluates the vegetation responses towards the rainfall variability in the Gomati basin during 1901-2015. To accomplish the same, high resolution observed daily gridded rainfall data from India Meteorological Department (IMD) was analysed using non-parametric trend test. The long-term rainfall showed significant decreasing trend (α=0.05) which varied from -0.96 to -4.89 per year. Identified trends in rainfall were then evaluated in tandem with the basin-wide changes in the vegetation signatures during the recent extreme years (two pairs of dry and wet years). Each pair of extreme years was assessed for its seasonal Normalised Difference Vegetation Index (NDVI) related to the seasonal rainfall variations with special emphasis to rice and wheat yields (major crops). Contribution of spatio-temporal occurrences of rainy days with that of the heavy rainfall events was also analysed. The findings suggest that the prevalent basin-wide long-term rainfall deficiency intensified during the extreme dry years e.g. 2002 and 2009 and impacted the health of vegetation in the basin. Vegetation of the basin was found closely related with rainfall variability; regular and well distributed occurrences of rainy days benefited the basin's vegetation as well as the yields of rice and wheat crops.**

***Index Terms:*** **Crop yield, Extreme weather events, NDVI, Rainfall variability, Gomati River Basin**

## I. Introduction

River basins are the most commonly used spatial units taken up to comprehend as well as to assess the impact of the changing climate on the water resources (Mishra and Lilhare et al. 2016; Cui et al. 2017; Deng et al. 2018). Intensification of the hydrological cycle in terms of its enhanced capacity to withhold considerably large amount of moisture in its atmospheric component has already disturbed the rainfall pattern over India in particular and around the world in general (Mall et al. 2006; Harding et al. 2013). This disturbance has negotiated itself in the form of alterations in various water balance parameters, be it altered runoff or be it altered potential evapotranspiration. Thus, the occurrences of basin wide hydro-meteorological events like extreme wetness (rainfall), extreme dryness (drought) or decrease in the revisit periods of frequent dry years intermittent with wet years have disrupted the basin hydrology worldwide (Awange et al. 2014; Gebre and Getahun 2016; Oguntunde et al. 2017; Pandey and Khare 2018). The association between the rain fed crop yield e.g. rice and the climate variability especially, the rainfall variability on a basin scale have not been explored much. However, many studies were focussed at the level of country and state (Kang et al. 2009; Mishra et al. 2013; Guan et al. 2015; Reda et al. 2015; Dhekale et al. 2017; Dubey and Sharma 2018; Prabnakorn et al. 2018; Bhatt et al. 2019). So, with the rising uncertainty in the rainfall variability across the Gangetic basin, it becomes important to take up the impact studies on crop yield at sub-basin scale to comprehend the regional influence of climate on agriculture. Rainfall and yields have been found to correlate with to each other; variability in rainfall resulted in yield variability (Kumar et al. 2004; Mall et al. 2006; Rowhani et al. 2011; Prasanna 2014). Therefore, an assessment of crop yield is determined by seasonal rainfall (dryness and wetness) over a site or in a region. Satellite derived Normalized Difference Vegetation Index (NDVI) is a very popular and efficient tool to validate such rainfall influenced crop yield studies (Quarmby et al. 1993; Kamthonkiat et al. 2005; Upadhyay et al. 2008; Son et al. 2013; Dutta et al. 2015; Pang et al. 2016; Prabnakorn et al. 2018). Gomti river basin in Ganga plains is the area of present study and there have been several studies dealing with its geological, geochemical, morphometry, geomorphology and water quality (physico-chemical analysis) aspects (Gupta and Subramanian 1994 & 1998; Singh et al. 2004 & 2005; Sarkar et al., 2010; Singh and Tandon, 2010; Srivastava et al., 2010 & 2011; Kumar et al., 2013; Jigyasu et al. 2015; Trivedi et al. 2016; Prakash et al. 2017). Environmental isotopes, e.g. δ18O and δD, were employed in a study by Singh et al. (2013) to explore and understand the impact of monsoon on the hydrological processes through an analysis of the isotopically depleted peaks corresponding to river discharge taken as proxy of the isotopic signature of the monsoon rainfall. Mishra et al. (2015) demarcated salt affected area using remote sensing techniques (using IRS LISS-III data) and it was found that the salt affected area is dominant along the right bank of the river. Dutta et al. (2018) stated that the environmental flow in Gomati river ecosystem is not up to mark and suggested some measures to restore it back.

Gomti river basin has attracted a number of government initiatives and programmes for improvement of its water quality as well as for saving its riverine flora and fauna. Gomati basin has a distinction of large agricultural contribution to the state of Uttar Pradesh (Mali et al. 2015). Quite a number of researchers have focused on how the cultivation of less water-intensive crops in the basin could help augment various conservation strategies to bring up the falling levels of water in the river. The basin has recently been studied for its virtual water content and various categories of water-footprint (Mali et al. 2015; 2017; 2018). Blue water foot-print of the basin was found to be 47.3% indicating considerable dependency of irrigation on basin water resources (Mali et al. 2018). The Gomati basin has been less studied on its hydro-meteorological aspects and that of Abeysingha et al. (2014) is the first attempt. Subsequently, they (op. cit.) have also taken up climate change scenario influenced hydrological model based simulation studies. They (op. cit.) estimated variation in the stream-flows in the mid and end centuries. According to Abeysingha et al. (2018), the basin is projected to witness increase in its runoff. The present study is an attempt to work out how extreme rainfall events influenced seasonal vegetation dynamics (crop yield) in the Gomati river basin (India). It is a study of response analysis of remotely sensed vegetation in the basin to the variability and trend in rainfall pattern. It covers agricultural land uses and also the natural vegetation along with plantations. Finally, the main objective of this study boils down to examine the relation between the long-term climate variability with the NDVI. Also nature of rainfall extreme events was studied in relation to rice and wheat crop yields to assess the impact of wet and dry events.

## II. STUDY AREA

The Gomati river basin is one of important sub-basins of the Ganga river basin (nearly 3.53% of total area of the Ganga basin, i.e. 30997.94 sq. km.) and drains (either partially or fully) eighteen districts of the state of Uttar Pradesh (12% of total area of the state) it joins the Ganga river at Kaithi in Jaunpur district (Rai et al. 2009; Dutta et al. 2015) (Fig. 1). The elevation gradient across the basin varies from 57 to 227 metre. The river has ten tributaries but Kathna, Saranyan, Sai and Kalyani are the major tributaries among them. Climate of the basin varies from semi-arid to sub-humid tropical in nature characterised by annual rainfall varying between 850mm to 1100mm and mean temperature ranging between minimum of 5ºC in winter to maximum of 45ºC in summer (Rai et al. 2009; Singh et al. 2013; Abeysingha et al. 2014). Several types of crops are grown in the districts within the basin rice, wheat, sugarcane, maize, pearl millet, gram (both red and black), lentil (masoor), pigeon pea, barley, mustard and potato are some of them to name. The source of irrigation is largely through bore wells and canals. Cropping intensity of these crops in the basin varied from 110 to 196.9%. Production-wise rice, wheat and sugarcane hold greater importance. Rice crop sown area out of total area is dependent on rainfall. Maize is more dependent on rain fed irrigation as per District Contingency Plans NICRA-ICAR (Rao et al. 2015; Rao et al. 2017). Major kharif crops are rice, jowar, maize and rabi crops are wheat, mustard etc. Kharif crops are concentrated in the central region and rabi crops are grown in the lower region of the basin (Mali et al. 2018). The total rice and wheat production in the basin (all districts put together) is approximately 4271tons and 7610 tons respectively as per NICRA-ICAR.

## III. MATERIALS AND METHODS

### *A. Data Used*

The daily observed IMD rainfall data of 0.25 X 0.25 degree resolution was considered for long-term (1901 to 2015) trend analysis. Also, the Tropical Rainfall Measuring Mission (TRMM), a joint mission of NASA and the Japan Aerospace Exploration Agency (JAXA) gridded datasets were used to compare and validate the rainfall data of IMD from 1997 to 2017 at 0.25 degree spatial resolution. The level three data product of TRMM-3B42 was used based on multi-satellite precipitation analysis with grid over the latitude band 50 N–S Apart from that, district-wise crop yield data (1998-2015) was taken for rice and wheat crops from the Ministry of Agriculture, Govt. of India. In addition, NDVI is worked out using SPOT-VGT data (1 km. resolution) and was used to validate crop and vegetation dynamics. The importance of vegetation indices assessing any region's overall status of crop growth have proven very helpful and can be relied upon to recognise the responses of crops to various regulatory phenomenon like hydro-meteorological parameters apart from the core meteorological drivers e.g. rainfall (Milesi et al. 2010; Zhang et al. 2017).

### *B. Comparison and Determination of Rainfall Data*

According to Kothwale and Rajeevan (2017), the years 2002 and 2009 were recorded as dry years and 2008 and 2013 as wet years for the central north-east region, one of the six homogenous monsoon regions of India, While year 2013 was all

India wet year with an 11% excess than long-term mean rainfall of the country but for central north-east region that year was a normal year. These extreme years (2002, 2008, 2009, 2013) were validated with rainfall dataset from TRMM for the basin vis-à-vis the observed climate variability of IMD data. These extreme years were scrutinised for their possible impacts on the yield anomalies for kharif and rabi crops of rice and wheat.

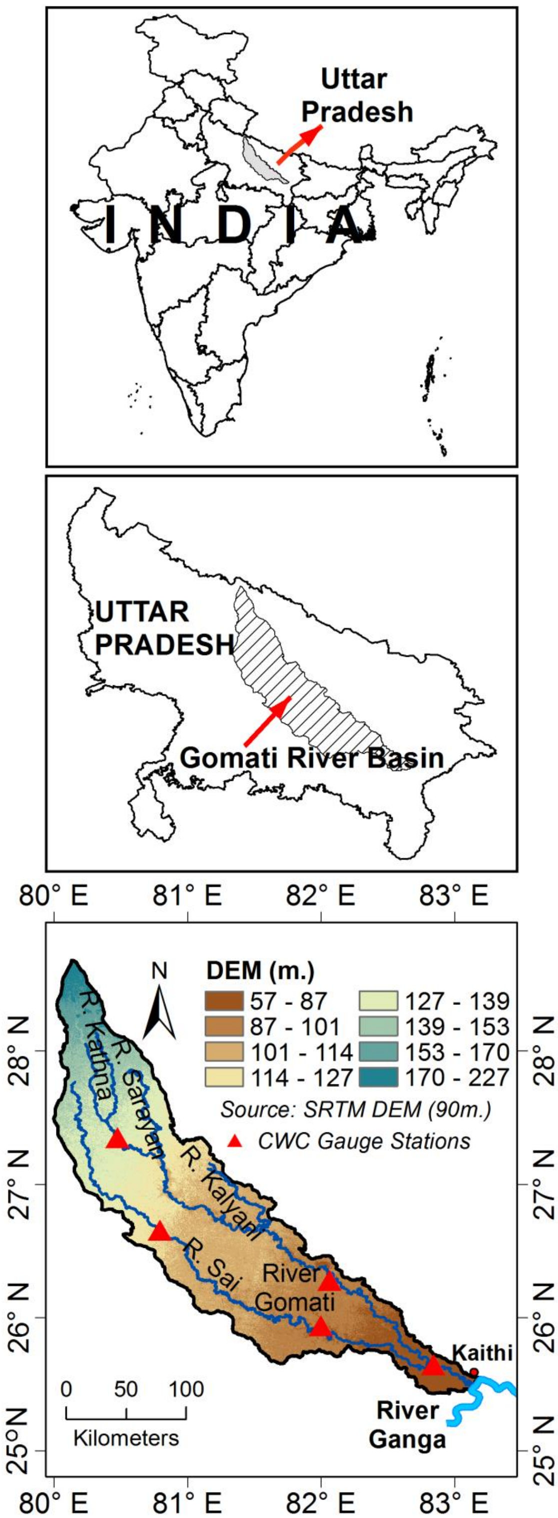

Fig. 1 Location map of the Gomati River Basin

*C. Rainfall Trend analysis using Modified Mann-Kendall (MMK) trend test*

Modified Mann-Kendall test is a popular tool to determine the long-term trend, recommended by the World Meteorological Organisation (WMO) and to analyse time-series data such as agricultural, meteorological, hydrological and so on. Basically, it is a rank based non-parametric test tool that assumes that the time series is serially uncorrelated whereas, the climate and hydrological data are serially correlated or auto correlated as well as non-normally distributed (Hamed and Rao 1998; Yue and Pilon 2004; Blain 2013). Therefore, to make the test function properly on such a time series removal of auto-correlation is preferred and is commonly done using pre-whitening (PW), Trend Free Pre-whitening (TFPW) and Modified Mann-Kendall (MMK) tests. These methods result in the removal of serial correlation through variance correction in the form of considered effective sample size (Taxak et al. 2014). Longobardi and Villani (2010) used the test to identify the trend in the 82 years long precipitation time series of the southern Italy. They found -35mm/10 years trend that had prevailed during the study period leading to decreased amount of precipitation. Mondal et al. (2012) speculated rainfall trend of Cuttack district using modified Mann-Kendall (MMK) test. A study by Chakraborty et al. (2013) on spatio-temporal rainfall variability of the Seonath sub-basin in Chhattisgarh, India also used MMK trend test. The test observed annual and seasonal decreasing rainfall trend in the basin they (op. cit.) also went on to identify the change point into the time series. Long term historic changes in the climatic variables of the Betwa basin was studied with the help of MMK test by Suryavanshi et al. (2014) which gave mixed results. Some stations in the basin observed decreasing rainfall and increasing trend for all stations in minimum temperature whereas, winter season witnessed increasing trend both in maximum and minimum temperature (op. cit.). Trend of various climatic parameters like rainfall, temperature, wind speed, relative humidity was analysed for whole of the state of Rajasthan (Kundu et al. 2015). Luo et al. (2016) undertook the annual trend analysis in water yield using Mann-Kendall test. All of these studies mark the efficiency of MMK test in climate variable trend analysis.

The Mann-Kendall test, formulated by Mann (1945) and Kendall (1975), statistic S is given in equation (1):

$$S = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} sgn\,(xj - xi) \qquad (1)$$

Where, S is Mann-Kendall statistic and *sgn* is the signum function. The application of trend test is done to a time series xi that is ranked from i = 1, 2,.........n-1 and xj and which is ranked from j = i+1, 2,..........n. For n < 10, then value of |S| is compared directly to the theoretical distribution of S derived by Mann and Kendall.

The variance statistic is given in equation (2):

$$\text{Var}(S) = [n(n-1)(2n+5) - \sum_{i=1}^{m} t(i)(i-1)(2i+5)]/18 \quad (2)$$

Where, t is considered as the number of tie ups to sample i.

The Z test statistics is given by equation (3):

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} \; if S > 0 \\ 0 \; if S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} \; if S < 0 \end{cases} \quad (3)$$

A positive value of Z indicates an increasing trend and negative value indicates decreasing trend. It is normally distributed.

*1) Sen's Slope Estimation.*

It is a non-parametric procedure to estimate slope of trend in a time series. For sample size of N, the slope (Q) is given by equation (4):

$$Q = (xj-xi)/((j-k)) \quad i=1, 2, \ldots, N \quad (4)$$

Where xj and xk are the data values at times j and k (j>k) respectively (Sen 1968).

*D. Long- term Rainfall Variability Considering both Rainy days and Rainfall Extremes*

The long-term rainfall variability was assessed with the help of MMK trend test. The long-term rainfall variability was further explored in terms of its number of rainy days (as per IMD a day with more than equal to 2.5mm. rainfall is said to be a 'rainy day') and various categories of extremes events (Table S1). Concentration of rainy days was also studied for rabi and kharif seasons. The occurrences of various categories of rainfall extremes, especially, the extremes events above 90$^{th}$ percentile, above 95$^{th}$ percentile and above 99$^{th}$ percentile were estimated for the extreme years selected for the study.

## IV. RESULTS

*A. Long-term Trend Analysis*

The long-term rainfall trend was analysed using the observed gridded daily IMD data. Overview of the linear trend analysis of eighteen districts falling within the basin points to a dominantly decreasing trend. On the contrary, Sitapur (Figure 2o), followed by Kheri (Figure 2i) and Jaunpur (Figure 2h) had shown positive trends though just very meager. The linear trends were further analyzed through time series test.

Table 1. Modified Mann-Kendall and Sen's slope test results for annual rainfall in the Gomati basin (1901-2015)

| Districts | Corrected Zc | P-value | Sen's slope | Variance |
|---|---|---|---|---|
| Allahabad | -2.46 | 0.01 | -1.72 | 171158.33 |
| Azamgarh | -3.65 | 0.00 | -2.72 | 141381.04 |
| Barabanki | -1.11 | 0.27 | -0.71 | 138231.13 |
| Chandauli | -4.89 | 0.00 | -1.68 | 45250.79 |
| Faizabad | -3.25 | 0.00 | -3.17 | 225280.87 |
| Ghazipur | -3.47 | 0.00 | -3.63 | 370993.03 |
| Hardoi | -1.75 | 0.08* | -1.23 | 166884.01 |
| Jaunpur | 0.24 | 0.81 | 0.13 | 239790.54 |
| Kheri | 0.69 | 0.49 | 0.62 | 171158.33 |
| Lucknow | -1.75 | 0.08* | -1.55 | 171158.33 |
| Pilibhit | -2.71 | 0.01 | -3.78 | 313821.73 |
| Pratapgarh | -3.19 | 0.00 | -2.53 | 169948.60 |
| Rae Bareli | -0.96 | 0.34 | -0.62 | 109331.68 |
| Shahajanpur | -0.96 | 0.34 | -0.62 | 109331.68 |
| Sitapur | -1.71 | 0.09* | -1.56 | 239565.91 |
| Sultanpur | -1.71 | 0.09* | -1.56 | 239565.91 |
| Unnao | -1.71 | 0.09* | -1.56 | 239565.91 |
| Varanasi | -2.47 | 0.01 | -2.33 | 224426.55 |

*****Value is significant at significance level alpha= 0.05

The Modified Mann-Kendall trend test was applied on 115 years' of rainfall which identified a decreasing trend (from -0.96 to -4.89). Both the Zc and Sen's Slope values on removal of serial correlation resulted mostly (16 out of 18 districts of the basin) into negative estimates which indicated towards decreasing trend in the long-term rainfall (Table 1). As a result, Jaunpur and Kheri were the only two districts for which the Zc statistic of the modified Mann-Kendall (MMK) test brought in a positive (0.24 and 0.69) trend.

These estimated increasing trends were not found to be significant as the corresponding p-values were higher than the significance level (alpha) set at 0.05 leading to acceptance of the null hypothesis (H0) which assumes that there is no trend in the subjected time series. Though the long-term rainfall anomaly across the basin measured seven districts with positive rainfall anomaly yet the MMK test could only detect two instances of increasing (positive) trend with none of them being significant (discussed later in section 4.2.). Hence, the outcome of the MMK test for the basin confirmed that it is rather a deficit with respect to long-term rainfall trend. Validation on the estimates of MMK test for the basin using the satellite datasets affirming the robustness of its estimated statistics for the time series analysis of rainfall is presented in the following sections.

*B. Validation by IMD Rainfall Data*

In the past decades since 1901, India has witnessed many meteorological extreme events as per various IMD assigned categories; out of these events representative events of 2002 (dry year), 2008 (wet year), 2009 (dry year) and 2013 (wet year) of recent occurrences were selected for validation purpose with TRMM. Figure 2 (a, b & c of the bottom panel) clearly indicates that TRMM dataset is more pronounced when compared with rainfall dataset from IMD. Zc, Sen's Slope and Tau values of TRMM are larger than that of IMD for the same duration (1998-2015) except for Jaunpur (Maighat) and Pratapgarh stations where the IMD is more pronounced (Fig. 3).

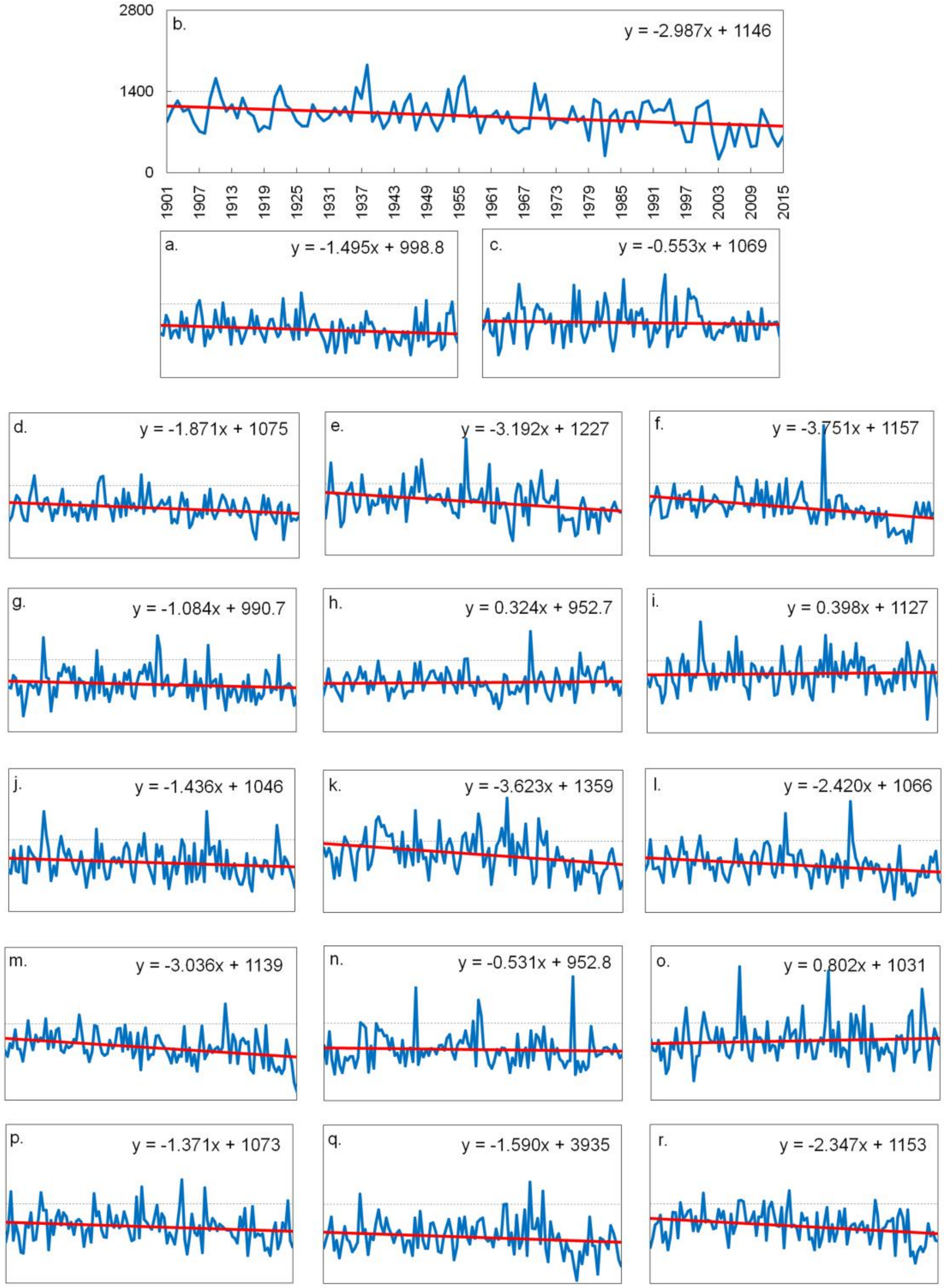


Fig. 2 Linear trends long-term (1901-2015) rainfall (in mm. on the primary axis) for all the districts falling in to the basin [a. Allahabad, b. Azamgarh, c. Barabanki, d. Chandauli, e. Faizabad, f. Ghazipur, g. Hardoi, h. Juanpur, i. Kheri, j. Lucknow, k. Pilibhit, l. Pratapgarh, m. Rae Bareli, n. Shahjahanpur, o. Sitapur, p. Sultanpur, q. Unnao, r. Varanasi].

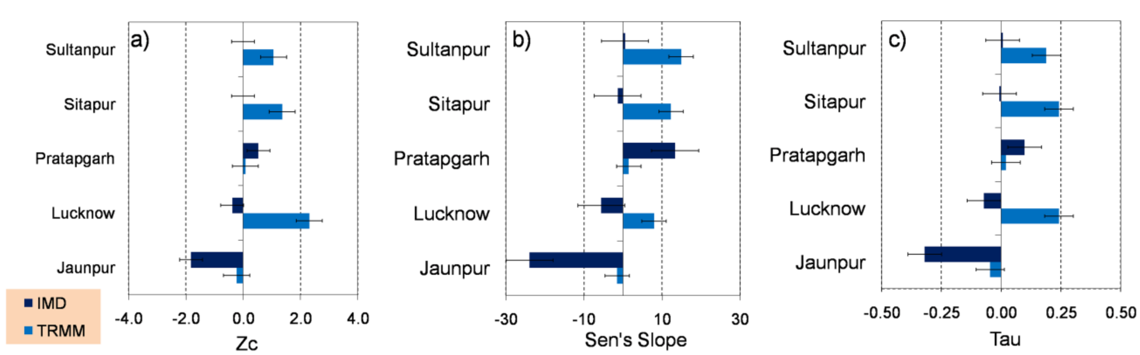


Fig. 3 Comparison of rainfall datasets of IMD with TRMM in terms of various MMK test estimates for the period of 1998 to 2015 in the Gomati basin.

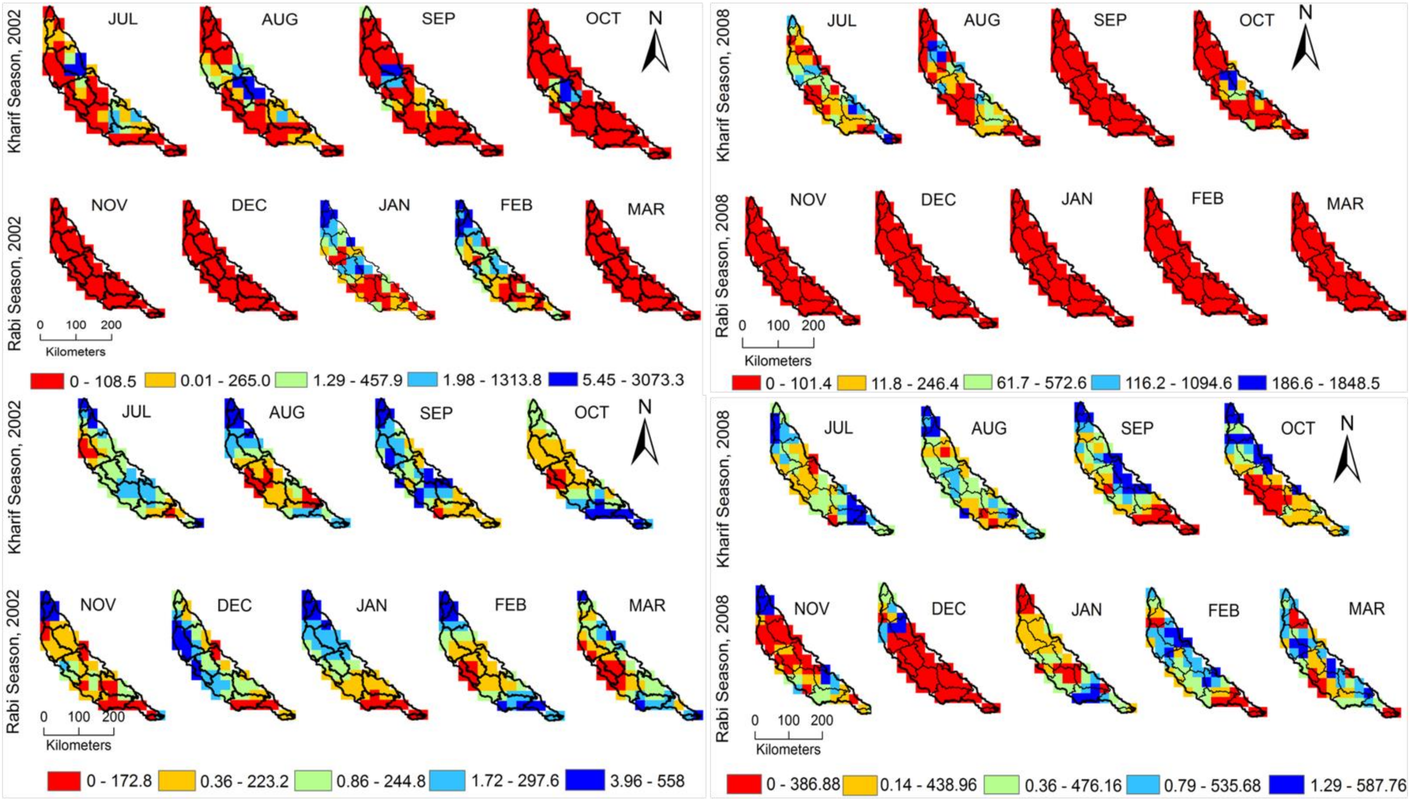


Fig. 4 Spatial pattern of rainfall of IMD (upper panel) and TRMM (lower panel) datasets for 2002 (dry year) and 2008 (wet year) [kharif and rabi season]

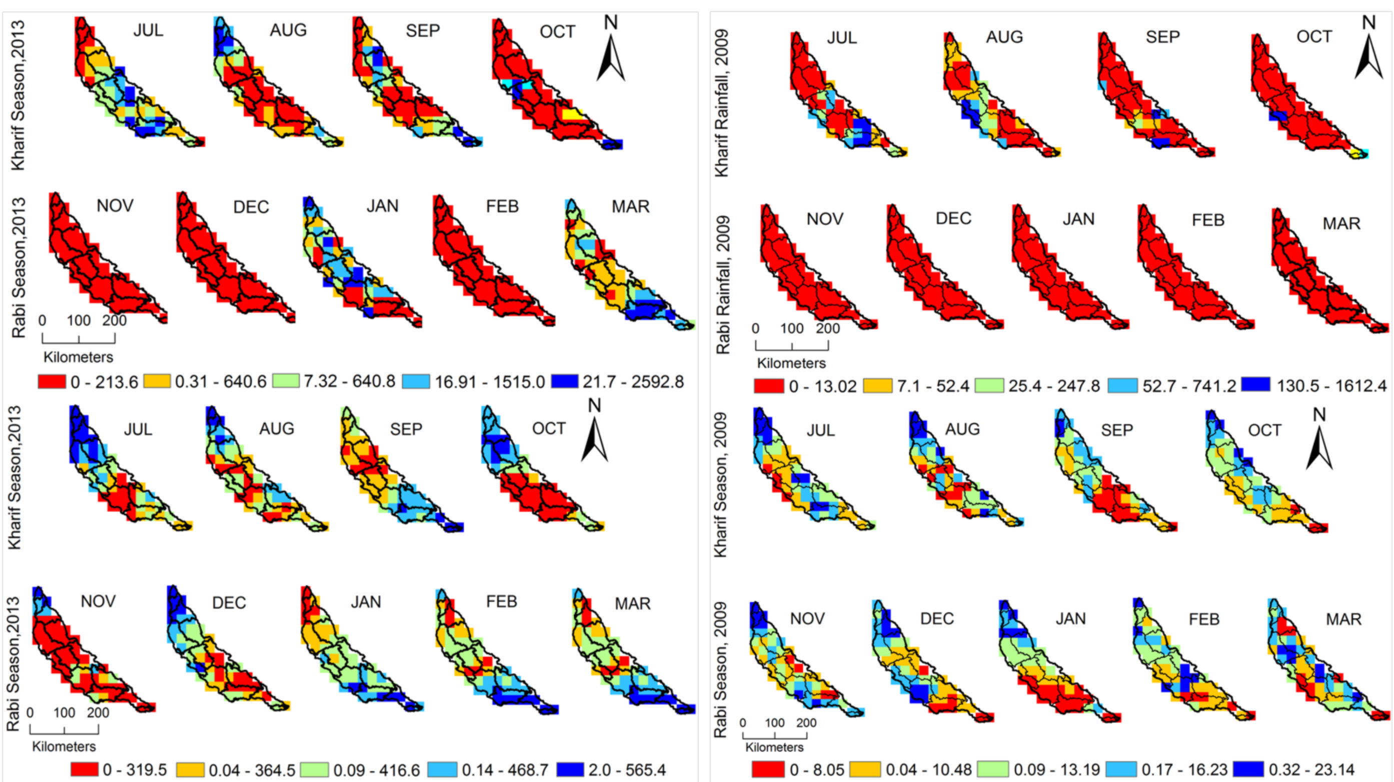


Fig. 5 Spatial pattern of rainfall of IMD (upper panel) and TRMM (lower panel) datasets for 2009(dry year) and 2013(wet year) [kharif and rabi season]

The TRMM data was considered for validation purpose owing to its accuracy and consistency of records as well as its suitability being a data set that has recently been in use for wide range of research from meteorological drought identification to hydrological modelling to agricultural studies (Cao et al. 2018) (Fig. 3). At Jaunpur, both IMD and TRMM are consistent with each other; however, the differences between test derived sets of estimates for the two data sets are considerably large but that may be a factor arising because of short time period of TRMM time series. Lucknow and Sitapur gauging stations show opposite results of validation whereas, the large differences between the sets of test estimates again demands for longer dataset used for such tests. Considerably negative trends for these stations were confirmed through the MMK test conducted for IMD's dataset (Table 1).

The validation was carried out for the gauging sites at Bani, Maighat, Neemsar, Pratapgarh and Sultanpur under the Central Water Commission, Govt. of India. As illustrated in Figure 3, monthly records of the gauge stations have shown a better consistency corresponding to TRMM datasets. IMD rainfall datasets for years 2002, 2008, 2009 and 2013 were further compared with TRMM dataset for both kharif (July to October) and rabi (October to March) seasons respectively. The basin holds a large share of agricultural land as the dominant land type which includes rain fed crop land too (Abeysingha et al. 2015). The kharif and rabi seasons were thus chosen for impact analysis of rainfall variability on seasonal yields. All kharif season months received higher rainfall for the wet years 2008 and 2013 whereas, during the dry years 2002 and 2009 the same months received notably less rainfall. The total monthly rainfall during each month of kharif season from TRMM datasets were more consistent when compared with that from the IMD datasets. Nevertheless, estimates of both of the datasets were in agreement with each other for all the gauging stations along the Gomati River.

Figures 4 and 5 bring out the fact that IMD data portrays the basin to be markedly deficit when compared to TRMM records. Both sets of deficit and wet years i.e. 2002-2008 and 2009-2013 when assessed for kharif season with that of IMD data indicate towards an alarmingly dry season except that in year 2013. Whereas, when rabi season was considered, except for 2002 and 2013, IMD data indicated that the basin received exceptionally scanty rainfall in the season. In case of TRMM data of kharif and rabi seasons, both the sets of deficit and wet years had reasonable distribution of rainfall. However, in case of IMD data the rabi seasons of 2008 as well as 2013, despite both being wet years, recorded as rather unusually dry. The months of from November to next year's March of 2008 and November, December and February of 2013 received really scanty rainfall. Rabi season rainfall of 2008 was lower than that of 2013. However, year given 2008 stood out as the wettest year of the decade 2000-2010 for the whole country (Figs. 4 and 5).

*C. Distribution of Rainfall Extremes*

The distribution of various categories i.e. 90th, 95thand 99th (Table 2) of rainfall percentiles (90th representing the moderate, 95th heavy and 99th very heavy rainfall events respectively) calculated for the basin corresponding to the extreme years indicates that the intensity of particular type of rainfall event dominated the wet and dry years (Dave and James 2017). Though overall the dry years 2002 and 2009 recorded poor attendance of all the three rainfall percentiles yet it was the 90th percentile that was estimated the least in these years. The 95th percentiles were comparatively were greater in the basin when compared to the occurrences of the 90th percentiles. The wet years, 2008 and 2013, received higher rainfall extremes (99th percentiles) with 2008 also marked by considerable presence of 95th percentiles (Fig. 6).

The rainy days were also found to be in agreement with wet and dry conditions that prevailed over the extreme years. 2008 and 2013 were 64.2% and 72.2% wetter than 2002 and 2009 respectively (Fig. 6 & 7).

**Table 2.** Intensity of rainfall events (in 24 hours)

| Sl. No. | Rainfall Event | Range (mm.) | Percentiles |
|---|---|---|---|
| 1. | Moderate | 15.6 - 64.4 | 65-95 |
| 2. | Heavy | 64.5 - 115.5 | 95-99 |
| 3. | Very Heavy | 115.6 - 204.4 | 99.0-99.9 |

(Modified from Dave and James, 2017)

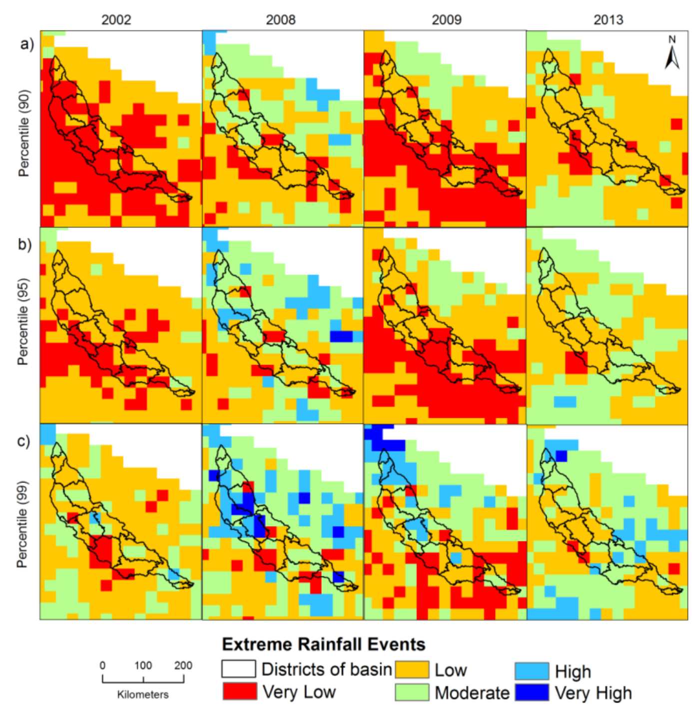


Fig. 6 Distribution of rainfall extreme events of various categories during the dry years (2002 and 2009) and wet years (2008 and 2103)

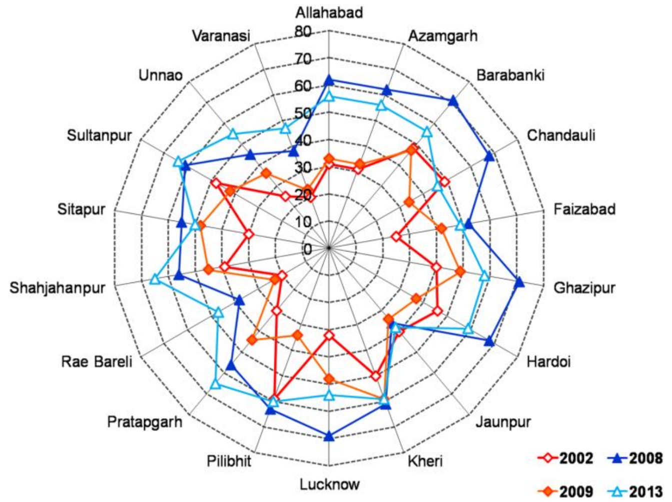

Fig. 7 Concentration of Rainy Days across the districts of Gomati Basin during the extreme years

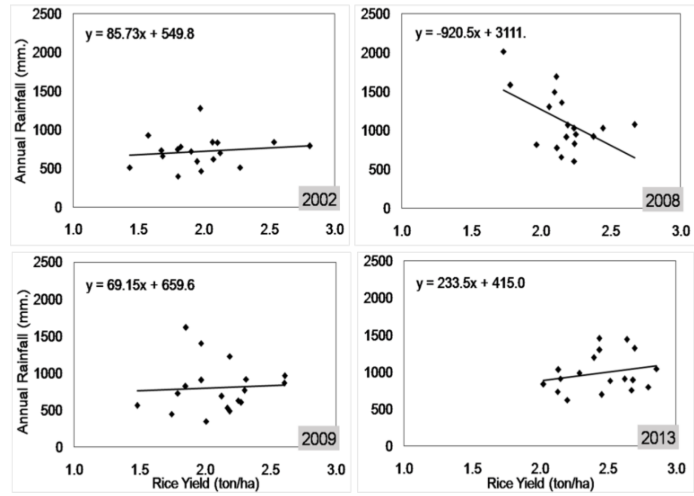

Fig.9 Correlation between annual rainfall (IMD) and rice yield for the study region

However, the year 2008 was dominated by the highest number of rainy days. So, even though when the extreme rainfall events were not much in number yet due to higher (lower) number rainy days in regular (irregular) frequency; the extreme years got characterized into wet (dry) years. Moreover, 2013 was typically wet due to the occurrences of a good number of rainy days in the month of October (Fig. 7).

*D. Impact of Rainfall Variability on Vegetation Cover*

In this study, district-wise SPOT-VGT mean NDVI values of kharif season were correlated with rice (kharif crop) yield. Changes in NDVI of crop cover, the role of rainfall has been well recognised as the key climatic parameter (Yang et al. 2016; Guan et al. 2018; Han et al. 2019). Nevertheless, the NDVI values showed superior correlation with yield in the extreme years i.e. 2002, 2008, 2009 and 2013 across the basin and the correlation of rice yield (ton/ha) and annual IMD based rainfall for extreme years were not that considerable (Figs. 8 & 9).

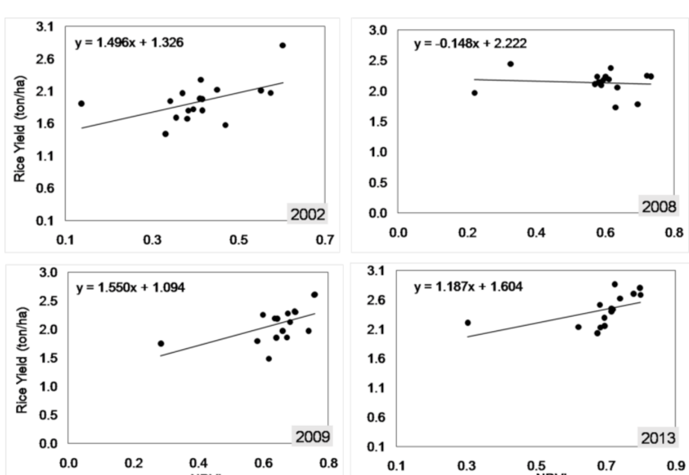

Fig. 8 Correlation between rice yield and NDVI for the study region

It was found to have a considerably negative correlation for the wet year 2008; 2008 holds the record of being wettest year since 2000 in the whole of Central North East monsoonal sub-division of India. Surprisingly, the kharif season (July to September) NDVI across the basin for the extreme years was in general was found to be higher in the wet years i.e. 2008 (variable between 0.33 to 1.0) and 2013 (variable between 0 to 1.0) as compared to that in the dry years i.e. 2002 (variable between0 to 0.94) and 2009 (variable between 0 to 0.97) (Fig. 10).

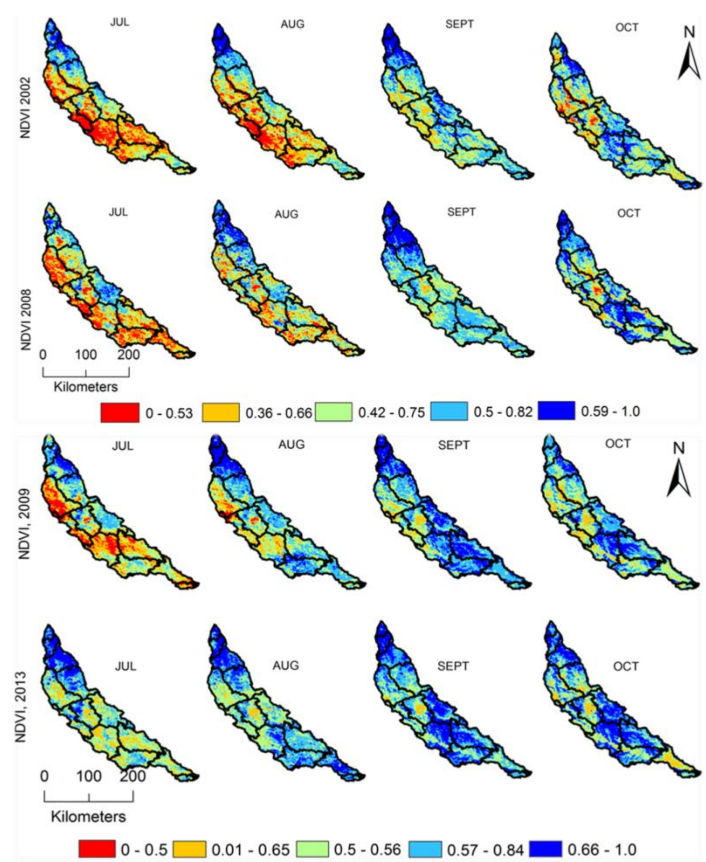

Fig. 10 Spatial pattern of NDVI for the extreme years 2002(dry) - 2008(wet) and 2009(dry) - 2013(wet)

## V. DISCUSSION

To confirm the variation in the kharif season NDVI values (the season for rice crop cultivation dominantly), district-wise average annual rice yield was also cross checked with respect to dry and wet years. All the districts put together and the district-wise estimates of rice yields across basin could not even reach up to 40 tons per hectare. Even during wet years (2008 and 2013), it hardly reached up to 45 tons per hectare (Figure 11a). Similarly, when wheat yields in region were compared they did soar up to 40 tons per hectare even in dry years and during wet years they were beyond the 50 tons per hectare yield estimate (Fig. 11b). The reason behind the difference in yields of two crops might be the occurrences of extreme rainfall events as they are generally higher during monsoons which coincide with the kharif season. Lately a study on adverse impact of climate change on the rain-fed rice cultivation predicted that the Northern and Eastern India would develop significant vulnerability towards intense rainfall events as far as rice is concerned (Singh et al. 2017). A moderate amount of rainfall is beneficial for growth of rice crop but heavy rainfall near the end of cropping season i.e. August or September is mostly destructive for rice yield (Ravedkar and Preethi 2012). Therefore, when during the dry years (2002 and 2009) rainfall had been scanty, the basin-wide effect was also clearly visible in

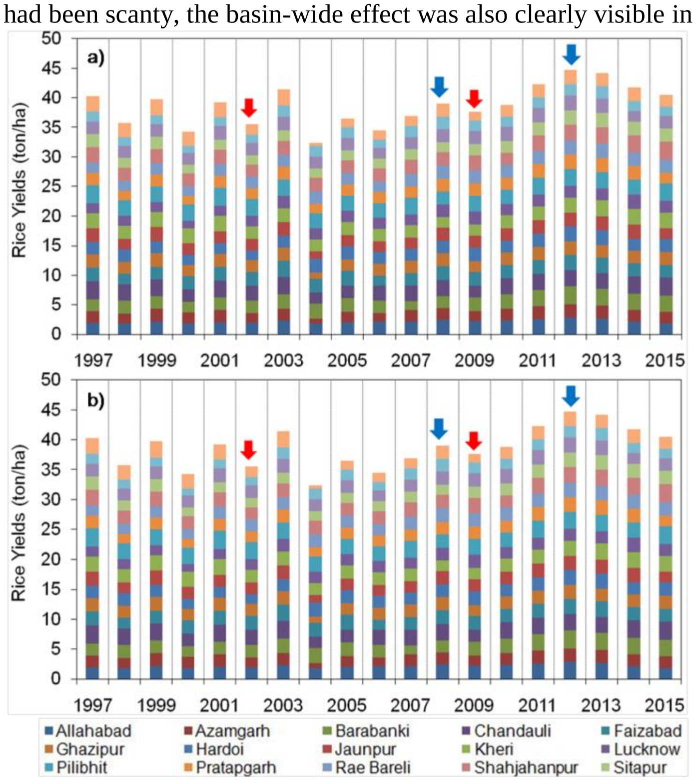


Fig. 11 District-wise (a) rice and wheat (b) yields during the dry (red arrow) and wet (blue arrow) years (Based on: DACNET, Govt. of India)

rice yields. Nevertheless, the overall wheat yield of the basin was better than that of the rice crops. The wheat being the irrigation dependant crop was less affected by deficit in rainfall. The reduced yields of rice were reflected in the form of poor NDVI values observed in the kharif months of the dry years. The vegetation has also been found to be directly correlated with increase in monsoon rainfall in a study that Kundu et al. (2016) conducted for North-West India. A greening tendency was confirmed for six rainfall datasets which also included the TRMM data for a period from 2000 to 2016 due the enhanced soil moisture conditions favouring the vegetation growth (vegetation indices varied from 0.4 to 0.8) (Jin and Wang, 2018). The dry years 2002 and 2009 were marked by lower vegetation health index during months of July and August (Fig. 10). As per wet years (2008 and 2013), the vegetation was healthier in 2013 than it was in 2008. Year 2008 was all India flood year and in the Gomati region the analysis into the rainfall extremes of the same year (the section on distribution rainfall extremes) endorsed a rather larger occurrence of heavy rainfall extremes (90 and 99 percentiles) when compared with the year 2013 (Fig. 6). Wet year 2013 was rather wet due to fewer rainfall extremes under all the three categories (90, 95 and 99 percentiles) but along with sufficient and evenly distributed rainy days from July to October (Fig. 6 & Fig. 7). Looking into the rice yields in various districts of the basin, it can be said that the influence of higher heavy rainfall events had adversely affected the yield (Fig. 9). The basin observed satisfactory rice yield in 2013 due to the considerable occurrence of rainy days throughout the cropping season.

The long-term rainfall trend over the Gomati basin was confirmed to be decreasing with the low Zc value ranging from -4.89 to -0.96. The lower basin reflects grimmer picture of dry condition than the upper basin. Even validation of TRMM data using the IMD data underscored the fact that variation in rainfall trend is rather negative (decreasing) in nature when IMD dataset is considered. Furthermore, the extreme years established a significant correlation among rainfall variability, occurrences of rainfall extremes as well as rainy days and vegetation cover dynamics over the basin. The vegetation cover including the crop cover was found healthy (1) in correspondence to wet years whereas, it was poor (0) for the dry years respectively.

## CONCLUSION

As sixteen out of eighteen districts witnessed negative rainfall trend over a long span of 115 years, the consistently prevailing deficient conditions in the Gomati river basin are an obvious assertion of going towards a general dry condition. Therefore, to sustain crops dependant on rainfall in this basin, augmentation of robust irrigation facilities to supplement the crop water requirement is the need of the hour. Except for Pilibhit, Shahjahanpur, Kheri, Sitapur and some parts of Barabanki districts (constituting largely the Northern part of the basin) all the other districts had very low NDVI in the dry years. Since 2000 the Central Northeast Monsoon region of India has very frequently been witnessing annual deficits (7 out of 17 years) (Kothawale and Rajeevan 2017) and as the Gomati Basin falls within in this region it becomes much too necessary to support the basin's agriculture in terms of timely irrigation and drought tolerant varieties.

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