# Spatio-temporal analysis of drought and aridity in Gomti basin

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*This study analyses the drought events for the Gomti basin in Uttar Pradesh (UP), India using the standardized precipitation index (SPI) at the spatial and temporal scales. Daily precipitation data for 14 districts in the Gomti basin for 41 years (1971–2011) were used to calculate the SPI for 1-month, 4-month, 6-month and 12-month time scales. Results for the 6-month (June–November) and 12-month time scales were similar and drought years were observed in 1972, 1979, 1987, 1993, 1994, 2002 and 2010. The 4-month SPI was analysed for the main monsoon months in the Gomti basin, i.e. from June to September. Results showed that significant drought occurred during the monsoon months of 1979, 1987, 1993, 2002, 2009 and 2010. For drought analysis at the spatial scale, the Kriging interpolation method available in ArcMap was used. The 12-month SPI showed that the frequency of severe and extreme drought was more in the upper regions of the basin during 1971–2000 whereas drought frequency was more in the central and lower regions of the basin during 2001–2011. Further, the de Martonne aridity index was calculated for the period 1971–2007 and its correlation with the 1-month SPI for the period 1971–2007 was evaluated.*

**Keywords:** de Martonne aridity index, Gomti basin, Kriging interpolation, spatial and temporal drought analysis, standardized precipitation index.

AGRICULTURE is one of the main sources of livelihood in Uttar Pradesh, contributing a large share to the state's output[1]. Farming operations depend heavily on rainfall and when precipitation amounts are inadequate, irrigation plays a crucial role in determining crop yields. The Gomti river basin in UP has a predominantly agrarian economy with 80% of crops being grown under full or supplementary irrigation[2]. Drought and aridity are important parameters that assist in estimating the irrigation demand.

Drought is a natural hazard that has significant negative impacts on the environment, agriculture and socio-economic conditions of the people. Drought is the manifestation of a long spell of deficit in precipitation. Depending on the approach used to measure drought, it can be classified as meteorological drought, hydrological drought, agricultural drought and socio-economic drought[3]. The India Meteorological Department declares a drought year for the country based on the deficit of rainfall. When the rainfall deficiency is more than 10% in 20–40% of the country, then IMD terms that year as All India Drought Year (now termed 'Deficient Year'). When the spatial coverage of drought is more than 40% then IMD declares it as All India Severe Drought Year (now termed 'Large Deficient Year')[4,5]. A number of drought indices have been developed and used by scientists around the world[6]. Of these, the standardized precipitation index (SPI) is most commonly used to quantify precipitation deficit. McKee *et al.*[7] developed the SPI for classification of drought in a region. This classification has been accepted internationally to define meteorological drought. The World Meteorological Organization uses the same criteria to define drought. SPI can be determined using rainfall data alone at variable timescales (1-month, 3-month, 6-month, 9-month, 12-month and 24-month).

The SPI makes drought assessment easier and has a wide range of meteorological, hydrological and agricultural applications[8]. Mishra and Desai[9] studied the frequency of drought occurrence in the Kansabati river basin using SPI and reported severe drought during the 1980s. Frequency of droughts for the period 1951–2007 in the Hunan Province in China was studied by Du *et al.*[10] using SPI at various time scales. They reported that during that period, more dry years were experienced in the upper reaches of the major rivers in the Hunan Province than the lower and middle reaches. Santos *et al.*[11] used the SPI at 1, 3, 6 and 12 month time scales to characterize drought events in mainland Portugal from September 1910 to October 2004. Pai *et al.*[12] compared two drought indices – the per cent of normal precipitation (PNP) and SPI for 458 districts in India covered by the southwest monsoon.

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Their results showed that SPI is a better drought index than PNP.

Ntale and Gan[13] compared SPI with the Palmer Drought Severity Index and the Bhalme–Mooley Index for East Africa and concluded that SPI is more suitable for analysing East African droughts since it can be more easily adapted to the local climate and only requires precipitation data. Potop *et al.*[14] used SPI along with the percentage of long-term precipitations and the Ped Drought Index for the period 1961–2007 for the Czech Republic to evaluate drought episodes and their potential impacts on winter and spring cereal crops.

Aridity has different definitions across different disciplines such as climatology, meteorology, hydrology and agriculture[15,16]. Penck[17] first defined an arid region as a place where annual evaporation exceeds precipitation. Beran and Rodier[18] defined aridity of a given region as the deficiency of available water in an ecosystem. Among the numerous aridity indices developed for the determination of irrigation demands[19], the de Martonne aridity index is one of the most commonly used, since it only requires mean monthly temperature and mean monthly rainfall data for a period. Zhang *et al.*[20] used SPI and the de Martonne aridity index for the Pearl River basin for the period 1960–2005 to classify anomalously wet and dry conditions. Shahid[21] studied the spatio-temporal variation in aridity and dry period in terms of irrigation demand for the 1959–2009 time period for Bangladesh using the de Martonne aridity index. His study revealed that dryness in Bangladesh decreased in the last fifty years and irrigation was required for more than six months in western Bangladesh. Livada and Assimakopoulos[22] compared SPI and de Martonne aridity index of 51 years for Greece and found a satisfactory correlation between the two indices. The SPI and the de Martonne aridity index were also used to observe variability in drought and aridity in the Barlad catchment in Romania and its potential impacts on hydrology[23]. De Martonne's aridity index was used along with five other indices by Lungu *et al.*[24] for Dobrudja territory to demonstrate that increasing aridity in the region is a real hazard.

From the above, it is clear that analysis of spatial and temporal trends of drought and aridity is important to understand the climatic variability and irrigation requirements in a region. In this study the SPI and de Martonne aridity index were determined for Gomti basin to describe the spatial and temporal variability in drought severity and aridity and irrigation requirements respectively. Additionally, a correlation between the two indices was evaluated.

## Data and methods

The Gomti river basin is part of the Indo-Gangetic plains of India (Figure 1). The Gomti basin comprises 31,240 sq. km area in the state of Uttar Pradesh in India[25]. The climate of the Gomti basin ranges from semi-arid to sub-humid tropical. The average annual rainfall in the basin varies from 850 to 1100 mm. Approximately 75% of the total rainfall occurs in the monsoon season (middle of June to middle of October)[26]. Districts in the Gomti basin are Bara Banki, Faizabad, Hardoi, Jaunpur, Kheri, Lucknow, Pilibhit, Pratapgarh, Rae Bareli, Shahjahanpur, Sitapur, Sultanpur, Unnao and Varanasi.

### *Data used*

Daily meteorological data consisting of minimum and maximum temperature for the period 1971–2007 and daily rainfall data for the period 1971–2011 for each district of Gomti basin available with the NICRA (National Innovations on Climate Resilient Agriculture, http://www.nicra-icar.in/nicrarevised/) web portal were used. Monthly and annual means were then computed from the daily data for each district of the Gomti basin.

### *Methods of analysis*

The SPI was used to assess the drought frequency at different time scales. The de Martonne aridity index was used to assess the episodes of dryness and irrigation demand. These are described in the following paragraphs.

### *Standardized precipitation index*

Precipitation deficit affects soil moisture, surface and subsurface flow, reservoir storage and groundwater

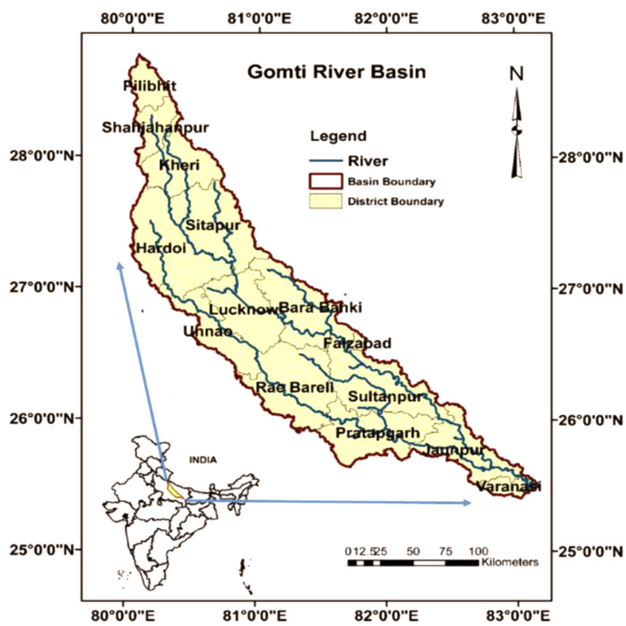


**Figure 1.** Location of the Gomti river basin in India[25].

recharge. Long-term deficit in precipitation may result in drying of streams, reservoirs and aquifers resulting in severe soil moisture deficit. Quantification of precipitation deficit at different time scales is required to study its influence on soil moisture, surface and subsurface flow, reservoir storage and groundwater recharge. SPI was developed by McKee *et al.*[7] to quantify the precipitation deficits at different time scales. According to McKee *et al.*[7], drought occurs when the value of SPI is continuously negative and reaches –1.0 or less. They defined the criteria for drought intensity based on SPI (Table 1). Drought ends when SPI becomes positive. SPI is computed from eqs (1) and (2).

$$\mathrm{SPI} = S\frac{t-(c_2t+c_1)+c_0}{((d_st+d_2)+d_1)t+1},\ t=\sqrt{\ln\frac{1}{H(x)^2}}, \quad (1)$$

$$G(x)=\frac{1}{\beta^{\gamma}\Gamma(\gamma)_0}\int_0^x x^{\gamma-1}\mathrm{e}^{-x/\beta}\mathrm{d}x,$$

$$x>0, \Gamma(\gamma)=\int_0^{\infty} x^{\gamma-1}\mathrm{e}^{-x}\mathrm{d}x. \quad (2)$$

where $x$ represents the rainfall values, $\beta$, $\gamma$ the scale parameter and shape parameter of the $\Gamma$ function, $S$ the positive and negative coefficients; $c_0$ is 2.515517, $c_1$ is 0.802853, $c_2$ is 0.010328, $d_1$ is 1.432788, $d_2$ is 0.189269, $d_3$ is 0.001308, $G(x)$ is the probability of precipitation distribution. $S = 1$ when $G(x) > 0.5$, $H(x) = 1 - G(x)$ and $S = -1$ when $G(x) \leq 0.5$, $H(x) = G(x)$.

### *Aridity index of E. de Martonne*

de Martonne[27] introduced an aridity index based on temperature and precipitation only. The monthly values of the index are calculated as

$$I_i=\frac{12P_i}{T_i+10}, \quad (3)$$

where $P_i$ is the monthly precipitation amount in mm and $T_i$ is the monthly mean air temperature in °C. Since the irrigation requirement depends both on temperature and rainfall, this index is used to identify the months when irrigation is necessary. This index may also be used to identify dry episodes in a region. According to the index, if $I_i < 30$, dry conditions may be observed and irrigation may be necessary. In general, irrigation becomes necessary when $I_i < 20$.

**Table 1.** Dryness/wetness categories based on SPI values[6,7]

| SPI | Category |
|---|---|
| ≥2.0 | Extremely wet |
| 1.50 to 1.99 | Severely wet |
| 1.00 to 1.49 | Moderately wet |
| 0.99 to –0.99 | Near normal |
| –1.00 to –1.49 | Moderately dry |
| –1.50 to –1.99 | Severely dry |
| ≤–2.0 | Extremely dry |

## Results and discussion

### *Standardized precipitation index*

The 12-month and 6-month SPI (June–November) were calculated for each of the 14 districts of the Gomti basin. A dry year occurs if SPI ≤ –1.00 (Table 1). During the period 1971–2011, at the basin level, drought years were observed for 7 years based on both the 12-month and 6-month SPI, i.e. in 1972, 1979, 1987, 1993, 1994, 2002 and 2010 (Figure 2). The drought conditions were mapped using the Kriging interpolation technique in ArcMap 10.0. At the spatial scale, based on the 12-month SPI, the frequency of severe and extreme drought was observed more for the upper districts of the basin from 1971 to 2000. During the early 2000s, the central region experienced more severe and extreme drought, whereas the lower districts of the basin experienced more severe and extreme drought in 2010. Figure 3 demonstrates this drought frequency for (a) upper region of the basin (districts Pilibhit, Shahjahanpur, Kheri, Sitapur, Hardoi), (b) central region (Bara Banki, Lucknow, Unnao, Faizabad, Pratapgarh, Sultanpur, Rae Bareli) and (c) lower region (Jaunpur, Varanasi).

The 4-month SPI for the monsoon months in Gomti basin (June–September) was calculated and drought frequency was observed more during the 2000s. Significant drought years were observed in 1979, 1987, 1993, 2002, 2009 and 2010. Kriging interpolation for these years is presented in Figure 4.

### *De Martonne aridity index ($I_i$)*

The aridity index developed by de Martonne identifies dry period in terms of irrigation demand, i.e. the months when irrigation is necessary. For the Gomti basin, irrigation was necessary for more than 8 months ($I_i < 20$) for all districts of the basin for the period 1971–2007. During this period, it was observed that for all the districts, the value of the index decreased on a monthly basis. This decrease still kept the index above 20 for some months; however lowering of its value implies that rainfall in some districts of the basin has been decreasing over the last 37 years. At the spatial scale, aridity index was lower for the districts in the lower region of the basin while the upper and central regions had higher values.

The comparison of the 1-month SPI and the de Martonne aridity index $I$ ($I = I_i/12$) showed that both

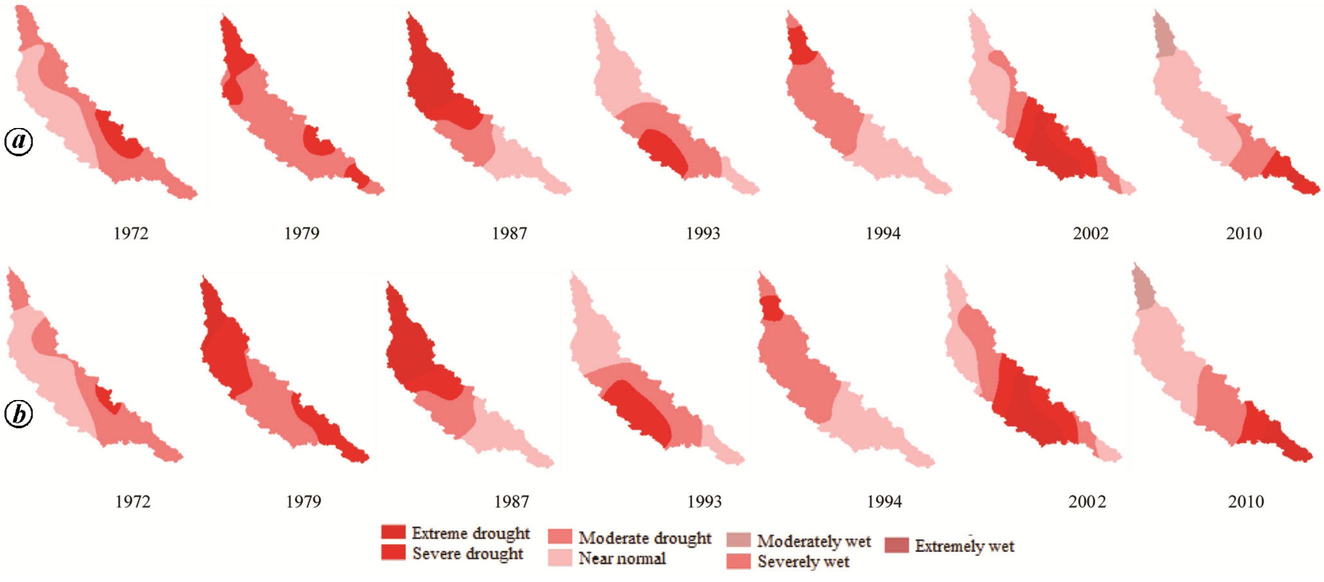


**Figure 2.** Drought years observed based on (***a***) 12-month SPI and (***b***) 6-month SPI.

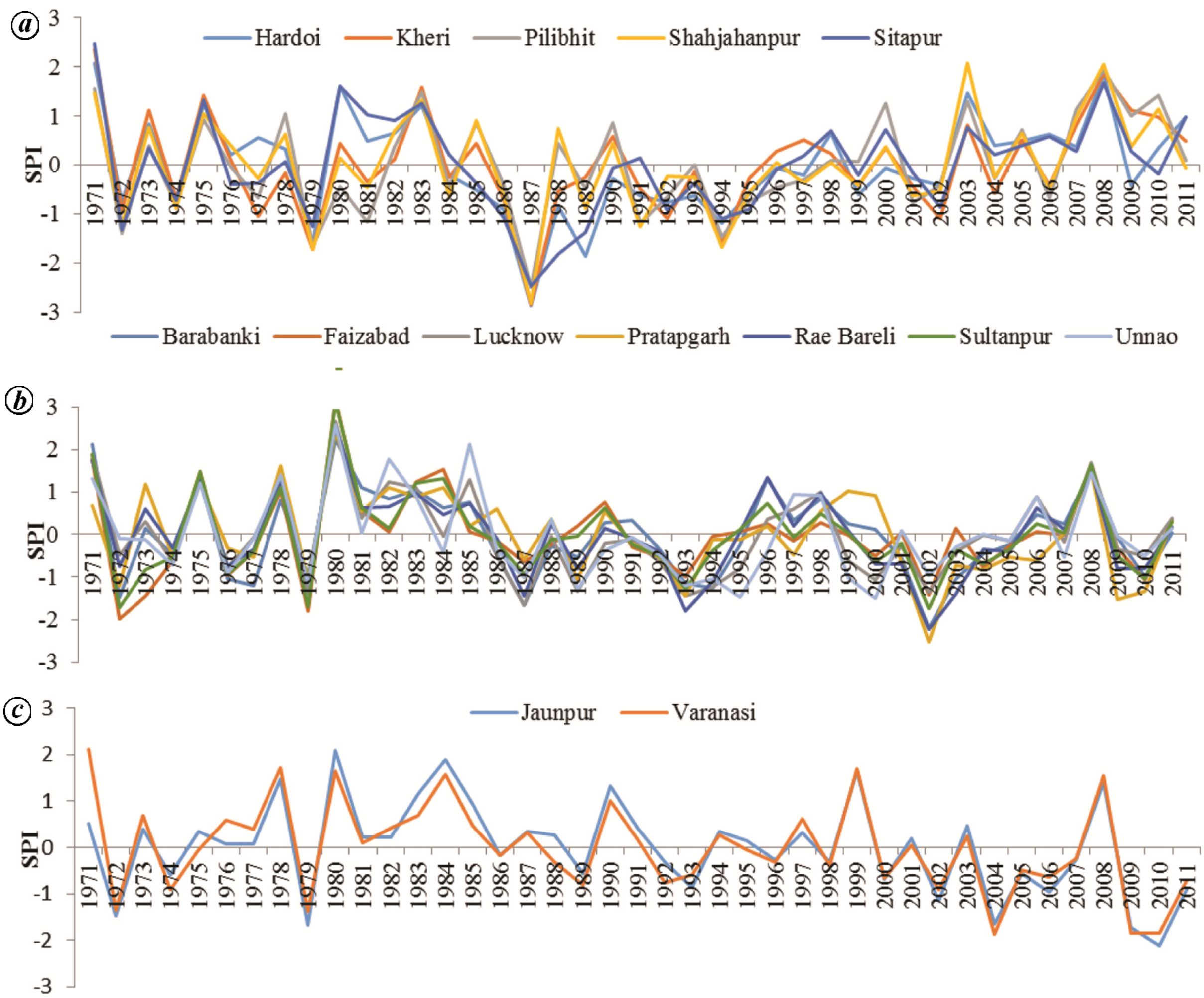


**Figure 3.** Drought frequencies for (***a***) upper region, (***b***) central region and (***c***) lower region of Gomti basin.

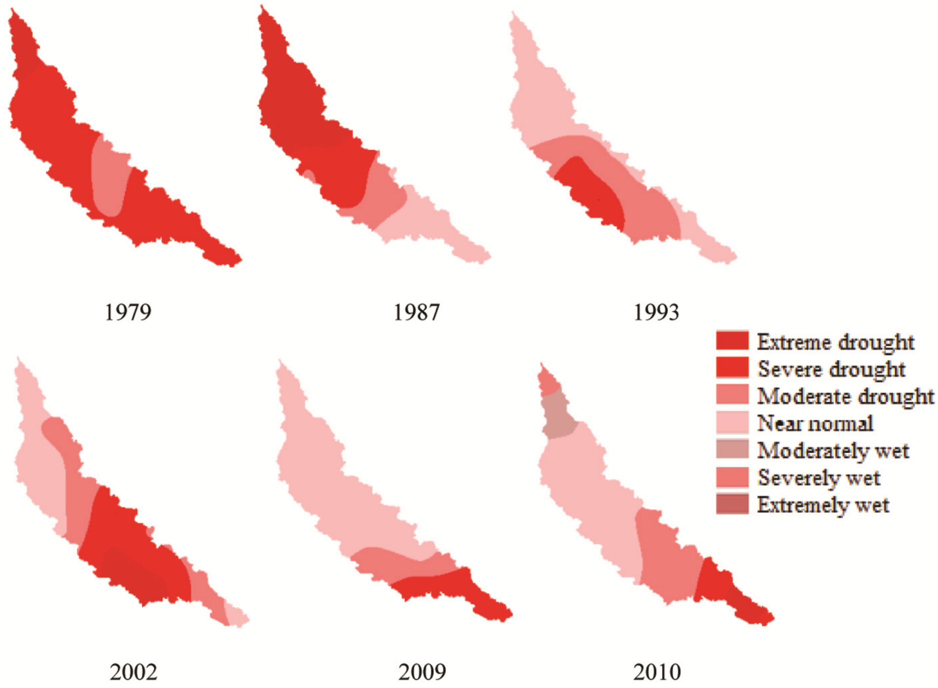


**Figure 4.** June–September 4-month SPI for Gomti basin.

indices were positively correlated (correlation coefficient ranging from 0.30 to 0.38 for all 14 districts). Although the correlation is linear, the indices are closer together for lower values and more scattered as the values increase (Figure 5).

## Discussion

Analysis of the 6-month SPI (June–November) and the 12-month SPI for Gomti basin yielded similar results. This indicates that the drought period in any particular year in the basin is primarily governed by the rainfall pattern from June to November. Analysis of rainfall trends using the Mann–Kendall test by Abeysingha *et al.*[28] showed that 1987 and 2002 experienced negative rainfall anomaly/drought which is also reported in the present study.

June–September are the main monsoon months in the basin and analysis of drought during these months is important from an agricultural perspective. Jha *et al.*[29] reported an increasing trend in dryness during the summer monsoon season in their study for the period 1951–2006 for the Gangetic plain. In the present study, based on the 4-month SPI, more drought years were observed during the 2000s although severity of the drought was more in 1979, 1987 and 1993.

The de Martonne index for the basin showed that the lower region of the basin experienced more dry episodes and aridity for the period 1971–2007. This result is consistent with the findings of Abeysingha *et al.*[28] which stated that rainfall has decreasing trend in the downstream areas of Jaunpur and Varanasi.

Finally, correlation between the 1-month SPI and the de Martonne aridity index ($I$) was found to be positive. This correlation is stronger for lower values of SPI and $I$ indicating that during a drought condition, irrigation demand naturally increases. For higher values of SPI, i.e. during wet conditions, irrigation demand automatically decreases. Since the de Martonne aridity index is dependent on both temperature and rainfall, the scattered higher values of $I$ may be attributed to increasing trend of mean temperature but both increasing and decreasing trend of rainfall for different districts in the basin[28,30].

The Gomti basin experienced drought in 1972, 1979, 1987, 1993, 1994, 2002 and 2010. Of these, only 1972, 1979, 1987 and 2002 were declared as major drought years in the country[31,32]. This suggests that drought at the regional scale and at the country level may not always occur in the same year. At the regional scale, there is poor spatial and temporal distribution of rainfall. There may also be local climate variations which affect the rainfall distribution. These could be the possible reasons for drought occurrence in the basin during 1993, 1994 and 2010, even when drought was not observed in the entire country. Since changes in temperature and precipitation are not globally uniform and considerable spatial and temporal variations in climate parameters exist at the regional level[33,34], it is important to analyse historical climate data at the regional level also. Such studies at regional scales help in defining historical drought years for smaller regions and in assessment of future irrigation requirements.

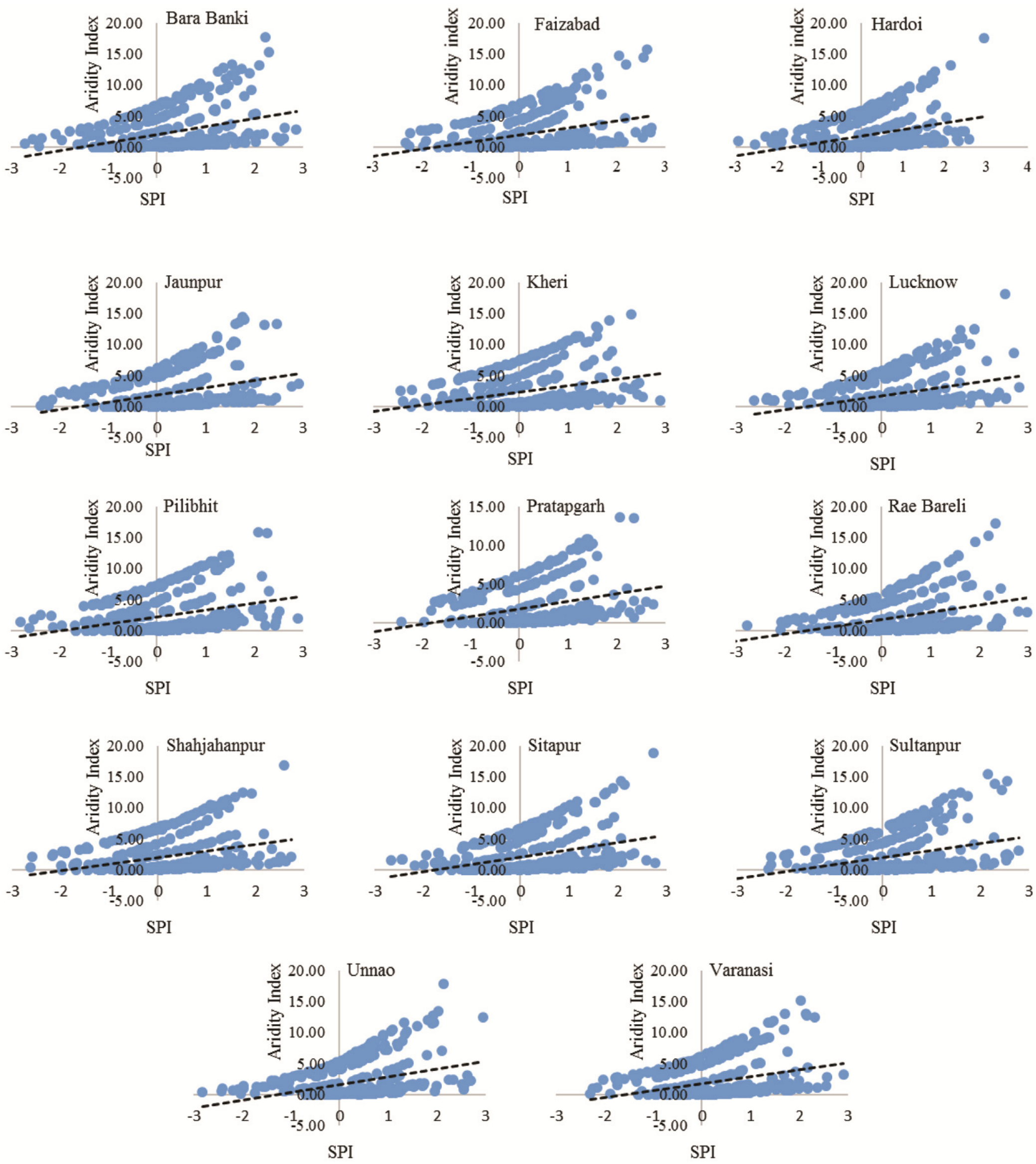


**Figure 5.** Scatter plots and correlation lines between de Martonne aridity index and SPI for all districts of Gomti basin.

## Conclusion

The spatial and temporal variability of drought and aridity was studied for the Gomti basin in Uttar Pradesh. Significant drought years were observed in 1972, 1979, 1987, 1993, 1994, 2002 and 2010. The Kriging interpolation method showed that during 1971–2000, the upper regions of the basin experienced more severe and extreme drought events. The central and lower regions experienced more drought during 2001–2011. Based on the de Martonne aridity index, it was found that irrigation in the basin was necessary for more than 8 months in a year. During the period 1971–2007, aridity was more for the lower regions of the basin. The 1-month SPI and the de Martonne aridity index showed a positive correlation. Understanding drought intensity and severity plays a vital role in agriculture, particularly in estimating irrigation requirements. It is suggested that such studies may be undertaken for other basins in India.

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