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Meteorological and hydrological drought characteristics in Bearma basin of Bundelkhand region in Madhya Pradesh

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ABSTRACT

Drought is a phenomenon that may occur in a large part of the catchment and may affect many components of the hydrological cycle. This study examined characteristics of the meteorological and hydrological droughts in Bearma basin of Bundelkhand region of M.P., which is regularly suffering from frequent droughts due to large variation in rainfall. An analysis was performed using daily time series data from 1976-77 to 2009-10. In the present study, meteorological drought characteristics were evaluated by identifying the drought years and Relative Departure Index (RDI). Drought prone zones and hydrological drought deficit characteristics, such as drought duration and deficit volume, were derived using the threshold level approach method. The frequency of meteorological drought varied between 1 in 3 years at Deori to 1 in 9 years at Damoh districts whereas its severity varied between mild and moderate droughts with severe droughts occurring once at Damoh, Hatta and Jabera during 1979-80. Meteorological droughts occur frequently but do not cover the whole catchment whereas hydrological droughts occur more frequently in Bearma basin. The relative departure index, an indicator of the drought proneness of a region has indicated equal priorities for both Rehli and Deori for taking up drought relief measures during drought situations. The hydrological drought characteristics were evaluated using the 'threshold level approach' identified during 1979-80 with the maximum hydrological drought severity with deficit of 261.01 Million Cubic metre (MCM), whereas a maximum of six hydrological drought events occurred during 1989-90. The study revealed relatively large differences in the spatial and temporal characteristics of hydrological and meteorological droughts in Bearma basin.

1. INTRODUCTION

Droughts cause major economic losses and human sufferings, affecting hundreds of millions of people and several studies have highlighted the need for drought prevention and mitigation plans (Wilhite and Wood, 1985; Wilhite *et al.,* 1986; Wilhite, 1996; Sangoyomi and Harding, 1995). It develops slowly and imperceptibly and may remain unnoticed for a long time unlike other natural hazards (Tallaksen and van Lanen, 2004). Due to their large spatial extent and long durations, droughts have significant economic, social and environmental impacts (Sheffield *et al.,* 2009). Drought generally initiates with the deficit of monsoon rains leading to meteorological drought and if prolonged, affects other sectors dependent on the water for its sustenance resulting in agricultural and hydrological droughts. Generally, the shortage in precipitation propagates through the hydrological system causing drought in different segments of the hydrologic system including unsaturated zone, groundwater and surface water (Peters *et al.,* 2006). The propagation of drought has been studied by Eltahir and Yeh (1999), Peters *et al.* (2003) and Peters *et al.* (2005) for groundwater systems also. Even though, the natural phenomena may be responsible for the initiation of droughts but certain studies have indicated that water resources like rivers and groundwater under human interventions are two times more vulnerable than those with less human interference like snow cover and precipitation (Shaban, 2009).

The spatial variations of droughts have been studied by (Demuth and Stahl, 2001; Chang and Teoh, 1995). Sivakumar (1992) stressed the importance of recognizing spatial patterns of extreme drought, which can then be used in the management of cultivated areas for crop selection and irrigation planning. According to recent drought studies (Feyen and Dankers, 2009; Dai, 2011), there is an increasing trend in drought extent and population affected by drought, which makes drought research and management a pressing issue. It is not possible to avoid meteorological droughts but it can be monitored and analysed by which their adverse impacts can be alleviated based on how well the droughts are defined and drought characteristics quantified (Smakhtin and Hughes, 2007). The various drought characteristics include drought magnitude, drought duration, spatial extent, drought intensity and severity. Spatial aspects of the drought including the area covered by it and the total deficit are the important characteristics of the event, as the size of the affected area provides a measure of the severity of the event (Andreadis *et al.,* 2005). Appa Rao (1991) found that most of the drought-prone areas with frequent droughts lie in arid and semiarid regions. Pandey (1999) studied the hydrological and agricultural aspect of drought in Kalahandi district of Orissa and found that the average frequency of drought in the district was 4 to 5 years. It was also observed that 2 to 3 intervening critical dry spells per year occurred during an average monsoon year. Smakhtin (2001) concluded that flow duration curve (FDC) is very useful for displaying the complete range of river discharges from low flows to flood events.

Surface water drought results directly from lesser surface runoff and indirectly from lower groundwater discharge in the catchment area. Therefore the hydrological droughts are the most visible type of droughts which result from deficit rainfall conditions. During periods of deficit rainfall condition, deviation from normal is greater for stream flow than rainfall. Surface water droughts can be identified through low flow analysis and deficit storage analysis of reservoirs. The flow duration curve (FDC) techniques as well as the low flow frequency analysis (LFA) do not provide any information on the length of continuous periods below a particular critical flow value for drought evaluation. To overcome this limitation, hydrological drought is characterized based on the 'theory of runs' resulting in periods during which the stream flow remains below a certain threshold. The theory of runs is used to identify the hydrological drought characteristics based on a threshold level.

2. MATERIALS AND METHODS

Study Area

The river Bearma is one of the important tributaries of Ken river system and drains through Narsinghpur, Jabalpur, Sagar, Damoh and Panna districts of Madhya Pradresh. This basin is located between 23^0 07′ N and $24^0$18′ N latitudes and $78^0$54′ E and $80^0$00 E longitudes which is bounded by Sonar basin on the west, Ken sub-basin on the east, Vindhyan ranges on the south and situated in Madhya Pradesh. The total catchment area of the elongated Bearma basin is 5890 km^2. A discharge gauging site is located at Gaisabad and the catchment area up to Gaisabad is about 5807.23 km^2.

Computation of Rainfall Characteristics

Mean, standard deviation and coefficient of variation of annual rainfall were computed for each of rain gauge station using standard formulae. The computation of the average rainfall was performed using ILWIS 3.6 wherein different layers were prepared namely, a base map delineating the boundaries of the basin and a map showing the location of rain gauge locations. The interpolation was performed using the nearest point interpolation algorithm and subsequently the interpolated map was crossed with the base map to obtain the area of influence of each rain gauge station. The Thiessen weights were computed as the ratio of influencing area at each station divided by the total basin area. The average annual rainfall was computed by using the following equation:

$$\left[P = \frac{\sum_{i=1}^{5} PiAi}{\sum_{i=1}^{5} Ai} \right] \qquad \text{.................. (1)}$$

Where, P_1, P_2, ... P_5 = point annual rainfall values at various rain gauge stations; A_1, A_2, ... A_5 = area of influence of the respective rain gauge station; and P = average annual rainfall.

Determination of Meteorological Drought

Identification of drought years

The frequency and severity of drought was determined based on the amount of rainfall deficit from normal rainfall values. A year is considered to be a drought year if the annual rainfall deficit is more than 25% of its normal. Furthermore, three classes of drought severity have been defined on the basis of these rainfall departures namely, a) mild drought for annual rainfall departures between -20% to -25%; b) moderate drought for annual rainfall departures between -25% to -50%; c) severe drought for departures greater than -50%. The annual rainfall departure analysis comprises of the following steps :

Determine the mean (X_m) for a set of annual rainfall data.

$$[X_m = \frac{1}{n}\sum_{i=1}^{n} X_i] \quad \text{..................} \quad (2)$$

Calculate departure (D_i) by subtracting the mean (X_m) from the individual annual rainfall (X_i)

$$[D_i = X_i - X_m] \quad \text{..................} \quad (3)$$

From resulted departure (D_i), the departure percentage ($D_{\%}$) is calculated as follows

$$\left[D_{\%} = \frac{D_i}{X_m} * 100\right] \quad \text{..................} \quad (4)$$

Relative departure index (RDI)

RDI has been developed to assess the relative drought proneness of the areas represented by five influencing rain gauge stations. It is a ranking procedure developed on drought severities obtained from departure analysis. The computation of the weighting scheme, designed on the basis of drought severity involves, a) assigning the weights based on drought severity: mild drought: 1, moderate drought: 2, severe drought: 3; b) summation of weights for all drought years; c) computation of relative departure index by dividing total weights at each rain gauge with number of years of data.

$$\left[RDI = \frac{\sum_{i=1}^{5} W_i}{N}\right] \quad \text{..................} \quad (5)$$

Where, W_i = total weights at each rain gauge; and N = total number of years of Analysis.

Identification of drought prone zones

The drought prone zones in the basin were identified based on the probability analysis of the annual rainfall at each station. A station is considered to be drought prone if the probability of occurrence of 75% of mean annual rainfall is less than 80%. The computations at each station include, a) calculation of mean rainfall; b) arrangement of data in descending order of rainfall magnitude; c) ranking the sorted data, rank (*m = 1, 2, 3...*) up to last record; and d) determination of probability (*P*),

$$\left[P = \frac{m}{N+1} x100\right] \quad \text{..................} \quad (6)$$

Calculation of 75% of mean rainfall

$$\left[X_{75} = \frac{x}{100} x100\right] \quad \text{..................} \quad (7)$$

The probability of exceedance of the 75% of mean rainfall (X_{75}) denoted as (P_{75}) is found from the computations and drought prone zones identified subject to the condition that: if $P_{75} < 80\%$, then the area is considered to be drought prone, else the area is not drought prone.

Evaluation of Hydrological Drought Characteristics

The variable threshold level approach at 75% dependable flow (Q_{75}), during each month was used for the identification of hydrological drought originates from the theory of runs. Yevjevich (1987), originally defined droughts as periods during which the water supply does not meet the current water demand. Both the water supplies as well as the water demand were expressed as time series, and a drought event was defined as a sequence of negative values in the supply minus demand series. The duration of the hydrological drought is characterized by the period of time during which stream flow remains below the specified threshold. If the duration is short, say 1 to 10 days, this may be considered as a period of low flow but may not be considered as the duration of drought. Therefore, the 'truncation level' and 'critical dry spell length', of flow to be considered as a drought event. Based on the crops grown and the soil types in Bundelkhand region, a critical dry spell length may be considered as continuous deficit of 10 or more days. The drought severities were estimated based on the cumulative shortages (deficit-sums of low flows) in stream flow below the truncation level persisting for the durations of 10 days or more. Each drought duration was associated with its severity (deficit-sum) (S), which is the sum of individual deficits in the successive epochs of the dry spell. Each dry spell has a severity, selected as S_i (*i = 1, 2, 3...*) computed as:

$$\left[S_i = \int_0^{d_i} \{Q_t - Q_{75}\} dt\right] \quad \text{..................} \quad (8)$$

Where, S_i is severity of drought event i; d_i is the duration of drought event i; Q_t is the stream flow at time t; Q_{75} is the truncation level (75% dependable flow for a particular month).

3. RESULTS AND DISCUSSION

Rainfall Variability in Bearma Basin

The Mean, standard deviation and coefficient of variation along with the weights of the influencing rain gauge stations were determined and are given in Table 1. The rain gauge station at Jabera influences about 33% of the catchment area followed by 26% by Deori and 20% by Damoh. The rainfall variability is quite high in the basin with the coefficient of variation from 24.4% (Jabera) to 30.5% (Damoh). The average annual rainfall in the Bearma basin is 1180 mm. The annual rainfall departure at Deori is given in Fig. 1.

Table: 1
Rainfall variation for Bearma basin

Sr. No.	Rain gauge station	Normal rainfall (mm)	Standard deviation (mm)	Coefficient of variation (%)	Area of thiessen polygon (km^2)
1.	Damoh	1210.40	360.80	30.5	991.76
2.	Hatta	988.80	332.53	26.6	1164.95
3.	Jabera	1223.40	295.77	24.4	1927.67
4.	Rehli	1184.50	275.82	27.9	251.90
5.	Deori	1251.40	299.34	24.5	1491.23

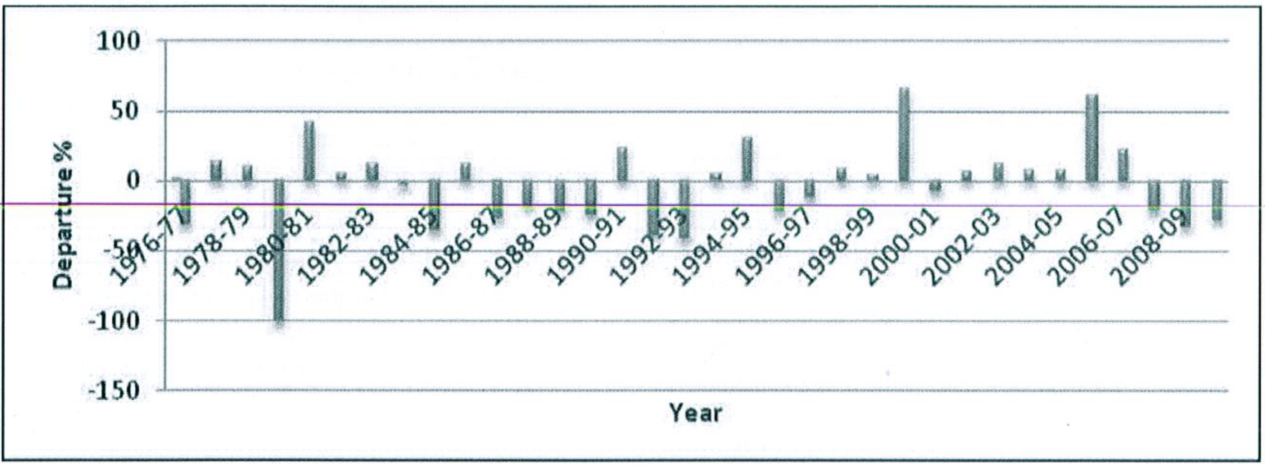

Fig. 1. Annual rainfall departure at Deori

Table: 2
Drought years at the influencing rain gauge stations in Bearma basin

S. No.	Year	Drought severity				
		Rehli	Deori	Damoh	Hatta	Jabera
1.	1976-77	Mild	Moderate	Normal	Moderate	Normal
2.	1979-80	Normal	Normal	Severe	Severe	Severe
3.	1982-83	Moderate	Normal	Normal	Normal	Normal
4.	1984-85	Moderate	Moderate	Normal	Mild	Normal
5.	1986-87	Moderate	Moderate	Normal	Normal	Normal
6.	1988-89	Moderate	Mild	Normal	Moderate	Normal
7.	1989-90	Normal	Mild	Normal	Normal	Normal
8.	1991-92	Moderate	Moderate	Normal	Normal	Normal
9.	1992-93	Normal	Moderate	Normal	Normal	Normal
10.	1995-96	Normal	Mild	Normal	Moderate	Normal
11.	1996-97	Normal	Normal	Moderate	Moderate	Mild
12.	1998-99	Normal	Normal	Moderate	Moderate	Moderate
13.	2000-01	Moderate	Normal	Normal	Normal	Mild
14.	2002-03	Normal	Normal	Moderate	Normal	Normal
15.	2004-05	Mild	Normal	Normal	Normal	Moderate
16.	2006-07	Moderate	Normal	Normal	Normal	Normal
17.	2007-08	Moderate	Mild	Normal	Normal	Normal
18.	2008-09	Normal	Moderate	Normal	Normal	Normal
19.	2009-10	Normal	Moderate	Normal	Normal	Normal

Identification of Drought Years

The drought years identified along with their severity for all the influencing stations are presented in Table 2. It was observed that drought events are occurring more frequently in Rehli and Deori in Sagar district as compared to Damoh, Hatta and Jabera in Damoh district. Generally, the drought severity varied between mild to moderate and severe droughts occurring only once during 1979-80 at all stations of Damoh district. Considerable spatial variability in the drought occurrence and severity was also observed.

Computation of Drought Frequency and RDI

The frequency of occurrence of drought for the various rain gauge stations was computed. Similarly, the RDI was also computed and is given in Table 3. It was observed that the drought frequency varies between 1 in 3 years at Deori to 1 in 9 years at Damoh which suggests that region in the basin falling in Sagar district was more susceptible to drought as compared to regions falling in Damoh district. The RDI which gives a measure of the relative drought proneness at various stations indicated that both Rehli and Deori were under the high priority and drought relief works needed to be initiated with more thrust in these blocks followed by Hatta, Jabera and Damoh.

Identification of drought prone zones

The identification of the drought prone zones in the Bearma basin was carried out based on the probability distribution of annual rainfall. The probability of exceedance of rainfall equivalent to the 75% of normal rainfall at each of the rain gauge station along with the drought condition is presented in Table 4. It can be observed that only Rehli is actually drought prone. However, the area influenced by Deori is presently not shown as drought prone area since the probability of exceedance of the 75% of mean rainfall is at the borderline of 80%. As such efforts for drought planning, management and mitigation measures should be focused more in Rehli and Hatta on a priority basis.

Table: 3
Drought frequency and RDI in Bearma basin

S.No.	Station	Drought frequency	RDI
1.	Rehli	1 in 3.5 years	0.53
2.	Deori	1 in 3 years	0.53
3.	Damoh	1 in 9 years	0.24
4.	Hatta	1 in 5 years	0.41
5.	Jabera	1 in 6 years	0.32

Evaluation of Hydrological Drought Characteristics

The hydrological drought characteristics including the onset (when stream flow falls below the truncation level) and termination of drought events (when flow exceeds the truncation level), severity and duration have been evaluated and presented in Table 5. The maximum severity of -238.258 MCM for a single drought event occurred during the period between 01 August, 1979 and 29 November, 1979 for a duration of 121 days, followed by a 47 days drought during 01 July, 2002 to 16 August, 2002 with severity of -210.389 MCM. A drought severity of more than -200 MCM during a single water year was observed only twice, during 1979-80 and 2002-03, with the maximum severity of -261.01MCM during 1979-80 followed by -216.219 MCM during 2002-03. Similarly, maximum drought duration for a single water year was 214 days in 1979-80 followed by 161 days in 1999-00.The comparison of the hydrological and meteorological drought during 1979-80 (having maximum hydrological drought severity) indicated that, Damoh, Hatta and Jabera faced severe meteorological drought whereas during 2002-03 (having second highest hydrological drought severity) only Damoh faced moderate meteorological drought. Therefore, it can be observed that even though the meteorological drought may often lead to a hydrological drought but establishing a direct relationship between the extent of the meteorological drought and severity of the hydrological drought is rather difficult.

4. CONCLUSIONS

The meteorological and hydrological drought analysis in Bearma basin has been carried out for planning of drought mitigation strategies and activities. On an average, the

Table: 4
Probability analysis of annual rainfall in Bearma basin

S.No.	Rain gauge	Rainfall at 75% probability (mm)	Probability of exceedance of rainfall equivalent of 75% of rainfall (mm)	Drought condition
1.	Rehli	887.60	79.64	Drought prone
2.	Deori	971.80	80.00	Normal
3.	Damoh	1027.98	87.71	Normal
4.	Hatta	832.90	81.97	Normal
5.	Jabera	1066.80	87.53	Normal

Table: 5
Hydrological drought characteristics for Bearma basin up to Gaisabad

Year*	Event	Onset of drought event	Termination of drought event	Severity (Million cu. m.)	Duration (days)
1976-77	I	19 November, 1976	30 November, 1976	-0.608	12
			Total	-0.608	12
	I	01 July, 1979	12 July, 1979	-19.626	12
1979-80	II	01 August, 1979	29 November, 1979	-238.258	121
	III	05 December, 1979	05 March, 1990	-3.127	81
			Total	-261.011	214
1981-82	I	20 August, 1981	02 September, 1981	-75.995	14
			Total	-75.995	14
1982-83	I	01 July, 1982	10 July, 1982	-15.038	10
			Total	-15.038	10
	I	24 July, 1984	09 August, 1984	-88.723	17
	II	19 September, 1984	30 September, 1984	-18.873	12
1984-85	III	19 October, 1984	31 October, 1984	-2.604	13
	IV	04 November, 1984	31 December, 1984	-3.942	58
			Total	-114.143	100
	I	01 July, 1985	15 July, 1985	-14.462	15
1985-86	II	27 August, 1985	11 September, 1985	-56.742	16
			Total	-71.204	100
	I	26 August, 1986	14 September, 1986	-55.194	20
	II	18 September, 1986	30 September, 1986	-34.562	13
1986-87	III	04 October, 1986	06 November, 1986	-12.276	35
	IV	08 November, 1986	30 November, 1986	-0.807	22
			Total	-102.838	90
1987-88	I	09 August, 1987	24 August, 1987	-107.520	16
			Total	-107.52	16
	I	11 September, 1988	30 September, 1988	-24.051	20
1988-89	II	16 October, 1988	31 October, 1988	-6.160	16
	III	10 November, 1988	30 November, 1988	-1.139	21
			Total	-31.35	57
	I	27 July, 1989	06 August, 1989	-65.369	11
	II	13 September, 1989	30 September, 1989	-28.889	18
1989-90	III	07 October, 1989	31 October, 1989	-6.817	25
	IV	06 November, 1989	31 December, 1989	-3.695	56
	V	22 January, 1989	31 January, 1989	-0.100	10
	VI	17 March, 1990	31 March, 1990	-0.198	15
			Total	-105.068	135
1990-91	I	22 October, 1990	31 October, 1990	-2.339	10
			Total	-2.339	10
	I	01 July, 1991	17 July, 1991	-26.689	17
	II	14 October, 1991	31 October, 1991	-4.112	18
1991-92	III	18 November, 1991	30 November, 1991	-0.753	13
	IV	19 December 1991	31 December 1991	-0.385	13
	V	11 January, 1992	31 March, 1992	-1.923	80
			Total	-33.681	141

Contd...

Year*	Event	Onset of drought event	Termination of drought event	Severity (Million cu. m.)	Duration (days)
1992-93	I	01 July, 1992	14 July, 1992	-24.192	14
	II	11 January, 1993	28 February, 1993	-0.706	49
	III	15 March, 1993	31 March, 1993	-0.130	17
			Total	-25.028	80
1993-94	I	22 July, 1993	31 July, 1993	-6.141	10
	II	21 January, 1994	31 January, 1994	-0.280	11
	III	19 March, 1994	31 March, 1994	-0.098	13
			Total	-6.519	34
1994-95	I	17 October 1994	31 October 1994	-3.074	15
	II	14 November 1994	30 November 1994	-1.383	17
	III	17 December 1994	31 December 1994	-0.442	15
			Total	-4.899	47
1995-96	I	14 October 1995	31 October 1995	-5.634	18
	II	17 November 1995	30 November 1995	-0.808	14
	III	04 December 1995	31 December 1995	-1.886	28
			Total	-8.328	60
1996-97	I	01 July 1996	12 July 1996	-20.623	12
	II	19 November 1996	30 November 1996	-0.582	12
	III	06 December 1996	31 December 1996	-1.788	26
	IV	08 January 1997	31 March 1997	-2.347	83
			Total	-25.339	133
1999-00	I	01 July 1999	16 July 1999	-17.947	16
			Total	-17.947	16
2000-01	I	21 October 2000	31 October 2000	-4.759	11
	II	02 November 2000	31 March 2001	-7.296	150
			Total	-12.055	161
2001-02	I	15 September 2001	03 October 2001	-29.856	19
	II	19 October 2001	31 October 2001	-3.386	13
	III	04 January 2002	02 February 2002	-0.810	30
			Total	-34.051	62
2002-03	I	01 July 2002	16 August 2002	-210.389	47
	II	02 October 2002	17 October 2002	-5.321	16
	III	20 December 2002	31 December 2002	-0.510	12
	IV	10 January 2003	23 January 2003	-0.668	14
			Total	-216.219	89
2005-06	I	06 December 2005	31 March 2006	-7.161	116
			Total	-7.161	116
2006-07	I	28 January 2007	09 February 2007	-0.708	13
			Total	-0.708	13
2007-08		24 January 2008	31 March 2008	-2.604	68
			Total	-2.604	68
2008-09	I	03 September 2008	12 September 2008	-9.352	10
			Total	-9.352	10

* The years during which no drought occurred were not represented in this Table.

frequency of occurrence of drought varies between 1 in 3 years to 1 in 9 years, whereas Rehli is the only drought prone block in the basin. The drought relief works to be carried out during periods of extensive droughts based on the priority classification (using RDI) which indicated that Rehli and Deori are priority blocks. The analysis clearly indicates that since the basin is subjected to frequent meteorological and hydrological droughts, rain-fed agriculture in the basin is virtually impossible without provision for adequate supplementary irrigation. Drought preparedness and a proactive drought management strategy are required to cope up with the droughts and alleviate the sufferings of the local population.

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