

# Streamflow Drought Severity Analysis of Betwa River System (India)

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**Abstract** Streamflow appraisal in time and space particularly in semi arid and dry sub humid regions has vital importance in the formulation of round the year plan of water uses comprising domestic & industrial water supply, irrigation scheduling, reservoir operation, in-stream flow maintenance etc. Drought severity analysis including the estimation of flow availability, drought duration, and deficit volume etc. was carried out using the 20–42 years (1960–2001) 10-daily streamflow data of five sites on the Betwa River system and. independent streamflow drought events were described by pooling the data, and severity of an independent drought event classified using a new drought severity index (DSI<sub>e</sub>) defined as a function of (1) the ratio of deficit flow volume to corresponding volume at the truncation level and (2) the ratio of duration of deficit flow to the maximum possible duration of the independent streamflow drought event. The study found that the upper reaches of river course were more prone to severe droughts than were the lower reaches. The drought events starting during August–November were more likely to be severe drought events than those in the other months.

**Keywords** Drought index · Drought severity · Low flow · Drought duration · Truncation level · Deficit flow

## 1 Introduction

In arid and semi-arid regions, water scarcity is often aggravated by climatic variability, uneven distribution of rainfall and water availability; posing serious threat to nature, quality of life, and economy (Hisdal and Tallaksen 2003) by interrupting usual agricultural and other developmental activities linked with water supply. Droughts in these regions are likely to have severe economic and social impacts due to lack of resources for their mitigation (Tallaksen and Lanen

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2004). The increasing demand of water in urban and rural areas, especially in semi-arid and dry sub-humid regions around the world (Dalezios and Bartzokas 1995), forces the hydrologists to have a realistic assessment of flows in streams in both time and space.

In India, rainy (or monsoon) season varies from 2–4 months in major part of the country, and the remaining 8–10 months are nearly dry, with very little or no rain. During lean (or non-rainy) period, the availability of water in streams, tanks, ponds, reservoirs etc. decreases sharply in drought prone areas of the country. Therefore, an appraisal of the available flows in rivers in both time and space becomes vital for year-plan formulation or modification of water uses comprising domestic/industrial water supply, irrigation scheduling, reservoir operation, in-stream flow maintenance, hydro-power generation etc., for sustainability of regional economic and ecological activities.

Drought implies a period of time when the supply of water can not meet the usual demand. Deficiency of rainfall of sufficient magnitude over prolonged duration and subsequent reduction in streamflow intervene with normal agricultural and economic activities of the region, leading to reduction in agriculture production and, in turn, affecting the normal life. Dracup et al. (1980) defined the drought in several ways considering the following: (1) Nature of water deficit, viz., precipitation, soil moisture or streamflow. (2) Basic time unit of data, viz., month, season or year. (3) Truncation for distinguishing low flows from high flows considering mean, median, mode or any other derived threshold. (4) Regionalization and/or standardization. For drought characterization, this study considers streamflow with its quantity below certain truncation level and lasting for a period of 30 or more number of days. However, various interpretations of drought are perhaps the main obstacles to its investigation (Dracup et al. 1980; Wilhite and Glantz 1985; Tate and Gustard 2000; and Tallaksen and Lanen 2004). Furthermore, affecting several facets of the society, it is usually not possible to define a unique measure of drought for its management (EEA 2001).

McMahon and Arenas (1982) reviewed low flows and their characteristics and suggested the need for improved methods for estimating low flow indices at ungauged sites. Beran and Rodier (1985) distinguished droughts from low flows and connected those with resource availability; classified hydrological droughts based on variation in duration, severity and season; and discussed them in terms of their effects on agriculture and hydropower. Smakhtin (2001) provided a comprehensive review of low flow studies, covering low flow generating mechanisms operating in natural conditions, anthropogenic factors governing low flows, methods of low flow estimation, relation between low flow indices, etc. Tallaksen and Lanen (2004) provided extensive discussions on the processes and estimation methods for droughts based on streamflow and groundwater availability; presented variety of techniques for assessment of low flows and hydrological droughts, including their prediction, forecasting and estimation at gauged/ungauged sites.

With growing concern on drought hazards and its impact on economy, several studies were undertaken in European countries during the last decade (EEA 2001). Bradford (2000) reported recent hydrological drought events in Europe; and Demuth and Stahl (2001) investigated their duration, magnitude, extent and sensitivity to environmental change using nearly 5000 daily streamflow series. Gustard and Cole (2002) related low flows with catchment characteristics, such as soil and geology. The international project Flow Regime from Experimental, International and Network Data (FRIEND) documented a variety of techniques applied to both at-site and regional data sets for analyzing hydrological droughts. Using daily time series from 15 (perennial) streamflow stations, Tate et al. (2000) analyzed the hydrological droughts in Southern Africa and found none of the considered approaches to be satisfactory for assessment of hydrological droughts across the whole region. Rossi et al. (1992) suggested a stochastic model for simulation of spatial and temporal variability of drought.

Kienzle (2006) suggested a procedure based on base flows derived from recession curves and streamflow hydrographs, and Zelenhasic (2002) suggested a simple, reliable and efficient procedure based on largest streamflow drought deficit and composite hydrograph recession curve. Identifying spatial and temporal trends in streamflow droughts, Wu et al. (2007) applied truncation level approach to define duration, severity and magnitude of a drought event in Nebraska. While assessing global droughts, their causes, predictability, monitoring, forecasting, impacts and approaches for drought management, Wilhite (2000) suggested drought management to be a multidisciplinary approach.

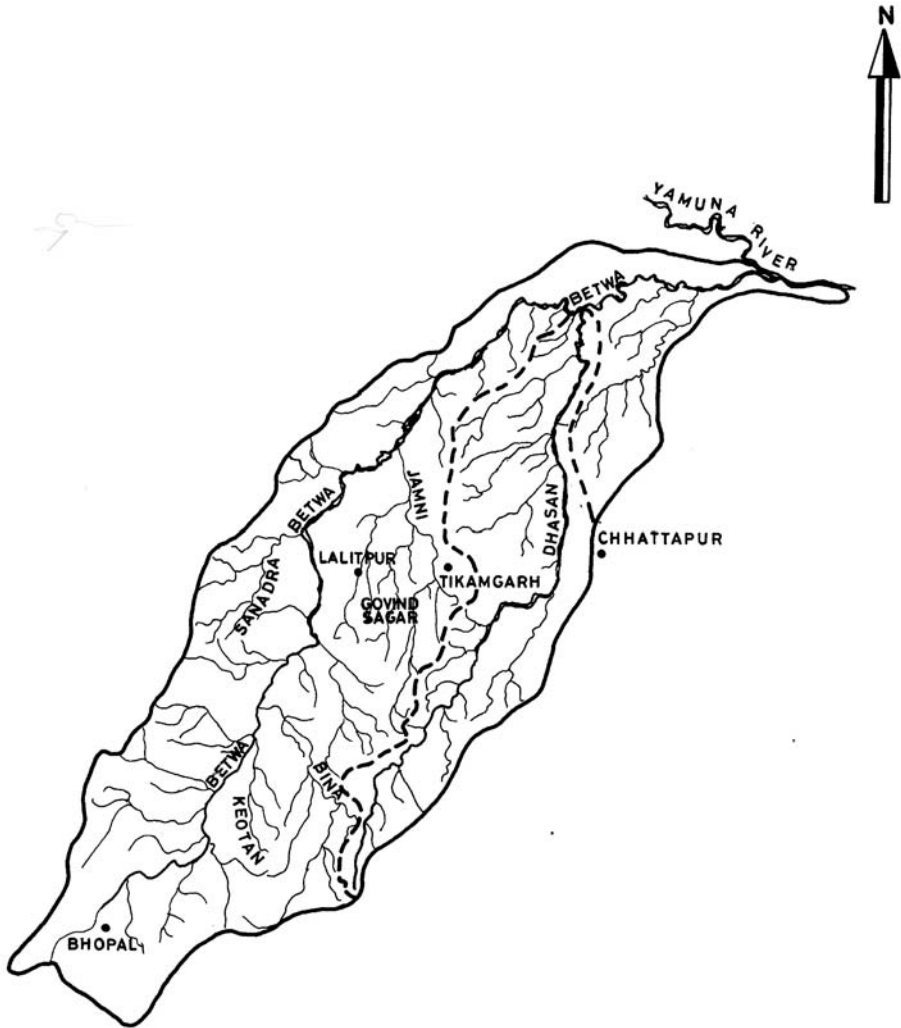
The above truncation level approach is widely applied for drought analysis using annual, monthly or daily series of river discharge (Yevjevich 1967; Sen 1980; Dracup et al. 1980; Kjeldsen et al. 2000; Hisdal and Tallaksen 2003; Hisdal et al. 2004). It helps provide an analytical interpretation of the expected availability of river flow; when the streamflow falls below truncation level, it is a drought. This level is frequently taken as a certain percentile flow and it is assumed to be steady during the considered month, season or year. Mathier et al. (1992) and Kjeldsen et al. (2000) extended the steady truncation concept to the variable one employing monthly and daily streamflows, respectively. Since the rainfall distribution in India is highly erratic and unevenly distributed in space and time, the high runoff variability does not warrant the use of annual truncation level. In addition, except the rivers of Himalayan origin, both surface runoff and groundwater feed all the rivers in India; effluent rivers replenish ground water during monsoon, and the process is reversed in the nonmonsoon (or lean) season. Thus, the availability of lean season flow in Indian streams is a manifestation of groundwater.

Recent experiences on drought occurrence indicate the upper parts of a basin to be more prone to dry conditions and water shortages than the lower parts (Pandey et al. 2004). Since the surface and groundwater flows stay for less time in the up-reaches than they do in the middle and/or lower reaches, the drought intensity varies with topographic location and time in the basin. For instance, since the river courses in up-reaches run dry during non-rainy season, these are prone to face earlier and more severe stress of water shortages during droughts than the lower parts of the basin.

Thus, the objective of the present study is to (a) assess the availability of flow at different sites of the Betwa river during normal and drought years; (b) investigate the hydrological drought characteristics in Betwa River basin using streamflow data; (c) determine independent drought events, their duration, and severity (= deficit volume) using the variable truncation level approach; and (d) derive streamflow drought severity index for Betwa basin.

## 2 Study Area

The Betwa sub-basin of Yamuna (Fig. 1) falls in the Bundelkhand region in central India between latitudes  $77^{\circ} 15'$  and  $79^{\circ} 45'$  N and longitudes  $23^{\circ} 5'$  and  $25^{\circ} 55'$  E. It originates in the Raisen district in Madhya Pradesh at an elevation of 475 m above mean sea level and joins river Yamuna near Hamirpur in Uttar Pradesh, traveling a total distance of about 564 km. The Bina, Bahaora, Guhari, and Dhasan rivers are the major tributaries of Betwa, draining the total area of about 43,319 sq. km. The basin is saucer-shaped with sandstone hills around its periphery. The topography and elevation (ranging from 700 to 300 m above mean sea level) cause variation in land use, from flat open wheat and gram growing areas to steep forest-covered hills. About a quarter of basin area contains vegetation ranging from thick forest to scattered bushes, its northern portion is covered with alluvial soils, the central part contains mixed red sandy and black soils, and the southern part has medium black



**Fig. 1** Index map of Betwa basin

soils. The average annual rainfall varies from 700 to 1,200 mm with an average annual rainfall of 1,138 mm, the average annual evaporation losses are of the order of 1,830 mm, and the average annual runoff is about 13,430 million cubic meter (MCM), out of which nearly 80% occurs in monsoon. The average annual runoff up to Matatila dam is about 6,000 MCM. Considering normal reservoir operation policy of filling and gradual depletion in monsoon, the annual evaporation from six reservoirs in the basin has been estimated to be of the order of 450 MCM (Chaube 1988).

## 2.1 Streamflow Characteristics and Data Used

The streamflow records (Table 1) were collected for the five sites in the Betwa river system. A preliminary investigation of discharge data showed the river up to Rajghat to be

**Table 1** Details of measurement sites and length of 10-daily discharge data

Sl No.	Gauge-discharge Site	Location	Catchment area (km <sup>2</sup> )	Length of flow records (years)	Stream type
1.	Garauli on Dhasan	79° 18' N 24° 38' E	840	21 (1982–2002)	Intermittent
2.	Basoda on Betwa	77° 45' N 23° 55' E	7,525	22 (1980–2001)	Intermittent
3.	Rajghat on Betwa	78° 12' N 24° 50' E	16,540	23 (1971–1993)	Intermittent
4.	Mohna on Betwa	79° 22' N 25° 42' E	27,670	18 (1984–2001)	Perennial
5.	Shahjina on Betwa	79° 56' N 25° 23' E	44,023	22 (1980–2001)	Perennial

intermittent in nature, i.e. dry in peak summer season (mid April to mid June), for nearly 64% of time during 1971–2001; and at Mohna and Shahjina, it was perennial. The course of river Dhasan up to Garauli site had been dry for 76% of time in April–June months during 1980–2001. It was however dry during January–June in severe droughts of 1987, 1989, and 1990. To ascertain explicit flow and drought characteristics, the Betwa River basin was sub-divided into four parts: Up-reach of Dhasan up to Garauli, up-reach of Betwa up to Rahghat, Middle reach of Betwa up to Mohna, and Lower-reach of Betwa up to Shahjina.

The study area falls in the semi-arid to dry sub-humid climatic region of India with a single rainy season (July–September) followed by dry winter, and then a very dry summer. An investigation of monthly rainfall records at various stations in the study area revealed the rainfall to be highly variable and unevenly distributed. The percentage annual rainfall departures were estimated to identify the occurrence of meteorological drought years during 1951–1998. The investigation further revealed the streamflows to vary significantly from season to season and even month to month. For nearly two-third of the time of the available data, the flow in Betwa at Basoda and Rajghat was zero after April, and persisted till the arrival of next monsoon. The flow in Betwa at Mohna and Shahjina was never zero, and the flow in river Dhasan was dry at Garauli in April–June for about three-fourth of the time during 1982–2001.

Using a large data base, Chaube (1988) estimated the mean annual rainfall ( $P_A$ ) in the Betwa basin as 1,138 mm and the potential evapotranspiration ( $ET_P$ ) in the range (1,643, 1,844) mm with mean potential evapotranspiration as 1,748 mm. Using the relationship between  $ET_P/P_A$  ratio and average drought, Pandey and Ramasastri (2001, 2002) computed the average frequency of (moderate to severe) meteorological droughts as once in 6 years. They also described the up-reaches of Betwa basin to be more prone to droughts and crop losses than the low reaches.

### 3 Methodology

#### 3.1 Estimation of Variable Truncation Level

A threshold can be chosen in a number of ways depending on the type of water deficit being studied. In some applications, it represents a well-defined flow quantity, such as

reservoir specific yield, percentage of mean or a percentile flow. The selection of percentile relies on the hydrological regime. For perennial rivers, a low threshold ranging ( $Q_{70}$ ,  $Q_{90}$ ) can be considered reasonable (Hisdal et al. 2004; Meigh et al. 2002). For intermittent and ephemeral rivers with majority of zero flows,  $Q_{70}$  would be zero. For ephemeral rivers of South African region, mean flow can be taken as threshold (Meigh et al. 2002). Based on the eight streamflow records of the same region, Tate and Freeman (2000) used thresholds ranging ( $Q_{12.5}$ ,  $Q_{90}$ ) depending on the proportion of zero flows. As an alternative, Kjeldsen et al. (2000) suggested  $Q_{75}$  of monthly flow duration curve.

A large monthly variation in river flows in the study area invoked the use of variable truncation level method. To this end, flow duration curves were developed for each month using the available 10-daily streamflow data (Table 1). The zero flows of intermittent streams of Dhasan at Garauli and Betwa at Rajghat (Table 1) were treated as follows.

The number of 'zero' and 'non-zero' flow values for each month were separated from the available flow records. The percentage probability of occurrence of the former in a given month was estimated as:

$$P_i = \frac{X_i}{N} \quad (1)$$

where  $P_i$  = probability of zero flow in the  $i$ th month,  $X_i$  = number of zero flow values in the  $i$ th month,  $N$  = total number of years of flow data for the  $i$ th month,  $i$  = an integer varying from 1 to 12. Arranging the non-zero flows of each zero-flow month in descending order to rank the highest value as 1 and the lowest as  $(N-X_i)$ , the joint probability of exceedance of non-zero flows was computed for the respective months as follows:

$$Pn_{z,j,i} = (1 - P_i) \frac{R_{j,i}}{N - X_i} \quad (2)$$

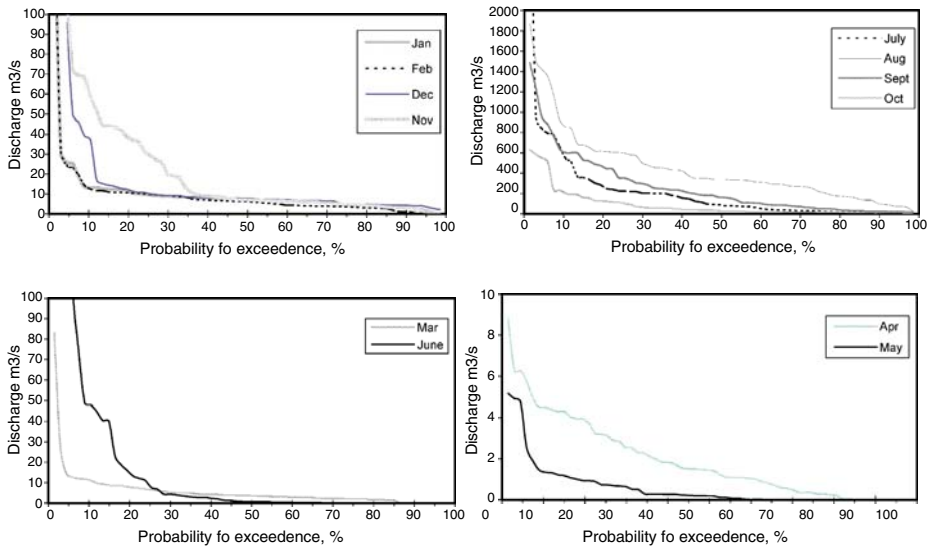
where  $R_{j,i}$  = rank of the  $j$ th flow value of the  $i$ th month,  $Pn_{z,j,i}$  = joint probability of exceedance of the  $j$ th value of non-zero flow in the  $i$ th month,  $i$  = an integer varying from 1 to 12 and  $j$  = an integer varying from  $1-(N-X_i)$ . Thus, the flow duration curve for each month was developed by plotting the probability of exceedance of non-zero flows ( $Pn_{z,j,i}$ ) against the corresponding discharge values in the  $i$ th month.

For perennial streams, the probability of exceedance was estimated using the Wiebill's plotting position formula:

$$Pn_{j,i} = \frac{R_{j,i}}{N + 1} 100 \quad (3)$$

where  $Pn_{j,i}$  = probability of exceedance of the  $j$ th value of flow in the  $i$ th month. Thus, to derive flow duration curves for determination of dependable flows at various probability levels, Eq. 2 was used for the April–June data of Basoda and Rajghat sites, and December–June data of Garauli site; and Eq. 3 for Mohna and Shahjina sites. As an example monthly flow duration curves for Basoda site are shown in Fig. 2.

In truncation level approach, droughts are assessed employing their three main characteristics, drought duration  $D$  (days, months, seasons or years), drought severity  $S$  (= total deficit), and magnitude  $M$  in terms of average deficit or the intensity (=  $S/D$ ). This approach is of pragmatic utility when certain minimum flow is required as, for example, in reservoir planning for water supply or in derivation of river abstractions etc. (Clausen and Pearson 1995; Stahl and Demuth 1999), and in determination of mean (Bonacci 1993), median (Griffiths 1990), and low percent exceedance flow (Zelenhasic and Salvai 1987).



**Fig. 2** Monthly flow duration curve for Betwa River at Basoda Site

Since the truncation level derived as a fixed (= 75) percentile of the flow duration curve for each month reflects a more realistic drought pattern than does a steady annual truncation level (Kjeldsen et al. 2000), the 75 percentile is taken to determine the truncation level, as shown in Table 2.

### 3.2 Assessment of Drought Duration and Severity

Some of the river courses in the study area usually run dry in summer at some of the sites, leading to truncation level equal to zero in this period, problematic in sense of drought

**Table 2** Estimated values of truncation level for the Betwa and Dhasan at various sites at 75th percentile of flow duration curve (m<sup>3</sup>/s)

Month	Truncation level at 75 <sup>th</sup> percentile of flow duration curve (m <sup>3</sup> /s) at sites				
	Betwa River				Dhasan River
	Basoda	Rajght	Mohna	Shahjina	Garauli
Jan	4.48	8.26	10.12	27.6	0.77
Feb	2.97	6.24	9.07	23.7	0.3
Mar	1.18	3.82	7.1	19.1	0
Apr	0	0.32	6.25	14.9	0
May	0	0	5.33	12.1	0
June	0	0	7.59	16.9	0
July	27.72	46.3	46.97	94.5	57.1
Aug	216.88	385.2	788.73	1,050.5	229.3
Sept	50.68	117.8	293.23	292.5	112.1
Oct	14.72	30.5	30.62	65.3	41.8
Nov	4.87	9.1	16.07	36.2	6.9
Dec	5.16	8.12	14.2	30.2	1.1

identification in terms of its beginning, continuance, and end. In this study, if a drought occurs in a rainy season and encroaches the following dry season for which truncation level is zero, the duration of drought is taken to continue with the same deficit volume as before the dry season. With the occurrence of rain, if the river flow falls below the non-zero truncation level, the drought is taken to continue, it ends otherwise.

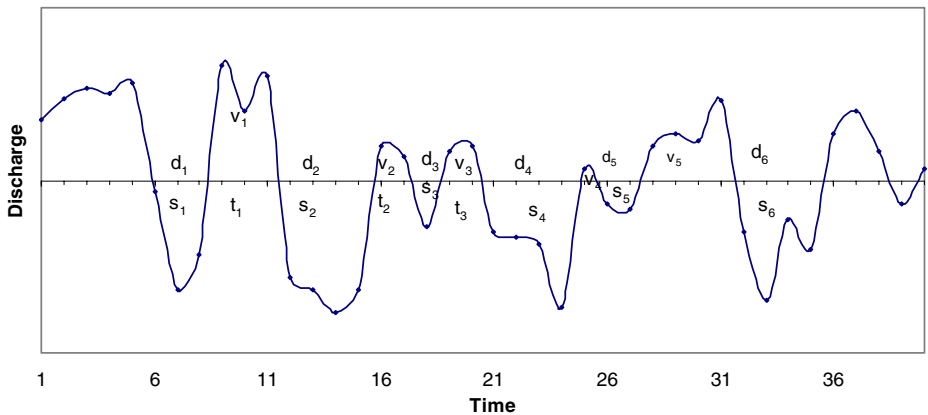
Using the available 10-daily flows (Table 1) and the above variable truncation level approach, a sequence of drought events was obtained. Each drought event was characterized by its duration  $D_i$ , deficit volume (or severity)  $S_i$ , and the time of occurrence  $T_i$ , as shown by a definition sketch in Fig. 3. Since the flow exceeds the threshold for a short period during the prolonged dry period, a long drought spell is divided into a number of minor drought events (for example, events 3 and 5 in Fig. 3). Since these droughts are mutually dependent, it is necessary to describe the independent sequence of drought events using some kind of pooling (Tallaksen et al. 1997), as follows.

If the ‘inter-event’ time  $t_i$  between the two droughts of duration  $d_i$  and  $d_{i+1}$  and severity  $s_i$  and  $s_{i+1}$  are, respectively, less than the predefined critical duration  $t_c$ , the mutually dependent drought events were pooled to form a drought event as (Zelenhasic and Salvai 1987):

$$d_{\text{pool}} = d_i + d_{i+1} \tag{4a}$$

$$S_{\text{pool}} = s_i + s_{i+1} \tag{4b}$$

Similar to the above, the two droughts can also be pooled if the ratio of inter-event excess-volume  $v_i$  to preceding deficit volume  $s_i$  is less than the predefined critical value  $p_c$ . Since these two methods are not consistent in some cases, Madsen and Rosbjerg (1995) suggested to pool the two subsequent events using Eq. 4a,b if (a) the inter-event time is less than or equal to a critical duration  $t_c$  and (b) the ratio of inter-event excess-volume and



- $Q_j$  = truncation level
- $d_i$  = drought duration
- $s_i$  = deficit volume (severity)
- $t_i$  = inter-event time
- $v_i$  = inter-event volume

**Fig. 3** A definition sketch of drought events



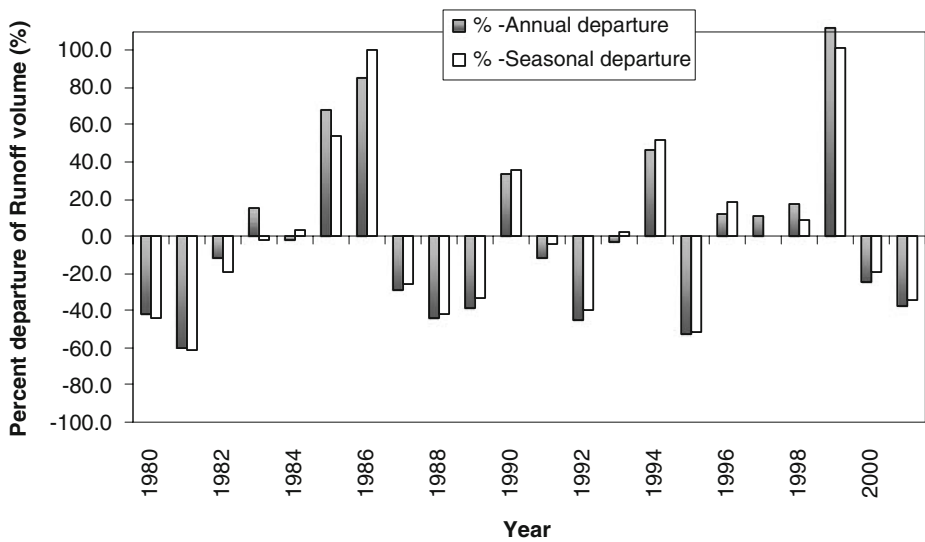


Fig. 4 Percentage departure of annual and monsoon runoff volume for Betwa at Basoda

preceding deficit volume is less the critical ratio  $p_c$ . A modification based on inter-event time and volume criterion (IC) (Tallaksen et al. 1997) suggested

$$d_{pool} = d_i + d_{i+1} + t_i \tag{5a}$$

$$s_{pool} = s_i + s_{i+1} - v_i \tag{5b}$$

Eqs. 5a and b are used to identify the drought characteristics in this study.

### 3.3 Proposed Drought Severity Index

Since the length of rainy season in Betwa Basin varies from 90 to 100 days and nearly 80–85% of the annual runoff occurs during this period only, a few heavy showers will suffice to produce the flow above the corresponding truncation level, and therefore, most of the independent hydrological droughts will terminate in the monsoon season. Therefore, it is reasonable to assume the maximum duration of an independent drought event not to exceed one year. To further describe the degree of hardship due to a drought event, a drought severity index ( $DSI_c$ ) of independent drought events is proposed and defined as a function of the ratios of (1) deficit flow volume to corresponding volume of the truncation level and (2) duration of deficit flow to the maximum possible duration of the independent streamflow drought event (= 365 days). Expressed mathematically,

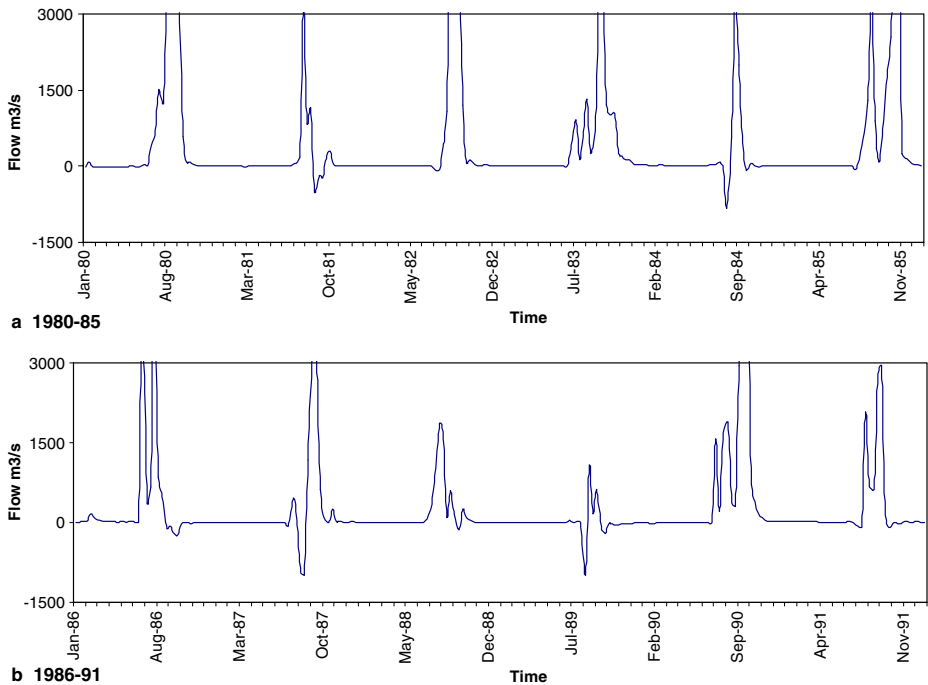
$$DSI_c = \frac{V_d}{V_{TL}} \frac{d_c}{d_m} \tag{6}$$

where  $V_d$  = deficit streamflow volume for the duration of drought event,  $V_{TL}$  = expected streamflow volume at truncation level flow for the duration of drought event,  $d_c$  = duration of independent drought event, and  $d_m$  = maximum duration of an independent drought event. In this study,  $DSI_c$  is used to define droughts as mild, moderate, severe or extreme.

#### 4 Analysis and Discussion of Results

The above 10-daily river flows when plotted (not shown) for typical drought and wet years showed substantial deviation in the flow magnitude of a month in dry and wet years. The percentage departure of annual and rainy season runoff from their respective means runoff values for Basoda are shown in Fig. 4. It is seen that in 1980, 1981, 1987–1989, 1995, 2000, and 2001, both annual and seasonal runoff were significantly less than the corresponding mean runoff at Basoda. For example, runoff departures were  $-53\%$  during severe drought in 1989, and the runoff surplus by  $+75\%$  and  $+100\%$  in exceptionally wet years, 1985 and 1999, respectively.

In severe drought year 1989, annual runoff departures up to  $-44\%$  from mean at Shahjina were observed, and in wet years 1985 and 1999, the runoff was surplus by  $+55\%$  and  $+94\%$  of mean annual runoff, respectively. However, the runoff behaviour was little different in lower reach at Shahjina and the seasonal runoff in 1982, 1985, 1990, and 1993 was less than the seasonal mean runoff by  $-40$  to  $-60\%$ , and the annual runoff considerably surplus by  $+50$  to  $+95\%$  of mean annual runoff during the same years. It indicates that the lower river reach with perennial flow contains significantly surplus annual runoff compared to the average annual runoff though the rainy season runoff was substantially less than its mean. However, the upper reach of Betwa at Basoda shows consistently the seasonal and annual runoff departures, which can be attributed to the following: (1) Uneven and erratic distribution of rainfall in the large Betwa basin. (2) Significant base flow contribution during lean period in the lower reaches. (3) Flow contribution from some unknown source



**Fig. 5** Flow deviation with respect to the variable truncation level for Betwa at Shahjina for the years 1980–1985 and 1986–1991

**Table 3** Streamflow drought events and their severity index for Betwa at Basoda site (1980–2001)

Sl. No.	Year of event	Onset date	Termination date	Duration	Severity (MCM)	Expected Runoff (MCM)	DSI <sub>e</sub>	Category of drought severity
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	
1	1980	Jan. 1, 1980	Jun. 10, 1980	160	-5.53	18	-0.12	Moderate
2	1981	Aug. 20, 1981	Dec. 20, 1981	120	-160	379	-0.14	Moderate
3	1984	Jul. 1, 1984	Jul. 30, 1984	30	-49	72	-0.06	Moderate
4	1986–1987	Sep. 1, 1986	Jan. 30, 1987	150	-115	207	-0.23	Severe
5	1988	Aug. 10, 1988	Sep. 20, 1988	50	-67	506	-0.02	Mild
6	1989–1990	Sep. 10, 1989	Jun. 30, 1990	270	-20	61	-0.25	Severe
7	1991	Sep., 20, 1991	Dec. 20, 1991	100	-34	147	-0.06	Moderate
8	1992–1993	Sep. 20, 1992	Jun. 30, 1993	260	-69	130	-0.37	Severe
9	2000–2001	Aug. 1, 2000	Jun. 30, 2001	310	-221	780	-0.24	Severe

in the lower reach. The plots (not shown) of runoff departure for Rajghat and Mohna sites also supported these attributes.

Except for the perennial river courses at Mohna and Shahjina, the other stream courses showed an intermittent characteristic, and at these locations, the probability of zero flow, for example, at Basoda, varied from 0.08 to 0.38 during February–June. At Rajghat, it was little lower, varying from 0.03 to 0.35; and it varied from 0.02 to 0.58 at Garauli during December–June. Based on these probabilities, the monthly flow duration curves for Betwa and Dhasan rivers were derived. Figure 2 shows the curves for Betwa at Basoda. These were utilized to estimate different dependable flows, and the values of variable truncation levels were obtained for 75% probability level for each month (Table 2). These values were used to distinguish the deficit and surplus flow periods, as shown in Fig. 5 for Shahjina, and independent drought events identified using the above pooling procedure.

Since 10 daily flow data were utilized, the minimum deficit flow duration was 10 days. Figure 5 exhibits some short duration (one or two 10-daily time step) surplus and deficit events. For example, a drought started during third 10-d step in August 1981 and deficit flow continued till second 10-d step of Dec. 1981, two inter-event surplus events occurred

**Table 4** Streamflow drought events and their severity index for Betwa at Rajghat site (1971–1992)

Sl. No.	Year of event	Onset	Termination	Duration	Severity-MCM	Expected runoff MCM	DSI <sub>e</sub>	Category of drought severity
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	
1	1973	10 Jan	20 Mar-1970	70	-4.3	37.0	-0.02	mild
2	1976	20 Sep-1976	30 Nov-1976	70	-27.6	204.4	-0.03	mild
3	1979	1 Aug-1979	10 Dec-1979	130	-698.9	1,413.4	-0.2	Severe
4	1980	10 Jan-1980	20 Jun-1980	160	-12.2	41.2	-0.13	Moderate
5	1981	20 Aug-1981	30 Sep-1981	40	-246.4	638.2	-0.04	mild
6	1984	1 Jul-1984	10 Aug. 1984	40	-191.4	452.8	-0.05	Moderate
7	1986–1987	20 Aug. 1986	30 Jan-1987	160	-87.8	783.3	-0.05	Moderate
8	1989–1990	10 Sep-89	10 Jun-90	270	-120.3	375.6	-0.24	Severe
9	1992	1 Jul-1992	10 Aug-1992	40	-195.0	452.8	-0.05	Moderate

**Table 5** Streamflow drought events and their severity index for Dhasan at Garauli site (1982–2001)

Sl. No.	Year of event	Onset date	Termination date	Duration	Severity-MCM	Expected runoff MCM	DSI <sub>c</sub>	Category of drought severity
(1)	(2)	(3)	(3)	(4)	(5)	(6)	(7)	(8)
1	1984	Jul. 10, 1984	Aug.10, 1984	30	-93.8	294.9	-0.03	Mild
2	1986–1987	Aug. 20, 1986	Aug. 20, 1987	320	-250.4	667.3	-0.33	Severe
3	1988–1989	Oct. 20, 1988	Jun. 20, 1989	240	-42.6	59.5	-0.47	Severe
4	1989–1990	Nov. 10, 1989	Jun. 10, 1990	240	-15.9	17.2	-0.61	Extreme
5	1994	Oct. 10, 1994	Nov. 30, 1994	40	-12.4	54.0	-0.03	Mild
6	1995–1996	Sep. 20, 1995	Jan. 20, 1996	90	-94.8	227.3	-0.10	Moderate
7	2000	Aug. 1, 2000	Sep. 30, 2000	60	-280.2	880.8	-0.05	Moderate

during first 10-d step of October, and again during first 10-d step of November 1981. To decide whether the drought period is counted from August 20 to December 20, 1981 or it be treated as terminated due to short duration inter-event surplus, Tallaksen et al. (1997) and Kjeldsen et al. (2000) ignored such minor peaks of very short period. It is because of intervening small wet spells terminating the negative impacts of the prolonged drought. For pooling, the inter-event critical duration ( $t_c$ ) was taken as three ten-daily time steps (= 30 days) and the critical volume ratio ( $p_c$ ) defined as the ratio of inter-event excess volume to preceding deficit volume for critical duration was taken as 1.0.

The identified independent drought events for different sites are given in Tables 3, 4, 5, 6 and 7, which also describe their duration, severity, intensity, and DSI<sub>c</sub>. Here, it is noted that the drought duration in col. 5 in the tables is the multiple of 10 for the reason of 10-daily data used. Based on DSI<sub>c</sub>, Betwa droughts were categorized as shown in Table 8. As seen from the table, the upper reaches of the Betwa River up to Basoda faced four severe droughts (Table 3) during 1986–1987, 1989–1990, 1992–1993 and 2000–2001 with DSI<sub>c</sub> as 0.23, 0.25, 0.37 and 0.24, respectively. On the other hand, the lower reaches of Betwa at

**Table 6** Streamflow drought events and their severity index for Betwa at Mohna site (1984–2001)

Sl. No.	Year of event	Onset	Termination	Duration	Severity MCM	Expected runoff MCM	DSI <sub>c</sub>	Category of drought severity
(1)	(2)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1	1986–1987	20 Aug. 1986	10 Jul 1987	320	-591.1	1757.8	-0.30	Severe
2	1988–1989	20 Oct-1988	30 Apr-1989	200	-277.0	732.7	-0.21	Severe
3	1989–1990	10 Sep-1989	10 Apr-1990	210	-429.5	738.1	-0.33	Severe
4	1991	20 Sep-1991	30 Oct-1991	40	-117.7	332.7	-0.04	Mild
5	1992	1 Jan-1992	20 Jul-1992	180	-73.0	199.0	-0.18	Moderate
6	1992–1993	20 Nov-1992	20 Aug- 1993	270	-670.5	1,653.2	-0.30	Severe
7	1994–1995	10 Oct-1994	10 Jul-1995	270	-121.2	263.3	-0.34	Severe
8	1995–1996	10 Nov-1995	10 July-1996	240	-56.1	223.0	-0.17	Moderate
9	1996–1997	20 Nov 1996	20 Jun-1997	230	-25.5	162.0	-0.10	Moderate
10	2000	1 Aug-2000	30 Aug-2000	30	-306.3	2,044.4	-0.01	Mild
11	2001	10 Sep-2001	30 Oct-2001	50	-349.3	586.1	-0.08	Moderate

**Table 7** Streamflow drought events and their severity index for Betwa at Shahjina 1980–2001)

Sl. No.	Year of event	Onset	Termination	Duration	Severity MCM	Expected runoff MCM	DSI <sub>e</sub>	Category of drought event
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	
1	1980	20-Feb-1980	20-May-1980	90	-87	205	-0.11	Moderate
2	1981	10-Aug-1981	10-Sep-1981	30	-790	1,413	-0.05	Moderate
3	1986–1987	20-Aug-1986	10-Aug-1987	365	-1819	4,364	-0.4	Severe
4	1987–1988	20-Dec-1987	20-Dec-1988	180	-12	247	-0.02	Mild
5	1988–1989	20-Dec-1988	10-Jun-1989	180	-48	305	-0.08	Moderate
6	1989–1990	10-Sep-1989	30-Jun-1990	290	-554	1,143	-0.39	Severe
7	1992	20-Jan-1992	29-Feb-1992	50	-104	264	-0.05	Moderate
8	1992	1-Jun-1992	20-July-1992	50	-126	251	-0.07	Moderate
9	1993	1-Aug-1993	30-Aug-1993	30	-748	2,723	-0.02	Mild
10	1995	1-Oct-1995	30-Nov-1995	60	-69	263	-0.04	Mild
11	1998	1-Nov-1998	10-Jan-1998	70	-32	199	-0.03	Mild
12	2000	1-Aug-2000	30-Dec-2000	150	-766	3,822	-0.08	Moderate
13	2001	1-Aug-2001	30-Sep-2001	60	-1463	3,481	-0.07	Moderate

Shahjina (Table 7), the severe drought events can be identified in 1986–1987 and 1989–1990 with DSI<sub>e</sub> values equal to 0.40 and 0.39, respectively. The drought events of 1992–1993 and 2000–2001, however, did not continue for a long duration as they did in the upper reaches at Basoda. Furthermore, DSI<sub>e</sub> of these events was also less than 0.20. The upper reach of Dhasan basin up to Garauli (Table 5) also faced severe droughts in 1986–1987 and 1988–1989 with respective significantly high DSI<sub>e</sub>-values of 0.47 and 0.33, and an extreme drought with DSI<sub>e</sub> equal to 0.61 in 1989–1990. In the middle reach of Betwa at Mohna (Table 6), along with other moderate and mild drought events, the severe droughts occurred in 1986–1997, 1988–1989, 1989–1990, 1992–1993, and 1994–1995. Notably, the patterns of drought events in both middle and upper reaches appear to be similar to each other. Furthermore, as seen from Tables 3, 4, 5, 6, 7, most severe drought events started during August–November and prolonged till June.

## 5 Limitation of the Study

The results of this analysis consist of all the limitations of the used truncation level approach. Further testing of the proposed DSI<sub>e</sub> index is necessary for greater reliability. The results are however useful for further quantification of water conservation/storage requirements for management of Betwa droughts.

**Table 8** DSI<sub>e</sub> based classification of droughts

DSI <sub>e</sub>	Drought strength
<0.01	Weak
0.01 to 0.05	Mild
0.05 to 0.2	Moderate
0.2 to 0.5	Severe
>0.5	Extreme

## 6 Conclusions

The following conclusions can be drawn from this study:

1. River course of Betwa up to Basoda and Rajghat showed intermittent streamflow characteristics, but it was perennial at Mohna and Shahjina sites.
2. Substantial (four to five times) deviation in runoff magnitude from corresponding mean flow was observed during typical drought and wet years.
3. The annual runoff volume in the lower perennial river course was significantly surplus even though the rainy season runoff was considerably less than its mean. However, the upper reach of Betwa at Basoda and Rajghat sites showed positive departure of annual runoff when seasonal runoff was positive, and vice versa.
4. Most of the severe drought events in Betwa basin had onset period during August–November. The drought events starting after November were of mild to moderate nature.
5. When the upper reaches of Betwa faced severe droughts, the lower reaches often faced moderate or mild droughts.

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