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CHAPTER 24

Assessment of Surface Storage Requirement for Mitigating Drought

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24.1 INTRODUCTION

A global growth in rural water requirements of semi-arid and dry sub-humid regions is observed in the last few decades (Dalezios & Bartzokas 1995), mainly due to expansion in agricultural activities and compelling need to meet increasing domestic and industrial demands due to rising population. Climatic variability, change and uneven distribution of resources also create water shortages and interrupt the usual water-linked activities, which lead to droughts. The availability of water resources, particularly during the lean (non-rainy) period is generally scarce in drought-prone areas. In India, for major part of the country, the rainy season or monsoon season (June-October) and non-rainy season (November-May) are clearly defined for all practical purposes. The knowledge of the amount and time distribution of available river flows is vital in formulation of the year plan for various water uses such as water supply for irrigation, industrial and drinking needs, in-streamflow maintenance, and hydro-power generation.

Rainfall is known to be the principal source of surface and groundwater flows in semi-arid and arid regions of India (Subramanya 1984). Groundwater flows determine the availability of lean season flow in the absence of precipitation over a prolonged period. The flows in major rivers are, however, attributed to groundwater/sub-surface flows or snowmelt runoff. The lean period discharge in a stream is affected by the temporal and spatial reduction or distribution of precipitation, including evaporation losses; type of soil and plant cover; catchment area, mean altitude, slope, drainage density, relief, etc.; and existence of lakes and swamps.

Low flow analyses to characterize droughts must address the magnitude, duration, and frequency of occurrence of low flows (Institute of Hydrology 1980; McMohan and Arenas 1982). The magnitude of low flow is the minimum value of 10-days average flow through a given section of stream during a specified period of time. It determines the amount of water available for use. The duration depends on natural as well as human generated conditions, and may reflect some specified water use practices (for example, irrigation cycle). It also depends on the period of water deficit tolerance. The frequency of occurrence of low flows reflects the risk of failure of a water supply scheme.

Since the deficiency of rainfall of sufficient magnitude over a prolonged duration and subsequent reduction in streamflow intervene the normal agricultural and economic activities, it adversely affects the normal life pattern and agriculture production in the Ken Basin in Bundelkhnd region in central India. According to India Meteorological Department, an area is designated as the drought-prone area if the rainfall is less than 75% of the normal (i.e. long term mean of annual rainfall) in 20% of the years examined. Therefore, it is important to distinguish the flow availability during a drought year and a normal (or non-drought) year. The truncation level (an analytical interpretation of the expected availability of water flow in a river) approach is widely employed in hydrological drought analyses utilizing the time series of river flows (annual, monthly or daily discharge) (Yevjevich 1967; Sen 1980; Kjeldsen et al. 2000). The flow in a river below the truncation level represents a drought; otherwise it is a normal or wet period.

The truncation level is generally taken as a certain percentile flow at a site, and assumed steady during the year. Mathier et al. (1992), however, used the monthly variable truncation levels. Because of the erratic and uneven distribution of rainfall in time and space, the employment of the variable truncation approach appears to be more appropriate than the fixed one (i.e., single annual value), especially for ephemeral streams that remain completely dry in a significant period of the year. Furthermore, in literature, this approach does not appear to have been applied to drought analyses of ephemeral streams. Thus, the objective of the present study is to (a) analyze the past drought events for duration and severity (or cumulative deficit below a desired demand level (Sharma 2000)) of two ephemeral Sonar and Bearma river basins using the monthly truncation approach, (b) assess the availability of flow during normal and drought years, and (c) provide an approximate estimate of the artificial surface storage for drought proofing.

24.2 STUDY AREA

24.2.1 Sub-basins

The Sonar and the Bearma river sub-basins of the Ken River system lie in the Bundelkhand region of Madhya Pradesh (M.P.). The index map of the sonar and Bearma sub-basins is shown in Fig. 24.1. The Ken river is one of the major tributaries of River Yamuna joining from its south river-bank. The Sonar and

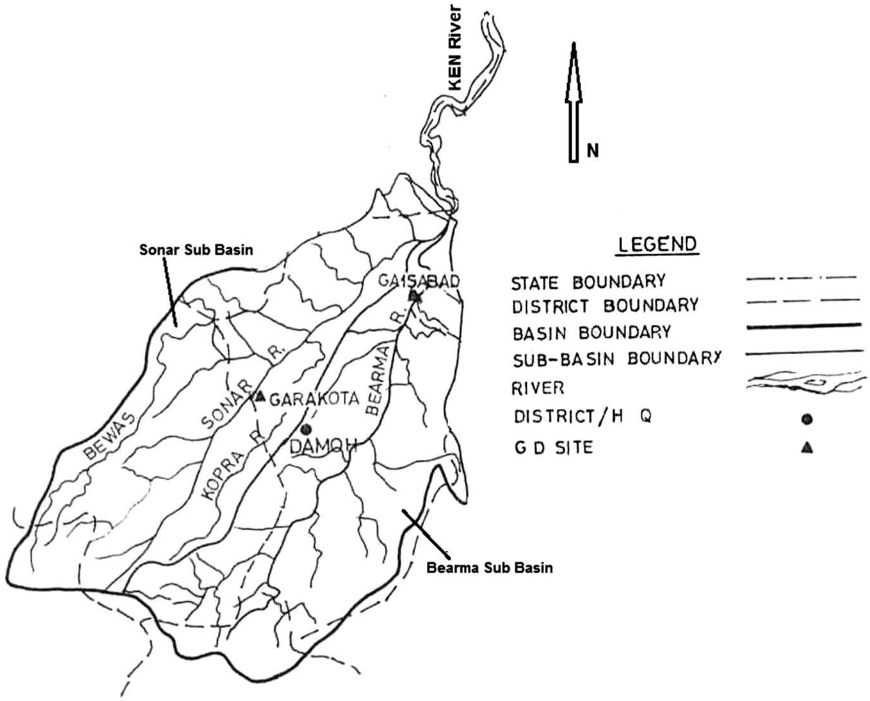

Figure 24.1. Index map of the Bearma and Sonar sub-basins of Ken River Basin

Bearma sub-basins contribute, respectively, about 23% and 21% of the area of Ken basin. The former is located between east longitudes 78°30′ and 79°55′ and between north latitudes 23°18′ and 24°22′, covering a total catchment area of 6550 sq. km. Its leaf type shape has an average width of about 40 km. It rises in the Raisen district and its major part falls in the Sagar (about 53%) and Damoh (about 36%) districts. This study utilizes the flow data of Garakota site (catchment area = 1750 sq. km).

The Bearma sub-basin is located between east longitudes 78°54′ and 80°00′ and between north latitudes 23°07′ and 24°18′ covering a total catchment area of 5890 sq. km. This river originates from Narsinghpur district and its major part (about 69%) fall in the Damoh district. The sub-basin has an elongated shape and low drainage density. The discharge records of the Gaisabad site (intercepting catchment area = 5803 sq. km.) has been used in the study.

24.2.2 Water Resources Potential and Existing Irrigation

The annual surface water yield of the Bearma and Sonar sub-basins at 75% dependability level is reported to be 2419 and 1439 MCM (million cubic meters). The utilizable groundwater potential is estimated as 524 and 439 MCM, respectively (NWDA 2002). In the Bearma sub-basin, the existing annual irrigation from surface water and groundwater is indicated to be 170.49 and 357.73 sq. km. with the corresponding utilization of 111.67 and 64 MCM, respectively. On the other hand, the annual irrigated areas from surface and groundwater in the Sonar sub-basin are 18.55 and 1036.59 sq. km. with the corresponding utilization of 16.18 and 89 MCM, respectively (NWDA 2002). Thus, the current annual surface water utilization for irrigation is about 4.6% and 1.2% of the annual water yield in the Bearma and Sonar sub-basins, respectively. However, the groundwater utilization in the respective sub-basins is 17.94 and 20.27%. Since the irrigated areas represent only 23.39% and 28.24% of gross cropped areas of the respective sub-basins, these can be implied as to be drought-prone areas according to the Central Water Commission (New Delhi) criterion: "If 30% area is irrigated in drought-prone area (taluka/tahsil), it can reasonably sustain a stable agriculture."

24.2.3 Climate and Soils

The study area belongs to dry sub-humid climate with a single rainy season (July-September) followed by dry winter and a very dry summer. Rainfall occurs mostly in monsoon months (June-September) with very few winter showers in the region. Mean annual rainfall in the region is between 1019 mm and 1224 mm with a maximum and minimum rainfall recorded as 2087 mm at Sagar in 1981 and 330 mm at Hatta in 1979, respectively. The rainfall over the sub-basins is highly variable and unevenly distributed.

Soils found on hill and hill ridges of the area vary from fine loamy to coarse loamy in texture and from greyish brown to dark reddish brown in colour. They are of shallow depth, contain low nutrient and/or organic matter, are highly erodible, and have poor water retention capacity. Plateau soils vary from yellowish brown to dark brown, and these are found in plane to gently undulating terrain of the Sagar and Damoh districts of Madhya Pradesh (India). Pediment soils occur on gently to undulating terrain in the sub-basins comprising the vast pediment and piedmont plains. They range from shallow to deep, coarse to medium in texture, but poor in nutrient. The fine loamy soils of alluvial plain are deep and rich in nutrient. Soils of disserted flood plain are very deep, well drained calcareous, gravelly, and posses abundant lime nodules. These are fine loamy in texture, yellowish brown in colour and low in organic matter content.

24.2.4 Land-use and Agricultural System

The forest areas in the Sonar and Bearma sub-basins encompass, respectively, 25.3% (1996–97) and 43.63% (1998–99) of their geological areas. Based on the land-use particulars of the Sonar and Bearma sub basins for the respective years 1998–99 and 1996–97, the crops largely grown in the sub-basin are wheat, paddy, maize, soyabean, jowar, arhar, ground nut, lintil, and sunflower. Wheat followed by pulses and oilseeds are major crops grown in Rabi season. Paddy and soyabean are the other dominating crops grown during Kharif season. Perennial and summer crops are not grown in the area. In general, the region has poor agricultural yield mainly due to widely practiced rainfed agricultural cropping system. The potential evapotraspiration in non-rainy months of the year (October-May) is exceedingly large compared to the corresponding monthly rainfall as shown in Fig. 24.2. Future agricultural and economic growth can, however, be realized by (a) extending irrigation facilities through the introduction of storage schemes and (b) applying soil moisture conservation practices (NIH 2001).

24.3 METHODOLOGY

24.3.1 Estimation of Truncation Level

Since a drought is defined as a period during which the streamflow is below the pre-set truncation level, it is necessary to determine the truncation level for a stream in terms of its flow. To this end, it is necessary to derive first the flow duration curves using monthly flow data. For ephemeral streams, zero flows are considered in the probability analysis as follows:

The number of 'zero' and 'non-zero' flow values for each month can be separated from the available flow records to determine the percentage probability of occurrence of zero flow in each month as:

$$P_i = \frac{X_i}{N} \tag{24.1}$$

where P_i = probability of zero flow in the i^{th} month; i = an integer varying from 1 to 12; X_i = number of zero flow values in the i^{th} month; and N = total number of flow records for the i^{th} month (i.e., number of years of records). Then, the non-zero flow values for each month are arranged in the descending order to rank the

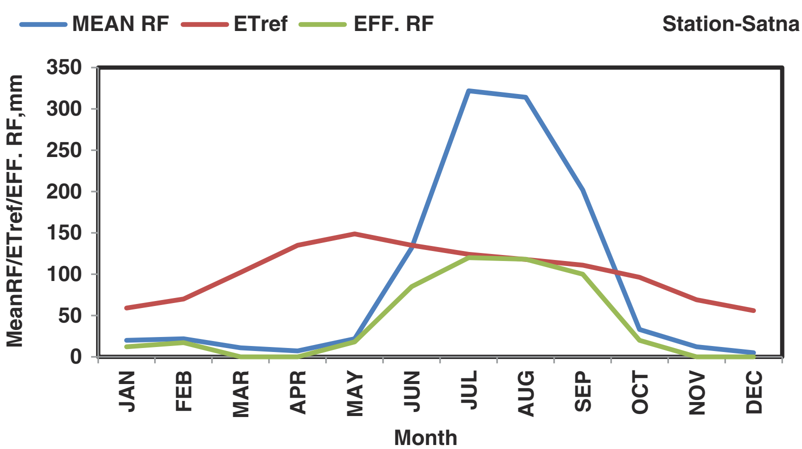

Figure 24.2. Plots of mean monthly values of rainfall (RF), potential evapotranspiration (ET_{ref}) and effective rainfall (EFF-RF)

highest as 1 and the lowest as (N-X_i) for computation of the joint probability of exceedance as:

$$Pnz_{j,i} = (1 - P_i)\frac{R_{j,i}}{N - X_i} \tag{24.2}$$

where $R_{j,i}$ = rank of the j^{th} flow value of the i^{th} month; $Pnz_{j,i}$ = joint probability of exceedance of the j^{th} value of the non-zero flow in the i^{th} month; i = an integer varying from 1 to 12; and j = an integer varying from 1 to (N-X_i). Thus, the flow duration curve for each month can be derived by plotting the joint probability of exceedance of non-zero flow values ($Pnz_{j,i}$) against the corresponding discharge values, and a truncation level corresponding to the fixed, e.g., 75 percentile (Kjeldsen et al. 2000), can be determined.

24.3.2 Estimation of Drought Duration and Severity

For estimation of drought duration and severity from intensity derivable for a known truncation level, one needs to describe the drought for ephemeral river basins running dry in lean seasons and leading to zero value of the truncation level. This problem specially occurs when a drought starting in a rainy (monsoon) season continues to the following dry period; should the drought from the rainy season continue to this dry period? If a drought occurs in the rainy season and continues to the dry season with a zero truncation level, the drought duration increases without altering the deficit volume. As soon as the truncation level attains a value greater than zero with setting up of the next rainy season, the drought is assumed to continue if the river flow is below the corresponding truncation level. On the other hand, if the river flow exceeds the truncation level, the drought is assumed to break, as illustrated below:

As shown in Fig 24.3, a sequence of drought events can be identified from the streamflow data using a suitable value of truncation level. Then, these events can be characterized by their duration, d_i, deficit volume (severity), s_i, and the time of occurrence, t_i. During a prolonged dry period, the flow often exceeds the threshold for a short period of time, and therefore, a long drought spell is divided into a number of minor drought events that will be mutually dependent. An appropriate definition of drought events will, however, include some kind of pooling to define an independent sequence of droughts (Tallaksen et al. 1997). According to Zelenhasic and Salvai (1987), if the 'inter-event' time, t_i, between two droughts with characteristic (d_i, s_i and d_{i+1}, s_{i+1}) is less than a predefined critical duration, t_c, the two events can be combined to define a single drought event as follows:

$$d_{pool} = d_i + d_{i+1};\ s_{pool} = s_i + s_{i+1} \tag{24.3}$$

A similar, but inter-event volume-based, approach can also be employed by pooling the two droughts if the ratio of the inter-event excess-volume, v_i, to the preceding deficit volume, s_i, is less than the predefined critical value p_c. For

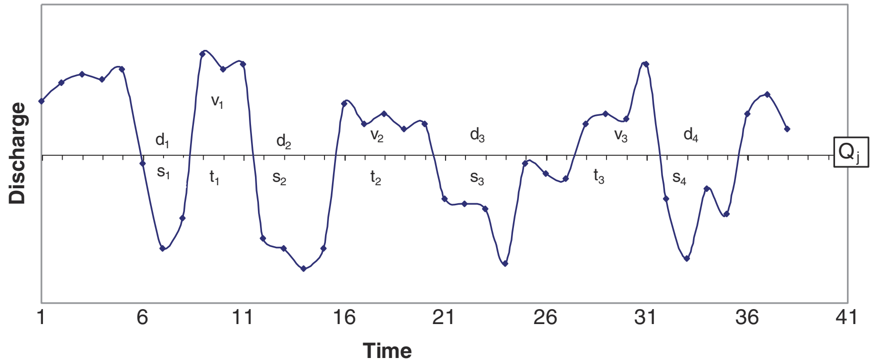

Figure 24.3. A definition sketch of streamflow drought events. Q_j = truncation level, d_i = drought duration, s_i = deficit volume (severity), t_i = inter-event time, v_i = inter-event volume

consistency reason, Madsen and Rosbjerg (1995) combined both the approaches with the following considerations: (i) the inter-event time is less than or equal to a critical duration, t_c, and (ii) the ratio of inter-event excess-volume to preceding deficit volume is less than a critical ratio, p_c. The resulting drought characteristics are given by Eq. 24.3, which was later revised slightly by Tallaksen et al. (1997), and an inter-event time and volume-based approach was suggested as:

$$d_{pool} = d_i + d_{i+1} + t_i;\ s_{pool} = s_i + s_{i+1} - v_i \qquad (24.4)$$

This equation is used in this study for computation of drought characteristics, viz., duration and severity.

24.3.3 Assessment of Storage Requirement for Drought Proofing

For an assessment of the storage requirement for drought proofing, an artificial reservoir of an appropriate capacity is assumed to exist at the outlet of the basin to augment the deficit during droughts. If the volumetric capacity of the reservoir is V_s, the corresponding depth of storage is H_s, and the depth of evaporation losses from free water surface for a given time unit (month) is $Ed_{j,}$ (where j = an integer varying from 1 to total number of months in the record), the maximum evaporation loss in the j^{th} month (Evm_j) will be:

$$Evm_j = \left[\frac{V_s}{H_s}\right] Ed_j \qquad (24.5)$$

Assuming the water-spread area varies with the storage linearly, the actual evaporation loss from available storage (Eva_j) (less than Evm_j) can be estimated as:

$$\mathrm{Eva_j} = \left[\frac{\mathrm{Evm_j}}{\mathrm{V_s}}\right]\mathrm{Sa_j} \tag{24.6}$$

The available storage (Sa_j) can be computed from water balance as:

$$\mathrm{Sa_j} = \mathrm{So_j} + \mathrm{Q_j} - \mathrm{Eva_j} - \mathrm{TLj} \tag{24.7}$$

where So_j = initial storages for the j^{th} month (i.e., $So_j = Sa_{j-1}$), Q_j = inflow to the storage in the j^{th} month, TL_j = truncation level for the j^{th} month and $0 \le Sa_j \le V_s$. A coupling of Eqs. 24.5–24.7 leads to

$$\mathrm{Sa_j} = \left[\frac{\mathrm{So_j} + \mathrm{Q_j} - \mathrm{TL_j}}{\left(1 + \frac{\mathrm{Ed_j}}{\mathrm{Hs}}\right)}\right] \tag{24.8}$$

For Ed_j, the evaporation losses were determined from the Penman (1963) method using meteorological data of the station at Jawaharlal Nehru Krishi Vishwa Vidhyalaya, Jabalpur, available from 1983 to 1995.

Also, there is an alternate procedure suggested by Adeloye et al. (2001) and McMahon and Adeloye (2005), which follows mass balance equation for assessing reservoir capacity using behaviour simulation and takes into account net evaporation loss from the reservoir surface

$$\mathrm{Sa_j} = \mathrm{So_j} + \mathrm{Q_j} - \mathrm{D_j} - \mathrm{E_j};\, 0 \le \mathrm{Sa_j} \le \mathrm{V}_s \tag{24.9}$$

where Sa_j is the storage at end of given month (L^3); So_j is the storage at the beginning of j^{th} month (L^3); Q_j is the inflow during j^{th} month (L^3); D_j is the release during j^{th} month (L^3); E_j is the evaporation loss during j^{th} month (L^3); and V_s is the reservoir storage capacity (L^3). The release D_j is different from the demand; indeed, depending on the available water and the operating policy, the release may be equal to, less than, or more than the demand. The main thing to ensure is that the inequality at the of equation (Eq. 24.9) is always satisfied.

Evaporation (L^3) requires the exposed surface area of the reservoir which is not a constant but varies with So_j in an assumed linear manner as follows:

$$A_j = aSo_j + b \tag{24.10}$$

where A_j = water spread area in j^{th} month (L^2); and a, b are constants. We can replace the area during the j^{th} month by the average, A_{vj}, over the month, i.e.,

$$A_{vi} = 0.5(Ao_j + Aa_j) = b + 0.5a(So_j + Sa_j) \tag{24.11}$$

$$\therefore E_j = e_j A_{vj} = e_j(b + 0.5a(So_j + Sa_j)) \tag{24.12}$$

where e_j = net (evaporation less direct rainfall) evaporation (L). Substituting the above for E_j in the mass balance equation and simplifying will give the required equation:

$$Sa_j = \lfloor So_j(1 - ae_j/2) + Q_j - D_j - be_j \rfloor / (1 + ae_j/2) \tag{24.13}$$

24.4 RESULTS AND DISCUSSION

Meteorological droughts are known to recur in the Sonar and Bearma sub-basins with an average frequency of once in 5 years (NIH 2001). The mean annual rainfall of these sub-basins which varies from 1014 mm to 1218 mm (out of which about 900–1000 mm is received during the monsoon period) is sufficient in normal conditions to meet the water requirement for different kharif crops grown in the region. However, because of the practiced rainfed irrigation as above, the untimely occurrence of rainfall greatly affects the kharif production. Here, it is noted that groundwater supply in the region is fairly uneconomical because of the deep water table. On the basis of general physiochemical characteristics of soils, shallow soils in the sub-basins appear to be unfit for crop cultivation due to their poor water retention capacity. However, the employment of soil and water management practices may make the deep to very deep soils tenable to water retention under rainfed/irrigated conditions (NWDA 2002).

An investigation of the available monthly streamflow records of the Sonar and Bearma rivers revealed that these rivers ran dry for few months during the lean season. The monthly flow hydrographs of Sonar at Garakota during typical drought (Fig. 24.4a) and wet (Fig. 24.4b) years show a substantial difference in the magnitude of flow in the corresponding months of the drought and wet years. For instance, in a typical drought year 1986, the flows in July and August were 350 MCM and 52 MCM, respectively, whereas the flows were of the order of 585 MCM and 500 MCM, respectively, during the typical wet year 1994. Similarly, the flow hydrographs of the Bearma river at Gaisabad (Figs. 24.4c and 24.4d) witness large reductions in streamflows during drought years compared to those in the corresponding months of the wet years. The analysis of data revealed that there have been a total annual flow departure from its mean by −86% and −66% during severe drought years 1979 and 1989, respectively, whereas the annual rainfall (mm) departed from its mean was in the order of −62% and −35%, respectively. Furthermore, a comparison of the total annual flow in Bearma river at Gaisabad during a severe drought year 1979 (458 MCM) with that of the typical wet year of 1978 (11398 MCM) shows about 25-fold deviation. It exhibits high inter-annual flow variability in both the streams. In addition, extensive reductions in the quantity of flows during the typical drought years were observed.

The probabilities of zero and non-zero flows in different months of the year were computed as described earlier (see Eq. 24.1) for both the rivers, and these are presented in Figs. 24.5 and 24.6. for the Sonar and Bearma rivers, respectively.