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Irrigation planning for sustainable rain-fed agriculture in the drought-prone Bundelkhand region of Madhya Pradesh, India

T. Thomas, P. C. Nayak and N. C. Ghosh

ABSTRACT

The recent spells of recurrent and consecutive droughts in the Bundelkhand region in Central India have led to uncertain rain-fed agriculture and its sustainability. Adequate knowledge of starting dates and lengths of dry spells has a considerable importance in rain-fed agriculture, irrigation planning, and various decision-making processes. The long dry spells incur heavy costs to the affected communities in the form of lost crop production and reduced crop yield, particularly in semi-arid regions. The sustainability of agriculture very much depends on the provision of supplemental irrigation during droughts, for which a detailed analysis of dry spells is a pre-requisite. An attempt has been made to study the temporal variation of dry spell lengths to identify whether it can be related to climate change. The dry spell analysis revealed that two critical dry spells with spell lengths of 10 days and more occurs invariably every year and therefore rain-fed agriculture needs adequate supplemental irrigation backup for sustainable operations under such a scenario. The supplemental irrigation requirements have been estimated for each critical dry spell period for all development blocks in each district, which will provide useful inputs to decision-makers for planning agricultural operations during an impending drought scenario.

Key words | critical dry spell, crop water requirement, irrigation management, probability analysis, rain-fed agriculture

T. Thomas
Ganga Plains South Regional Centre,
National Institute of Hydrology,
Walmi Campus,
Bhopal,
Madhya Pradesh,
India

P. C. Nayak (corresponding author)
Deltaic Regional Centre,
National Institute of Hydrology,
Siddartha Nagar,
Kakinada-533 003,
AP,
India
E-mail: *nayakpc@yahoo.co.in*

N. C. Ghosh
Ground Water Hydrology Division,
National Institute of Hydrology,
Roorkee-247667,
Uttrakhand,
India

INTRODUCTION

Based on the findings of various studies it is now becoming increasingly clear that there is a definite change in the global climate with an increasing trend in the average air temperatures and change in the rainfall distribution pattern, due to which the crop growth period is expected to shorten (IPCC 2008). The knowledge of the starting dates, spell lengths and frequency of critical dry spells (CDS) have a significant importance for achieving maximum benefits from dry land agriculture and also provide inputs to the various decision-making processes, including deciding suitable crop varieties of requisite maturity duration and also for planning supplemental irrigation and field agricultural operations. Dry spells also affect other vital sectors such as health, power generation, fisheries and water distribution systems, leading to a direct adverse impact on the economy (Jayawardene *et al*. 2005).

Since forecasting of dry spells is a difficult task due to the vagaries of nature and complexities involved in climate processes, it is generally felt that analysis for critical dry spell lengths is helpful for drought planning under rain-fed conditions. Dry spell is a period where the weather has been dry for an abnormally longer period of time, but not as severe as drought, but is very crucial for rain-fed agriculture in semi-arid areas (Wilhite & Glantz 1985). To achieve maximum benefits from dry land agriculture, as is the case in Bundelkhand region in Central India, the knowledge of distribution of dry spells within the monsoon season is valuable information for the success or failure of crops. When

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the spatial and temporal distribution of rainfall is erratic during the growing season, the crops may start to wilt, ultimately reducing the crop yield. The extent of damage depends on the frequency of occurrence of dry spells of various durations, the soil moisture holding capacity of soil and crop type. A dry spell can occur at the start, mid or late season of the crop growth period. When dry spells occur at the late season stage of a crop, the growing season gets shortened. It is reported that crop yields have been reduced significantly due to late season dry spells (Araya *et al.* 2010). Many authors have defined a dry spell as a spell length of non-consecutive days without appreciable rainfall (Stern 1980; Sivakumar 1992; Sharma 1996; Ceballos *et al.* 2004; Gong *et al.* 2005). In many studies, days with rainfall less than 0.10 mm/day have been considered as a dry day. However, sometimes, such analysis may not be useful for assessing the crop water demands, as it does not consider the evaporative demands of the crop. The severity of a dry spell not only depends on its frequency and duration, but also on the crop stage during which it occurs.

Reliable estimation of the onset and withdrawal of monsoon could help optimize rainwater use in semi-arid areas (Sivakumar 1992; Ati *et al.* 2002; Raes *et al.* 2004; Kipkorir *et al.* 2007; Mugalavai *et al.* 2008). The major causes of crop failure, particularly in semi-arid rain-fed agriculture, is due to the occurrence of frequent dry spells, with dry spell lengths of 10 days or more, depending on the soil–crop combination type (Segele & Lamb 2005; Araya *et al.* 2010). Information on the length of dry spells is useful in deciding suitable crop variety and can be used in decision-making with respect to provision of supplementary irrigation and other agricultural farming operations (Sivakumar 1992).

Several statistical methods have been used to determine drought risk, based on dry spells in daily precipitation series including Markov chain (Lana & Burgueño 1998; Martín-Vide & Gómez 1999) and various probability distributions namely, exponential, Eggenberger-Polya (Berger & Goossenes 1983) and truncated negative binomial (De Arruda & Pinto 1980; Nobilis 1986; Douguedroit 1987, 1990) have been tried. However, these distributions do not exhibit good fit to the extremes of the dry spell series (Gabriel & Neumann 1957; Flannigan & Harrington 1988; Perzyna 1994). Vicente & Begueria (2003) estimated the extreme dry spell risk in the middle Ebro valley and found that the generalized Pareto distribution combined with partial duration series gives better results than the Gumbel distribution fitted to annual maximum series.

Giuseppe *et al.* (2005) developed a model for dry and wet spells and a separate model for very long dry spells and evaluated the spell distribution between the two periods between 1970–2000 and 1860–1970 for four Italian sites and found that the probability of extreme dry spell has increased during the winter season, which is also the period during which the area receives considerable precipitation. Sivakumar (1992) conducted an empirical analysis of dry spells for agricultural applications in West Africa, and observed a pronounced reduction in drought risk for cereal crops from initiation phase to flowering phase. Belachew (2002) studied the sustainability of rain-fed agriculture in Ethiopia and found that two dry spells of 16 and 21 days occur in the Abraminch State area with a probability of 70 and 45%, whereas two dry spells of 13 and 17 days occur at Kola Shara Farmers' farmland with a probability of 94 and 79%, respectively.

Nasri & Moradi (2011) carried out frequency analysis of annual maximum dry spell lengths for Ishfan province in Iran using 10 distribution functions and the generalized logistic distribution was identified as the best regional distribution. As the dry period in 1 year is not necessarily the same in another year, the knowledge of behaviour of these patterns has become even more important to understand (Mathugama & Peiris 2011). Given that agriculturists are mainly concerned with actual crop water stress, the analysis would be more meaningful if it considered dry spells in relation to meeting crop water demands (Barron *et al.* 2003).

STUDY AREA

Bundelkhand is a cultural–geographic region in Central India, bounded by Vindhyan Plateau in the south, Yamuna River in the north, Ken River in the east and the Rivers Betwa and Pahuj in the west. It is located south of Yamuna River, between the fertile Gangetic plains stretching across northern Uttar Pradesh (U.P.) and the highlands of Central Madhya Pradesh (M.P.) and lies between 23°08′ N to 26°30′ N latitude and 78°11′ E to 81°30′ E longitude covering an area of 71,619 km^2. The map showing the Bundelkhand region is given in Figure 1.

Bundelkhand remains administratively divided between the two states of U.P. and M.P. Bundelkhand region in M.P. comprising six districts (as given in Table 1), despite its rich resources such as forests and minerals, is a region in deep distress and crisis. The region once known for its traditional water management systems namely, the Bundela and Chandelatanks, is now considered as a water-deficit drought-prone area owing to neglect of traditional systems. The advent of cultivating water-intensive commercial crops coupled with the lack of water resources development and management has led to constant water-stressed conditions and recurrent drought occurrences. About 82% of the population is dependent on agriculture. The analysis has been limited for the six districts of Bundelkhand region in M.P. since most of the river systems originate in these districts with practically no irrigation facilities being created owing to the rugged topography of the region. However, the remaining seven districts falling in U.P. have sufficient surface water storage structures with the rivers being perennial and ample scope for ground water exploitation too. Therefore supplemental irrigation planning is necessary for providing life-saving irrigation water to the standing crops during the CDS for the Bundelkhand region in M.P.

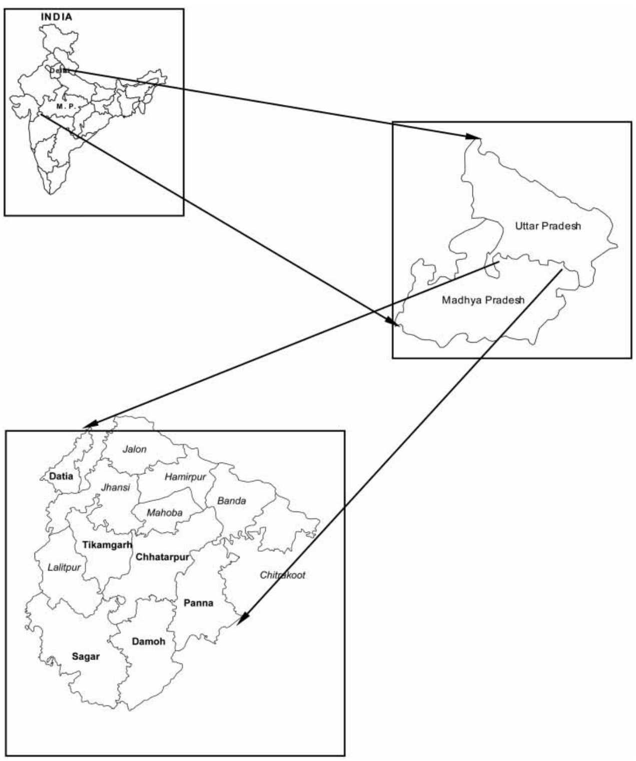

Figure 1 | Index map showing the Bundelkhand region.

The Bundelkhand region has a semi-arid to sub-tropical climate with the average annual rainfall varying between 825 mm in Datia district and 1,123 mm in Sagar district. More than 90% of the annual rainfall is received during south-west monsoons from mid-June to early October, but most of it is lost to runoff owing to very few irrigation schemes. In general, the rainfall pattern in this region is highly erratic and uncertain with very high coefficient of variation (>30%). The humidity ranges between 91 and 93% during July and August and 11 and 13% during April and May. Betwa, Bebas, Bina, Dhasan, Sonar, Bearma, Jamuni, Kopra and Ken are the major rivers draining into the River Yamuna, a major tributary of the River Ganga. The topography is highly undulating with rocky outcrops and boulder-strewn plains characterized by rolling hills and fertile valleys in the south, which slope down towards the Indo-Gangetic plains to the north. The elevation ranges between 600 m above mean sea level (msl) in the southern part and 150 m msl near the River Yamuna.

The Bundelkhand region is prominently composed of Vindhyan rocks represented by sandstone, limestone and shale in the southern part and granites with alluvium soils on top mixed with rocky and boulder outcrops. The major soils include alluvial, red and yellow, mixed red and black and medium black soils. Soil erosion is a persistent problem that is aggravated by the hilly landscape, high winds and the poor quality soils, leading to widespread growth of gullies.

The Bundelkhand region was densely forested until the late 18th century but extensive agricultural expansion, poor land management practices and large-scale commercial logging have considerably reduced the forested area. Much of the region suffers from acute ecological degradation due to top soil erosion and deforestation, leading to low productivity of the land. Wheat and soyabean are the principal crops grown in the rabi and kharrif season, respectively. Jowar, arhar, til, wheat and gram are the other crops grown in the region. The variability of the hydrological cycle due to climatic changes and lack of proper management of scarce water resources makes the situation worse during drought years.

Table 1 | Rainfall data availability and crop and river information for Bundelkhand in M.P.

S. No.	Name of development blocks	Data availability	Area, major river systems and crops
Sagar district			
1.	Banda	1981–82 to 2009–10	Area: 10,252 km^2; Rivers: Bina, Sonar, Dhasan, Bebas; Crops: soyabean, wheat, gram, other pulses
2.	Shahgarh	1992–93 to 2009–10	
3.	Garhakota	1993–94 to 2009–10	
4.	Rehli	1976–77 to 2009–10	
5.	Deori	1976–77 to 2009–10	
6.	Kesli	1992–93 to 2008–09	
7.	Sagar	1976–77 to 2009–10	
8.	Jaisinagar	1987–88 to 2008–09	
9.	Rahatgarh	1987–88 to 2009–10	
10.	Bina	1985–86 to 2008–09	
11.	Khurai	1976–77 to 2009–10	
12.	Malthone	1976–77 to 2009–10	
Chhatarpur district			
1.	Chhatarpur	1966–67 to 2009–10	Area 8,687 km^2; Rivers: Ken, Dhasan, Kutni, Kail; Crops: wheat, gram, other pulses, soyabean, sesame
2.	Bijawar	1966–67 to 2009–10	
3.	Buxwaha	1975–76 to 2009–10	
4.	Laundi	1966–67 to 2009–10	
5.	Nowgong	1980–81 to 2009–10	
6.	Rajnagar	1984–85 to 2009–10	
7.	Gaurihar	1985–86 to 2009–10	
8.	Badamalhera	1984–85 to 2009–10	
Tikamgarh district			
1.	Tikamgarh	1958–59 to 2009–10	Area: 5,048 km^2; Rivers: Dhasan, Jamni, Sadhni, Ur, Bargi, Gorar; Crops: wheat, other pulses, gram, soyabean, sesame, groundnut, mustard
2.	Baldevgarh	1981–82 to 2009–10	
3.	Jatara	1958–59 to 2009–10	
4.	Palera	1991–92 to 2009–10	
5.	Niwadi	1958–59 to 2009–10	
6.	Prithvipur	1984–85 to 2009–10	
7.	Orcha	1993–94 to 2009–10	
Panna district			
1.	Panna	1964–65 to 2009–10	Area: 7,135 km^2; Rivers: Bearma, Mirhasan, lower Ken; Crops: gram, wheat, rice, other pulses
2.	Gunera	1984–85 to 2009–10	
3.	Pawai	1964–65 to 2009–10	
4.	Shahnagar	1982–83 to 2009–10	
5.	Ajaygarh	1964–65 to 2009–10	
Damoh district			
1.	Damoh	1950–51 to 2009–10	Area: 7,306 km^2; Rivers: Bearma, Sonar, Bewas, Kopra, Barna, Banne, Hiran; Crops: gram, wheat, rice, soyabean, other pulses
2.	Hardua Morar	1984–85 to 2009–10	
3.	Hatta	1950–51 to 2009–10	

(*continued*)

Table 1 | continued

S. No.	Name of development blocks	Data availability	Area, major river systems and crops
4.	Jabera	1950–51 to 2009–10	
5.	Majghawan Hansraj	1950–51 to 2009–10	
6.	Mala	1950–51 to 1972–73	
Datia district			
1.	Datia	1950–51 to 2009–10	Area: 2,038 km^2; Rivers: Sind, Pahuj, Betwa; Crops: wheat, gram, soyabean
2.	Seondha	1950–51 to 2007–08	

OBJECTIVES OF THE STUDY

Regarding the above background of the climatic vagaries in Bundelkhand region, which has now become a regular feature, it is imperative to investigate the characteristics of dry spells including onset, spell length and frequency so as to estimate the supplemental irrigation requirements during the dry spell durations. The task becomes more challenging as the dry spell period in 1 year is not necessarily the same in another year, but understanding the behaviour of these dry patterns is crucial. The various study elements which ultimately culminate in the main objective of estimating supplemental irrigation requirements include, identification of drought-prone areas, evapotranspiration estimation, determining the dates of onset and withdrawal of monsoon, dry spell analysis for determining dry spell characteristics including starting dates, spell lengths and frequency of dry spells and estimation of crop water requirement and irrigation requirement.

DATA USED AND METHODOLOGY

The daily rainfall data at 40 rain gauge stations located at the block headquarters in each of the six districts have been used in the analysis. The data availability was however not uniform with different data lengths in the different blocks of various districts. The information on the data availability and the major crops grown and rivers traversing the districts is given in Table 1. Also, the meteorological data, including maximum and minimum temperature, wind speed, sunshine hours, and relative humidity; the agricultural data, including cropping pattern, crop durations and crop coefficients; and the soil information, including soil type, soil depth, hydraulic conductivity and infiltration capacity, have been used to carry out the comprehensive analysis to meet the various objectives of this research.

Identification of drought-prone blocks

The probability analysis of annual and seasonal rainfall is used to identify the drought-prone blocks in the study area. An area can be considered to be drought prone if the probability of occurrence of 75% of mean annual or seasonal rainfall is less than 80% (CWC 1982). The mean annual rainfall has been computed by taking the arithmetic average of the annual rainfall data. Subsequently, the annual rainfall series has been sorted in descending order and ranks assigned from 1,2, … , N, up to the last record and Weibull's distribution fitted to the ranked data for computing probability of exceedance using Equation (1).

$$P = \frac{m}{N+1} \times 100 \tag{1}$$

If the probability corresponding to the 75% of mean rainfall is less than 80%, the development block is considered to be drought prone. The probability for each block in the study area has been estimated and a point map prepared in ILWIS 3.0, GIS software. The raster map has been generated by interpolating the point map containing the probability values and, subsequently, the area has been classified into drought-prone and non-drought-prone areas.

Estimation of reference evapotranspiration

The evapotranspiration estimates are essentially required for the computation of water requirement of crops and subsequent irrigation water planning. In this study, evapotranspiration is basically required for identification of the dates of monsoon onset and wet spells. Reference evapotranspiration refers to the evapotranspiration rate from a reference surface, not short of water supplies. It is assumed that water is abundantly available at the transpiring surface, and therefore the soil factors do not affect evapotranspiration. The FAO Penman–Monteith method is now recommended as the sole standard method for definition and computation of reference evapotranspiration (Allen *et al*. 1998). In this study, the FAO Penman–Monteith method has been used for computation of reference evapotranspiration using weather data (Allen *et al*. 1998) and is given by Equation (2).

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{900}{T + 273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{2}$$

where, ET_o = reference evapotranspiration [mm/day], R_n = net radiation at the crop surface [MJ/m^2/day], G = soil heat flux density [MJ/m^2/day], T = mean daily air temperature at 2 m height [°C], u_2 = wind speed at 2 m height [m/s], e_s = saturation vapour pressure [kPa], e_a = actual vapour pressure [kPa], e_s–e_a = saturation vapour pressure deficit [kPa], Δ = slope vapour pressure curve [kPa/°C], γ = psychometric constant [kPa/°C]. The daily and monthly reference evapotranspiration is computed based on the daily climatic data of maximum temperature, minimum temperature, wind speed, relative humidity and sunshine hours.

Determination of the onset of effective monsoon

The selection of crop varieties and time for seedbed preparation are governed by onset, termination and length of monsoon including rainfall which plays a very significant role in the success of agricultural crops. The daily rainfall data have been analysed critically to identify the onset of effective monsoon and number of rainy days. The date of onset of effective monsoon can be defined as the date of commencement of a wet spell satisfying the following criteria:

- The first day's rain in a 7-day spell is not less than average daily evapotranspiration (ET).
- At least 4 out of 7 days are rainy days with not less than 2.5 mm of rain each day.
- The total rain during the 7-day spell is not less than (5ET + 10) mm.

The onset of the effective monsoon for each year has been estimated for each block in the study area based on the above criteria. The mean date of onset of effective monsoon is calculated as

$$D_m = \sum_{i=1}^{n} \frac{X_i}{n} \tag{3}$$

where, D_m = mean date of effective monsoon; X_i = date of onset of effective monsoon in ith year ($i = 1, 2, \ldots .n$); n = total number of years for which rainfall date is being analysed. The standard deviation of the date of onset of effective monsoon from its mean date is calculated as

$$\sigma = \left[\frac{\sum_{i=1}^{n} X_i^2 - \left(\sum_{i=1}^{n} X_i/n\right)^2}{n - 1}\right]^{1/2} \tag{4}$$

The median date of EMO has also been estimated after arranging in ascending order of the dates of EMO X_i ($i = 1, 2, \ldots n$) for n years. If the number of years (n) is odd, the middle value is considered as the median date of EMO. In the case (n) is even, the median date is the arithmetic mean of two middle values.

Dry spell analysis and estimation of CDS

Although the definition of a dry spell may vary depending on the objectives and methodology used in each study, the definition of a dry spell is based on the length of consecutive dry days that seems appropriate. Different researchers have used different thresholds for defining dry day and CDS. A dry spell was first defined and used in British rainfall in 1919 as a period of at least 15 consecutive days with rainfall <1.0 mm (Douguedroit 1987). However, the definition of a dry day should also include crop evapotranspiration requirements apart from rainfall criteria to make it more useful for crop operations. Similarly, the minimum number of consecutive dry days required to define a critical dry spell has to be identified in a meaningful manner depending on the practical problem and based on the combination of soil type and crops grown in the region. In Sri Lanka, for paddy cultivation, it is reasonable to consider a dry spell of 7 or more days while for coconut cultivation the corresponding value would be 30 days (Mathugama & Peiris 2011).

The distribution of rainfall in the Bundelkhand region is not uniform during the monsoon season and the occurrence of regular dry spells is a common phenomenon. After the onset of monsoon, a dry spell is determined as the intervening period of dry days between two consecutive wet spells. A sequence of wet spells preceded and succeeded by a dry spell is referred to as the duration of wet period during which there is no water supply problem. Dry days are considered as days having rainfall less than 2.5 mm. A wet spell can be defined as (Sahoo 1993):

- a rainy day with rainfall equal to or more than 5ET; or
- a spell of 2 consecutive rainy days with rainfall total of at least 5ET; or
- a 7-day period having at least 3 or 4 rainy days with a total rainfall not less than 5ET.

On the basis of crop–soil combination, the minimum length of a dry spell is considered as 10 days, which becomes critical for the major crops grown in the Bundelkhand region in M.P.

Estimation of crop water requirement

The crop coefficients of various crops which vary during the different crop growth stages have been used along with the reference crop evapotranspiration to compute the crop evapotranspiration on a 10-daily basis considering the four crop growth stages using Equation (5) as

$$ET_{\text{crop}} = ET_o \times K_c \tag{5}$$

where, ET_{crop} = crop evapotranspiration (mm/day), ET_o = reference evapotranspiration (mm/day); K_c = crop coefficient.

Crop water demand is governed by weather and crop conditions and most of the current water demand models are non-spatial models, as they use point data of reference evapotranspiration and crop coefficient values (Doorenbos & Pruitt 1977). Crop coefficient (K_c) is an important parameter for irrigation scheduling and water allocation. The coefficients (K_c) are influenced by crop type, soil evaporation, climatic conditions and crop growth stages. Many field experiments have been conducted by different researchers and implementing agencies to measure the actual evapotranspiration and K_c for different crops. The K_c values used by different agencies vary over a wide range, especially their distribution over a 10-daily period. Crop coefficient values taken from the literature may provide a practical guideline for scheduling irrigation, but considerable error in estimating crop water requirement can occur due to their empirical nature (Jagtap & Jones 1989).

The ground cover, crop height and leaf area changes with the development of crop and thus, K_c for a given crop also varies accordingly. The crop growth stages are divided into four categories over the growing period, namely initial stage, crop development stage, mid-stage and late season stage (FAO 1998). In this study, K_c is selected based on a comprehensive literature review and an assessment of crop periods based on the latest agronomic information. The cropping seasons vary for individual crops but generally occur in the well-defined seasons that is, the rabi and kharrif seasons. Rabi crops are sown after the rainy season is over (post-monsoon) during October and November, and harvested in spring during March and April. These crops grow in lower temperatures than kharrif crops, which are sown during June (monsoon) and harvested during October and November. Generally, the crop duration of major seasonal crops varies from 3 to 6 months.

Crop evapotranspiration has been computed on a 10-daily basis considering the four crop growth stages and crop coefficients for various crops. During the rainy season in tropical and semi-tropical regions, a great part of the crop's water needs are satisfied by rainfall, while during the dry spells as well as during non-monsoon season, the major supplies to meet the crop water requirements should come from irrigation water supplies. The effective rainfall is that portion of the rainfall, other than surface runoff and deep percolation that is stored in the root zone of the plants and used by it for its growth and depends on the climate, soil texture, soil structure and depth of root zone. In this study, the effective rainfall has been computed using the USDA Soil Conservation Service Method.

Estimation of irrigation water requirement

The net irrigation water requirement (NIR) for each of the crops during the various stages of crop growth on a 10-daily basis has been arrived at by reducing the effective rainfall from evapotranspiration requirements of the respective crop and is given as

$$NIR = C_{use} - Eff_{rain} \quad (6)$$

where, NIR = net irrigation requirement, C_{use} = consumptive use requirements, Eff_{rain} = effective rainfall.

The gross irrigation requirement (GIR) is derived by dividing the net irrigation requirement by the field channel efficiency and conveyance losses. The field channel

Table 2 | Drought-prone blocks in Bundelkhand region of M.P.

S. No.	Name of block	Mean annual rainfall (mm)	Probability of 75% mean rainfall (%)	Drought condition
Sagar district				
1.	Banda	1001.09	77.23	Drought prone
2.	Shahgarh	1013.58	78.30	Drought prone
3.	Garhakota	1057.91	77.39	Drought prone
4.	Rehli	1179.75	74.87	Drought prone
5.	Deori	1242.62	78.26	Drought prone
6.	Kesli	1145.86	75.13	Drought prone
Chattarpur district				
1.	Chattarpur	1005.6	77.42	Drought prone
2.	Bijawar	1129.1	78.22	Drought prone
3.	Buxwaha	1047.9	71.19	Drought prone
Tikamgarh district				
1.	Tikamgarh	984.7	75.55	Drought prone
2.	Baldevgarh	798.4	70.20	Drought prone
3.	Jatara	822.8	76.80	Drought prone
4.	Palera	909.6	70.96	Drought prone
5.	Niwadi	852.6	79.56	Drought prone
6.	Orcha	701.5	73.13	Drought prone
Panna district				
1.	Panna	1207.5	75.65	Drought prone
2.	Pawai	1120.8	70.74	Drought prone
3.	Ajaygarh	1053.1	66.66	Drought prone
Damoh district				
1.	Hardua Morar	1005.7	78.33	Drought prone
2.	Hatta	1034.4	79.21	Drought prone
Datia district				
1.	Datia	854.7	77.21	Drought prone
2.	Seondha	794.6	76.81	Drought prone

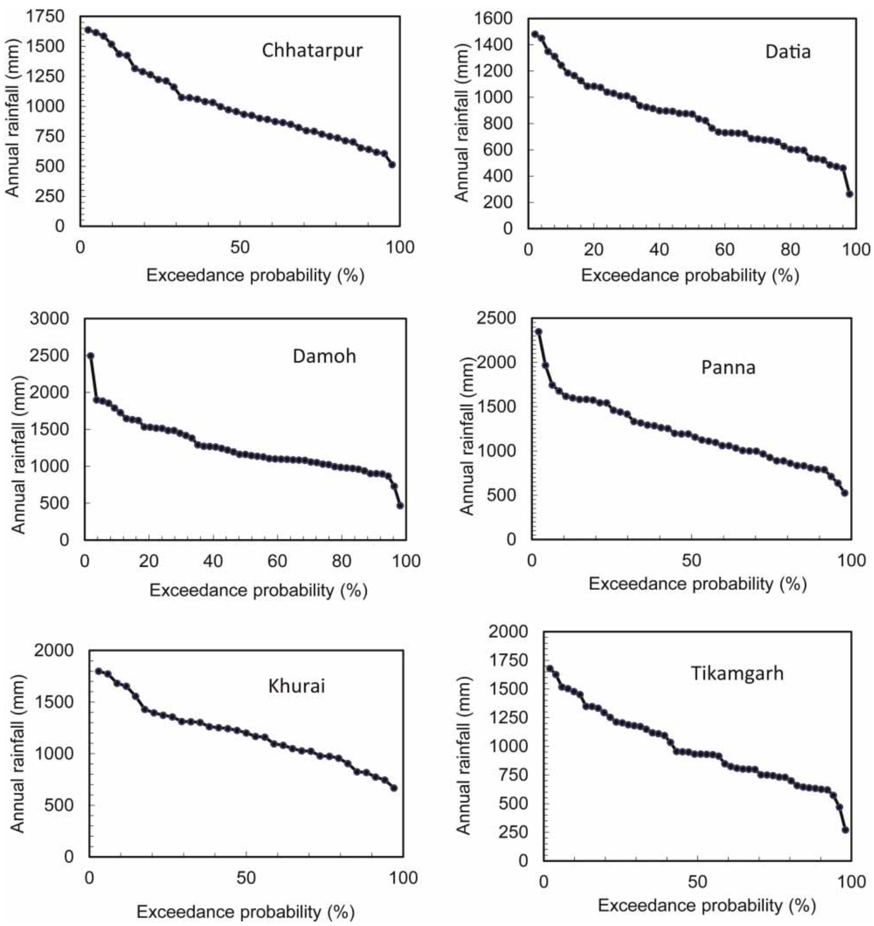

Figure 2 | Probability distribution of annual rainfall.

efficiency is considered as 0.70 whereas the conveyance losses are taken as 0.80. The GIR is computed by

$$\mathrm{GIR} = \frac{\mathrm{NIR}}{\eta_f * \xi_c} \quad (7)$$

where, GIR = gross irrigation requirement, η_f = field channel efficiency, ξ_c = conveyance losses.

ANALYSIS AND RESULTS

Identification of drought-prone blocks

The identification of the drought-prone blocks in the various districts has been carried out on the basis of probability analysis of annual and seasonal rainfall. The probability of occurrence of rainfall equivalent to 75% of normal rainfall for the various districts is presented in Table 2. It has been estimated that 6 out of 12 blocks in Sagar district, 3 out of 8 blocks in Chhatarpur district, 6 out of 7 blocks in Tikamgarh district, 3 out of 5 blocks in Panna district; 2 out of 6 blocks in Damoh district and both blocks of Datia district are identified as drought-prone blocks. Except for Sagar and Damoh districts, most of the blocks are drought-prone in the remaining four districts. The probability distribution of the annual rainfall at a few blocks is given in Figure 2. The map showing the drought-prone areas in Bundelkhand region in M.P. is given in Figure 3. All subsequent analysis for planning for sustainable agriculture has been limited to these drought-prone blocks.

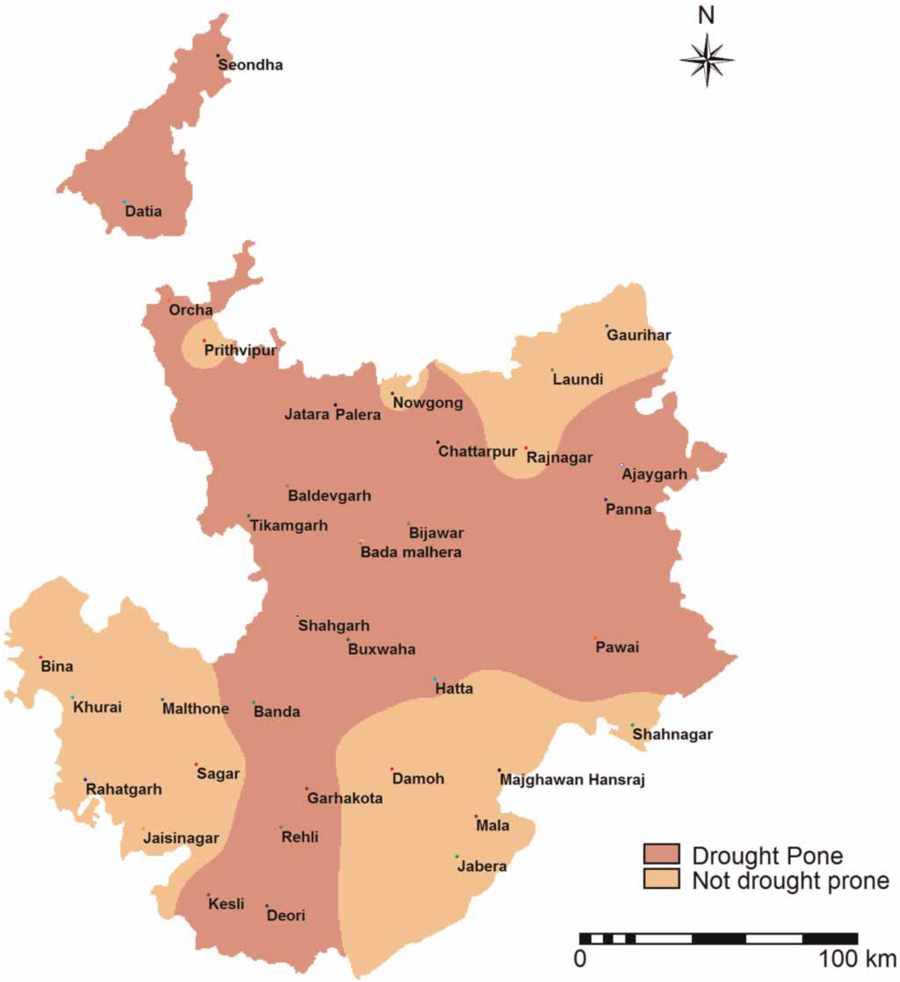

Figure 3 | Drought-prone area map of Bundelkhand region in M.P.

Table 3 | Climatic data and reference evapotranspiration (ET_o) at Sagar

Month	Maximum temperature (°C)	Minimum temperature (°C)	Humidity (%)	Wind speed (km/day)	Sunshine (hours)	Solar rad. (MJ/m^2/d)	ET_o (mm/day)
January	24.6	11.5	51.0	94.0	9.0	16.9	2.90
February	27.3	13.7	44.0	95.0	10.0	20.2	3.77
March	32.7	18.6	32.0	99.0	9.1	21.4	4.87
April	38.1	23.3	24.0	96.0	9.8	24.2	5.91
May	40.9	26.3	28.0	117.0	10.2	25.3	6.87
June	37.4	25.4	54.0	183.0	7.7	21.6	6.26
July	30.8	23.5	81.0	229.0	6.1	19.1	4.45
August	28.9	22.8	87.0	198.0	5.3	17.5	3.73
September	30.6	22.2	76.0	115.0	6.6	18.2	3.98
October	32.1	20.2	55.0	73.0	8.6	19.0	3.92
November	29.1	16.2	44.0	70.0	9.5	17.8	3.17
December	25.8	12.4	49.0	78.0	9.0	16.1	2.69

Estimation of reference evapotranspiration

The daily reference has been computed by the FAO Penman-Monteith method considering the effective rainfall during the rainy days as per USDA Soil Conservation Service method. The monthly variation of the climatic variables along with the average daily evapotranspiration at Sagar is presented in Table 3. The maximum ET_o occurs during the summer months of May and June at the rate of 6.87 and 6.26 mm/day, respectively, whereas the minimum ET_o occurs during December and January at the rate of 2.69 and 2.90 mm/day, respectively. The annual average rate of ET_o is 4.38 mm/day at Sagar.

Onset and withdrawal of effective monsoon

The onset, termination and distribution of rains during the monsoon season plays a very significant role in the success of agricultural crops, particularly in the semi-arid regions under the rain-fed agriculture system. Because of the large

Table 4 | Onset and withdrawal of effective monsoon in the various drought-prone blocks

S. No.	Name of block	Mean date of onset of monsoon	Standard deviation of onset (days)	Median date of onset of monsoon	Mean date of withdrawal of monsoon
Sagar district					
1.	Banda	2 July	12	30 June	18 September
2.	Shahgarh	4 July	16	6 July	23 September
3.	Garhakota	22 June	11	23 June	30 September
4.	Rehli	22 June	11	21 June	24 September
5.	Deori	26 June	12	25 June	26 September
6.	Kesli	28 June	18	26 June	26 September
Chattarpur district					
1.	Chattarpur	2 July	15	3 July	22 September
2.	Bijawar	3 July	13	3 July	26 September
3.	Buxwaha	29 June	16	28 June	24 September
Tikamgarh district					
1.	Tikamgarh	7 July	17	8 July	23 September
2.	Baldevgarh	10 July	15	11 July	24 September
3.	Jatara	8 July	15	7 July	23 September
4.	Palera	12 July	21	29 June	18 September
5.	Niwadi	7 July	14	6 July	23 September
6.	Orcha	9 July	19	8 July	21 September
Panna district					
1.	Panna	4 July	20	4 July	25 September
2.	Pawai	28 June	15	27 June	27 Sept
3.	Ajaygarh	2 July	12	29 June	26 September
Damoh district					
1.	Hatta	1 July	15	30 June	20 September
2.	Hardua Morar	3 July	8	4 July	23 September
Datia district					
1.	Datia	7 July	15	7 July	22 September
2.	Seondha	12 July	14	11 July	19 September

variability of monsoon rainfall and its erratic distributional pattern, a single crop is grown in the rabi season in many areas. The rainfall data have been analysed critically along with the computed daily evapotranspiration to identify the onset and withdrawal of effective monsoon.

The mean and standard deviation of the date of onset of effective monsoon has been computed for all the drought-prone blocks. The mean and median dates of onset and withdrawal of effective monsoon for the various drought-prone blocks are given in Table 4. The study reveals that the onset of monsoon takes place by the first to second week of July and withdraws by the third week of September and considerable rainfall occurs mostly during the 3 months of July, August and September.

Dry spell analysis and estimation of CDS

Rainfall distribution during the monsoon season is highly non-uniform and frequent dry spells occur in the study area. Extremely high variability in rainfall coupled with a higher evaporative demand creates severe constraints for crop growth and yields in the semi-arid agriculture-dominated

Table 5 | CDS in drought-prone blocks of Bundelkhand in M.P.

		First CDS		Second CDS	
S. No.	Name of block	Probable period of commencement	Average length in days	Probable period of commencement	Average length (days)
Tikamgarh district					
1.	Tikamgarh	July-III week	17	August-III week	16
2.	Jatara	July-III week	17	August-IV week	21
3.	Palera	July-III week	20	August-III week	15
4.	Niwadi	July-III week	19	August-II week	17
5.	Orcha	July-III week	15	August-II week	18
Chattarpur district					
1.	Chhatarpur	July-III week	19	August-II week	18
2.	Bijawar	July-IV week	18	August-IV week	19
3.	Buxwaha	Aug-I week	14	August-IV week	16
Panna district					
1.	Panna	July-II week	17	August-IV week	14
2.	Pawai	July-III week	15	August-IV week	28
3.	Ajaygarh	July-III week	15	August-IV week	15
Sagar district					
1.	Banda	July-III week	15	August-IV week	15
2.	Shahgarh	July-IV week	17	August-III week	14
3.	Garhakota	July-I week	14	August-II week	17
4.	Rehli	July-IV week	17	August-IV week	18
5.	Deori	July-III week	14	August-III week	17
6.	Kesli	July-II week	17	August-IV week	23
Datia district					
1.	Datia	July-III week	20	August-III week	15
2.	Seondha	July-II week	17	August-IV week	19
Damoh district					
1.	Hatta	July-III week	15	August-IV week	15
2.	Hardua Morar	July-II week	13	August-II week	19

regions of Bundelkhand. The identification of the number of dry spells, duration, frequency and distribution during the growing period is vital for sustainable rain-fed agriculture, on the basis of which, the sowing dates, crop varieties, intercultural operations and protective irrigation can be planned. After the onset of the monsoon, a dry spell is determined as the intervening period of dry days between any two consecutive wet spells.

The prominent crops grown in the Bundelkhand region are wheat, gram, bajra and sorghum along with soyabean, jowar and paddy in a few districts. Based on the crop–soil combination, the minimum length of a CDS is considered to be 10 days, beyond which the rainwater deficit becomes critical for the survival of major crops. The probable period of commencement of CDS and their duration for the drought-prone blocks of various districts of Bundelkhand region in M.P. is given in Table 5. Generally, two CDSs occur in most years in the drought-prone blocks for which supplemental irrigation planning is necessary. It is also observed that the duration of the first and second CDS is similar for all the drought-prone blocks, the variation in spell length being 14–20 days for the first CDS and 14–23 days for the second CDS. The variation in the dry spell lengths for Bundelkhand region in M. P. during the first and second CDS is given in Figures 4 and 5, respectively.

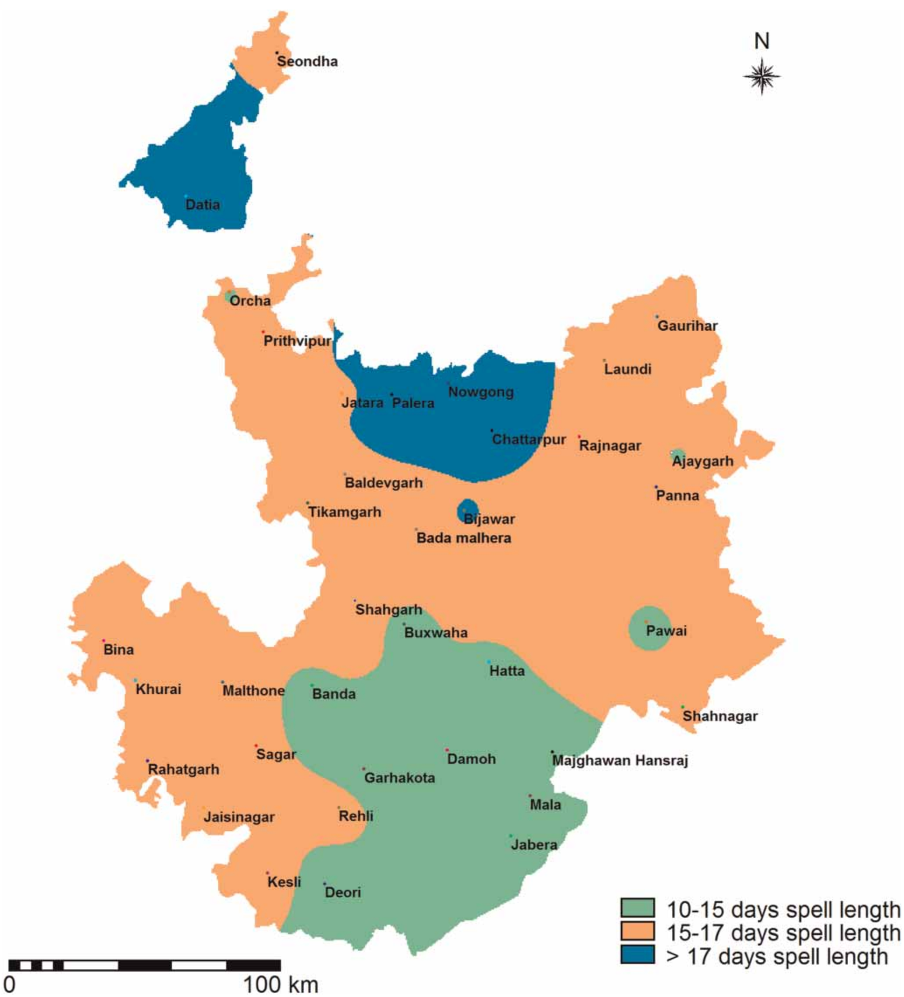

Figure 4 | Variation in the dry spell length during the first CDS for Bundelkhand region in M.P.

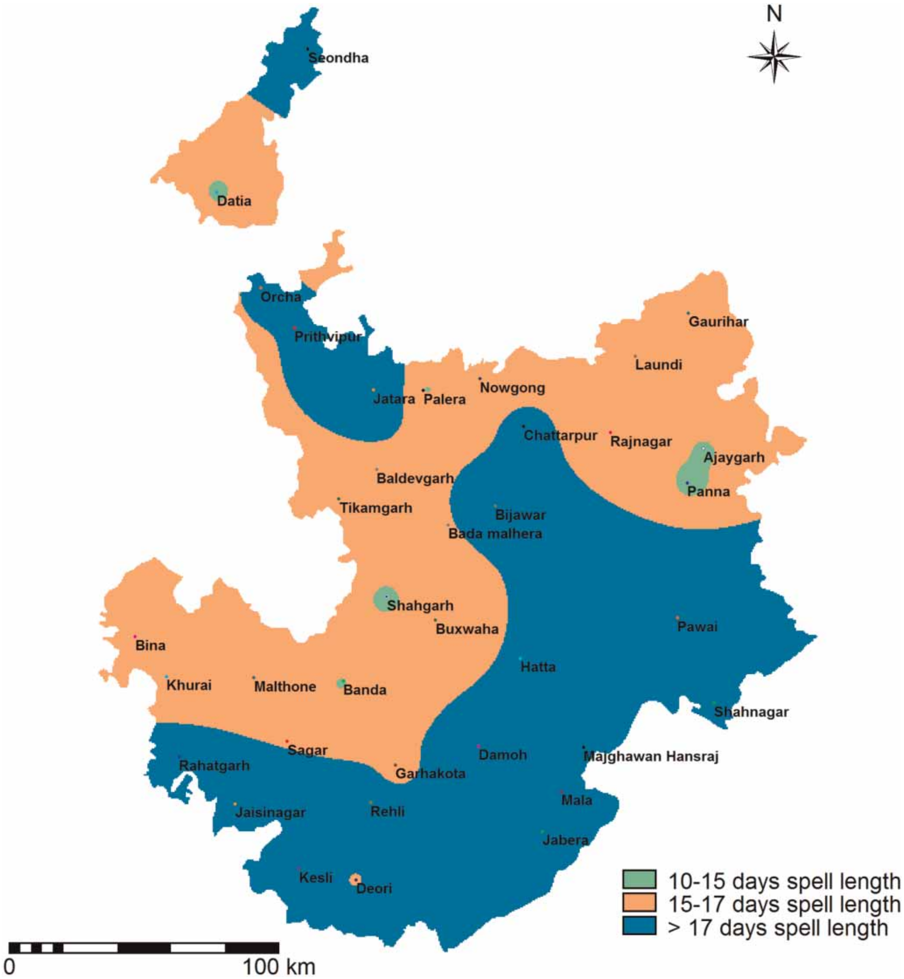

Figure 5 | Variation in the dry spell length during the second CDS for Bundelkhand region in M.P.

Estimation of crop water requirement and irrigation requirement

The crop water requirement and irrigation requirement have been estimated for crops grown during the kharrif (monsoon) season for provision of life-saving supplemental irrigation required during the CDS. In Sagar district, soyabean is the major crop grown during the kharrif season. Vegetables are the other major crop after soyabean, but along with these two crops, the irrigation requirement has also been computed for jowar which is suited to dry areas. The irrigation requirement has also been computed for paddy, which even though a water-intensive crop, gives an estimate of the maximum irrigation water requirement, if one decides to switch over to paddy crop, subject to favourable soil and climatic conditions. The computations of supplemental irrigation water requirement have been limited to the first and second CDS only for the drought-prone blocks in the study area as given in Table 6.

In Chhatarpur district, the major crops are til, arhar and vegetables. However, the irrigation water requirement for paddy, soyabean and jowar have also been computed, in case farmers are encouraged to grow crops like soyabean and jowar in the kharrif season, which is presently not the case, as only one crop of wheat is grown in the rabi season. The total irrigation water requirement for both the CDS, is 15.82 mm for til, 20.79 and 32.37 mm for jowar and soyabean. Rice has the maximum irrigation requirement of 46.58 mm followed by vegetables with 42.43 mm.

Table 6 | Irrigation water requirement during CDS in Bundelkhand region

Sagar district

S. No.	Name of block	Critical dry spell (CDS)	Irrigation requirement (mm) Rice	Soyabean	Vegetables	Jowar
1.	Banda	I CDS	22.84	05.89	16.07	03.52
		II CDS	43.03	48.19	43.32	34.51
		Total	*65.87*	*54.08*	*59.39*	*38.03*
2.	Garhakota	I CDS	34.02	09.83	21.05	06.77
		II CDS	64.36	65.79	65.14	37.87
		Total	*98.38*	*75.63*	*86.19*	*44.64*
3.	Deori	I CDS	14.17	03.38	4.83	02.54
		II CDS	59.72	63.58	10.77	40.61
		Total	*73.89*	*66.93*	*15.60*	*43.15*
4.	Rehli	I CDS	32.29	12.47	28.94	03.80
		II CDS	57.33	62.16	55.99	50.43
		Total	*89.62*	*74.63*	*84.93*	*54.24*
5.	Kesli	I CDS	28.61	09.28	20.19	06.37
		II CDS	15.15	17.19	13.29	12.82
		Total	*26.47*	*26.47*	*33.49*	*19.19*
6.	Shahgarh	I CDS	48.30	24.03	23.05	14.02
		II CDS	50.67	54.10	35.49	36.18
		Total	*98.91*	*78.13*	*58.54*	*50.18*

Chattarpur district

S. No.	Name of block	CDS	Irrigation requirement (mm) Rice	Soyabean	Vegetables	Jowar	Arhar	Til
1.	Chhatarpur	I CDS	29.28	13.20	25.02	8.01	10.14	09.27
		II CDS	17.30	19.17	17.41	12.78	6.11	6.55
		Total	*46.58*	*32.37*	*42.43*	*20.79*	*16.25*	*15.82*
2.	Bijawar	I CDS	06.30	00.00	05.10	00.00	00.00	00.00
		II CDS	28.75	31.14	27.68	26.39	06.14	17.69
		Total	*35.05*	*31.14*	*32.78*	*26.39*	*6.14*	*17.69*
3.	Buxwaha	I CDS	11.99	08.23	12.08	05.52	03.59	03.85
		II CDS	32.14	35.14	28.84	28.18	15.86	13.06
		Total	*44.13*	*43.37*	*40.92*	*33.70*	*19.45*	*16.91*

Tikamgarh district

S. No.	Name of block	CDS	Irrigation requirement (mm) Macca	Til	Udad	Arhar	Jowar	Vegetables	Soyabean	Rice
1.	Tikamgarh	I CDS	23.0	04.1	08.4	05.3	04.5	31.2	09.7	35.3
		II CDS	29.3	16.3	33.9	16.4	25.4	30.5	33.1	30.2
		Total	*52.3*	*20.4*	*42.3*	*21.7*	*29.9*	*61.7*	*42.8*	*65.5*
2.	Jatara	I CDS	24.1	12.8	17.2	13.1	13.9	27.2	17.3	29.7
		II CDS	62.5	38.4	70.5	42.7	61.1	61.8	70.3	65.8
		Total	*86.6*	*51.2*	*87.7*	*55.8*	*75.0*	*89.0*	*87.6*	*95.5*

(*continued*)

Table 6 | continued

Tikamgarh district

			Irrigation requirement (mm)							
S. No.	**Name of block**	**CDS**	**Macca**	**Til**	**Udad**	**Arhar**	**Jowar**	**Vegetables**	**Soyabean**	**Rice**
3.	Niwadi	I CDS	13.3	05.5	09.7	15.0	17.0	38.4	22.6	41.7
		II CDS	50.9	34.8	54.6	12.0	16.4	25.0	21.2	24.7
		Total	*64.2*	*40.3*	*64.4*	*27.0*	*33.4*	*63.4*	*43.8*	*66.4*
4.	Orcha	I CDS	24.8	10.1	14.1	11.4	10.9	32.3	15.2	37.2
		II CDS	39.7	18.6	42.4	16.4	28.4	41.7	39.5	41.0
		Total	*64.5*	*28.7*	*56.5*	*27.8*	*39.3*	*74.0*	*54.7*	*78.2*
5.	Palera	I CDS	32.8	15.1	20.8	15.73	16.56	39.81	21.1	43.7
		II CDS	20.8	20.9	22.7	13.08	17.93	21.93	21.7	21.5
		Total	*53.6*	*35.9*	*43.5*	*28.81*	*34.49*	*61.74*	*42.8*	*65.2*

Panna district

			Irrigation requirement (mm)			
S. No.	**Name of block**	**CDS**	**Rice**	**Soyabean**	**Jowar**	**Vegetables**
1.	Pawai	I CDS	21.86	06.59	04.84	08.93
		II CDS	23.49	26.12	20.52	32.72
		Total	*45.35*	*32.71*	*25.36*	*41.65*
2.	Panna	I CDS	32.86	10.23	07.60	27.61
		II CDS	29.02	31.32	25.16	29.00
		Total	*61.88*	*41.55*	*32.76*	*56.61*
3.	Ajaygarh	I CDS	26.18	13.35	3.33	15.95
		II CDS	39.40	40.44	21.96	22.22
		Total	*65.58*	*53.79*	*25.29*	*38.17*

Damoh district

			Irrigation requirement (mm)			
S. No.	**Name of block**	**CDS**	**Rice**	**Soyabean**	**Vegetables**	**Jowar**
1.	Hatta	I CDS	25.37	12.56	23.36	7.53
		II CDS	25.86	28.86	25.95	21.46
		Total	*51.23*	*41.42*	*49.31*	*28.99*
2.	Hardua Morar	I CDS	04.76	00.00	00.00	00.00
		II CDS	12.26	11.20	12.92	4.00
		Total	*17.02*	*11.20*	*12.92*	*4.00*

Datia district

			Irrigation requirement (mm)			
S. No.	**Name of block**	**CDS**	**Rice**	**Soyabean**	**Vegetables**	**Jowar**
1.	Datia	I CDS	16.73	1.07	12.88	0.00
		II CDS	56.83	52.93	55.36	52.15
		Total	*73.56*	*54*	*68.24*	*52.15*
2.	Seondha	I CDS	18.72	7.28	15.88	4.63
		II CDS	38.60	39.17	38.97	32.89
		Total	*57.32*	*46.45*	*54.85*	*37.52*

The important crops grown during the kharrif season in Tikamgarh district include macca, til, udad and arhar among other crops. The total irrigation water requirement for both the CDS varies between a minimum of 20.37 mm for til to a maximum of 65.58 mm for rice. The water requirement is more during the second CDS as compared to the first CDS. In Panna district, no major crops are grown in the kharrif season, however, soyabean, jowar and vegetables are suggested along with paddy, wherever field conditions are suitable. The water requirement during the first CDS is comparatively less than second CDS requirements. The total irrigation requirement varies between 32.76 for jowar to a maximum of 61.88 mm for rice in Panna block.

As compared to the other districts in Bundelkhand region of M.P., Damoh district has fewer drought-prone blocks, namely, Hatta and Hardua Morar out of seven blocks in the district. The maximum irrigation requirement is at Hatta for all crops, with a requirement of 51.23 mm for rice and 28.99 mm for jowar during both CDS. Similarly, the irrigation requirement has been computed for both the drought-prone blocks in Datia district for paddy, soyabean, vegetables, jowar and arhar. The map showing the total

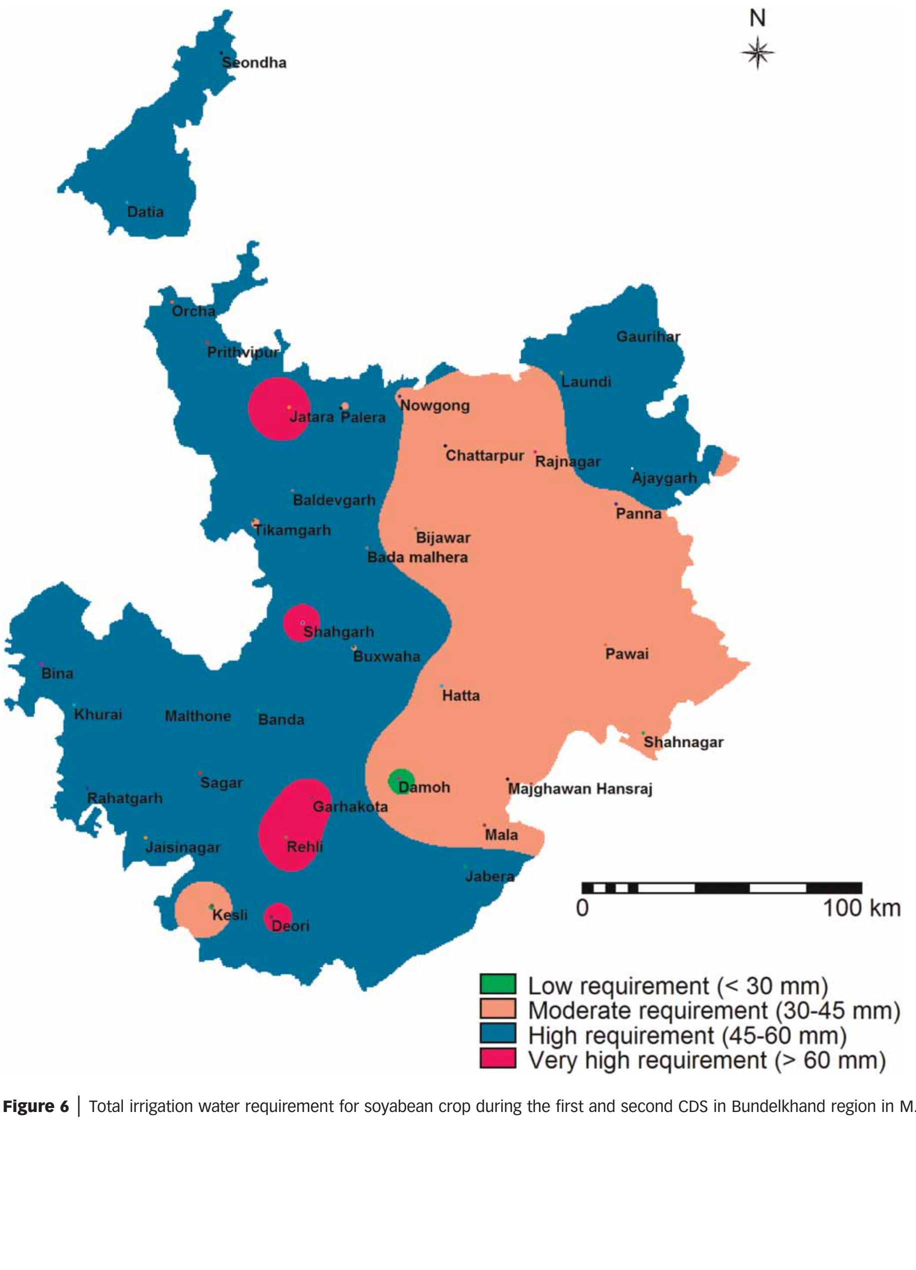

Figure 6 | Total irrigation water requirement for soyabean crop during the first and second CDS in Bundelkhand region in M.P.

irrigation water requirement for soyabean crop during the first and second CDS in Bundelkhand region in M.P. is given in Figure 6. In order to meet the supplemental irrigation demands to assist with the water stress to the standing crops and prevent them from permanent wilting, small storage structures can be planned on the minor tributaries traversing the area. Also, an alternative cropping pattern requiring less watering during its various crop growth stages can be another option. Conjunctive use of surface and ground water may be another tool, wherever the situation is favourable to meet the supplemental irrigation requirement partly from groundwater.

SUMMARY AND CONCLUSIONS

A major challenge of drought research is to develop suitable techniques for forecasting the onset and termination of droughts. The length and frequency of dry spells are the two common variables analysed in most studies. A considerable portion of the study area comprising 22 out of 40 blocks is identified to be drought-prone. The onset of monsoon occurs by the first to second week of July while the withdrawal is complete by the third week of September and the crop calendar and crop varieties can be selected based on this vital information. Two CDS of duration of 10 days or more frequently occur every year in most of the drought-prone blocks, for which provision of supplemental irrigation is necessary. The situation of increasing critical dry spell lengths coupled with the high variability in the rainfall pattern is a matter of serious concern for the underdeveloped and water-scarce Bundelkhand region and calls for all-inclusive planning and preparedness to tackle the recurrent drought scenario. It has been observed that the probability of occurrence of the first and second CDS is very high and planning is required for provision of supplemental irrigation to prevent the wilting of standing crops leading to reduced yields and crop failures. In a few years some of the blocks experienced three CDS but the probability of occurrence of the third CDS is very low. It can be concluded that to prevent the crops from permanent wilting and substantial yield reduction, provision for adequate supplementary irrigation is a necessity for the sustainability of rain-fed agriculture. Future research on dry spells can be geared towards prediction of the starting dates of CDS, lengths of CDS and forecasting the future patterns of dry spells which will generate useful information for the various stake-holders and decision-makers (Mathugama & Peiris 2011).

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