



## ASSESSMENT OF VULNERABILITY TO DROUGHT TOWARDS EFFECTIVE MITIGATION PLANNING: THE CASE OF KEN RIVER BASIN IN INDIA

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### ABSTRACT

*Vulnerability to drought varies with space and time and it depends on physiographic, meteorological, hydrologic, social and other factors. The physiographic factors are static physical features of basin viz., topography, slope, land use, soil type, soil depth, proximity to river reach, elevation zones and population density. The meteorological and hydrological factors are monthly rainfall departures from corresponding mean and soil moisture deficit, respectively. The spatial information of multiple factors has been categorized in various sub-classes and maps have been prepared using ArcGIS. A differential weighting scheme has been used to integrate different sub-classes of various factors. The proposed methodology has been applied in the Ken River Basin in Bundelkhand region located in central India. The Soil and Water Assessment Tool (SWAT) model has been applied to demarcate hydrologically homogeneous areas called Hydrologic Response Units (HRUs) based on land use, slope and soil type, and to estimate spatial and temporal distribution of soil moisture in the study basin. The Soil Moisture Deficit Index (SMDI) has been computed from the soil moisture estimates obtained using SWAT. An Integrated Drought Vulnerability Index (IDVI) has been defined as the sum of weights of various factors scored by corresponding HRU (Hydrologic Response Unit) divided by the sum of the maximum weight value of the factors. The HRUs with higher value of IDVI represent the areas with high degree of vulnerability to drought and vice versa. The maps thus obtained were validated using the documented information and field surveys. The maps thus prepared showed very good demarcation of areas vulnerable to different degree of vulnerability to drought. Verification of vulnerable areas was made through physical field observations in the study basin. The methodology presented in this paper puts forward a useful and reliable tool for quantitative assessment and demarcation of zones vulnerable to drought. The proposed methodology can be used for proactive as well as near real time assessment, monitoring and planning of response actions to cope with drought.*

**Keywords:** Drought Vulnerability Index, SWAT Model, Soil Moisture Deficit Index, Rainfall Departure, Ken Basin in India

### INTRODUCTION

A drought is defined as relative deficit below average water availability, either in the form of rainfall, river flow, reservoir storage, ground water availability and soil moisture for certain period of time. Thus, drought is a temporary climatic phenomenon and refers to relative deficit of water compared to usual/average availability of water at a given time and space. The impact of droughts on agriculture, water

availability, and regional social and economic activities depends on various regional climatic, physiographic, hydrologic, and socio-economic factors (Alcamo et al. 2008; Pandey and Ramasastri 2002; Pandey et al. 2010; Vinit et al. 2015).

In the prevailing present literature, it is often stated that the drought is a complex phenomenon and it is difficult to provide a precise and universally accepted definition of drought due to

<i>Box: Definition of Terms</i>		
<b>Drought</b>	<b>Aridity</b>	<b>Water Scarcity</b>
<p>Drought is defined as a relative deficit in a given area compared to its average or usual water availability, either in the form of rainfall, river flow, surface/ground water storages or due to combination of these for certain period of time. <i>Thus, drought is a temporary phenomenon.</i></p>	<p>Aridity refers to persistently short supply of water even in normal circumstances. It is a climatic attribute of the region. It applies to the persistently dry regions like arid areas &amp; deserts, where, water is always in short supply. <i>Thus, aridity is a permanent climatic feature of the region.</i></p>	<p>The water scarcity refers to long-term unsustainable use of water resources, which water managers can influence. <i>Or in other words, it is associated to over exploitation of water resources when demand for water is more than its availability.</i> <i>Thus, the water scarcity is human induced phenomenon.</i></p>

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its varying characteristics and impacts across the different regions of the world (Wilhite, 2000; MoA, 2009). Further, the words 'drought', 'aridity' and 'water scarcity' is more often used synonymously. However, in actual sense, the above words are completely different. Through this article, it is also intended to put forward a crystallized and precise definition of 'drought', aridity and 'water scarcity' as given in following box.

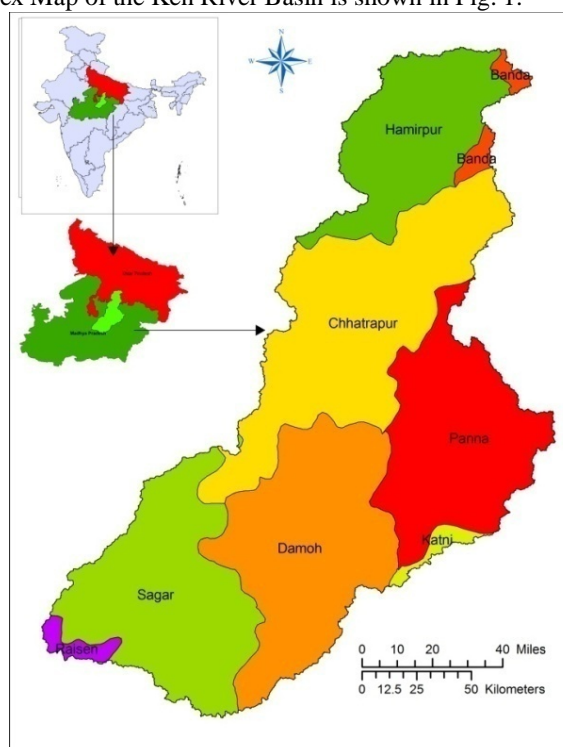
The vulnerability to drought refers to a degree of exposure of an area to water deficit or shortage. It depends on regional physiographic features, climatic, hydrologic, environmental and socio-economic factors including ability to cope with drought. The vulnerability to drought varies with time and space. Areas that have higher exposure and low coping capabilities would have highest risk from a given drought event and vice-versa. The degree of exposure to drought or water deficit depends on climatic, hydrologic, environmental, socio-economic activities and physical characteristics like topography, land-use, soil type, soil depth, surface water storage and water demands in the region (Wilhelmi et al., 2002; Hamouda, 2009). Drought vulnerability thus depend upon on multiple factors such as topographic features, soil, land used, water resources development (irrigation supports), in-situ water conservation, utilizations of ground water, and regional water demand for domestic, industrial and agriculture activities etc.(Pandey et al. 2010; Jain et al. 2015). Thus, vulnerability to drought has dimensions of time and space (Downing and Bakker 2000; Wilhite 2000). The social vulnerability to drought is complex and it is reflected by society's capacity to anticipate, cope with and respond (Tsakiris and Pengalou 2009, and Iglesias et al. 2009b). Keeping in view the experiences and emerging lessons in development and implementation of drought management plans, Iglesias et al. (2009a) emphasized to adopt risk-based approaches for different levels of vulnerability to meet the challenges of coping with impacts of drought and water shortages. Also, Iglesias et al. (2009b) proposed methods for evaluating social vulnerability to drought using the natural resource structure, the economic capacity, the human and civic resources, and aspects of agricultural innovation etc. They weighted the above factors appropriately and computed final value of the vulnerability index. The severe drought events recently occurred all over the world have increased awareness of the harmful impacts and realization to effective reduction of related impacts through appropriate mitigation measures planned in advance (Rossi et al., 2007). The inspiration of concept for derivation of drought vulnerability map was originally taken from the 'DRASTIC' methodology for groundwater pollution assessment (Aller et al., 1987), Eastman et al. (1997) for food security mapping, and Thiruvengadachari and Gopalkrishna (1993) for drought mapping. Wilhelm and Wilhite (2002) and Wilhelmi et al.(2002) described drought vulnerability for the state of Nebraska in U.S.A. using biophysical and social factors in spatial domain. Pandey et al (2010) suggested a method to assess vulnerability to drought using uniform weighing scheme for all physical, meteorological and other factor. Iglesias et al (2009b) presented guidelines to develop drought management plans using risk-based approach to mitigate the drought impact at different vulnerabilities.

The purpose of this study is to propose a new method for assessment of vulnerability to drought using a differential weighing scheme for integration of various meteorological, physiographic, hydrologic, socio-economic and other factors. It is believed that the factual method for assessment of vulnerability to drought, which assimilate multiple factors in spatial and temporal domain using GIS, can be helpful to decision makers in visualizing the hazard and to disseminate

the concept of vulnerability to stakeholders, natural resource managers, agricultural producers and others.

### **DESCRIPTION OF THE STUDY AREA**

The Ken River basin is located in central India between north latitudes 23<sup>0</sup>07' and 25<sup>0</sup> 54' and east longitudes of 78<sup>0</sup> 30' and 80<sup>0</sup> 40'. The river Ken originates at an altitude of 550.0 m above mean sea level (msl) and drains a total basin area of 28,692 km<sup>2</sup> before it joins river Yamuna at an elevation of about 87.0 m above msl. The average elevation of the plain areas of the basin is about 328 m above mean sea level (msl). Fig. 1 shows the location map of the Ken Basin in India. The study basin belongs to the semi-arid and dry sub-humid climatic region of India with a single rainy season (June-September) followed by dry winter, and then a very dry summer. The average annual rainfall in the basin varies from 1250 mm near its origin to 800 mm near its confluence with Yamuna River with an estimated basin averaged annual rainfall of about 1165 mm (Pandey et al. 2008). The basin receives about 90% of its mean annual rainfall during south-west monsoon (June-September). The Upper reaches of river basin have hilly terrain covered with thick forests and undulating topography. The soil varies from mixed red and black soils to medium black soils. Northern most parts of the basin have patches of sandy loam soils also. The Location and Index Map of the Ken River Basin is shown in Fig. 1.



**Fig. 1: Location and Index Map of the Ken River Basin**

### **DESCRIPTION OF APPROACH**

It is understood that geographical location, physical characteristics of watershed, surface and ground water availability, variability of rainfall, regional climatic factors and socio-economic factors are responsible for water deficits and crop loss during drought in the study basin (District Statistical Handbook 1993 & 2007; Pandey et al., 2010 and Jain et al, 2015). During this study in the year 2006-2010,

comprehensive field investigations were carried out in the Ken basin to monitor the onset and progression of droughts, quantification magnitude of drought severity and the extent of impact of drought on extent of area sown and crop yield. Fortunately, droughts occurred in the year 2006 and 2007 in the study basin (Pandey et al. 2010). The agriculture sector is usually the first to get affected by drought because of its dependence on soil moisture which depletes rapidly during extended dry periods (Narsimhan and Srinivasan, 2005). Besides the deficiencies of rainfall, the depletion of soil moisture and reduction in stream flow play a vital role in the determination of onset and severity of drought event. Soil moisture and stream flow greatly depend upon the various physiographic factors such as type of soil, land use, topography, slope, geographic location of the basin and season. Spatial distribution of soil type, land use and land cover affect rate of infiltration, permeability, soil's moisture holding capacity and evapotranspiration (ET) of a region (Liu et al. 2008; Rose and Peters 2001; Gregory et al. 2006; Price et al. 2010). Spatial variability in precipitation and ET may also result from differences in topographic characteristics, such as aspect and elevation among watersheds. Further, topography of an area, land use and geomorphology affect stream flows (Vivoni et al. 2008; Tetzlaff et al. 2009; Price et al. 2011). Thus, the above discussed physiographic factors influence the availability of water and degree of water deficit/scarcity in a basin in space and time during drought. The measured values of soil moisture and stream flow are often not available in a basin at desired locations. Therefore, a distributed hydrologic model is preferred for soil moisture assessment. Also the areas with similar land-use, soil type and slope steepness behave in the same way in terms of their hydrologic response (Arnold et al., 1998). The Soil and Water

Assessment Tool (SWAT) model (Neitsch et al., 2005) is capable to discretize the basin area into hydrological response units (HRUs) which have similar land use, soil type, and slope and provides estimates for soil moisture, evapotranspiration, surface runoff etc at the level of HRU.

In view of the above, this study is taken up to assess vulnerability to drought in time and space in the Ken River basin in Madhya Pradesh, India. The major aim of this study is to devise a method for integration of various factors for spatial and temporal assessment of vulnerability to drought using a variable weighing scheme for various factors.

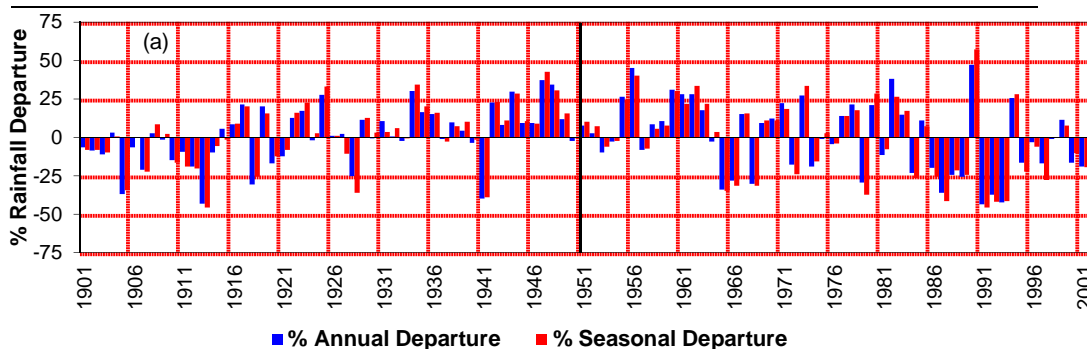
**Analysis of Meteorological Drought in the Study Basin**

India Meteorological Department (IMD) defines an area or region to be drought affected if it receives less than 75% of its normal rainfall (Appa Rao, 1986). Accordingly in the present study, a year and a monsoon season (June-Sept) are considered as drought years and drought season respectively, if the total amount of rainfall over an area is deficient by 25% or more from corresponding mean values. Monthly rainfall data of 12 rain gauge stations for a period of 110 years from 1901-2011 (data missing for the year 2003) have been used in the analysis. In the present study, meteorological drought characteristics of the study basin have been assessed for monthly, seasonal and annual time scales. The meteorological droughts in a study basin are characterized on the basis of duration (period of rainfall deficit), severity (magnitude of rainfall deficiency), and frequency (drought recurrence).

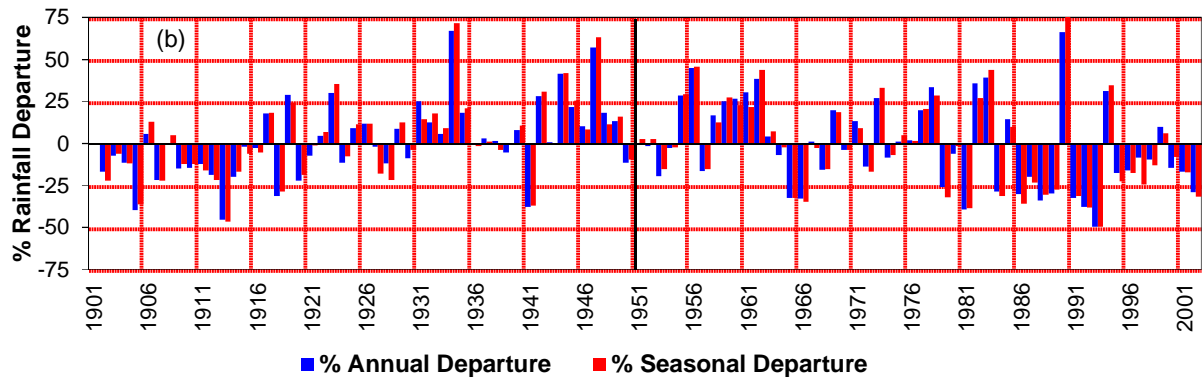
Annual and seasonal rainfall departures with respect to corresponding mean values (RD-Mean) have been computed using the equation (Eq.1) for various stations in the Ken basin for the entire period of records starting from 1901 to 2011 to

**Table1. Criterion adopted to classify a year into different categories**

Sr. No.	Rainfall Received in any year	Category
1	>125 % of Mean	Wet
2	125 % - 110% of Mean	Mild Wet
3	109% - 90% of Mean	Average
4	89% - 75% of Mean	Mild Dry
5	74% - 65% of Mean	Moderate Drought
6	64% - 50% of Mean	Severe Drought
7	<50% of Mean	Extreme Drought



**Fig. (2a): Plots of Annual and Seasonal Rainfall Departure for station Chhattarpur**



**Fig. 2(b): Plots of Annual and Seasonal Rainfall Departure for station Sagar**

demarcate a year or season as wet year, normal year or drought year. Criterion used to demarcate wet and dry season or year is shown in Table 1.

$$RD - Mean(\%) = \frac{(x_i - \bar{x}_i)}{\bar{x}_i} \times 100 \dots\dots\dots(1)$$

Where,  $x_i$  represents the rainfall for a given month, season or a year and  $\bar{x}_i$  represent the long term average for a corresponding month, season or year.

The sample plots of annual and seasonal rainfall departures for Chattarpur and Sagar stations are shown in Fig. 2(a & b), respectively. As can be seen from Fig. 2(b), the basin experienced drought once in every five years on an average in later half of the past century. Major drought years identified from the rainfall departure analysis are 1905, 1913, 1918, 1941, 1965, 1966, 1987, 1989, 1991, 1992, 1993, 2002, 2006, 2007, 2009, 2010. The maximum annual rainfall deficit could be recorded as -50 % of annual mean in Sagar district. It is also evident from the analysis that the occurrences of annual droughts coincide with seasonal droughts. It is revealed that the deficiency of rainfall during monsoon season (June to Sept.) is primarily responsible for occurrence of drought and water stress in subsequent part of the year in the study area.

**Proposed Differential Weighting Scheme to Integrate Multiple Factors**

In light of the discussions in the preceding sections, a differential weighting scheme is proposed as given in Table 2 considering the relative significance of various factors on

vulnerability to drought. In Table 2, the choice of the range of weighted values for various factors is based on the assumption of relative degree of influence of a factor in overall vulnerability to drought. In the proposed scheme, the soil moisture deficit represented as Soil Moisture Deficit Index (SMDI, Narsimhan and Srinivasan, 2005) and rainfall deficiency in the form of rainfall departure are considered as the most influential factors and hence SMDI and rainfall departure have been assigned the highest weight range from 0 to 25 (Table 2). The land use and relative elevation have been considered moderately influential factors and hence assigned a range of numerical weight values vary from 0 to 10. It is a known fact that the water demand and availability varies considerably with land use types and elevation zones, respectively. The slope, soil type, soil depth, distance from river reach and population density have been taken as relatively less influential factors and numerical weight values for these factors range from 0 to 5. This is termed as “differential weighing scheme” because different ranges of weights have been assigned to various groups of factors. The weight value of 0 indicates that the sub-class of a given factor is causing least affect in vulnerability to drought. On the other hand, a higher weight value indicates that the sub-class is severely causing vulnerability to drought. For example, heavy (clay) soils have greater water holding capacity than sandy soils. Hence, sandy soils are assigned more weight value than heavy soils. Similarly, different weights have been assigned to various sub-classes of other factors too.

**Table 2: Weights assigned to various sub-classes of considered drought vulnerability factors**

Sr.No.	Factors	Sub-lasses of drought vulnerability factors	Weights of different classes of factors
	(i)	(ii)	(iii)
1.	Land Use	Water Bodies (Areas under submergence)	-100
		Waste Land	0
		Range Land	2
		Pasture Land	4
		Forest	6
		Urban Land	8
2.	Irrigation Support	Irrigated	-5
		Un-irrigated (rainfed)	5

3.	Elevation zones	Lower elevation zone	<140m	1
			140m-210m	2
			210m-280m	3
		Middle elevation zone	280m-350m	4
			350m-420m	5
			420m-490m	6
		Upper elevation zone	490m-560m	7
			560m-630m	8
			630m-700m	9
			>700m	10
4.	Slope	0-2%	1	
		2%-5%	2	
		5%-8%	3	
		8%-12%	4	
		>12%	5	
5.	Distance from River Reach	Upto 1km	1	
		1-3 km	2	
		3-5km	3	
		5-7 km	4	
		>7km	5	
6.	Soil Texture	Clay	1	
		Loam	2	
		Silt Loam	3	
		Silt	4	
		Sand	5	
7.	Soil Depth (mm)	>=1000	1	
		<1000 to >=800	2	
		<800 to >=600	3	
		<600 to >=400	4	
		<400	5	
8.	Population Density/Km <sup>2</sup>	0-100	Low	1
		100-200	Moderate	2
		200-300	Medium	3
		300-400	High	4
		400-500	Very High	5
9.	Soil Moisture Deficit Index (SMDI)	> -0.5	Near Normal	0
		-0.5 to -1	Dry Spell	5
		-1 to -2	Mild Drought	10
		-2 to -3	Moderate Drought	15
		-3 to -4	Severe Drought	20
		< -4.0	Extreme Drought	25
10.	Rainfall Departure	>-10%	Near Normal	0
		-10% to -15%	Dry Spell	5
		-15% to -25%	Mild Drought	10
		-25% to -35%	Moderate Drought	15
		-35% to -50%	Severe Drought	20
		<-50%	Extreme Drought	25

Different layers of spatial maps of physiographic, climatic and hydrologic factors are prepared using ArcGIS software and weights proposed in Table 2 are assigned to various subclasses of factors. The weights assigned to various sub classes of factors are integrated using a simple scheme of addition of weight at corresponding HRU level. The composite weight value scored by selected HRU divided by the sum of maximum weight values of each factor represents Integrated Drought Vulnerability Index (IDVI). Thus, the IDVI has been defined as the ratio of sum of assigned weight value of each factor to the sum of the maximum weights of all selected

spatial and temporal factors. Consequently, quantitative assessment of degree of vulnerability to drought for given HRU has been mathematically estimated using following equation (Eq. 2).

$$IDVI = \frac{\sum_{i=1}^n W_i}{\sum_{i=1}^n W_{i_{max}}} \dots\dots\dots(2)$$

Where,

IDVI = Integrated Drought Vulnerability Index;

$W_i$	=	Weight scored by HRU for $i^{\text{th}}$ factor
$W_{i_{max}}$	=	Maximum weight of $i^{\text{th}}$ factor
n	=	Number of factors under consideration

The appraisal of IDVI at HRU scale indicates that a geographic area, i.e. HRU, showing greater numeric value of IDVI is more vulnerable to drought than that of less value.

**Essence of Multiple Factors Affecting Vulnerability to Drought**

Vulnerability to drought depends on numerous factors including physiographic, meteorological, hydrological, agricultural, socio-economic and environmental factors. These factors can be categorized as: (i) *Static factors*: which do not change with time but may vary with space only. For example topography, land use, slope, soil type, soil depth, etc. (ii) *Semi static factors*: which change with the phase of development like irrigation support, water resources development, storage schemes, cropping pattern, population density, etc. and (iii) *Dynamic factors*: which change with space and time, for instant, rainfall, streamflow, soil moisture etc.

An integrated drought vulnerability index (Eq. 2) includes various factors such as meteorological, hydrological, agricultural, socio-economic and environmental factors. The integrated drought index is designed in an attempt to overcome some of the ambiguities in drought indices. It is unique because it incorporates information from so many distinct types of drought information resources. The dynamic layers are dependent on time and linked to time series data. Space-time or dynamic layers may be including: precipitations, evapotranspiration, mean temperature, groundwater levels, surface water storage, and environmental needs.

The physiographic factors considered in the present study are land use, slope, relative elevation of a place, distance from river reach, soil texture, soil depth, irrigation support, and population density. The significance of sub-classes of various physical factors is discussed in the following sections.

**Land Use:** Land use is one of the important factors influencing vulnerability to drought. Landuse information is obtained by classifying Landsat ETM+ satellite data (NASA, 2003). Land use in the study basin is dominated by rainfed crop cultivation (about 53.8%) followed by forest (23.48%) and other uses including pasture, water bodies, waste and residential land (22.72%) etc. Among the various land uses, it is implicit that agriculture becomes the first sufferer due to water scarcity and drought compared to forest and other land uses because of its dependence on soil water. Therefore, agricultural lands are considered most vulnerable land use class to drought and assigned highest weight value. On the other hand, range land and waste land are least significant, and therefore, considered as less responsive to water shortages and the less weight values have been assigned to these classes. The relative weights of vulnerability to different land uses are given in Table 2. The spatial distribution of land use in the basin is shown in Fig. 3. The area under water bodies is

assigned negative weight value of -100 to mask them, since areas under water bodies are considered as non-vulnerable to drought.

**Irrigation:** Irrigation support in a basin can be one of the key factors in the assessment of vulnerability to drought. There are very few minor and medium irrigation projects in the Ken river basin. The Bariyarpur command area, as shown in Fig.4, in the Ken River basin having irrigation command area of approximately 572 Km<sup>2</sup> is assigned negative weight value of -5 (Table2) to ascribe the irrigation command as area under low vulnerability zone, because the command areas are less exposed to short term water scarcity due to irrigation support. However, rest of the area under rainfed agriculture is assigned higher weight value of 5, because of its full dependence on rainfall.

**Slope:** The slope map of the study basin is obtained from the elevation data obtained from SRTM (Jarvis et al., 2008) and the basin has been categorized into five slope classes viz. 0-2%, 2-5%, 5-8%, 8-12% and more than 12%. Spatial distribution of these slope classes in Ken basin is shown in Fig. 5. It is established from various studies that the soil moisture stay for relatively longer time in plain land areas followed by areas with mild and steep slopes. Hence, the areas with lesser slopes are considered least vulnerable to drought compared to moderate and higher slopes. In this case, slopes in the range from 0-2 % are categorized as least vulnerable to drought, followed by moderate and higher slopes. Thus, the relative weights assigned to each slope category are shown in Table 2.

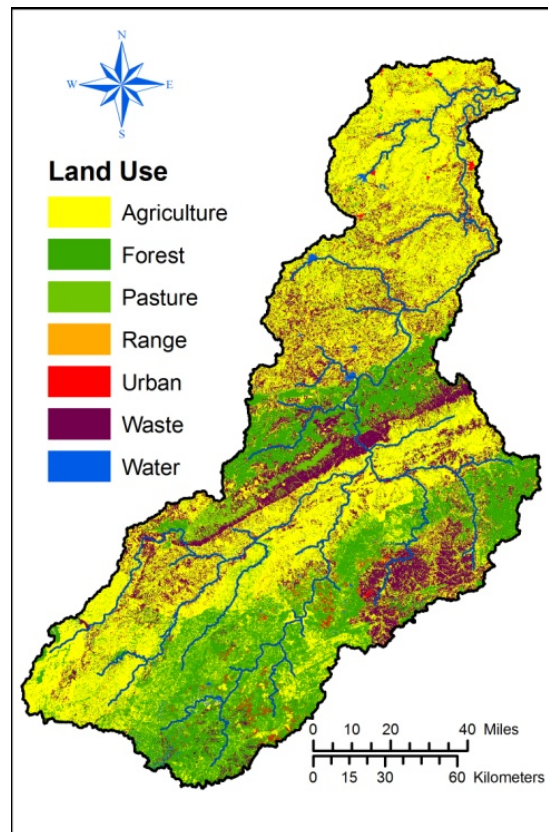
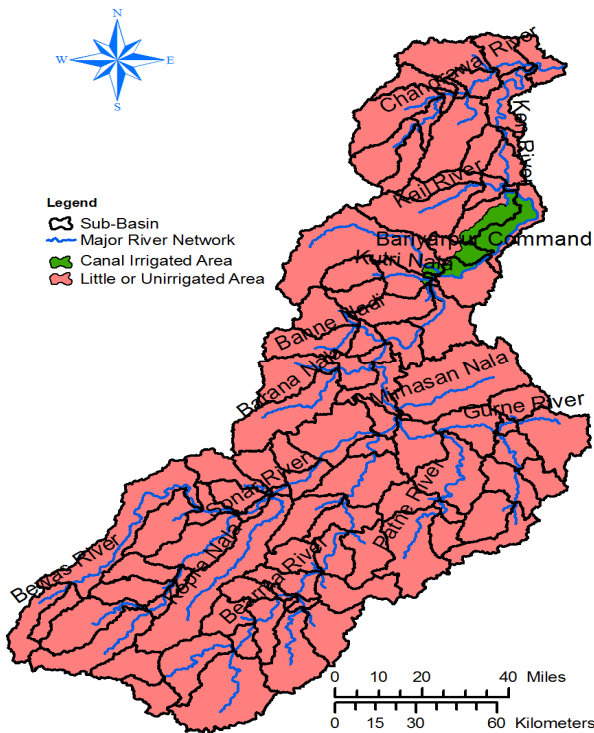


Fig. 3: Land Use Map of Ken River Basin

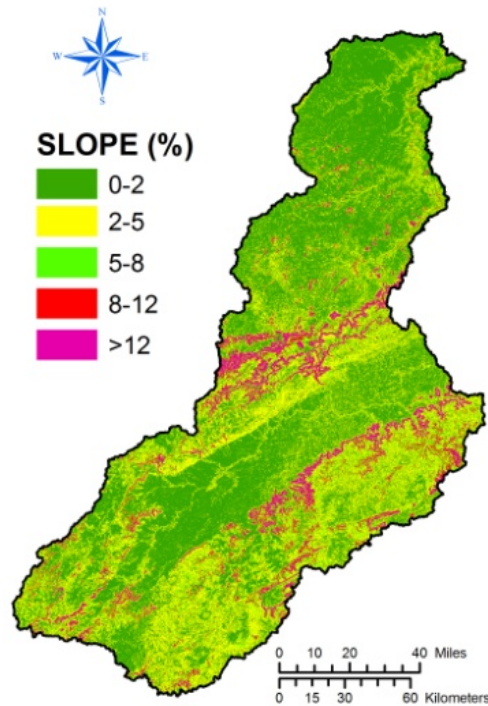


**Fig. 4: Irrigation support in Bariyarpur Command Area Map**

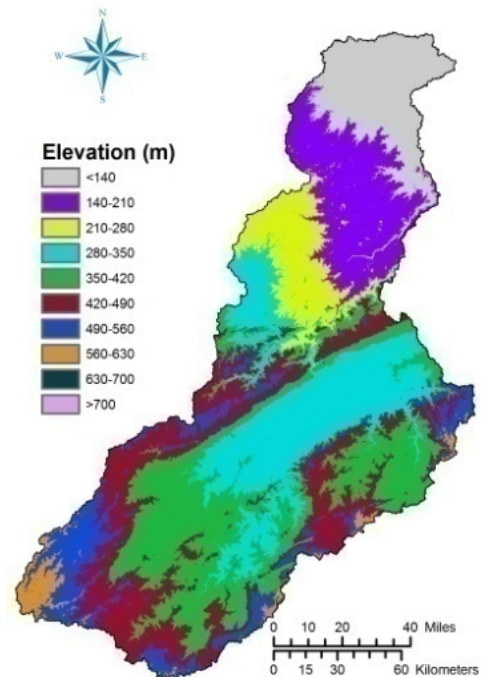
**Elevation Zones:** Water availability greatly depends on elevation of the place in the basin. To indirectly account for the water availability at different elevations, Ken basin is divided into three elevation zones. These elevation zones are lower elevation zone (up to 280 m), middle elevation zone (280 m - 490 m) and upper elevation zone (more than 490 m). The upper elevation zone have mostly hilly and undulating topography with average slopes >6% and streams of 1<sup>st</sup> and 2<sup>nd</sup> order which are mostly ephemeral in nature. The upper reach areas do not sustain flow beyond October/ November and therefore have zero or lowest surface water availability during non-rainy season. The middle elevation zone encompass land areas with average slopes between 2-6% and streams of 3<sup>rd</sup> and 4<sup>th</sup> order having flow in streams upto December and January months and have moderate surface water availability. The lower elevation zone includes areas with average slopes <2% and stream flows are intermittent to perennial. Also, the lower sections of basin often get more time for water retention than upper and middle parts. Therefore, upper reaches of the basin may be considered more vulnerable followed by middle and lower reaches of the basin. The relative weights assigned according to vulnerability to water scarcity of each elevation category are being given in Table 2. The elevation distribution of the study basin is shown in Fig. 6.

**Distance from River Reach:** It is assumed that areas closer to river courses are less vulnerable to water scarcity because of more recharge potential and ground water availability relatively for longer period in comparison to areas distant from the river course. Accordingly, the basin area has been

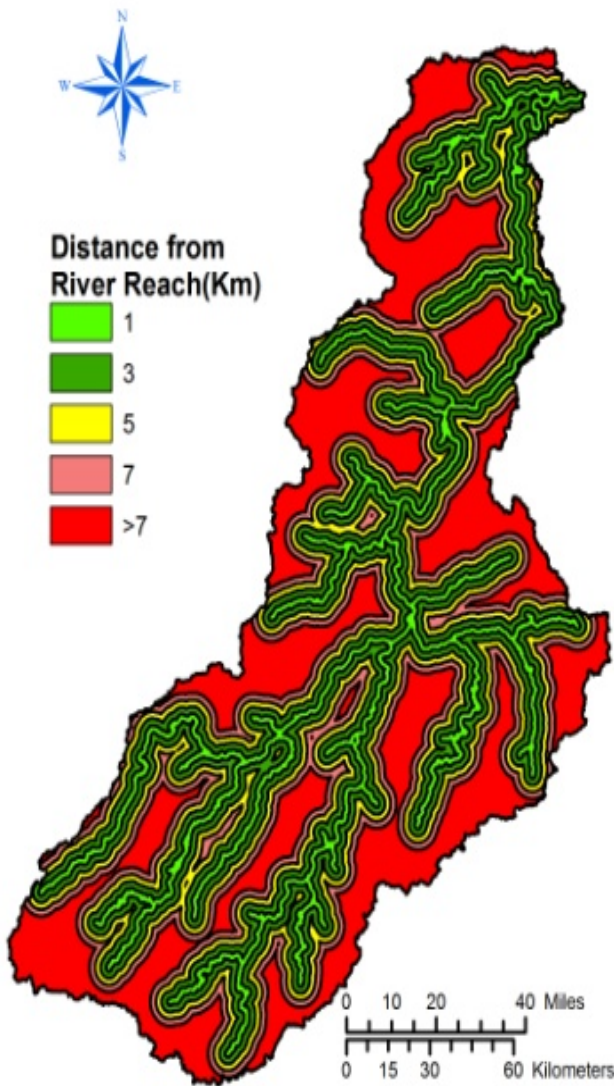
divided into five sub-classes depending upon the distance from the river course as shown in Fig.7. The area within one kilometer of the river boundary is considered as least vulnerable, while areas beyond 7 km distance are considered as highly vulnerable. The weights assigned to various categories according to distance from the river reach are given in Table 2.



**Fig. 5: Slope Map of the Ken Basin**



**Fig. 6: Elevation zone in Ken River Basin**



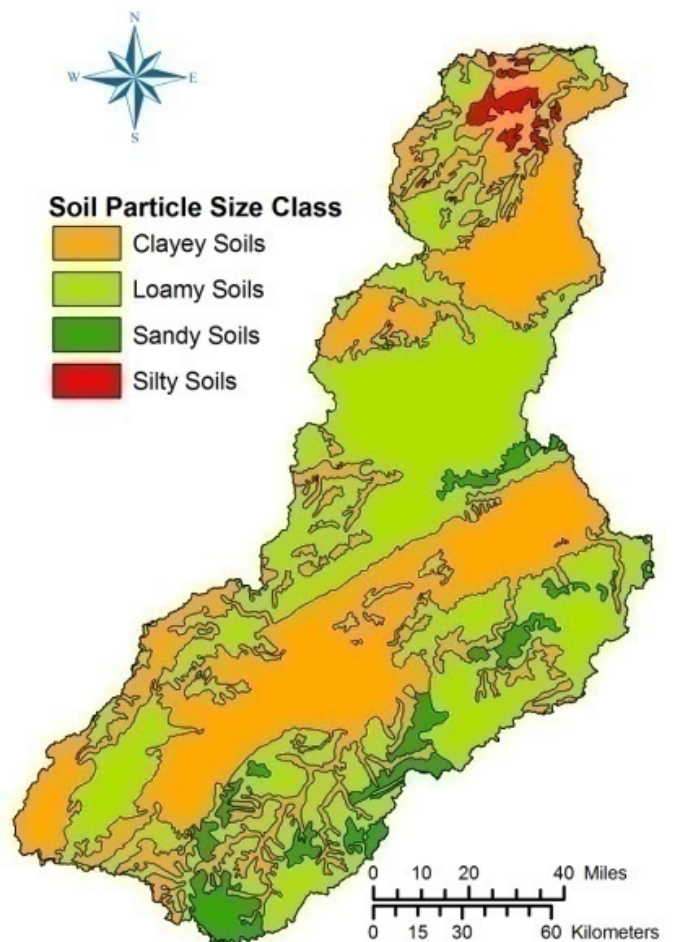
**Fig. 7: Map showing the Distance from the River Reach**

**Soil Type:** One of the main functions of soil is to store moisture and supply it to plants during non-rainy periods. The available moisture storage capacity of soil determines the time span for which particular type of soil could sustain dry spells in supplying moisture to plants for their survival. The soil map is digitized from hardcopy maps obtained from National Bureau of Soil Survey and Land Use Planning (NBSS&LUP) of the State of MP and UP and Soil Series of India (NBSS, 1994). Soils in the Ken River basin are classified into four major textural classes- viz. clay, loam, silt and sand as shown in Fig.8. Out of which Clay soils are considered least vulnerable to drought because they retain more moisture compared to other types of soils (Blencowe et al., 1960). On the other hand, gravelly sandy loam soils hold least moisture and are most vulnerable to drought. Thus, soils having greater water holding capacity indicate low vulnerability to drought because root-zone has more available-water for plants. However, light soils have less available water for plants and signify high vulnerability to drought. Accordingly, areas with

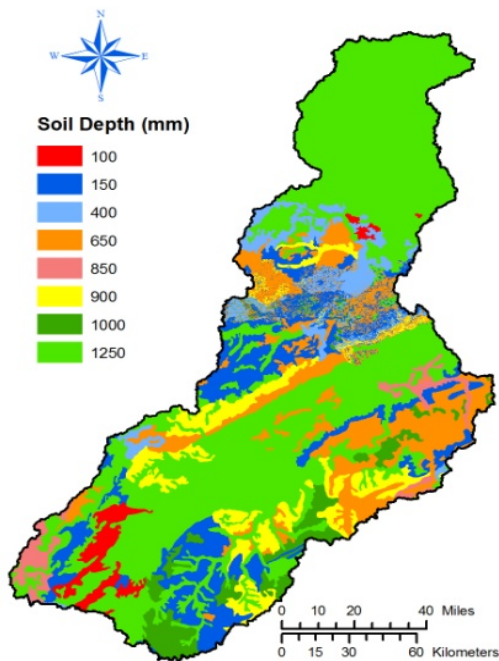
lighter soils are considered relatively more vulnerable than clayey soil areas.

**Soil Depth:** The soil depth largely controls total soil water storage for plants (McColley and Hodgkinson, 1970). Soils having more depth are capable to supply more water to plants and are considered as less vulnerable to drought and vice versa. Spatial distribution of soil depth in the study basin is shown in Fig. 9.

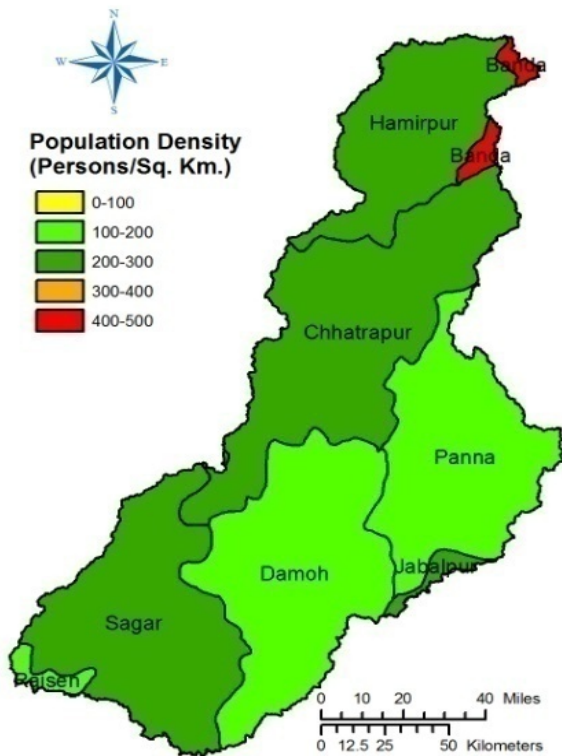
**Population Density:** The pattern of water demand in an area is also affected by population density and it is considered as one of the important factors for water scarcities in lean periods (non-rainy season). In this study, areas with higher population density are considered to be more vulnerable than those with less population density. It is because the higher population density areas would have relatively more water demand and hence more susceptible to water scarcity during drought. Accordingly highly populated cities, towns and bigger villages are considered to be more vulnerable. The areas with less population and hence low water demand category are less vulnerable. Relative spatial distribution of population density in the study area is shown in Fig.10.



**Fig. 8: Textural Classification of Soil type in Ken River Basin**



**Fig. 9: Spatial Distribution of varying Soil Depth in Ken River Basin**



**Fig. 10: Population Density Map of Districts in Ken River Basin**

**Meteorological and Hydrological Factors:** The rainfall deficiency is primary climatic factor responsible for occurrence of drought and subsequent relative water and soil

moisture shortage.. In order to assess vulnerability to drought in spatial and temporal domain, the percentage rainfall deficiency/excess with respect to mean value and the deficit of soil moisture in the form of SMDI are included as factors varying with time and space. Depending on the magnitude of SMDI and percentage deficiency of rainfall from mean during a given month, the values of weight from 0 to 25 are assigned as shown in Table 2. Positive values of SMDI represent either normal or wet condition, hence considered insignificant and has been assigned 0 weight, while SMDI below -4 , considered as critical soil moisture and poses serious threat to crop growth, is assigned weight value of 25. Similarly, rainfall deficiency up to 10 % with a weight value of 0 has been considered insignificant, whilst rainfall deficiency more than 50% with a weight value of 25 has been considered as severe rainfall deficiency.

***Delineation of Hydrologic Response Units (HRUs) using SWAT-Model***

The Soil and Water Assessment Tool (SWAT) model is a distributed hydrologic model developed to quantify runoff yield with reasonable accuracy in large ungauged basins. It provides continuous simulation of hydrological processes (evapotranspiration, surface runoff, percolation, return flow, soil moisture, groundwater flow, channel transmission losses, pond and reservoir storage, channel routing and field drainage) at the level of Hydraulic Response Units (HRUs). The model can be run with a daily time step. SWAT divides the whole basin into sub-basins using topography. Each sub-basin is divided into hydrological response units (HRUs), which are unique combinations of soil, slope and land cover. Complete description of the SWAT model is available elsewhere (Neitsch et al., 2005). The SWAT model is preferred in this study because it provides distributed assessment of water balance components in time and space. Therefore, the desired assessment of soil moisture deficit could be obtained in time and space to quantify the distribution of vulnerability to drought in time and space in the Ken basin.

The SWAT model is calibrated to obtain estimates of different hydrological components at the level of HRUs of the Ken basin. For calibration of SWAT model, database on land use, soils, and weather is required. ArcGIS and Erdas imagine softwares are used as a pre-processor for preparation of database for use in the SWAT model. Using the spatial data on DEM, landuse and soil described earlier, entire area of the Ken basin is divided into 104 sub-watersheds, which are further segregated into 7942 HRUs. The available rainfall data of fourteen raingauge stations and temperature data of two temperature gauge stations for a period (1982-1997) and corresponding stream flow data at four gauging stations detailed in Table 3 are used for calibration and validation of the SWAT model. Available hydrological data is split into two groups of which data from 1982 to 1990 is used for calibration of the model parameters and data from 1991 to 1997 is used for model validation. The model’s ability in simulating the stream flow is evaluated based on visual comparison and statistical criteria such as Nash-Sutcliffe Efficiency (NSE, Nash and Sutcliffe, 1970) and coefficient of determination ( $R^2$ ).

**Table 3: Location of gauge and discharge sites and data availability in Ken basin**

Gauging Site	River on which Located	Drainage Area (sq.km.)	Elevation (m)	Length of flow data used
Garhakota	Sonar	5823.52	362	1984 to 1997
Gaisabad	Bearma	1335.72	291	1982 to 1997
Madla	Ken	20566.4	194	1982 to 1997
Banda	Ken	25302.6	92	1982 to 1997

**Assessment of Soil Moisture Deficit Index (SMDI)**

Soil moisture is an important hydrologic variable that controls various land surface processes. Although only a small percentage of total precipitation is stored in the soil, soil moisture reserve is critical for sustaining agriculture, pasture, and forestlands. It is a good measure for agricultural drought monitoring. In spite of its importance to agriculture and drought monitoring, information about soil moisture is not widely available on a regional scale. This is partly because soil moisture is highly variable both spatially and temporally and is therefore difficult to measure on a large scale (Narasimhan et. al., 2005). However, SWAT model is capable of estimating soil moisture at sub-basin as well as HRU level. SWAT model estimated available soil water is used for computation of SMDI as described by Narasimhan and Srinivasan (2005). The SMDI can be calculated on an incremental basis as (Narasimhan and Srinivasan, 2005)

$$SMDI_j = 0.5 SMDI_{j-1} + \frac{SD_j}{50} \dots\dots\dots(3)$$

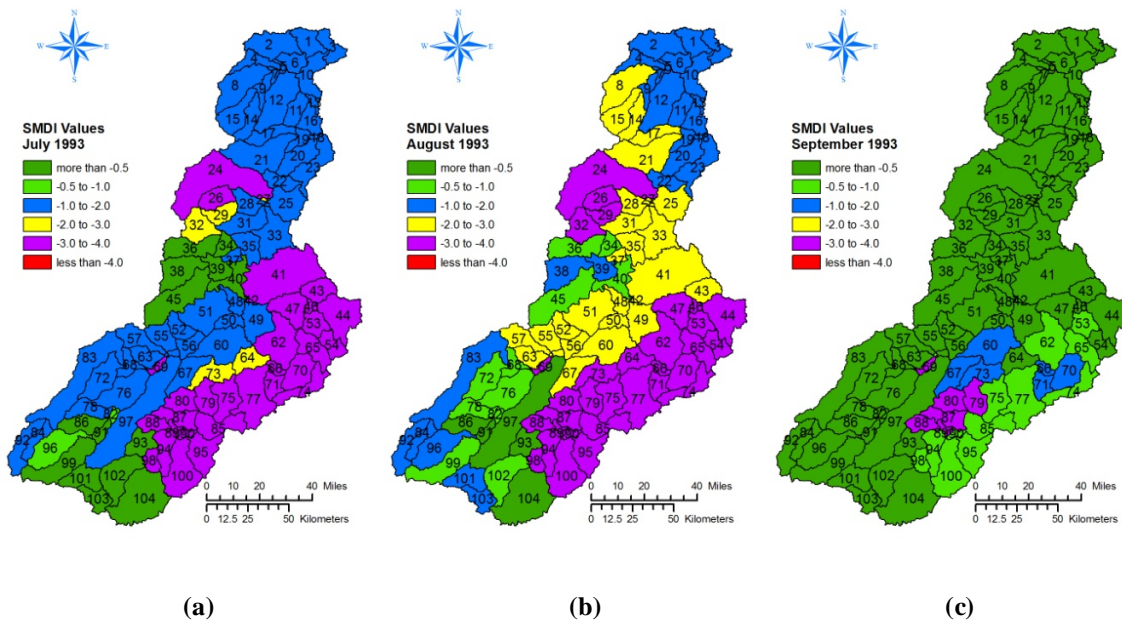
where,  $SMDI_j$  represent the soil moisture deficit index for the given month and  $SMDI_{j-1}$  represents soil moisture deficit during previous month. The complete algorithm for calculating SMDI at desired time step is available in Narsimhan and Srinivasan (2005).

SMDI during any month may range from - 4 to + 4 representing dry to wet conditions (Table 4). Using the

equation (Eq. 3), SMDI is calculated for the entire period of record (1982 to 1997) for all sub-basins. The spatial distribution of SMDI computed during the worst drought year 1993 identified previously, for the months of July, August and September are presented in Figs. 11(a-c). From Figs. 11(a-c) it is evident that during the months of July and August 1993, most part of the basin area was under mild to severe drought condition. However, due to good amount of rainfall during the month of September 1993, most part of the basin recovers from soil moisture deficit to normal soil moisture conditions.

**Table 4: SMDI Classification**

Class	SMDI	Condition
1	4.0 or more	Extremely Wet
2	3.0 to 3.99	Very Wet
3	2.0 to 2.99	Moderately Wet
4	1.0 to 1.99	Slightly Wet
5	0.5 to 0.99	Incipient Wet Spell
6	0.49 to -0.49	Near Normal
7	-0.5 to -0.99	Incipient Dry Spell
8	-1.0 to -1.99	Mild Drought
9	-2.0 to -2.99	Moderate Drought
10	-3.0 to -3.99	Severe Drought
11	-4.0 or less	Extreme Drought



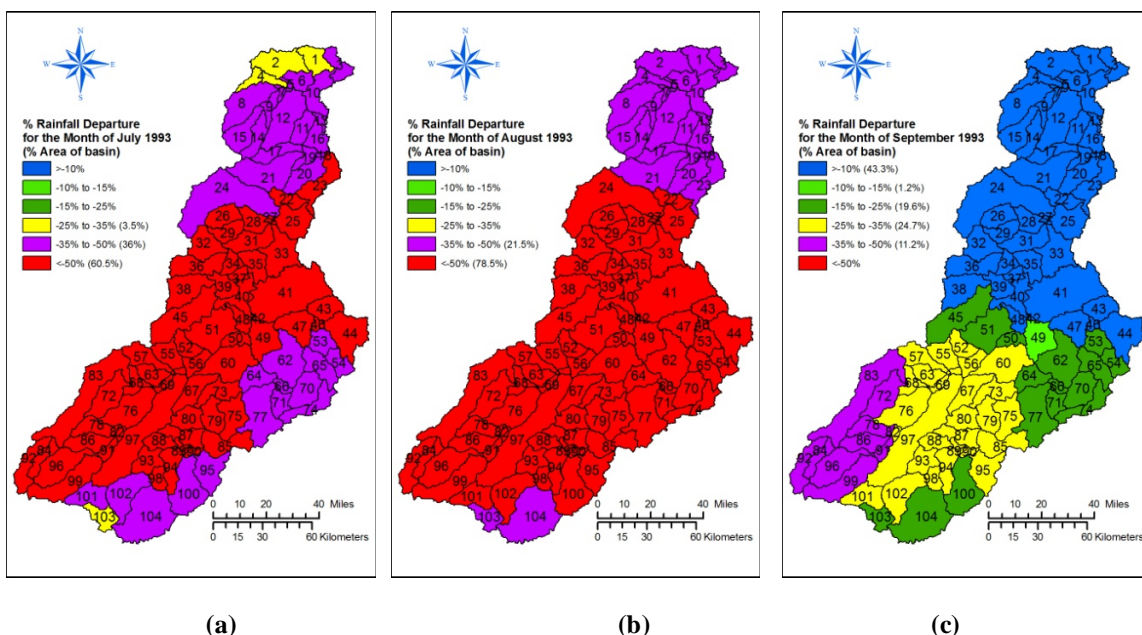
**Fig. 11: SMDI Map of Ken River Basin for the Month of (a) July (b) August (c) September 1993**

**Assessment of Monthly Rainfall Departure**

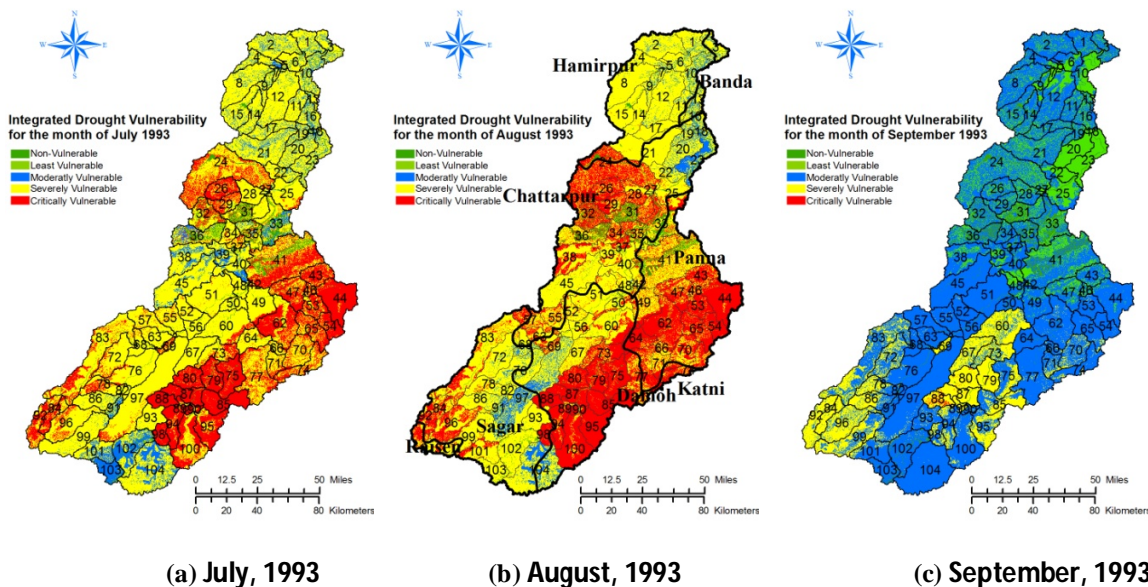
For the present study, monthly rainfall data of 12 rain gauge stations for a period of 110 years from 1901-2011 (data missing for the year 2003) have been used to calculate the monthly rainfall values of 104 sub-basins. The monthly rainfall departure from long term mean of the corresponding month for all sub-basins has been calculated using the equation (Eq.1). The year 1993 was recorded as worst drought year with maximum annual and seasonal rainfall deficiency. The monthly rainfall departure for July, August and September months of the year 1993 is used as the climatic factor in the study for assessment of vulnerability to drought. The spatial extents of rainfall departure during these months are presented in Figs.12(a-c).

**Integration of Multiple Factors and Demarcated Zones Vulnerable to Drought**

To achieve integrated assessment of vulnerability to drought both in spatial and temporal domains, the maps of various physical factors (Fig. 4 to 10) have been combined with SMDI maps, Figs. 11(a-c) and rainfall departure maps Figs.12(a-c) for the months of July, August and September, 1993, using proposed weighing scheme (Table2). The resulting output maps of spatial distribution of vulnerability to drought during the months of July, August and September, 1993 are shown in Fig.13(a-c), respectively as illustration. Similar maps for other less drought vulnerable years are also generated (not shown here) for further analysis. The composite maps depicting IDVI values have been categorized into five classes i.e. Non-Vulnerable, Least Vulnerable, Moderately Vulnerable, Severely Vulnerable and Critically Vulnerable based on the values of IDVI. The limiting values of IDVI for above classes along with estimates of area under different vulnerability classes are also presented in Table 5.



**Fig. 12: Spatial Distribution of Rainfall Departure for the month of (a) July, (b) August and (c) September, 1993**



**Fig.13: Integrated Vulnerability to drought for the months of (a) July, (b) August and (c) September during drought year 1993 using proposed differential weighing scheme**

**Table 5: Area demarcated with differential weighing scheme under different vulnerability classes using rainfall departure during July, August and September months in a drought year 1993**

	Values of IDVI	Vulnerability	Area under different vulnerability classes (km <sup>2</sup> )					
			July 1993		August 1993		September 1993	
1	≤0	Non-Vulnerable	963.10	3.36	963.10	3.36	963.10	3.36
2	>0 to ≤0.2	Least Vulnerable	0.00	0.00	0.00	0.00	4226.98	14.73
3	>0.2 to ≤0.4	Moderately Vulnerable	2118.28	7.38	1467.31	5.11	18804.12	65.54
4	>0.4-≤0.7	Severely Vulnerable	18513.99	64.52	16559.87	57.71	4660.40	16.24
5	>0.7	Critically Vulnerable	7097.47	24.74	9702.56	33.82	38.23	0.13

**RESULTS AND DISCUSSION**

From the resulting figures it is found that the application of proposed methodology clearly distinguishes the degree of vulnerability to drought during various months of a drought year (1993). For instance, the significant part of the basin areas were under severe and critical classes of vulnerability to drought during the July and August months of 1993. This is because the rainfall deficiency with respect to mean value in different sub-watersheds of Ken basin was ranging from -32 % to -61% and -45% to -56% for July and August months of 1993, respectively. However, there was good rainfall during the month of September, 1993, therefore, basin areas under critical and severe category reduced significantly (Fig.12(c)). This indicates that the method is sensitive to rainfall departures and identifies realistic distribution of vulnerability to drought in time and space.

Table 5 indicates that approx. 25.74%, 33.82% and 0.13% of the basin area was critically vulnerable to drought during the months of July, August and September respectively in the year 1993. These critically vulnerable patches were located in western parts of Sagar district as well as northern parts of the Chattarpur district and South Eastern parts of Damoh and Panna Districts during these months (Fig. 13). From the agricultural reports, it was found that, in the areas identified with critical and severe vulnerability throughout the rainy season, paddy crop yield was very low due to water stress during Kharif Season in 1993. These critical areas appear to be fully justified as city of Sagar is located in the western ridge areas with low surface and ground water availability plus very high municipal water demands. This corroborates favorably with the documented information of the region for the year 1993 i.e. (District Statistics Handbook, 1993& 2007). On the other hand, the areas which received good amount of rainfall during the month of September (Fig. 12(c)) have recovered from critical vulnerability and identified under moderate category of vulnerability to drought (Fig. 13(c)). These areas of basin fall in Hamirpur and Banda districts of Uttar Pradesh, wherein, the production loss to the Kharif crop was less than 30% of the average production. However, in Sagar and Damoh districts it was of the order of more than 60% (District Statistics Handbook, 1993). Also, the area covered by sub-basin no. 18, 20, 22, 23 and 25 that fall under canal command could recover fully from drought vulnerability due to irrigation support. Integrated drought vulnerability

index (IDVI) has been defined as the sum of weights of various factors scored by corresponding HRU divided by sum of the maximum weight value of each factor. Thus, the composite map showing spatial distribution of vulnerability to drought has been prepared. The HRUs with higher value of IDVI represents the areas with high degree of vulnerability to drought and vice versa. The maps thus obtained have been validated using the documented information and field surveys. It is believed that the proposed methodology may be used as a reliable tool for demarcation of zones vulnerable to drought. The output maps from proposed differential weighing scheme were compared with that of uniform weighing scheme suggested by Pandey et al., 2010. It was found that the maps, generated using differential weighing scheme, present clear demarcation of the areas under moderate, severe and critical categories of vulnerability to drought compared to other one. It is therefore concluded that the differential weighing scheme provides more realistic assessment of vulnerability to drought and may help decision makers in appropriate planning of drought mitigation strategies.

The Ken basin belongs to dry-sub humid climatic region of India, and therefore calls for the appropriate drought mitigation measures to moderate the impacts of recurring droughts. The dry-sub humid climatic regions face drought with average frequency of once in every 5 or 6 years and the occurrence of severe drought events in about once in 10 or more years. The expected persistence of drought events are commonly for two consecutive years. The suggested mitigation option for such areas may be as follows:

- Increase in water storages in tanks and reservoirs
- Water conservation/ in-situ water retention through gully checks and water harvesting/stop dams
- Intensive Groundwater Recharge may be a better option to enhance groundwater availability
- Within stream water storages and Water diversions may be used to enhance both surface and ground water availability in such areas.
- Inter-basin water transfer – remain a better mitigation option for bringing prosperity in such regions.

- Recycling of wastewater and its use in irrigation may enhance the ability to cope with drought.

## SUMMARY AND CONCLUSIONS

The paper illustrates a real application new methodology devised to assess vulnerability to drought in spatial and temporal scales using physiographic, meteorological, hydrologic and social factors. The physiographic factors are static physical features of basin which include topography, slope, land use, soil type, soil depth, proximity to river reach, elevation zones and population density. The climatic and hydrologic factors are dynamic in nature which include rainfall departure from corresponding mean and soil moisture deficit, respectively. Spatial information of different factors has been classified in various sub-classes and maps have been prepared using ArcGIS. A differential weighting scheme has been used to integrate various ? (factors aspects )to assess vulnerability to drought. The SWAT model has been applied to demarcate hydrologically homogeneous areas called HRUs in respect of land use, slope and soil type, and for estimation of spatial and temporal distribution of soil moisture in the study basin. Subsequently, Soil Moisture Deficit Index (SMDI) has been calculated using the available soil moisture estimates from SWAT model. The relevance of the method has been demonstrated for the Ken River Basin in India. The conclusions drawn from the study are as follows.

1. Integration of physiographic, meteorological, hydrologic and social ?provide pragmatic assessment of vulnerability to drought in space and time.
2. Proposed integrated drought vulnerability index (IDVI) defined as the sum of weights of various factors scored by corresponding HRU divided by sum of the maximum weight value of each factor leads to assessment of composite impacts of significance of various factor in vulnerability to drought and hence it is more rational.
3. The areas demarcated using proposed methodology has been validated using the documented information and comprehensive field surveys and the prepared map showed very good agreement with the physical observations made in the study basin.
4. It is believed that the proposed methodology may be used as a reliable tool for demarcation of zones with different level of vulnerability to drought. Therefore, near effective real time drought monitoring is feasible and appropriate mitigation actions can be planned to reduce the adverse impacts of drought.

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