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Drought Risk Assessment Under Changing Climate for Semi-Arid Central-East Region of Gujarat, India

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Abstract

Present research developed drought risk index (DRI) under changing climate by analyzing multiple indicators of drought hazards (DHI) and drought vulnerability (DVI) for semi-arid central-east region of Gujarat, India. The daily gridded rainfall data of 1951 to 2020 time period having 0.25° spatial resolution were collected from Indian Meteorological Department (IMD) to analyze drought characteristics. The Standardized Precipitation Index (SPI) method at 6 monthly time step indicating seasonal drought was utilized to assess peak drought years and major historical drought events. DHI was assessed by considering near, moderate, severe and extreme drought events along with spatiotemporal variability of drought trend magnitude obtained from Sen's slope method which addressed the research gap of analyzing drought hazards under changing climate. DVI was analyzed by considering total water availability, population density, land use types, irrigated area and regional slope. Current study identified peak drought events for 1961, 1965, 1974, 2002 and 2015 years with 1985 to 1987 time period being the longest drought duration for major parts of the study region. About 30 % of the grid points showed negative trend magnitude indicating increasing drought intensity in the near future. The IDW interpolation, reclassify and weighted sum tools were employed in GIS environment to prepare DHI, DVI and DRI raster maps which were categorized in five classes of low, medium, high, severe and extreme. The central-east region of Gujarat observed approximately 47, 60 and 37 percentage area under severe to extreme classes for DHI, DVI and DRI respectively which should be prioritized for sustainable water resources management under changing climate.

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Keywords

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Drought;
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Introduction

Drought is a climatic phenomenon that can be described for a region with deficit precipitation which is less than the normal amount, re-occurring for a prolonged time period.[1,2] Droughts have the potential to cause extreme damages to the crop production, water scarcity and socio-economic instability for a country like India along with hazardous situations of forest fires and public health risks.[3,4] Short-term droughts are often analyzed from hydro-meteorological data whereas long-term drought assessments are based on hazards, vulnerability and drought risk aspects which help in enhancing mitigation and adaptation measures.[5] Characteristics such as intensity, duration, extreme historical events and the spatiotemporal variability have most generally been used in drought assessments.[6] Based on the deficit rainfall, Standardized Precipitation Index (SPI) developed by Mckee *et al*. (1993)[7] have been utilized world-wide to analyze droughts considering its simplicity and robustness.[8-16]

Drought events have accelerated under changing climate especially in semi-arid to arid regions due to warming temperatures, high evapotranspiration losses, reduced soil moisture content and scanty uneven rainfalls.[17,18] For semi-arid region such as Gujarat state, Patel *et al*.[8] used SPI method to analyze droughts based on station data (160 points) of 1981 to 2003 time period found 1982 to 1987 being the most extreme drought period with significant drought risks in northern, central, Kachchh and Saurashtra regions. For northern and central Gujarat regions, moderate to extreme drought events and drought associated hazards were analyzed using finer resolution (0.25°) IMD gridded data of 1951 to 2020 time period by employing trend assessment of drought time series (SPI6) revealed negative magnitude of trend for eastern parts in both the regions indicating intensifying droughts for the near future.[15,16] Bandopadhyay and Saha10 adopted CRU gridded data (90 km resolution) to analyze spatiotemporal variations in drought for Gujarat utilizing four different indices including SPI, also revealed drought hazard zones for northern, eastern and central regions.

Region specific drought assessments are useful in better policy making towards mitigation and adaptations however, long-term drought management requires a comprehensive analysis of hazards, vulnerability and drought risk which include multiple indicators of hydro-meteorological and socio-economic parameters.[5,19,20] Numerous studies on drought vulnerability have focused on a basin level assessment[1,21-23] but only a few studies have explored sub-district or Taluka (block) level drought risk assessment.[24,25] Shahid and Behrawan (2008)19 analyzed drought risk at district level for Bangladesh using the hazards and vulnerability conceptual framework in which drought hazards were obtained from SPI-6 time series to best characterize seasonal droughts revealing approximately 34% area in the northern parts under high to very high drought risks. Kim *et al*.[20] carried out drought risk assessment at district level for South Korea by adopting the composite hazards and vulnerability framework categorized in low, moderate, high and very high risk levels revealing 11 out of 229 districts under high to very high drought risks. Swain *et al*.[23] performed a district level comprehensive drought vulnerability assessment for Narmada river basin in India which included groundwater depth along with other socio-economic indicators such as population density, topography slope, land use land cover, etc. revealing 26 out of 35 districts to be highly vulnerable to droughts. Palchaudhuri and Biswas[24] worked out drought risk assessment at block level for Puruliya district of West Bengal in India by analyzing fourteen different hydro-climatic and socio-economic parameters with the help of analytical hierarchy process which revealed severe drought affected about 14 blocks of the study area.

Present research has assessed Taluka level drought risks by considering multiple indicators of hazards and vulnerability which is the need of the hour that has not been effectively explored for semi-arid regions of Gujarat state. The novel aspect in current study while developing drought risk map is the addition of trend magnitude of SPI6 time series (TD) in drought hazards and total water availability (TWA) in drought vulnerability as the most significant indicators which has not been included in any of the aforementioned studies. The main objectives in current study were to analyze major historical drought events associated with drought hazards, to assess spatiotemporal variability of drought under changing climate, to analyze drought vulnerability and drought risks at Taluka level that will help in enhancing present water policies for sustainable management of water resources.

Materials and Methods

Study Area and Data Collection

The research focuses on the central-east region of Gujarat, covering the districts of Panchmahal, Dahod, and Mahisagar. This region spans approximately 9,650 km² and lies between latitudes 22.28°N to 23.47°N and longitudes 73.35°E to 74.48°E. It experiences a semi-arid climate, characterized by uneven distribution of precipitation. The southwest monsoon, occurring from mid-June to September, contributes to an annual average rainfall of approximately 700 mm. The region's temperature varies seasonally, with daily maximums ranging from 28°C in winter to around 40°C in summer, while minimum temperatures range from 11°C in winter to 25°C in summer. Two major water conservation structures Kadana dam on Mahi River located in the northern parts and Panam dam on Panam River located in the central parts are the available surface water sources that cater to various water demands of the study region. The majority of population residing in the region comes under tribal community working in agriculture and animal husbandry. About 55% of rural agriculture is rain-fed and 45% is irrigated from surface water sources. Total Water Availability (TWA), Population Density (PD) and Irrigated area (IRRG) indicators at Taluka (block) level have been obtained from the reports of Pradhan Mantri Krishi Sinchai Yojana26 district handbooks. High spatial resolution gridded rainfall datasets (0.25°) for the period 1951 to 2020 were sourced from the India Meteorological Department, with 23 grid points proving useful in current study. The elevation data was taken from the United States Geological Survey (USGS) using Shuttle Radar Topography Mission (SRTM-DEM) at a 30-meter resolution. The topographic variation within the study region ranges from an elevation of 33 meters above mean sea level in the western lowlands to approximately 750 meters in the eastern highlands.

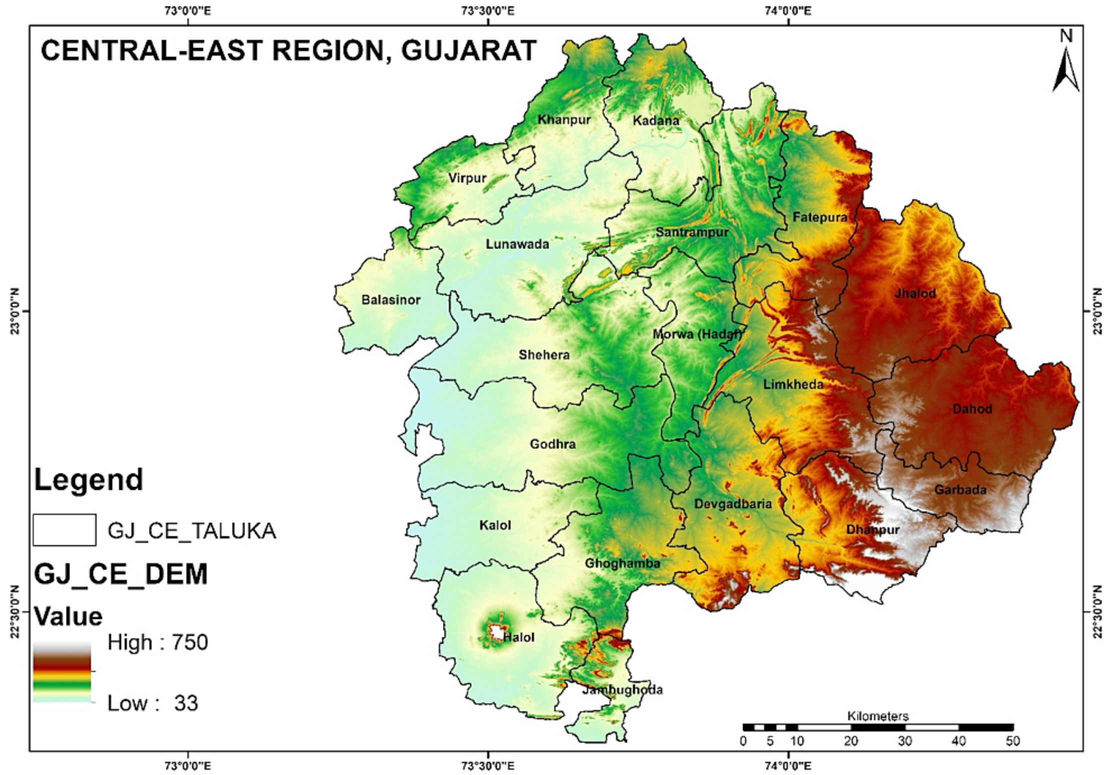

Fig.1: Central-East region of Gujarat with digital elevation (DEM)

Research Methodology

Present research was worked out in through a structured four step process. The first step involved collection and organization of relevant meteorological data to apply SPI-6 method to analyze peak drought years and major historical drought events. In the second step, indicators of drought hazards (DHI) such as Trend magnitude of Drought series (TD) as well as Near (ND), Moderate (MD), Severe (SD) and Extreme (ED) Drought events were assessed. In the third step, indicators of drought vulnerability (DVI) such as Total Water Availability (TWA), Population Density (PD), Land Use Land Cover (LULC), Irrigation area (IRRG) and Slope Topography (SLOPE) were analyzed. In the final step, spatially distributed raster maps of all the hazards and vulnerability indicators were developed using IDW interpolation in GIS-framework.[8,16] These maps were reclassified (1 to 5) in natural breaks[15,19] and assigned with appropriate weights to develop DHI, DVI and Drought Risk Index (DRI) maps by employing Weighted Sum and Raster calculation tools. The IMD gridded daily data of 1951 to 2020 time period were transformed into monthly rainfall time series data, which were further analyzed for trend magnitude and drought evaluation using R-studio (version: 2024.12.0+467) software with ‘trend’ and ‘SPEI’ packages respectively.

Table 1: Drought Categories and corresponding SPI ranges

Sr.	Drought Category	SPI Range
1	Non Drought	SPI >= 0
2	Near Drought (ND)	-0.99 =< SPI < 0
3	Moderate Drought (MD)	-1.49 =< SPI < -1.0
4	Severe Drought (SD)	-1.99 =< SPI < -1.5
5	Extreme Drought (ED)	SPI =< -2.0

Table 2: Drought Hazard indicators with respective Weights and Ratings

Sr.	Drought Hazard Indicator	Natural Break classification : Ratings	Weight
1	Trend of Drought SPI-6 Series (TD)	(-0.0081) – (-0.0030) : 5 (-0.0029) – (0.0000) : 4 (0.0001) – (0.0015) : 3 (0.0016) – (0.0038) : 2 (0.0039) – (0.0114) : 1	5
2	Extreme Drought (ED) No. of events/70 years	(1.19) – (1.96) : 5 (0.81) – (1.18) : 4 (0.59) – (0.80) : 3 (0.33) – (0.58) : 2 (0.00) – (0.32) : 1	4
3	Severe Drought (SD) No. of events/70 years	(3.32) – (4.71) : 5 (2.76) – (3.31) : 4 (2.17) – (2.75) : 3 (1.34) – (2.16) : 2 (0.00) – (1.33) : 1	3
4	Moderate Drought (MD) No. of events/70 years	(10.23) – (12.00) : 5 (09.27) – (10.22) : 4 (08.54) – (09.26) : 3 (07.65) – (08.53) : 2 (05.53) – (07.64) : 1	2
5	Near Drought (ND) No. of events/70 years	(24.95) – (28.00) : 5 (23.44) – (24.94) : 4 (21.70) – (23.43) : 3 (19.49) – (21.69) : 2 (16.00) – (19.48) : 1	1

Standardized Precipitation Index (SPI)

The Standardized Precipitation Index (SPI) method, introduced by McKee *et al.*,[7] requires monthly rainfall time series data as a fundamental input for drought assessment. Due to the simplicity and robustness of the SPI method, it has been extensively adopted in a vast number of studies.[9,15] The classification of drought from SPI values have been described in Table 1. The SPI values less than zero, indicate near to extreme drought and the time period for which the SPI values remain negative has been considered as major drought events. The SPI method, applied at a six-month interval, is commonly used for mid-term seasonal drought[19] analysis. This approach compares the rainfall of six consecutive months in a given year with the corresponding six-month periods across all available years.[6] The SPI method is generally formulated as shown in (Eq.1) where SPIi represents Standardized Precipitation Index, R_i is month-wise rainfall, $\overline{R_i}$ is the mean of time series and SD_i is the standard deviation, all associated with of i[th] monthly rainfall.

$$SPI_i = \frac{R_i - \overline{R_i}}{SD_i} \qquad \text{...(1)}$$

Drought Hazard Index (DHI)

Drought hazards have often been estimated based on the occurrence probability.[20] In present research, the SPI-6 values calculated at each grid point for all the years (1951-2020) were categorized as per Table 1 and the sum of number of drought years from near (ND) to extreme (ED) classes were determined under drought hazards. The major drought events in ND, MD, SD and ED were spatially distributed using IDW interpolation technique in GIS environment. These raster maps were further reclassified in ratings 1 to 5 using Natural Break (Jenks) classification[16,19] and assigned with appropriate weights as described in Table 2.

Table 3: Drought Vulnerability indicators with respective Weights and Ratings

Sr.	Drought Vulnerability Indicator	Natural Break classification : Ratings	Weight
1	Total Water Availability (TWA) in Million Cubic Meter (MCM)	024 – 051 : 5 052 – 087 : 4 088 – 118 : 3 119 – 174 : 2 175 – 382 : 1	5
2	Population Density (PD) in person/km^2	611 – 766 : 5 514 – 610 : 4 436 – 513 : 3 351 – 435 : 2 298 – 350 : 1	4
3	Land Use Land Cover (LULC) class	Agriculture Land : 5 Built up Land : 4 Trees, Vegetation : 3 Pasture, Barren : 2 Water body : 1	3
4	Irrigation Area in Percentage (IRRG)	23 – 30 : 5 31 – 42 : 4 43 – 49 : 3 50 – 57 : 2 58 – 75 : 1	2
5	Slope Topography (SLOPE) in % rise	> 30 (%) : 5 15 – 30 (%) : 4 08 – 15 (%) : 3 03 – 08 (%) : 2 00 – 03 (%) : 1	1

The current study has considered trend magnitude of drought series (TD) estimated from sen's slope[27] as the most significant indicator of drought hazard assessment under changing climate which denoted drought prone regions for the near future thus it has been given the highest weight (W=5). The DHI was developed from weighted sum of TD, ED, SD, MD and ND with w and r representing weights and ratings as formulated in (Eq.2).

$$DHI = (TD_w{*}TD_r) + (ED_w{*}ED_r) + (SD_w{*}SD_r) + (MD_w{*}MD_r) + (ND_w{*}ND_r) \quad ...(2)$$

Drought Vulnerability Index (DVI)

Drought vulnerability has generally been analyzed as a relative measure by comparing regional sensitivity.[20] In current study, multiple indicators such as TWA, PD, LULC, IRRG and SLOPE were selected based on the adequacy to explain regional sensitivity and adaptability as well as data availability of these indicators.[28] TWA indicate overall availability of water resources, crucial for sustaining agriculture, ecosystems, and human needs, directly influencing drought vulnerability. Higher population density (PD) increases water demand and stress on resources, amplifying drought impacts in densely populated areas. Various LULC types determine surface conditions (e.g., vegetation, urban areas) that affect water retention, runoff, and drought vulnerability. Higher IRRG reduces drought impacts by supplying during rainfall shortages. Steeper SLOPE increases runoff and reduces water infiltration, limiting the natural recharge of groundwater and makes such areas more vulnerable to drought conditions. The DVI was formulated (Eq.3) by weighted sum of TWA, PD, LULC, IRRG and SLOPE with weights and ratings as described in Table 3.

$$DVI = (TWA_w{*}TWA_r) + (PD_w{*}PD_r) + (LULC_w{*}LULC_r) + (IRRG_w{*}IRRG_r) + (SLOPE_w{*}SLOPE_r) \quad ...(3)$$

Drought Risk Index (DRI)

Drought risk has been assessed as a function of drought hazards and vulnerability as formulated in (Eq.4)[5,19,20] as explained by the fifth assessment report (AR5) of Intergovernmental Panel on Climate Change. DRI is the most useful tool as it incorporates the occurrence of drought events as well as its potential social and economic impacts to identify critical zones that need to be prioritized for drought mitigation.

$$DRI = DHI * DVI \quad ...(4)$$

Table 4: Peak Drought events with Drought Hazard indicators at each grid point

Sr.	Peak	Year	TD	ND	MD	SD	ED	Sr.	Peak	Year	TD	ND	MD	SD	ED
1	-1.98	1987	0.0018	22	6	6	0	13	-2.15	1985	0.0021	17	7	4	1
2	-1.61	1986	-0.0009	28	10	2	0	14	-1.79	1985	-0.0043	20	11	3	0
3	-2.10	1987	0.0006	23	9	3	1	15	-2.05	1974	-0.0072	27	8	1	1
4	-2.17	1987	0.0001	24	7	4	1	16	-1.82	1965	0.0020	23	9	3	0
5	-1.61	1986	-0.0089	23	10	4	0	17	-2.39	1965	0.0074	29	3	1	3
6	-1.86	1985	0.0093	23	8	3	0	18	-2.01	1985	-0.0019	23	7	3	1
7	-1.80	1985	0.0016	25	8	3	0	19	-2.50	1961	0.0047	20	10	2	1
8	-1.87	1974	0.0030	16	12	4	0	20	-2.87	1961	0.0059	25	9	0	1
9	-1.92	1972	-0.0081	28	9	3	0	21	-1.86	1961	0.0022	21	8	5	0
10	-1.72	2015	-0.0049	24	9	3	0	22	-2.34	2002	0.0096	20	9	2	2
11	-2.02	1965	0.0023	26	6	3	1	23	-1.82	1966	0.0125	20	9	5	0
12	-2.39	1965	0.0087	26	8	1	2	----------							

Results

Present research on drought risk (DRI) mapping under changing climate for the semi-arid central-east region of Gujarat was achieved by evaluating drought characteristics from SPI-6 time series as well as by developing drought hazard (DHI) and drought vulnerability (DVI) indices. The regional average of SPI-6 values and their linear trend represented in Figure 2 indicated an overall positive nature of drought trend (m = 0.0016), pointing towards increasing wet spells and decreasing dry spells in the current study. Frequent dry spells were detected in the early part of the drought series (1961-1966, 1984-1987), whereas higher wet spells were experienced in recent times for the majority of the grid points, indicating the influences of changing climate. Extreme drought events were observed in the years 1961, 1965, 1974, 1985, 1987, and recently in 2002 at various grid points, as described in Table 4. Approximately 30% of the grid points denoted a negative nature of the drought trend, revealing decreasing wet spells and increasing dry spells in the near future for these pockets.

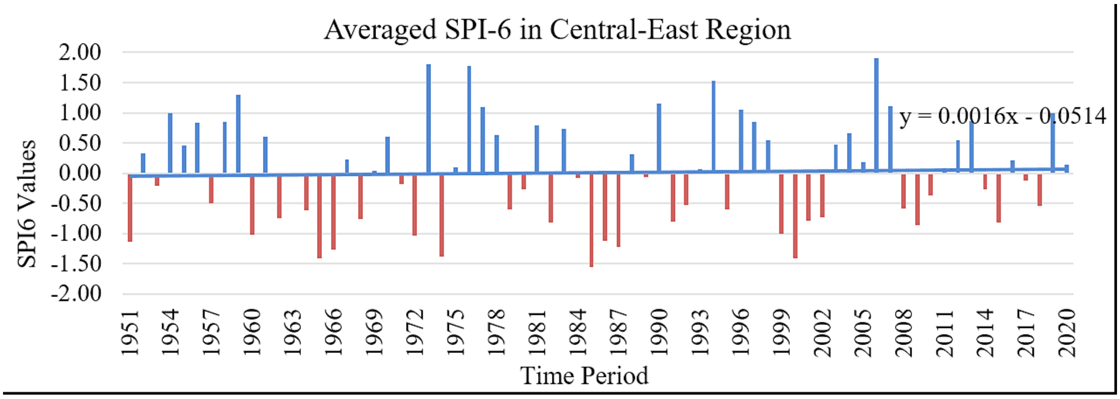

Fig. 2: Average SPI-6 values in Central-East region for (1951 – 2020) time period

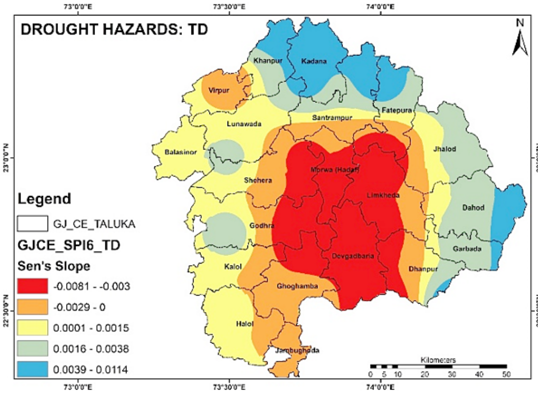

Fig. 3: Trend of Drought SPI-6 series (TD)

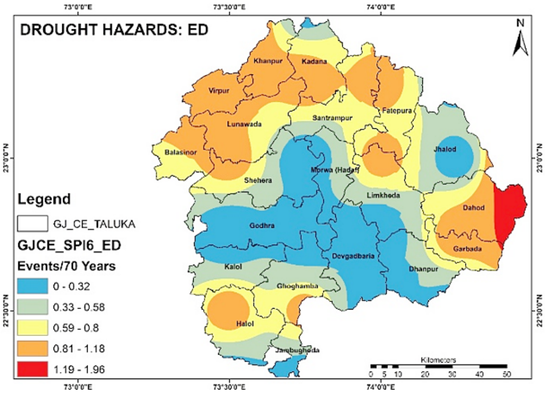

Fig. 4: Extreme Drought events (ED)

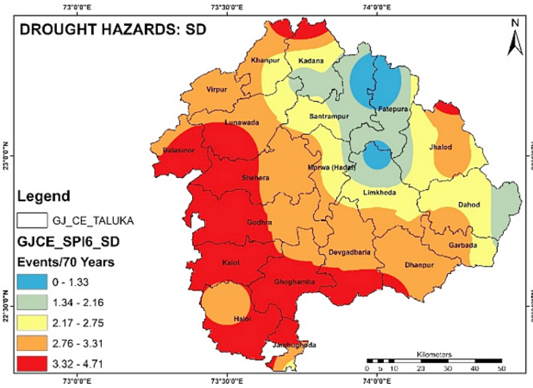

Fig. 5: Severe Drought events (SD)

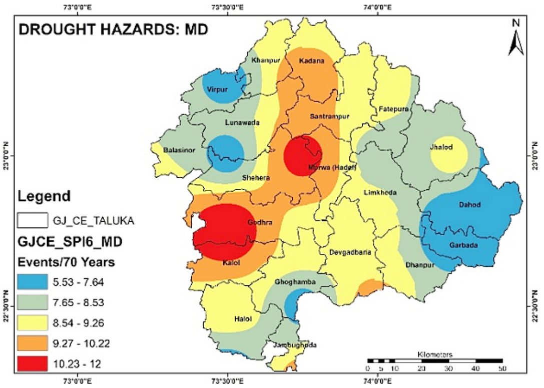

Fig. 6: Moderate Drought events (MD)

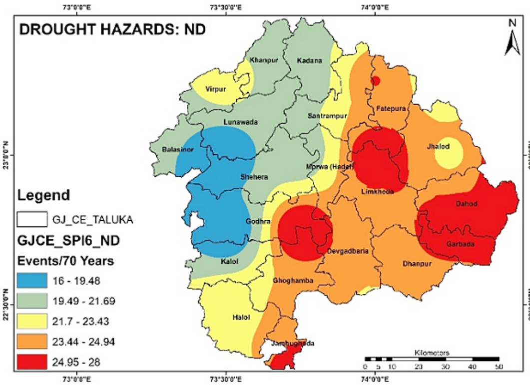

Fig. 7: Near Drought events (ND)

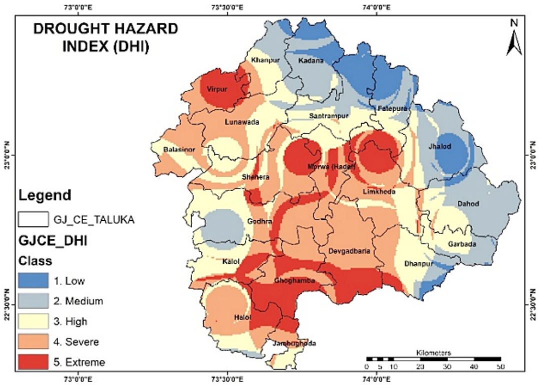

Fig. 8: Drought Hazard Index (DHI)

Drought Hazard Index (DHI)

Trend of Drought SPI-6 series (TD) was considered the most crucial drought hazard indicator in the present study, as it captures changes in rainfall patterns where negative trends reveal worsening drought conditions for the near future. Figure 3 illustrates the spatial distribution of TD, highlighting negative trends delineated by orange and red colors for major parts of the study region. Extreme Drought events (ED) (Figure 4) were observed in a few pockets in the northern and eastern parts, with Dahod Taluka experiencing the highest number of extreme events based on historical data.

Severe Drought events (SD) (Figure 5) revealed an increasing drought severity from north-east to south-west. Moderate Drought events (MD) (Figure 6) indicated that Kadana, Morwa, Godhra, and Kalol Taluka in the central and western parts experienced the highest number of moderate events. Near Drought events (ND) (Figure 7) were more prevalent in the central and eastern parts, impacting Dahod, Garbada, Ghoghamba, and Limkheda Taluka.

Drought Hazard Index (DHI), developed using GIS-based weighted sum analysis (Equation 2), was categorized into five levels (low, medium, high, severe, and extreme) (Figure 8). Major parts of the study area were classified under high to extreme drought hazard levels, particularly in Ghoghamba, Halol, Kalol, Devgadhbaria, Virpur, Limkheda, and Morwa Taluka.

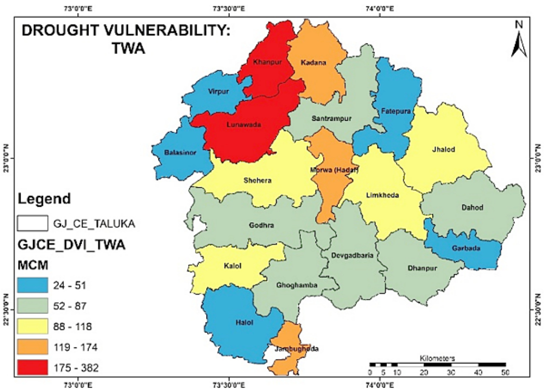

Fig. 9: Total Water Availability (TWA)

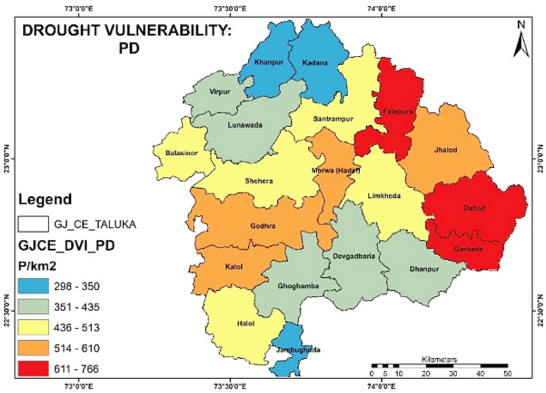

Fig. 10: Population Density (PD)

Drought Vulnerability Index (DVI)

Water availability was selected as a key indicator for drought vulnerability assessment. The Total Water Availability (TWA) (Figure 9) was estimated as the sum of surface and groundwater availability (in MCM) at the Taluka level. The lowest TWA values less than 50 (mcm) were recorded in Virpur, Halol, Garbada, Fatepura, and Balasinor Taluka, indicating higher vulnerability.

Population Density (PD) (Figure 10) was obtained from PMKSY district handbooks. The highest PD values observed more than 600 person/km^2 for Dahod, Garbada, and Fatepura Taluka indicated higher drought vulnerability. Land Use Land Cover (LULC) directly influences water availability, infiltration and evaporation rates which has been considered as an important indicator in drought vulnerability assessments.[21-23] The LULC map of 2020 time period for the study region (Figure 11) was obtained from Sentinel-2 land cover explorer (Esri, Impact Observatory). In present research, agricultural land and built up classes covering about 65 and 8 (%) of study area have been assigned with highest vulnerability ratings. Other LULC classes such as vegetation and trees (4 %) with medium ratings as well as pasture land (18 %), water body (4 %) and barren land (2%) have been assigned with lower ratings.

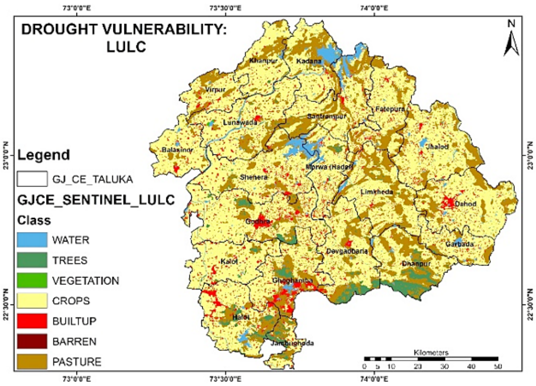

Fig. 11: Land Use Land Cover (LULC)

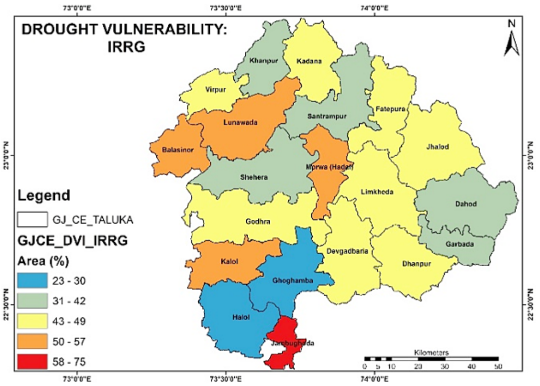

Fig. 12: Irrigation Area percentage (IRRG)

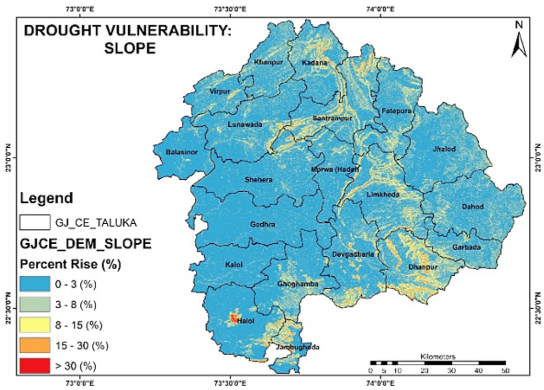

Fig. 13: Slope Topography (SLOPE)

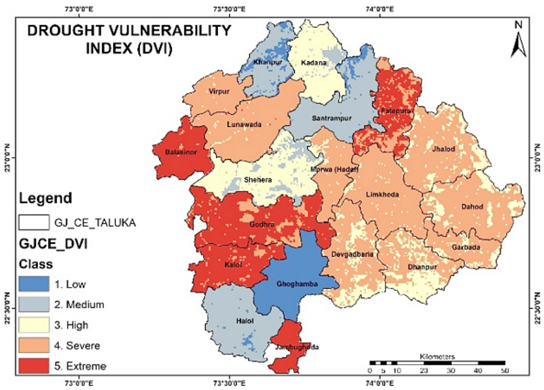

Fig. 14: Drought Vulnerability Index (DVI)

Irrigation area in percentage (IRRG) is a direct measure of regional adaptability relating less irrigated area (%) with high vulnerability.[1,5,20] Halol and Ghoghamba Taluka showed lowest IRRG as seen in Figure 12, demarcated by blue color indicating higher drought vulnerability whereas Jambughoda Taluka was found with highest IRRG making it less vulnerable.

SLOPE in present research was developed from SRTM-DEM having 30 m resolution by utilizing spatial analysis tools in GIS environment. The SLOPE map developed from percent rise method was reclassified as per India-WRIS classification of soil slope. Pavagadh Mountains in Halol Taluka along with a few pockets scattered in the eastern parts (Figure 13) were found with steep slopes indicating high vulnerability.

The Drought Vulnerability Index (DVI), developed using a GIS-based weighted sum approach (Equation 3), was categorized into five levels (low, medium, high, severe, and extreme) (Figure 14). The majority of Talukas exhibited high to extreme vulnerability, with Kalol, Godhra, Jambughoda, Balasinor, and Fatepura Taluka showing the highest levels.

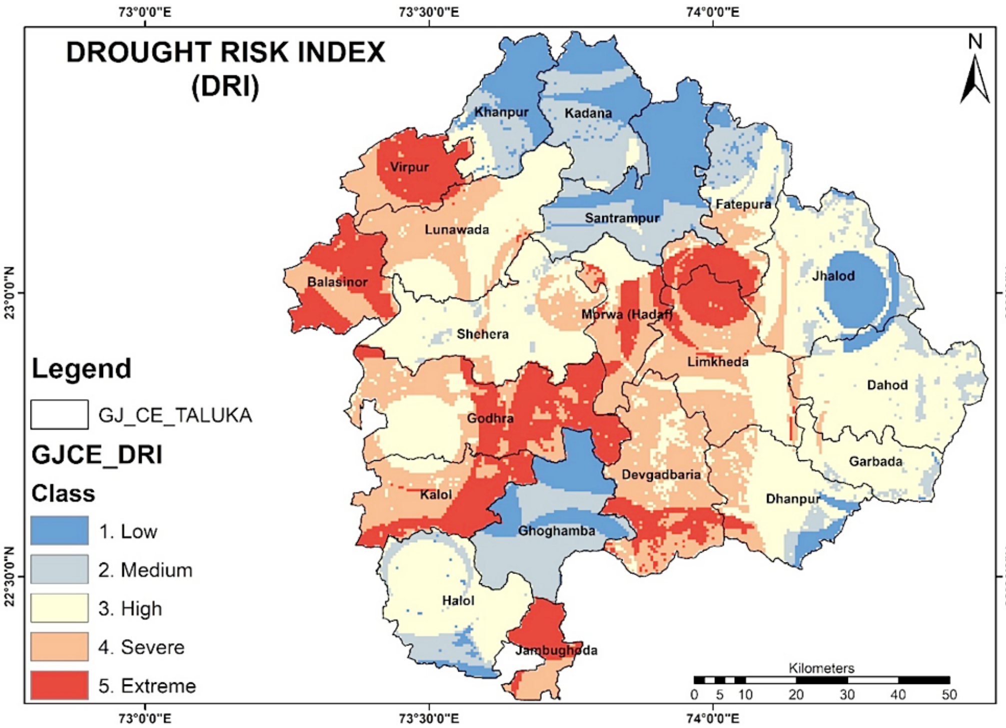

Fig. 15: Drought Risk Index (DRI)

Drought Risk Index (DRI)

Drought Risk Index (DRI) as explained in (Eq.4) was developed in GIS environment with the help of reclassify and raster calculation tools. The spatial distribution of DRI for the study region highlighted by Figure 15, showing reclassified DRI map in five categories (low, medium, high, severe and extreme) described increasing levels of drought risk from blue to red color patterns. The product of hazards and vulnerability has narrowed down on the most crucial pockets mainly located in the central parts of the study region with high to extreme levels of drought risks. Kalol. Godhra, Jambughoda, Devgadhbaria, Limkheda, Morwa, Balasinor and Virpur Taluka were found with severe to extreme risk levels.

The area (%) distributions in DRI, DVI and DHI have been stated in Table 5, indicating approximately 37, 60 and 47 (%) of the region under severe to extreme classes in the respective indices. DRI covered about 73 (%) area under high to extreme levels of drought risk whereas 27 (%) area in low to medium risk levels. Present research highlighted Taluka level assessment of drought hazards, vulnerability and risk mapping categorized in 1 to 5 classes indicating low to extreme levels which have been tabulated in Table 6, obtained from zonal analysis in GIS environment. Such zonal statistics pointed towards Devgadhbaria and Limkheda Taluka in Dahod district, Balasinor and Virpur Taluka in Mahisagar district as well as Kalol, Morwa and Jambughoda Taluka of Panchmahal district with severe (4) and extreme (5) levels of all three indices DHI, DVI and DRI.

Table 5: Area (%) distribution in DHI, DVI and DRI indices

Sr.	Classification	DRI	DVI	DHI
1	Low	12.48	6.78	7.79
2	Medium	14.16	15.69	19.31
3	High	35.89	17.10	25.84
4	Severe	22.43	41.75	31.19
5	Extreme	15.04	18.69	15.87

Table 6: Class wise distribution of DHI, DVI and DRI at Taluka (Block) level

Sr.	District	Taluka	DHI	DVI	DRI	Sr.	District	Taluka	DHI	DVI	DRI
1	Dahod	Dahod	2	4	3	11	Mahisagar	Lunawada	3	4	3
2	Dahod	Devgadbaria	4	4	4	12	Mahisagar	Santrampur	2	2	1
3	Dahod	Dhanpur	3	4	3	13	Mahisagar	Virpur	5	4	5
4	Dahod	Fatepura	3	5	3	14	Panchmahal	Ghoghamba	5	1	2
5	Dahod	Garbada	3	4	3	15	Panchmahal	Godhra	3	5	4
6	Dahod	Jhalod	2	4	2	16	Panchmahal	Halol	4	2	3
7	Dahod	Limkheda	4	4	4	17	Panchmahal	Jambughoda	4	5	5
8	Mahisagar	Balasinor	4	5	5	18	Panchmahal	Kalol	4	5	4
9	Mahisagar	Kadana	2	3	2	19	Panchmahal	Morwa (Hadaf)	4	4	4
10	Mahisagar	Khanpur	3	2	2	20	Panchmahal	Shehera	4	3	3

Discussion

The results highlighted that drought risk varies significantly across the study region, with the central parts experiencing the highest risk due to a combination of high hazard levels and high vulnerability. The spatial distribution of DHI, DVI, and DRI indicates that immediate attention should be given to Talukas like Devgadhbaria, Limkheda, Balasinor, Virpur, Kalol, Morwa, and Jambughoda, which exhibited severe to extreme levels of all three indices.

The causes of these drought risk patterns can be attributed to multiple climatic and anthropogenic factors. Reduced and erratic monsoonal rainfall patterns combined with increasing evapotranspiration due to rising temperatures contribute to heightened drought severity.[19] Additionally, over-extraction of groundwater for irrigation, deforestation, and unsustainable agricultural practices have exacerbated water stress in these regions.[20] Steep topography in some areas leads to increased surface runoff, further limiting groundwater recharge.[23]

The effects of such drought risk patterns include declining agricultural productivity, food insecurity, economic distress among rural communities, and heightened competition for water resources. Long-term drought conditions can also lead to land degradation, loss of biodiversity, and forced migration due to water scarcity. The findings align with previous studies by Patel *et al.*,[8] which also identified moderate to severe drought risks in the central-east region of Gujarat. Policy recommendations should focus on drought-resistant agricultural practices, efficient irrigation techniques, groundwater recharge measures, and improved water management strategies. Future research should incorporate additional socio-economic variables and employ Multi-Criteria Decision Methods like the Analytical Hierarchy Process to refine indicator weights and ratings.

Conclusion

Present research is an original work revealing drought risk assessment for semi-arid central-east region of Gujarat, India which pointed attention towards Taluka level assessment for better preparedness in disaster management against drought under changing climate. The research highlighted effectiveness of SPI-6 as a drought hazard indicator which was able to capture short-term and seasonal precipitation deficits that are important for agricultural planning and water resource management. The study identified significant spatial variability in drought hazards with inclusion of trend magnitude of drought time series as well as in drought vulnerability with addition of total water availability and percent irrigation area which showcased the combined effects of climatic and socio-economic variables in drought risk mapping for semi-arid regions. Present research outcomes emphasize that drought hazards, vulnerability and risks vary significantly within the central-east region, highlighting the need for developing location-specific mitigation and adaptation strategies such as drought-resistant crops, efficient irrigation systems, and reforestation as part of disaster management.

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Conflict of Interest

The authors do not have any conflict of interest.

Data Availability Statement

Data will be made available upon reasonable request.

Ethics Statement

This research did not involve human participants, animal subjects, or any material that requires ethical approval.

Informed Consent Statement

This study did not involve human participants, and therefore, informed consent was not required.

Permission to Reproduce Material from other Sources

Not Applicable.

Author Contributions

- **Daksh H. Soni:** Conceptualization, Methodology, Data Collection, Analysis, Writing original draft.
- **Dr. Geeta S. Joshi:** Funding Acquisition, Resources, Supervision.

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