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Agricultural drought hazard assessment in Maharashtra, India

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Abstract: This study presents assessment of agricultural drought hazard in Maharashtra state, India, utilizing Standardized Soil Moisture Index. The analysis integrates six indicators to develop an agricultural drought hazard map that categorizes districts into distinct hazard levels, ranging from low to severe. Findings reveal significant variations in drought characteristics, with certain districts in the Vidarbha region experiencing prolonged and severe drought impacts over the 41-year period. Coastal western districts of Maharashtra exhibit unexpectedly high severity scores, challenging traditional assumptions about their susceptibility to drought. Central regions of Maharashtra, including the Deccan plateau and Vidarbha, emerge as hotspots for frequent drought occurrences and intense drought conditions. Hazard mapping reveals significant drought risk in specific districts, notably in the Vidarbha region, characterized by persistently high hazard levels. This study underscores the importance of informed decision-making and proactive measures to mitigate the impact of agricultural drought on vulnerable communities and livelihoods in Maharashtra.

Key words: Hazard; drought; drought properties

1. INTRODUCTION

Agricultural drought poses a significant threat to food security and livelihoods in regions reliant on rainfed agriculture, such as Maharashtra, India (Niranjan Kumar et al., 2013). Maharashtra is one of the most agriculturally productive states in India, with a diverse cropping pattern ranging from cereals and pulses to cash crops like sugarcane. However, the state is highly susceptible to drought due to its semi-arid climate and erratic rainfall patterns, resulting in frequent water shortages and crop failures (Todmal, 2023; Udmale et al., 2014).The consequences of agricultural drought reach far beyond immediate crop losses, impacting rural economies, food availability, and overall socio-economic well-being. Smallholder farmers, comprising a significant portion of Maharashtra's agricultural workforce, frequently endure the brunt of drought-induced hardships, which further exacerbates poverty and vulnerability in these communities.

To address the challenges posed by agricultural drought, comprehensive hazard assessment is essential. This assessment involves analysing various drought properties like duration, severity, intensity, and total number of drought events that contribute to drought hazard and help identifying potential risk. Agricultural drought occurs when there is an imbalance between water supply and demand, leading to insufficient soil moisture for normal crop growth (Crow et al., 2012). According to the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC, 2022), risk can be quantified as a function of hazard, vulnerability, exposure, and response. This study aims to assess the drought hazard in a frequent drought area in Maharashtra, India. To comprehensively investigate drought risk, selecting suitable drought indicators for hazard analysis and appropriate drought vulnerability indicators along with a suitable aggregation method for vulnerability analysis are essential steps (Sahana et al., 2021).

The present study aims to develop district-level agriculture drought hazard map using the Standardized Soil Moisture Index (SSMI). Among various drought assessment indices include Precipitation Effectiveness Index (Thornthwaite, 1931), Rainfall Anomaly Index (RAI) (Van Rooy, 1965), Palmer Drought Severity Index (PDSI) (Palmer, 1965), Standardized Precipitation Index

(SPI) (Mckee et al., 1993), the Standardized Soil Moisture Index is notable for its ability to sensitively indicate the dynamic equilibrium between precipitation, groundwater supply, and evapotranspiration. Additionally, it offers the benefits of straightforward calculation and takes into account the characteristics of data distribution (Zhou et al., 2019). By identifying areas and communities most vulnerable to agricultural drought, policymakers and stakeholders can prioritize resource allocation, enhance preparedness, and implement targeted interventions to build resilience and mitigate impacts. By using soil moisture data, the study seeks to identify spatial patterns of drought occurrence and assess the impact on agricultural systems. The findings will contribute to evidence-based decision-making and the development of effective drought management strategies tailored to the needs of Maharashtra's agricultural sector. This study seeks to provide insights and recommendations that can inform policies and practices aimed at reducing the adverse impacts of drought on farmers and rural communities.

2. DESCRIPTION OF STUDY AREA

The study area, Maharashtra, India, is located approximately between 15.6° N to 22.0° N latitude and 72.6° E to 80.9° E longitude shown in Figure 1. Maharashtra spans over 307,713 km^2, bordered by the Arabian Sea to the west and neighbouring states including Gujarat, Madhya Pradesh, Chhattisgarh, Telangana, Karnataka, and Goa. The Maharashtra, encompasses diverse geographical features ranging from coastal plains along the Arabian Sea to the Western Ghats Mountain range and the Deccan Plateau. Maharashtra experiences a tropical and subtropical climate with distinct seasons: summer, monsoon, and winter. Rainfall is critical for agriculture, with the southwest monsoon bringing most of the annual precipitation. However, rainfall is erratic and unevenly distributed, leading to frequent droughts and water scarcity issues. Agriculture is a vital sector, with a wide variety of crops cultivated including cereals, pulses, oilseeds, sugarcane, and cotton.

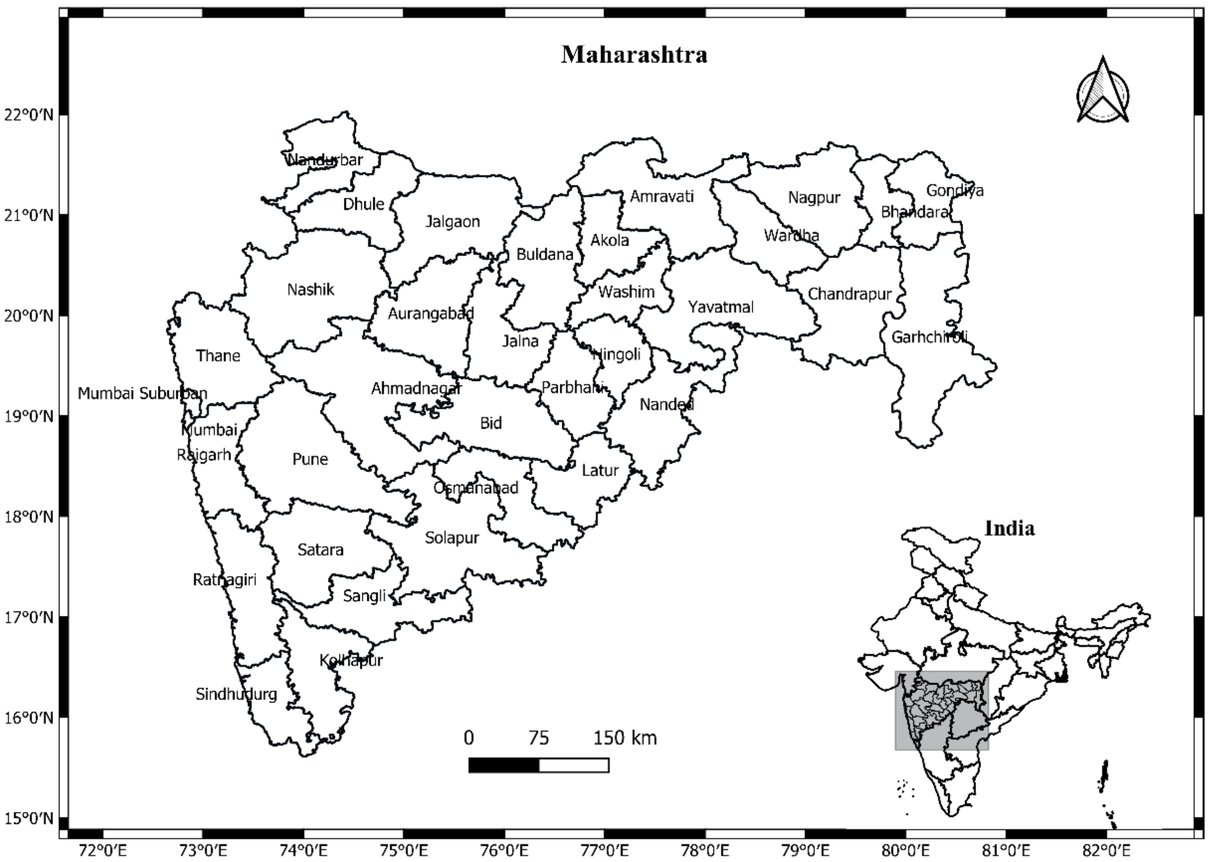

Figure 1. Study area map of Maharashtra

The population is predominantly rural, with agriculture serving as a primary livelihood source. Konkan and Western Ghats regions receive the highest rainfall. In contrast, interior parts of Maharashtra, particularly in rain shadow areas like Vidarbha, receive significantly less rainfall, often below 1,000 mm annually (Nair and Mirajkar, 2021).

3. MATERIALS AND METHODS

3.1 Data

For computation of agricultural drought hazard, the root zone soil moisture data from the Global Land Evaporation Amsterdam Model (GLEAM) available at 0.25° for the period 1980 -2021 was used. The data was further regrided to 0.125° and was masked over the district to get area averaged soil moisture. GLEAM data (https://www.gleam.eu/) is derived from a combination of sources, including satellite and reanalysis data for radiation and temperature, satellite-based vegetation optical depth, and a blend of gauge-based, satellite, and reanalysis precipitation data.

3.2 Methodology

3.2.1 Standardized Soil Moisture Index

In order to compute the agricultural drought hazard, first the Standardised Soil Moisture Index (SSMI) is computed using monthly soil moisture data using Equation 1 (Han et al., 2021).

$$SSMI_{ij} = \frac{(SM_{ij} - \mu_{SMi})}{\sigma_{SMi}} \quad (1)$$

where $SSMI_{ij}$ is the SSMI for month i and year j, SM_{ij} is the mean soil moisture values, μ_{SMi} and σ_{SMi} are the mean and standard deviations of soil moisture of month i across all years. The SSMI is a unitless measure utilized for detecting drought events.

3.2.2 Drought Properties

After computation of SSMI, the drought properties duration, severity, intensity and total number of drought events are calculated using run theory (Ganguli and Reddy, 2012; Maccioni et al., 2015). The duration (D) of a drought is defined as the number of consecutive monthly intervals where the SSMI remains below a specified threshold value (SSMI < -0.8). The minimum duration of a drought event is considered to be 1 month, as drought is characterized at the monthly time scale.

Drought Severity (*S*) is calculated as the cumulative sum of SSMI values within the duration of the drought event. For convenience, the severity of drought event *i*, denoted as S_i (where i = 1, 2, …., T), is considered positive and is computed using the following equation (Mckee et al., 1993).

$$S_i = -\sum_{i=1}^{D} SSMI_i \quad (2)$$

Drought intensity is defined as the ratio of drought severity (*S*) to drought duration (*D*). This provides a measure of how severe the drought conditions are relative to the length of time over which they persist. The formula to calculate drought intensity (*I*) is given by,

$$I = \frac{S}{D} \quad (3)$$

This calculation allows for the assessment of drought intensity, taking into account both the magnitude (severity) and duration of the drought event.

The total number of drought events (T) is typically defined as the count or frequency of distinct periods during which drought conditions occur within a specified time frame.

3.2.3 Hazard Assessment

To compute the drought hazard score, the study taken six indicators such as maximum duration (D_{max}), duration sum (D_{sum}), severity sum (S_{sum}), maximum intensity (I_{max}), mean intensity (I_{mean}), total number of drought events (T). These indicators are given scores from 1 to 5 based on equal quantile shown in Table 1. Finally, the indicators are combined to give the drought hazard score given by:

$$DHS = score\ (D_{max}) + score\ (D_{sum}) + score\ (S_{sum}) + score\ (I_{max}) + score\ (I_{mean}) + score(T) \quad (4)$$

The drought hazard score is normalised to get the drought hazard index (DHI) as given by:

$$DHI = \frac{DHS - DHS_{min}}{DHS_{max} - DHS_{min}} \quad (5)$$

Table 1. Hazard indicator classification for period 1980-2021

Score	Hazard indicators range					
	D_{max}	D_{sum}	S_{sum}	I_{max}	I_{mean}	T
1	4-5	34-78.4	39.4-81.1	0.886-1.021	0.886-0.981	13- 22
2	5-6	78.4-86.2	81.1- 87.6	1.021-1.09	0.981-1.008	22- 22
3	6-6	86.2- 92.2	87.6-96.1	1.09-1.138	1.008-1.053	22- 23
4	6-6	92.2-96.6	96.1- 100.4	1.138-1.165	1.053-1.098	23- 24
5	6-9	96.6-119	100.4-115	1.165-2	1.098-2	24- 27

4. RESULTS AND DISCUSSION

4.1 Spatial distribution of drought properties

The drought properties duration, severity, intensity and total number of drought events were computed. Sum of all the drought durations for each district is computed, and Figure 2 illustrates the cumulative durations of drought conditions at the district level throughout Maharashtra, India, based on an analysis of monthly data spanning from 1980 to 2021. The districts are color-coded according to the total number of months they experienced drought conditions during this period. The colour gradient begins with light beige, representing the shortest durations of drought (34-78.4 months), and progresses to dark brown, indicating the most extended durations (96.6-114 months). Districts shaded in dark brown signify the most severe drought impacts, having endured the longest periods of drought over the analyzed 41 years. This visual representation helps to identify spatial patterns of drought durations across Maharashtra.

The maximum duration of drought conditions was computed for various districts of Maharashtra, India and is shown in Figure 3. The maximum duration plot shows that for most of the districts the maximum duration was varying in the range of 4 to 8 months. Western districts generally show less maximum drought months, typically ranging from 4 to 5 months. The highest value is seen in few districts of Vidarbha region and Nandurbar district. This regional analysis underscores the importance of targeted management strategies to address varying drought impacts throughout the state.

The sum of all the drought severity were computed for each district of Maharashtra and shown in Figure 4. The colour gradient ranges from light beige to dark brown, with light beige representing the least severe drought conditions and dark brown indicating the most severe. Surprisingly, the coastal western districts, which are expected to be less susceptible to drought due to maritime influences, are found to be having high severity scores ranging from 100.4 to 111.2, depicted in dark brown. This suggests significant drought impact despite the geographical advantage. Conversely, the central and some northeastern districts are represented with lower severity scores (39.4 to 81.1 in light beige), indicating milder drought conditions. This distribution highlights the complex interplay of climatic factors across the state, and underscores the need for region-specific drought management strategies that address these unique patterns of drought severity.

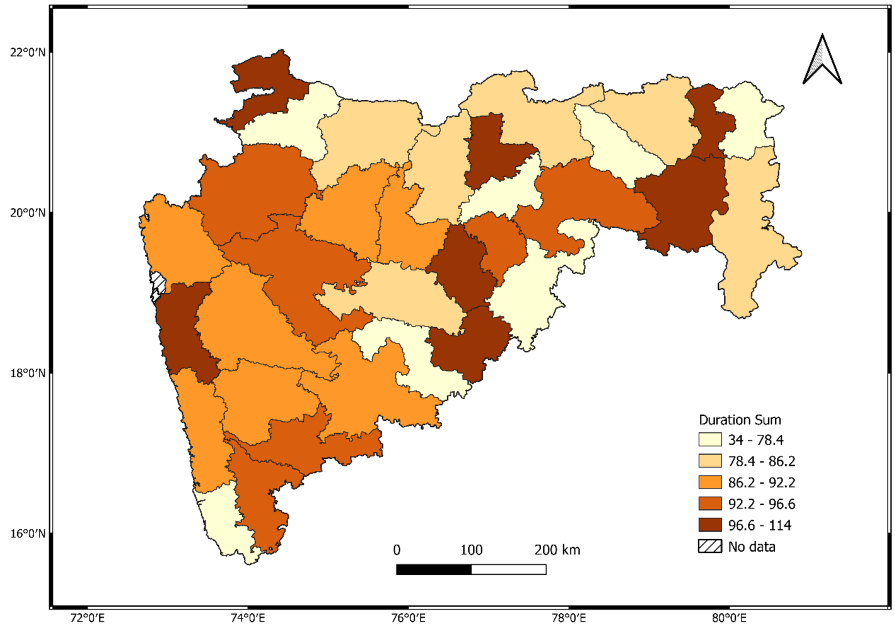

Figure 2. District-level spatial distribution of duration sum over Maharashtra

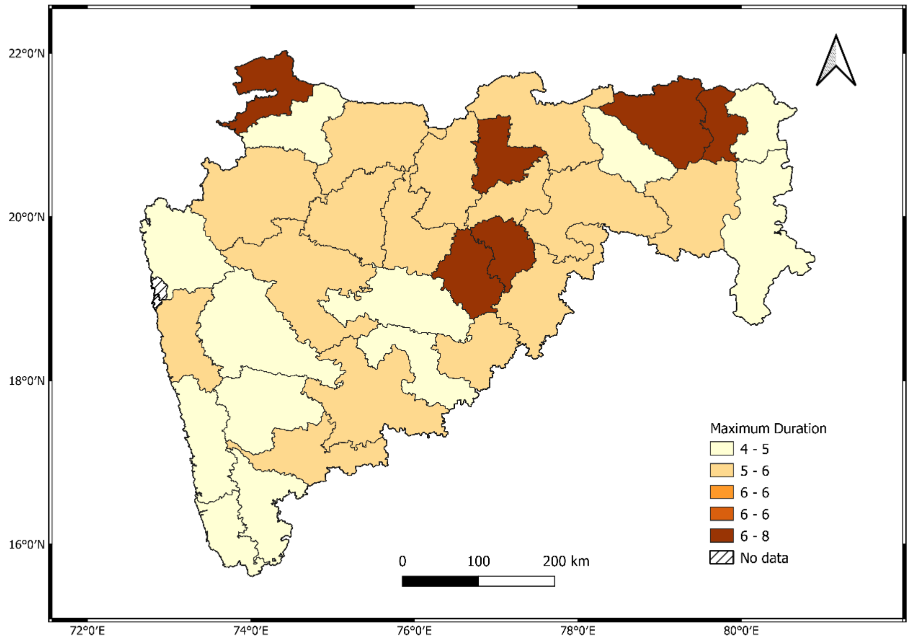

Figure 3. District-level spatial distribution of maximum drought durations over Maharashtra

The total number of drought events recorded in each district of Maharashtra, India, from 1980 to 2021 is depicted in Figure 5. The colour gradient on the map ranges from light beige, indicating regions that experienced between 13 to 22 drought events, to dark brown, where districts encountered 24 to 26 drought events. Notably, the central regions of Maharashtra, particularly areas in the Deccan plateau and Vidarbha regions, are marked in dark brown, highlighting their susceptibility to frequent drought occurrences. The eastern and western districts show a slightly lower frequency of drought events, represented by shades of orange and light beige, suggesting a lesser drought impact compared to the central regions. This geographical distribution indicates that the central areas of the state, known for their agrarian economies, face more frequent drought challenges, emphasizing the need for focused drought management and mitigation strategies in these areas.

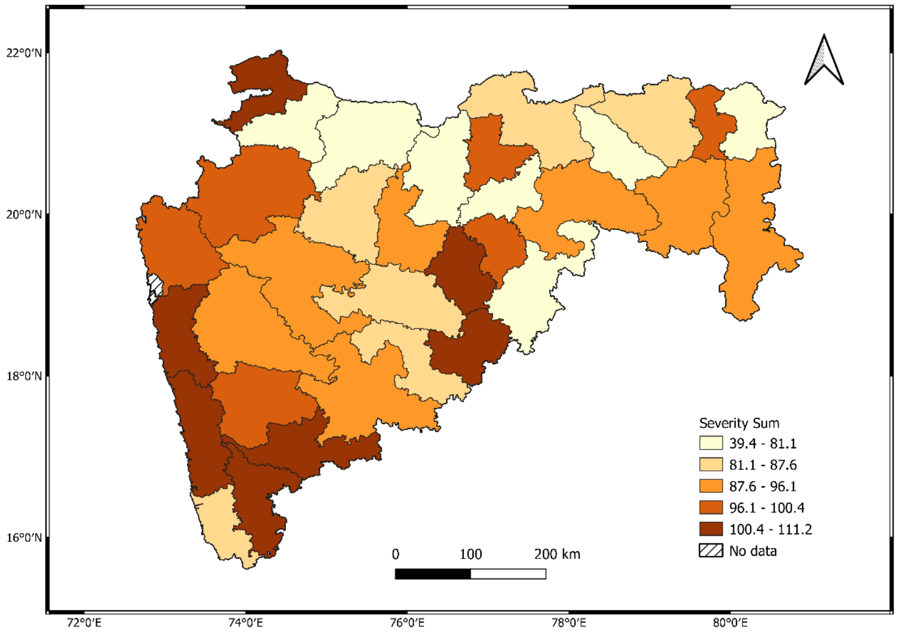

Figure 4. District-level spatial distribution of drought severity sum over Maharashtra

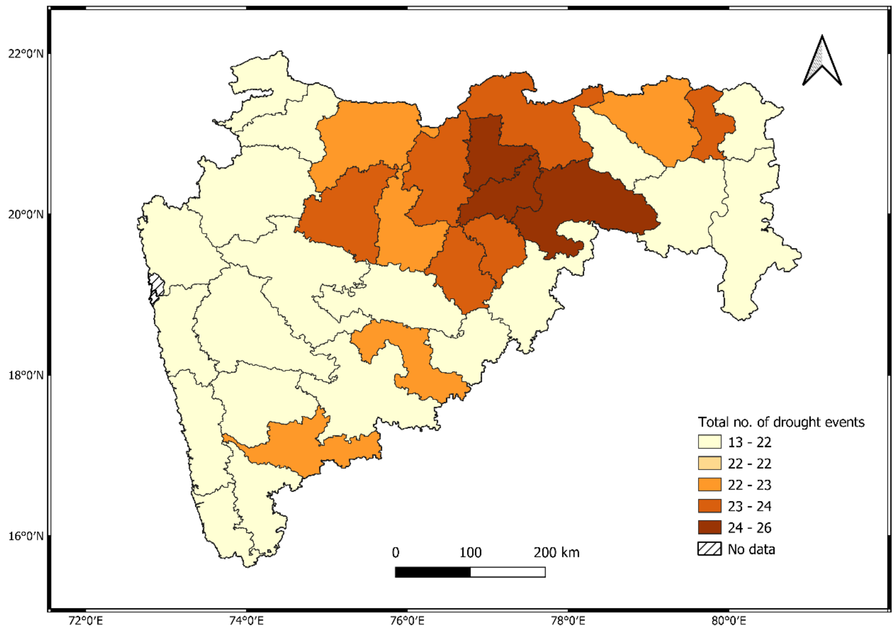

Figure 5. District-level spatial distribution of total number of drought events over Maharashtra

The intensity of drought is computed by severity divided by duration; hence it makes use of these two properties, the study considers both maximum intensity and mean intensity to compute the hazard. The mean intensity of drought events across different districts of Maharashtra, India, is shown in Figure 6. The lightest beige represents the least severe drought conditions, with a mean intensity ranging from 0.886 to 0.981. The western and some districts in central parts of

Maharashtra are marked in darker shades, indicating a mean intensity range from 1.053 to 1.098, pointing to more severe drought conditions. The darkest brown areas, signifying the highest mean intensities from 1.098 to 1.239, are primarily located in the western districts of Maharashtra.

The maximum intensity of drought events across Maharashtra, India, shown in Figure 7. It can be seen that the maximum intensity is higher in the southern districts of Maharashtra that was not the case for mean intensity hence the selection of different indicators and the combination of all is very important to get the accurate hazard map. The lightest beige, showing an intensity range of 0.886 to 1.021, mostly covers the central upper districts, suggesting these areas have experienced relatively milder maximum drought conditions. The South-Eastern regions (Khandesh to Desh and Marathwada) of Maharashtra, the colours darken to shades of orange and deep brown, indicating increasing maximum drought intensities, with values ranging from 1.09 to 1.239. These regions, particularly those shaded in the darkest brown, represent the highest maximum intensities and are concentrated in the southern parts of the Maharashtra, highlighting a significant vulnerability to severe drought conditions. This spatial distribution is crucial for identifying high-risk areas and developing targeted interventions to mitigate the effects of extreme droughts.

4.2 Agricultural Drought Hazard

Different drought properties showed different spatial distributions across different regions, hence it is important to include all drought properties and not just the maximum but also mean values. The agricultural drought hazard index is computed using Equation 4 for each district, by combining six indicators to prepare the drought hazard map for the study area. The agricultural drought hazard map is shown in Figure 8. The hazard levels are categorized into five distinct classes: low, mild, moderate, high, and severe, ranging from low (0 - 0.262) to severe (0.738 - 1). The severe hazard districts include Raigarh, Ratnagiri, Latur, Parbhani and Bhandara. The Vidarbha region shows all type of hazard classes. But mostly the districts are in high to severe category. The low hazard district includes Gondiya, Wardha, Dhule, Jalgaon, Buldana, Bid, and Osmanabad. Few districts in central Maharashtra are in mild drought hazard class. The mild drought hazard class includes some districts in eastern Maharashtra, Satara, and Solapur districts. The districts namely Thane, Nashik, Akola, Hingoli, and Chandrapur falls in high drought hazard class.

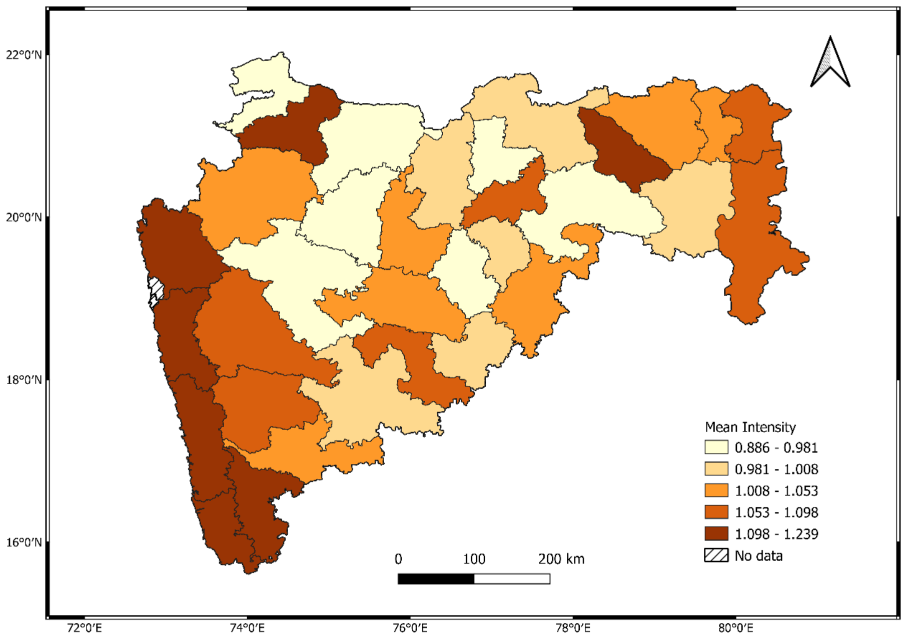

Figure 6. District-level spatial distribution of mean intensity of droughts over Maharashtra

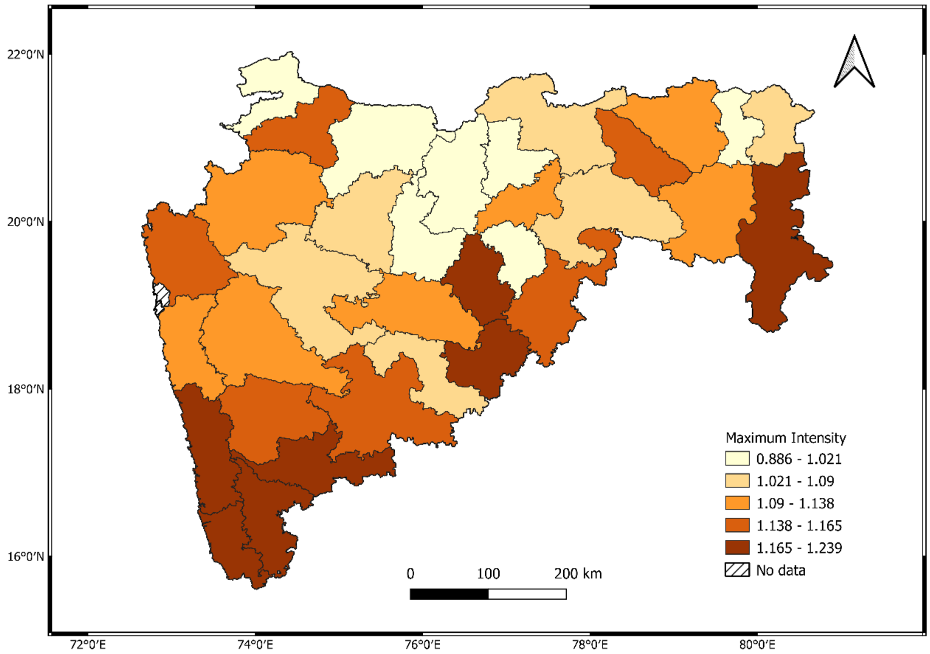

Figure 7. District-level spatial distribution of maximum intensity of droughts over Maharashtra

Datta and Reddy (2023) has revealed significant drought hazard in the Vidarbha region spanning from 1981 to 2020.The reliability-resilience-vulnerability analysis by Ganjir et al. (2024) also found Vidarbha and Marathwada region are high drought prone regions. The low and mild drought hazard can be mostly found in the Central Maharashtra region. This holistic approach to drought hazard assessment provides valuable insights into regional drought management.

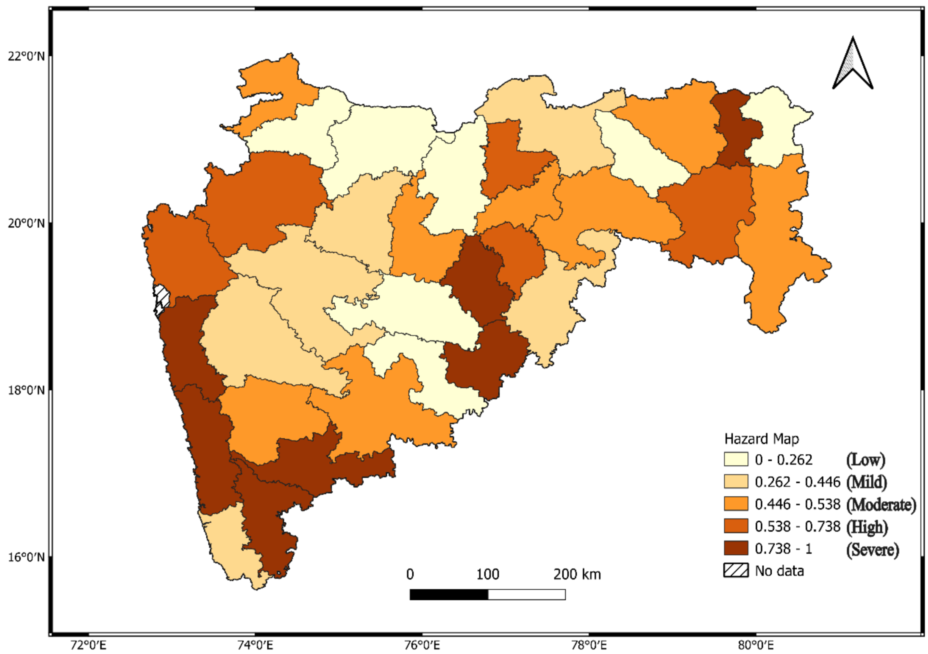

Figure 8. District-level agricultural drought hazard map of Maharashtra (1980-2021) based on SSMI hazard scores, classified into five classes: low, mild, moderate, high, and severe.

5. SUMMARY AND CONCLUSIONS

This study conducts a comprehensive assessment of drought hazard in Maharashtra at the district level using the Standardized Soil Moisture Index (SSMI). Drought properties are synthesized using run theory to derive the Drought Hazard Index (DHI). The duration of drought events varies widely across different districts of the state, with some experiencing prolonged periods of drought over the 41-year period. Certain districts in Maharashtra, particularly in the Vidarbha region, have consistently endured severe and prolonged drought impacts, as evidenced by the cumulative durations and severity scores. Coastal western districts, traditionally considered less susceptible to drought due to maritime influences, exhibit unexpectedly high severity scores, emphasizing the complexity of climatic factors influencing drought patterns. Central regions of Maharashtra, including the Deccan plateau and Vidarbha, are identified as hotspots for frequent drought occurrences, highlighting the agricultural vulnerability in these areas. Drought intensity, reveals areas with more intense and prolonged drought conditions, particularly in the western and central parts of the Maharashtra state. Maximum drought intensity is observed in the lower districts of Maharashtra, emphasizing the need for targeted interventions to address extreme drought impacts in these regions.

Drought hazard mapping identifies significant drought risk in specific districts, notably in the Vidarbha region and western districts of Maharashtra where hazard levels remain consistently high and severe. This comprehensive hazard assessment underscores the critical importance of informed decision-making and proactive measures to mitigate the impact of drought on vulnerable communities and agricultural livelihoods in Maharashtra.

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