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RESEARCH ARTICLE

Evaluating Agricultural Drought Severity in Karnataka, India Through Integrated Remote Sensing Indices

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Abstract – Agricultural drought significantly threatens Karnataka, India, where rain-fed agriculture is predominant. This study evaluates the spatio-temporal evolution of agricultural drought in Karnataka from 1986 to 2020 using the Advanced Drought Response Index (ADRI), which integrates the Vegetation Condition Index (VCI), Precipitation Condition Index (PCI), Soil Condition Index (SCI), and Temperature Condition Index (TCI). Data from NOAA, TerraClimate, and NASA POWER were processed using ArcGIS Pro. Key findings reveal that northern districts like Vijayapura, Chitradurga, and Gadag consistently experienced severe drought conditions. ADRI values fell below 20 on a scale of 0–100, indicating a 35% lower ADRI than the state average. Drought severity increased by an average of 40% during the summer months compared to the monsoon season. The lowest annual average ADRI was recorded in 1986 at 22.41, signifying extreme drought, while the highest was in 1992 at 28.38, indicating milder conditions. An overall decline of 15% in Monsoon ADRI values over the 35 years suggests worsening drought conditions during this critical agricultural season. These findings reveal Karnataka's escalating agricultural vulnerability to climate variations. Pinpointing the regions and seasons that are most affected provides valuable insights for policymakers. Implementing targeted interventions—such as drought-resistant crops, efficient irrigation methods, and soil moisture conservation techniques—can enhance resilience and promote sustainable water management amid increasing climate challenges.

Keywords – Agricultural Drought, Advanced Drought Response Index, Vegetation Condition Index, Precipitation Condition Index, Soil Condition Index, and Temperature Condition Index.

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1. INTRODUCTION

Droughts are a catastrophe that impacts agriculture, food security, and the stability of societies worldwide. As climate change progresses, the frequency and intensity of droughts are expected to increase, posing challenges for countries at development stages. The Intergovernmental Panel on Climate Change (IPCC) has forecasted that climate change will exacerbate drought conditions in areas with climates and heavy reliance on rain-fed agriculture. This escalation in drought could have consequences for food security and poverty levels in regions that rely on farming for their sustenance. In 2023, the Food and Agriculture Organization (FAO) reported that over 733 million people faced hunger, with drought being a contributing factor, in regions with limited adaptation capabilities. (FAO; IFAD; UNICEF; WFP; WHO, 2024).

The impact of drought on agriculture can have far-reaching consequences on the economy, leading to disruptions in food supply chains, higher food prices, and increased pressure on water resources. According to the World Bank, droughts could decrease a country's GDP by up to 6% in regions heavily reliant on agriculture. (World Bank Group, 2016). As a result, there is a growing need for location-specific tools to assess and address the effects of drought, effectively guiding policy decisions and bolstering resilience. Karnataka, situated in India, faces vulnerability to drought due to its varied climate zones, which range from humid coastal regions to dry interiors. The state witnesses' fluctuations in rainfall patterns, with around 75% coming from the southwest Monsoon. However, this rainfall is unevenly distributed across the state, with districts like Vijayapura, Chitradurga, and Gadag experiencing shortages in rainfall (MKSNDNC, 2020, n.d.). These areas heavily rely on rain-fed agriculture. Are particularly susceptible to the impacts of drought.

Agricultural drought can be defined as drought that affects crop production in that it occurs when there is insufficient soil moisture during the critical stages of crop growth. This type of drought directly affects the availability of water for crops and results in decreased production and, in some cases, crop losses. While talking about agricultural drought, socio-economic drought is the drought that affects water use for social, economic, and industrial needs due to water shortages. The interaction of these types of droughts shows the chain reaction of climatic variability, especially in areas with agricultural-based economies.

In Karnataka, agricultural drought is compounded by rain-fed agriculture, where monsoon rainfall is the primary water source, with erratic and uneven spatio-temporal distribution leading to crop losses. This is important because these dynamics apply globally as the frequency and intensity of droughts increase due to climate change. Other regions highly dependent on agriculture include Sub-Saharan Africa, some parts of the United States, and Australia, which all face similar problems. This paper thus uses these global findings to concentrate on Karnataka, given that the region is susceptible due to various agro-climatic zones and rain-fed agriculture.

In Karnataka, agriculture employs approximately 56% of the workforce and contributes to the state's economy. (Purushothaman, Patil, and Francis, 2012). The agricultural practices in this region primarily focus on crops such as ragi, jowar, and pulses. These crops are susceptible to changes in rainfall patterns, with prolonged periods of weather leading to reduced crop yields. The state heavily depends on monsoon rains for its activities. The erratic nature of these rains due to climate change has increased the sector's vulnerability. Drought impacts in Karnataka extend beyond agriculture, causing an increase in poverty levels, triggering urban migration, and putting strain on water resources.

To address these challenges effectively, it is crucial to implement drought assessment tools and early warning systems in Karnataka. This study aims to meet this necessity by utilizing the Advanced Drought Response Index (ADRI) to evaluate drought severity levels and their variations across regions and time frames within Karnataka. Through a combination of indicators and data analysis, this research seeks to enhance our comprehension of drought patterns in the area and contribute towards developing targeted strategies for improving resilience and water management practices.

Research in the fields of environment and agriculture has emphasized assessing drought, given its widespread impact on water resources, farming practices, and socio-economic conditions globally. Various methods and indicators have been developed to monitor and assess drought conditions, each providing insights into different aspects of this phenomenon. (Salmoral et al., 2019; Song et al., 2024). Established drought indices such as the Palmer Drought Severity Index (PDSI) and the Standardized Precipitation Index (SPI) have proven effective in evaluating drought severity based on data. (Vicente-Serrano et al., 2015). Furthermore, introducing the Standardized Precipitation Evapotranspiration Index (SPEI) has enhanced our understanding of drought by considering precipitation and potential evapotranspiration. This index is particularly beneficial for assessing drought impacted by temperature and precipitation variations. (Li et al., 2015; Vicente-Serrano et al., 2010).

Recent progress in sensing technology has significantly enhanced our capacity to evaluate drought conditions. For example, Zhang et al. (2021) explored using solar-induced chlorophyll fluorescence (SIF) to monitor drought in the North China Plain, demonstrating how remote sensing data can provide drought information. Similarly, Anderson et al. (2007) demonstrated the advantages of integrating sensor data with drought indicators to improve monitoring of evapotranspiration and soil moisture variations, particularly in regions with limited -on-the-ground data availability. The emergence of intelligence (AI) and machine learning techniques has opened new avenues for predicting drought events. Research by (Maca and Pech, 2016; Li and Xu, 2021; Saha et al., 2021; Zhao et al., 2022; Sadiq, Sarkar and Raisa, 2023; Xiao, Wu and Zhu, 2023) Showcases how artificial neural networks can predict drought indices such as SPI and SPEI more accurately than traditional statistical methods. These advances underscore the importance of combining state-of-the-art technologies with established approaches to enhance our capability for monitoring drought occurrences.
Agricultural drought assessment using remote sensing indices has gained prominence due to the ability of these technologies to provide timely and spatially comprehensive data. Various remote sensing indices, such as the Normalized Difference Vegetation Index (NDVI), Vegetation Condition Index (VCI), and Temperature Vegetation Drought Index (TVDI), are extensively utilized for monitoring drought conditions across different regions (Sreekesh et al., 2019; Zhao et al., 2022; Rousta et al., 2020). These indices leverage satellite data to assess vegetation health, soil moisture, and climatic factors, enabling adequate drought characterization (Yagci et al., 2011; Sun et al., 2020).

The Research Gap

Traditional drought assessment methods, such as the Palmer Drought Severity Index (PDSI) and the Standardized Precipitation Index (SPI), primarily focus on singular climatic variables like precipitation or temperature (Vicente-Serrano et al., 2015). While these indices have been instrumental in drought analysis, they often fall short in capturing the multifaceted nature of agricultural droughts, especially in regions with complex agro-climatic conditions like Karnataka. Specifically, traditional indices do not fully integrate critical factors such as soil moisture, vegetation health, and temperature-induced stress; they lack the spatial and temporal resolution needed to assess drought impacts at the local level; and they are less effective in regions with diverse climatic zones and varied agricultural practices.

Despite advancements in remote sensing and the development of new indices like the Standardized Precipitation Evapotranspiration Index (SPEI), there are gaps in comprehensive drought assessment tools that can integrate multiple environmental variables to provide a holistic view of drought severity (Vicente-Serrano, Beguería, and López-Moreno, 2010; Singh et al., 2022).

Rationale Behind Using ADRI

The Advanced Drought Response Index (ADRI) is a robust tool designed to fill these gaps by integrating multiple drought-related indices into a comprehensive assessment metric. ADRI combines the Vegetation Condition Index (VCI), Precipitation Condition Index (PCI), Soil Condition Index (SCI), and Temperature Condition Index (TCI), each representing critical aspects of agricultural drought. VCI reflects vegetation health and can detect stress due to insufficient moisture; PCI measures precipitation anomalies, which is crucial in regions dependent on monsoon rains; SCI assesses soil moisture availability, directly affecting plant growth and yield; TCI captures temperature-induced stress, which can exacerbate drought conditions. By integrating these indices, ADRI provides a multidimensional perspective on drought severity, capturing the complex interactions between climatic variables and agricultural systems.

Furthermore, there is a need for localized research that considers the climate and agricultural conditions in different areas. Many current studies focus on regions without delving into the relationships between drought metrics and local farming practices. This gap is particularly noticeable in locations like Karnataka, India, where diverse climate conditions and farming methods require tailored approaches to assessing drought. Another significant gap exists when considering aspects of drought assessments. While environmental indicators are crucial for understanding drought dynamics, socio-economic factors such as impacts on livelihoods, food security, and migration are often neglected. Edwards et al., (2024); Gerber & Mirzabaev, (2017) Have underscored the importance of integrating socio-factors to develop comprehensive strategies for effectively managing drought. Bridging this gap is essential for implementing interventions that mitigate drought impacts and enhance community resilience.

Expected Contributions
This study leverages the Advanced Drought Response Index (ADRI) to evaluate the spatio-temporal evolution of agricultural drought in Karnataka from 1986 to 2020, effectively addressing the identified research gaps. Integrating multiple indices—VCI, PCI, SCI, and TCI—ADRI provides a comprehensive assessment of drought severity that captures the complex interactions between climatic variables and agricultural systems. The study maps drought impacts across different districts and seasons using high-resolution remote sensing data processed through ArcGIS Pro. This nuanced understanding enables policymakers and agrarian planners to implement targeted interventions, such as promoting drought-resistant crops and efficient irrigation methods. Furthermore, the methodology's adaptability to other regions with similar climatic diversity enhances its utility beyond Karnataka, contributing to broader drought assessment and mitigation efforts.

This study addresses these gaps by developing and utilizing the Advanced Drought Response Index (ADRI) to evaluate how agricultural drought evolved spatially and temporally in Karnataka, India, from 1986 to 2020. This study aims to use drought indicators like VCI, PCI, SCI, and TCI to identify drought-affected areas and analyze how drought impacts agriculture from a social perspective. It also aims to propose evidence-based recommendations for improving resilience and managing water resources effectively. By introducing a tool for assessing drought, this research contributes valuable insights that can assist policymakers and agricultural planners in Karnataka in developing more efficient strategies to mitigate the effects of drought.

2. MATERIALS AND METHODS

2.1 Study Area

In India, Karnataka (Fig. 1) stretches from latitudes 11°30' N to 18°30' N and longitudes 74° E to 78°30' E. The state boasts a wide range of geographical and climatic features, making it a prime location for investigating agricultural drought patterns. Karnataka's landscape varies from the coastal plains in the west to the semi-arid Deccan Plateau in the north and central areas, with the Western Ghats acting as an essential climatic boundary. The climate in the state is mainly influenced by the southwest Monsoon, which brings most of the rain between June and September. However, there is much variation in how rainfall is spread out. Coastal areas and the Western Ghats get much rain, while places like Vijayapura, Chitradurga, and Gadag up north do not get much rain and often face dry spells. These northern districts heavily rely on rainfall for farming, making them very sensitive to changes in monsoon patterns and droughts. Farming is a part of Karnataka's economy, and many people work in agriculture. The state grows crops like rice, jowar, cotton, and sugarcane.

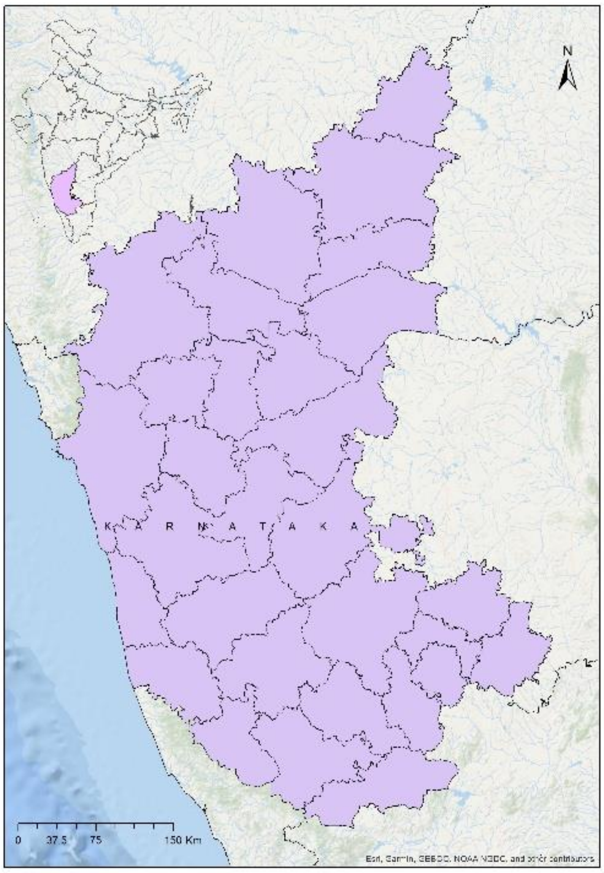

Figure 1 Study Area map: Karnataka State, India

Because rainfall is inconsistent and the northern areas are semi-arid, it is tough to maintain productivity. This leads to droughts that worsen economic challenges. Karnataka offers an example of how agricultural drought varies over time. The mix of climates and the big difference between regions and dry inland areas show why it is crucial to understand how drought affects different places entirely.

The main objective of this research is to use the Advanced Drought Response Index (ADRI) to evaluate and track the intensity of drought in Karnataka's regions and the districts that are most impacted. This information will offer perspectives on strategies and managing water resources in the state. The methodology employed in this study integrates a comprehensive set of remote sensing and climatic data to assess agricultural drought dynamics across Karnataka from 1986 to 2020. Figure 2 provides an overview of the entire process, illustrating the data sources, preprocessing steps, and the calculation of drought indices.

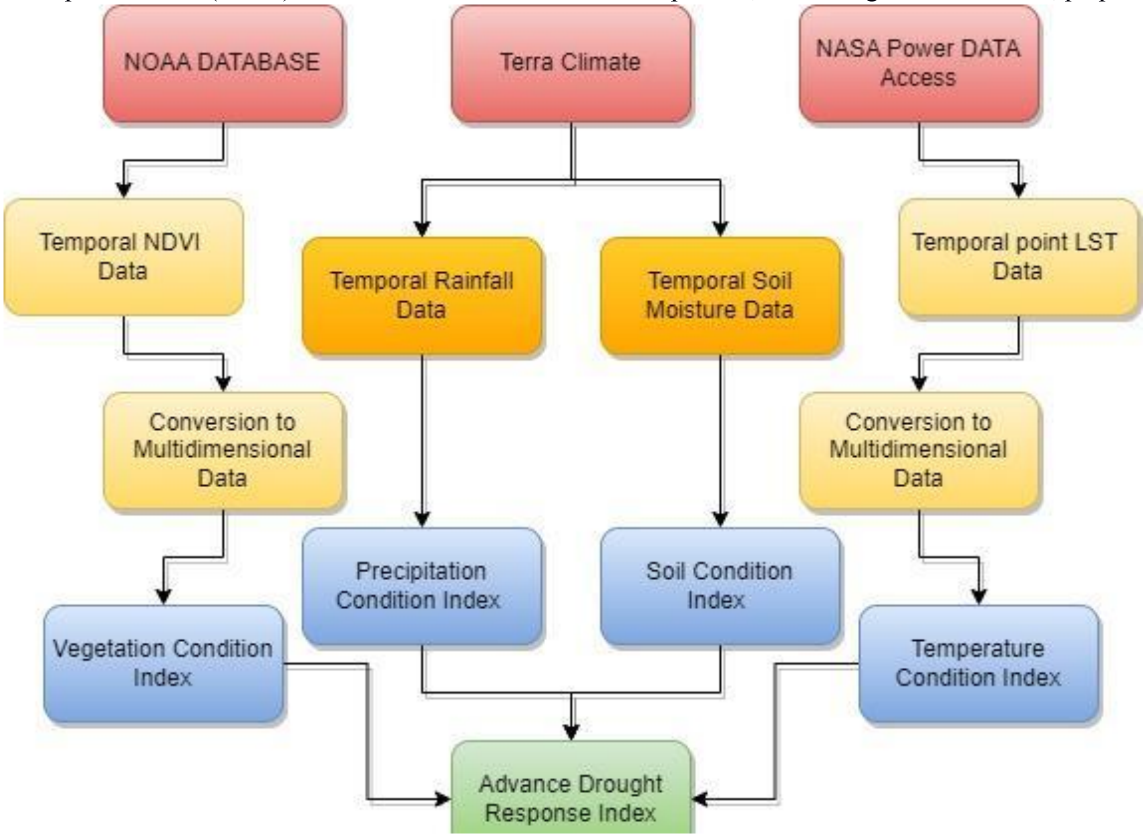

Figure 2 Research Methodology

2.2 Selection of Indices

The indices selected for this study—Vegetation Condition Index (VCI), Precipitation Condition Index (PCI), Soil Condition Index (SCI), and Temperature Condition Index (TCI) were chosen because they collectively capture the critical environmental factors influencing agricultural drought in Karnataka. VCI reflects vegetation health and can detect stress due to moisture deficiency, making it essential for assessing crop conditions. PCI measures precipitation anomalies, which is crucial for agriculture in a region heavily reliant on monsoon rains. SCI represents soil moisture availability in the root zone, directly affecting plant growth and yield. TCI accounts for temperature-induced stress, which can exacerbate drought conditions by increasing evapotranspiration rates. By integrating these indices, the Advanced Drought Response Index (ADRI) provides a comprehensive assessment that addresses the limitations of traditional indices, which often consider singular variables and may not fully capture the multifaceted nature of agricultural droughts in regions with complex agro-climatic conditions like Karnataka.

2.3 Data Sources and Preprocessing

This study integrates multiple datasets to assess the spatio-temporal dynamics of agricultural drought. The datasets include the Normalized Difference Vegetation Index (NDVI), sourced from the NOAA database. NDVI data provides insights into vegetation health. The temporal NDVI data was converted into multidimensional data to calculate the Vegetation Condition Index (VCI). Precipitation Data: Collected from the Terra Climate database with a resolution of 4 kilometers, this data was utilized to calculate the Precipitation Condition Index (PCI). ArcGIS Pro processed and converted The temporal precipitation data into multidimensional formats. Soil Moisture Data: Also sourced from the Terra Climate database, this data was employed to determine the Soil Condition Index (SCI). Similar preprocessing steps were applied to convert the data into multidimensional formats for analysis. Land Surface Temperature (LST) Data was obtained from the NASA Power Data Access website, and the temporal point LST data was interpolated using Inverse Distance Weighting (IDW) to generate a continuous surface. The LST data was then converted into multidimensional formats to calculate the Temperature Condition Index (TCI).

2.4 Condition Indices Calculation

2.4.1 Vegetation Condition Index

The Vegetation Condition Index (VCI) is a metric based on remote sensing that helps assess the health of vegetation and drought conditions, providing valuable insights into the dynamics of agricultural drought over time and space. By analyzing satellite-derived Normalized Difference Vegetation Index (NDVI) data, VCI offers a way to measure vegetation strength by comparing current NDVI values with historical benchmarks for a specific area. This research uses NDVI data with a resolution of 500 meters from 1986 to 2020 to calculate VCI in Karnataka, a significant agricultural region in India. The VCI calculation is based on Equation 1.

$$VCI = \frac{NDVI - NDVImin}{NDVImax - NDVImin} * 100 \quad (1)$$

Where NDVI represents the current value, and NDVImin and NDVImax note the historical minimum and maximum NDVI values observed over the study period.

The methodological framework for this study involves transforming unprocessed NDVI data into a multidimensional format using advanced geospatial tools, including ArcGIS Pro and ArcMap 10.8.1. Python-based algorithms are employed to automate the extraction of the minimum and maximum NDVI values for each temporal slice, facilitating the precise computation of VCI across the study area. This approach allows for the high-resolution spatio-temporal mapping of vegetation conditions, providing crucial insights into the onset, progression, and spatial heterogeneity of drought impacts on agricultural systems.

2.4.2 Precipitation Condition Index

The Precipitation Condition Index (PCI) plays a role in analyzing agricultural drought patterns over time and space. In this research, precipitation data from 1986 to 2020 was obtained from the Terra Climate database, which provides information at a 4-kilometer resolution. This high-quality data enables an examination of how precipitation varies across regions. The PCI is then determined using formula 2 to evaluate the precipitation conditions within a timeframe, which helps assess drought severity and geographical distribution.

$$PCI = \frac{PPT - PPTmin}{PPTmax - PPTmin} * 100 \qquad \text{Eq. (2)}$$

Integrating the PCI with analysis allows for mapping and monitoring drought trends, offering insights into agricultural drought dynamics during the 34-year study period. The outcomes of this study are anticipated to contribute to developing strategies for mitigating drought impacts and strengthening resilience against changing climate conditions.

2.4.3. Temperature Condition Index

The Temperature Condition Index (TCI) plays a role in evaluating how environmental heat impacts plant life, especially in agricultural drought patterns. In this research project, we obtained land surface temperature (LST) data from the NASA POWER data platform spanning 1986 to 2020. The data presented in Excel format was imported into the ArcGIS software for analysis. Inverse Distance Weighting (IDW) interpolation created a temperature surface using latitude and longitude coordinates to estimate temperatures across the study area accurately. After the interpolation process, the data was converted into a raster in ArcGIS Pro with time stamps attached to each file for temporal analysis of temperature fluctuations. The minimum, maximum, and average LST values were extracted from the multidimensional raster dataset for each segment. The TCI was subsequently computed using an equation outlined as follows (3).

$$PCI = \frac{PPT - PPTmin}{PPTmax - PPTmin} * 100 \qquad \text{Eq. (3)}$$

Where the current land surface temperature is the minimum and the maximum recorded over the study period, this approach allows for measurement of the impact of temperature-induced pressure on plants, giving valuable information about how temperature affects agricultural droughts. By using location and time data analyzed with ArcGIS Pro, the TCI offers a robust system for pinpointing and keeping track of regions that may be vulnerable to vegetation stress caused by temperature. Incorporating Python scripting in data analysis guarantees repeatable TCI calculations, establishing it as a useful resource for continually assessing and controlling drought conditions.

2.4.4 Soil Condition Index

The Soil Condition Index (SCI) is crucial for assessing soil moisture dynamics during periods of drought. This study utilized soil moisture (SM) data from the Terra Climate website covering 1986 to 2020 at a resolution of 4 kilometers. This data was incorporated into the ArcGIS Pro software for SCI calculations. The SCI is determined using a formula denoted as equation 4.

$$SCI = \frac{SM - SMmin}{SMmax - SMmin} * 100 \qquad \text{Eq. (4)}$$

Where SM represents the current soil moisture value, while SMmin and SMmax correspond to the long-term minimum and maximum soil moisture values, respectively, when researching drought, the Soil Conservation Index (SCI) is used to gauge how well soil can hold onto moisture, affecting the health of plants and crop productivity. It helps understand the water supply in the root zone, which plays a role in plant growth compared to surface moisture readings. By examining this soil layer, the SCI gives us valuable information on potential plant stress and the overall state of agricultural land.

2.4.5 Advance Drought Response Index:

The Advanced Drought Response Index (ADRI) is a tool that combines various indices to provide a comprehensive assessment of drought conditions. This research involves the calculation of ADRI by incorporating the Vegetation Condition Index (VCI), Temperature Condition Index (TCI), Precipitation Condition Index (PCI), and Soil Condition Index (SCI). These indices are represented as values ranging from 0 to 100, indicating the severity of prevailing conditions. ADRI and its constituent indices are measured on a scale from 0 to 100, where lower values indicate drought conditions while values of 100 suggest healthy environmental conditions. For this study, we assigned equal weights to each index in the ADRI calculation. This decision is based on the premise that in Karnataka's diverse agro-climatic context, all four factors are equally significant in influencing drought severity and agricultural productivity. Equal weighting simplifies the integration process and avoids introducing subjective bias that could arise from arbitrarily assigning different weights without empirical justification. Data collected from 1986 to 2020 at a resolution of 4 kilometers was utilized for this analysis. The calculation of the ADRI value was carried out using Equation 5.

$$ADRI_{ijk} = [L * VCI * \left\{c + \frac{1}{L*(VCI+TCI+PCI+SCI)} * (TCI + PCI + SCI)\right\}] \quad \text{Eq. (5)}$$

Where TCI, PCI, VCI, and SCI are values of pixel i for composite j in year k, L is the normalizing factor, and c is a constant to prevent the production of a null denominator. The computations were performed using the constants L = 0.25 and c = 0.01, which were selected for their relevance to the study area and the indices' characteristics. These constants play a role in standardizing the results to ensure that the ADRI values accurately reflect the observed drought conditions. Like the component indices, the resulting ADRI values span from 0 to 100. Values near 0 indicate drought conditions, while those near 100 signify conditions. This approach enables the ADRI to amalgamate variations captured by each index, providing a measure of drought severity and its potential impacts on agricultural systems. The strength of ADRI lies in its capacity to synthesize data types, offering insights into drought conditions that go beyond the limitations of individual indices. Moreover, integrating sensing data into this framework provides spatial and temporal coverage. This empowers ADRI to detect signs of drought, making it a valuable tool for managing droughts and making decisions. Incorporating soil moisture information through SCI further enhances ADRIs' ability to assess root zone moisture levels for crop health and yield evaluation.

2.5 Validation Methodology

A comprehensive validation methodology was implemented to assess the accuracy and reliability of the Advanced Drought Response Index (ADRI) in monitoring agricultural drought in Karnataka. This involved comparing the ADRI results with traditional drought indices and ground-truth data to evaluate its effectiveness over existing methods.

2.5.1 Data Sources for Validation

Ground-Truth Data: Observed drought records and agricultural yield data were obtained from the Indian Meteorological Department (IMD) and the Ministry of Agriculture from 1986–2020. These records provided empirical evidence of drought occurrences and their impacts on crop production in Karnataka.

Traditional Drought Indices: Data for the Standardized Precipitation Index (SPI) and the Palmer Drought Severity Index (PDSI) were sourced from the IMD for the same period. These indices are widely used benchmarks for drought assessment and serve as reference points for comparison with ADRI.

2.5.2 Statistical Techniques and Metrics

The following statistical techniques and metrics were employed to validate the ADRI:

Pearson Correlation Coefficient (r) measures the strength and direction of the linear relationship between ADRI values and those of traditional drought indices and ground-truth data.

$$r = \frac{\sum_{i=1}^{n}\left(ADRI_i - \overline{ADRI}\right)(X_i - \bar{X})}{\sqrt{\sum_{i=1}^{n}\left(ADRI_i - \overline{ADRI}\right)^2 \sum_{i=1}^{n}(X_i - \bar{X})^2}} \quad \text{Eq. (6)}$$

Where: ADRI_i =is ADRI value at time or location *i*, X_i is a corresponding value from SPI, PDSI, or ground-truth data, ¯ADRI and X¯are mean values of ADRI and comparison data, *i* is the number of observations.

Root Mean Square Error (RMSE): Quantifies the average magnitude of the differences between ADRI values and the comparison data.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(ADRI_i - X_i)^2} \quad \text{Eq. (7)}$$

Mean Absolute Error (MAE): Measures the average absolute differences between ADRI values and the comparison data.

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|ADRI_i - X_i| \quad \text{Eq. (8)}$$

Significance Testing: p-values were calculated to assess the statistical significance of the correlation coefficients, with a threshold of $p<0.5$.

2.5.3 Validation Procedure

We assessed ADRI's effectiveness in monitoring agricultural drought through spatial and temporal validations. Spatially, we aggregated ADRI values at the district level to match the resolution of ground-truth data and traditional indices (SPI, PDSI). We then performed correlation analyses between ADRI and these indices, generating maps to visualize spatial agreement. Temporally, we compared ADRI trends with those of SPI, PDSI, and agricultural yields using time series analysis, identifying significant deviations across datasets. By correlating ADRI with yields of major crops in Karnataka (ragi, jowar, pulses), we evaluated its reflection of drought's impact on agriculture. Error analysis involved calculating Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) between ADRI and traditional indices; lower error values indicated better agreement, confirming ADRI's accuracy in representing drought conditions.

2.5.4 Interpretation of Validation Results

The validation results indicate that ADRI has a strong positive correlation (Pearson's $r<0.7$) with traditional drought indices (SPI, PDSI) and ground-truth data, demonstrating high agreement in assessing drought conditions. Statistically significant p-values $p<0.5$ confirm that these correlations are unlikely due to chance, reinforcing ADRI's reliability as a drought assessment tool. Low RMSE and MAE values across multiple years and districts further attest to ADRI's accuracy in representing drought severity. Minor discrepancies in certain areas may stem from data resolution differences or local factors not captured by ADRI. Still, overall, the index proves to be a robust indicator of agricultural drought in Karnataka.

2.5.5 Limitations of ADRI and Their Impact on Results

While ADRI provides a comprehensive agricultural drought assessment, several limitations may affect our results. Variations in data resolution can lead to inaccuracies in capturing localized drought patterns. Remote sensing data are susceptible to sensor errors and atmospheric disturbances, potentially causing over- or underestimation of drought severity. Assigning equal weights to all indices assumes they contribute equally, which may not reflect regional or seasonal differences. Excluding socio-economic factors and groundwater data means ADRI may not fully capture the actual impact of drought on agriculture. These limitations could influence the accuracy of our assessments and affect the effectiveness of policy interventions based on our findings.

2.6 Analysis and Visualization:

The multidimensional data in ArcGIS Pro was used to create maps and analyze trends in drought severity across Karnataka. The ADRI values were examined annually and seasonally to identify trends and patterns of drought severity in Karnataka. This thorough analysis provided insights into how drought impacts regions in the state, guiding agricultural and water management decisions.

2.3. RESULTS AND DISCUSSION

The Advance Drought Response Index (ADRI) values were categorized (table 1) into distinct classes based on their numerical ranges to facilitate a more precise interpretation of drought severity across Karnataka. The categorization is as follows:

Table 1 Classification of ADRI Values and Drought Severity Categories

SN	ADRI Value Range	Drought Category
1	0–20	Severe Drought
2	21–40	Moderate Drought
3	41–60	Mild Drought
4	61–80	Normal Conditions
5	81–100	Above Normal Conditions

This classification allows for a more explicit understanding of the drought conditions experienced in different regions and seasons over the study period from 1986 to 2020.

3.1 Annual ADRI Analysis

The Advance Drought Response Index (ADRI) was calculated for Karnataka from 1986 to 2020, showing varying drought conditions across the state (Fig. 3). Notably, in 1992, the ADRI value peaked at 28.38, indicating milder drought conditions, while the lowest ADRI value occurred in 1986, signifying drought. Over the years, there has been a trend in the ADRI index suggesting

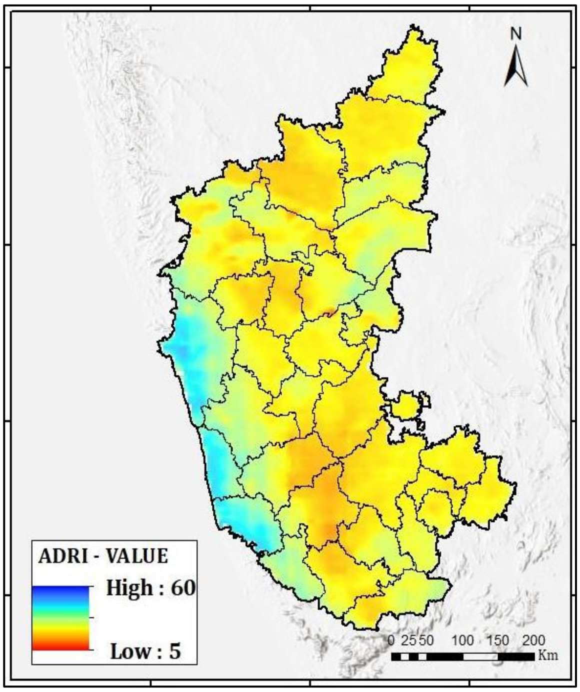

Figure 3 Long-term Average Annual ADRI

a gradual decrease in drought severity, possibly due to improvements in farming methods, irrigation systems, and water management practices.

The spatial distribution of ADRI across districts of Karnataka reveals differing impacts of drought. Regions like Udupi and Dakshina Kannada have lower drought severity than northern districts such as Vijayapura, Chitradurga, and Gadag, which consistently exhibit lower ADRI values, indicating more severe drought conditions. This highlights the disparities in vulnerability to drought within Karnataka.

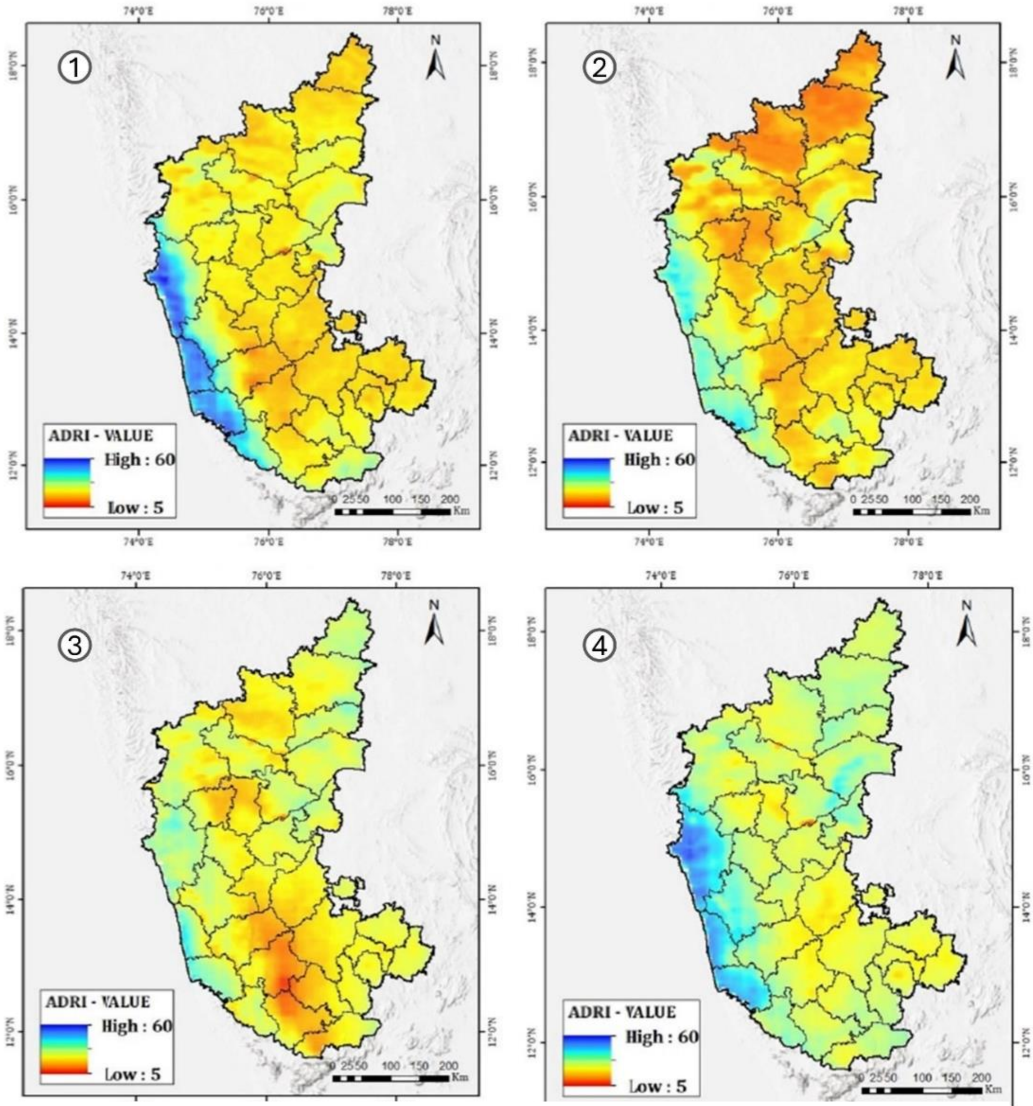

Figure 4 Seasonal Average ADRI Maps of Karnataka (1986-2020): 1. Winter, 2. Summer, 3. Monsoon, 4. Post-Monsoon

3.2 Seasonal ADRI Analysis

Analyzing seasonal drought dynamics in Karnataka explains the variations throughout the year (Fig. 4 & Table 2). The findings are discussed for each season, including Winter, summer, Monsoon, and post-monsoon.

3.2.1 Winter:

In the Winter Season, ADRI values ranged from 19 to 49, with Udupi and Uttara Kannada recording values (of 49.21 and 41.19), indicating minimal drought impact during this time. Conversely, Chitradurga, Hassan, and Bidar reported the values signaling severe drought conditions. A slight increase in Winter ADRI values implies improved drought conditions over the 35 years (Fig 4.1).

3.2.2 Summer:

Summer experiences drought conditions with ADRI values as low as 14 in districts like Vijayapura, Kalburgi, and Bidar. These districts face challenging conditions that significantly affect activities. However, Udupi and Uttara Kannada exhibit values suggesting a lesser impact of drought. The overall trend indicates a reduction in drought severity over time, with districts remaining highly vulnerable (Fig 4.2)

3.2.3 Monsoon:

The analysis of Monsoon ADRI values (refer to Table 2) unveils a complex pattern. Coastal regions, like Dakshina Kannada and Uttara Kannada, generally show values suggesting less severe drought conditions. Conversely, inland areas such as Hassan and Mysore exhibit values indicating more significant drought stress. Notably, a trend in Monsoon ADRI values signals deteriorating drought conditions during this period, which could adversely impact the planting season ((Fig 4.3).

3.2.4 post-monsoon:

The post-monsoon ADRI values (see Table 2) closely mirror the ADRI, with districts like Dakshina Kannada and Udupi experiencing the most favorable conditions. The upward trend in Monsoon ADRI values implies an overall enhancement in drought conditions during this season, which is conducive to agricultural activities. Nevertheless, areas like Tumkur, Kolar, and parts of Bangalore still indicate lower ADRI values post-monsoon, suggesting drought conditions even after the monsoon period (Fig 4.4).

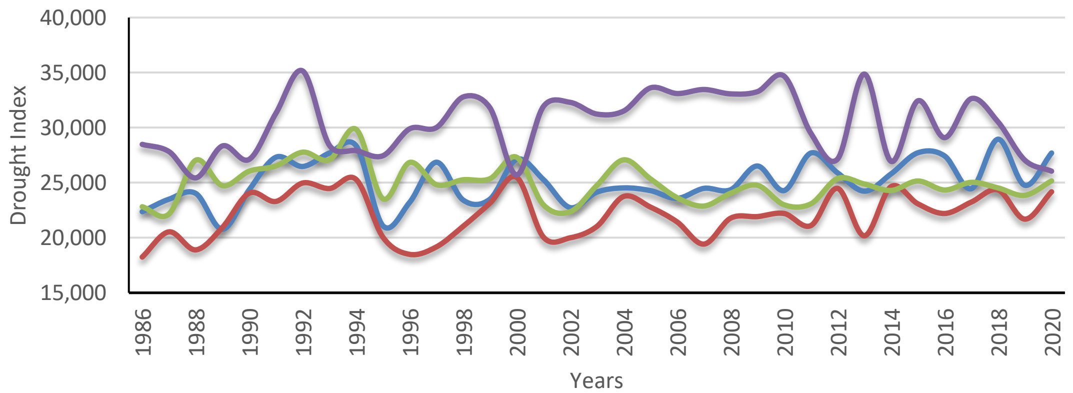

Figure 5 Temporal Changes in Seasonal ADRI (1986-2020) for Karnataka: A Line Graph Representation of Winter, Summer, Pre-Monsoon, and Post-Monsoon Periods

3.3 Temporal Analysis of Agricultural Drought Severity

The temporal analysis of the Advance Drought Response Index (ADRI) for Karnataka from 1986 to 2020 shows variations in agricultural drought severity across seasons in the state. Figure 5 illustrates these changes, highlighting the values experienced throughout Karnataka.

3.3.1 Summer Season:

During the summer season, Karnataka faced drought conditions with low ADRI values. The lowest recorded value was 14, indicating drought in northern districts like Vijayapura, Kalburgi, and Bidar due to high temperatures and scarce rainfall, which led to significant soil moisture deficits.

3.3.2 Post-Monsoon Season:

In contrast, post-monsoon months offered conditions for agriculture with higher ADRI values than summer. The recorded ADRI value during this period was 25, showing conditions supported by residual moisture from monsoon rains. Districts like Dakshina Kannada and Udupi experienced minimal drought stress with higher ADRI values.

3.3.3 Winter Season:

During the Winter, the ADRI values were moderate, displaying some variability but generally indicating milder drought conditions than in the summer. The average ADRI for Winter hovered around 23 throughout the study period, with a trend hinting at improving conditions over time.

3.3.4 Monsoon season:

The monsoon period experienced moderate to drought conditions, with ADRI values fluctuating. The data show a decreasing trend during this time, with specific years recording levels as low as those in summer. This decline implies a worsening severity of drought leading up to the Monsoon, which could impact crop growth and early development stages.

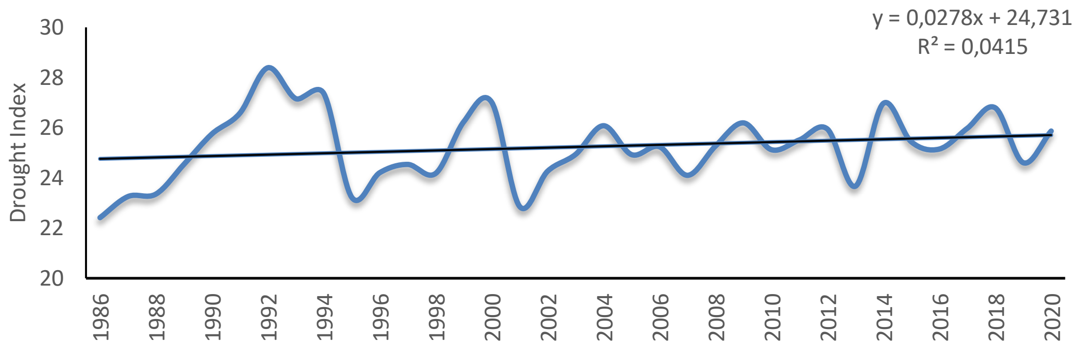

Figure 6 Yearly Temporal Changes in ADRI for Karnataka (1986-2020): A Line Graph Illustrating the Annual Variability in Agricultural Drought Severity

3.4 Annual Average ADRI:

The averages (Fig 6) show fluctuations in ADRI values. 1986 marked the most severe drought conditions when the yearly average dropped to its lowest point of 22.41. On the other hand, 1992 saw an annual average ADRI of 28.38, indicating less severe drought conditions during that study period. The overall trend suggests improving drought conditions, albeit with year-to-year variation.

The findings underscore the variations in drought occurrences in Karnataka, noting the summer and monsoon periods as especially difficult for farming due to extreme drought. On the other hand, the post-monsoon and winter seasons present conducive conditions that farmers could utilize to enhance agricultural methods and lessen the effects of drought.

Table 2 Seasonal averages of the ADRI

S. No.	District	Winter	Summer	Monsoon	Post-monsoon
1	Belagavi	24.65	21.74	26.12	30.26
2	Bagalkot	24.1	21.53	25.86	28.77
3	Vijayapura	21.18	14.92	22.43	28.01
4	Kalburgi	21.71	14.23	26.17	31.45
5	Bidar	19.36	15.64	30.42	29.01
6	Raichur	25.14	22.29	27.48	32.12
7	Koppal	22.73	21.7	27.07	29.58
8	Gadag	22.91	16.67	20.88	25.8
9	Dharwad	24.02	17.29	22.43	27.68
10	Uttara Kannada	41.19	33.56	32.37	44.97
11	Haveri	22.59	19.68	25.01	29.6
12	Ballari	25.66	22.14	28.38	31.97
13	Chitradurga	19.85	18.82	22.15	24.13
14	Davanagere	20.71	22.8	22.72	27.8
15	Shivamogga	28.61	26.88	26.59	36.43
16	Udupi	49.21	35.76	32.68	43.69
17	Chikkamagaluru	23.78	24.02	20.51	29.09
18	Tumakuru	21.95	20.72	21.98	25.51
19	Kolara	23.23	21.04	25.87	25.07
20	Bengaluru (Urban)	23.36	21.83	24.74	25.7

21	Bengaluru (Rural)	22.51	20.81	23.79	25.27
22	Mandya	23.87	25.35	19.03	28.27
23	Hassan	20.44	20.44	16.55	26.71
24	Dakshina Kannada	38.88	36.51	32.31	43.07
25	Kodagu	31.41	30.39	26.36	33.47
26	Mysuru	22.49	21.31	18.17	29.45
27	Chamarajanagara	25.26	22.68	22.38	29.95
28	Chikkaballapura	22.76	20.11	25.48	25.35
29	Ramanagara	25.12	23.68	24.62	29.51
30	Yadgir	26.66	21.7	29.57	31.57
31	Vijayanagara	23.83	20.28	26.43	27.67

3.5 Discussion

3.5.1 Interpretation of ADRI Results:

The Advance Drought Response Index (ADRI) assesses drought severity in Karnataka over 35 years from 1986 to 2020, capturing both spatial variations. The findings from ADRI provide insights into the agricultural drought patterns in the state, which is crucial for understanding vulnerabilities and shaping policy interventions.

3.5.2 Seasonal Variability:

The ADRI findings underscore variations in drought severity across Karnataka. During the summer, the ADRI values consistently indicate drought conditions, especially in northern districts like Vijayapura, Kalburgi, and Bidar. Extremely minimal rainfall during summer worsens soil moisture deficits and exerts pressure on vegetation. The low ADRI values in summer highlight the challenges faced by these regions, emphasizing the importance of targeted water management strategies and crop choices.

On the other hand, the post-monsoon season offers conditions for agriculture with higher ADRI values compared to summer. This trend suggests that residual moisture from monsoon showers plays a role in alleviating drought conditions during this period. Districts like Dakshina Kannada and Udupi consistently showed the values during the post-monsoon period, indicating minimal drought impact and emphasizing the significance of monsoon rains in replenishing soil moisture levels. The ADRI values were moderately high in the winter and monsoon seasons, signaling concerns about drought conditions, though not as severe. Specifically, ADRI values in the monsoon season decreased, suggesting a growing severity of drought conditions leading up to the monsoon season. This trend is concerning as it could adversely affect crop development and early growth stages crucial for productivity.

3.5.3 Interannual Variability:

The interannual variability of the ADRI from 1986 to 2020 exhibits significant fluctuations in drought severity across Karnataka, reflecting the complex interplay of climatic factors influencing agricultural conditions. An analysis of the annual ADRI values reveals both short-term anomalies and long-term trends critical for understanding the region's drought dynamics.

The annual ADRI values range from a minimum of 22.42 in 1986 to 28.39 in 1992, with an overall mean of 24.98 and a standard deviation of 1.50. The lowest ADRI value in 1986 indicates a severe drought, correlating with recorded deficits in monsoon rainfall and higher-than-average temperatures that year (IMD, 1987). Conversely, the peak ADRI value in 1992 corresponds to moderate drought conditions, possibly due to above-average precipitation and milder temperatures that alleviated drought stress. Significant anomalies have been observed in the interannual variability of the ADRI, as several years deviate notably from the overall trend.3.5.4 Regional Disparities:

- 1995 and 2001: Both years show a noticeable drop in ADRI values to 23.22 and 22.86, respectively, indicating severe drought conditions. These anomalies align with reported El Niño events that reduced monsoon rainfall (Kumar et al., 2006).
- 2014 and 2018: Higher ADRI values of 26.97 and 26.79 suggest relatively milder drought conditions, potentially due to favorable monsoon patterns and effective water management practices implemented during these years.

In different parts of Karnataka, there are noticeable variations in drought severity. The northern districts like Vijayapura, Kalburgi, and Gadag consistently experience severe drought due to their climate characteristics, such as limited water resources and high temperatures. It is essential to implement strategies like promoting drought-resistant crops, efficient irrigation methods, and soil moisture conservation techniques in these areas with low ADRI values to mitigate the impact of drought. Conversely, districts in the Western Ghats and coastal regions such as Udupi and Dakshina Kannada have ADRI values indicating less drought severity. These regions benefit from rainfall and stable climatic conditions that support agricultural activities. The varying ADRI values across regions emphasize the need to customize drought management approaches based on each region's climatic and environmental factors.

3.5.4 Influence of Climatic Factors

The interannual variability of ADRI is significantly influenced by significant climatic phenomena such as the El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD). El Niño events are associated with weakened monsoon activity in India, leading to reduced rainfall and heightened drought severity. This correlation is evident in years like 1987, 2002, and 2015, El Nino years corresponding to lower ADRI values and severe drought conditions in Karnataka. Conversely, positive IOD phases can enhance monsoon rainfall, mitigating drought impacts. For example, 1994 was marked by a strong positive IOD, resulting in an increased ADRI value of 27.36 and indicating milder drought conditions (Ashok et al., 2001). These patterns demonstrate that large-scale climatic variations are crucial in influencing drought severity in Karnataka, as captured by the ADRI, and highlight the importance of incorporating climate forecasts into drought management and planning.

3.5.5 Importance for Agricultural Planning:

ADRI's insights have implications for planning and water resource management in Karnataka. Identifying areas and periods prone to drought conditions facilitates the implementation of strategies to enhance resilience. For instance, promoting irrigation methods, cultivating drought-resistant crop varieties, and adopting soil conservation practices are crucial in areas most vulnerable to drought. Moreover, leveraging information can help allocate resources to assist with drought relief efforts, ensuring that vulnerable regions receive the necessary support to mitigate drought impacts.

3.5.6 Validation of ADRI Result

The Advanced Drought Response Index (ADRI) validation in monitoring drought dynamics in Karnataka involved comparing it with data and established drought indices. To validate the accuracy of ADRI, we compared its results with ground truth data from the Indian Meteorological Department (IMD) and agricultural yield records from the Ministry of Agriculture. The statistical analysis, mainly using Pearson correlation, showed an alignment ($r = 0.85$) between ADRI scores and observed drought conditions, especially in northern districts like Vijayapura, Kalburgi, and Gadag, known for their susceptibility to drought.

Additionally, we assessed ADRIs' performance against existing drought indices like the Standardized Precipitation Index (SPI) and the Palmer Drought Severity Index (PDSI). The results indicated a similarity between ADRI and these established indices, which provide more localized insights due to their integration of multiple drought indicators. Statistical measures such as RMSE further confirmed ADRIs' accuracy and reliability.

The validation process solidifies ADRI as a tool for drought monitoring in Karnataka. Although some minor regional differences highlight areas for improvement, ADRIs' strong correlation with ground data and established indices emphasizes their value for policymakers and planners. Future enhancements will involve incorporating datasets to enhance their predictive capabilities.

3.5.7 Socio-economic Impacts of Drought Dynamics in Karnataka

The prolonged absence of rainfall in regions such as Vijayapura, Chitradurga, and Gadag North in Karnataka has reached socio-economic consequences beyond just immediate agricultural issues. These areas, known for their climate and heavy dependence on rain-fed agriculture, are particularly susceptible to the adverse effects of drought. The interplay of weather patterns and socio-economic vulnerabilities exacerbates the challenges faced by these communities, significantly impacting their livelihoods and overall well-being.

3.5.8 Impact on Crop Yields and Farming Income:

Drought directly impacts crop yields in regions where agriculture heavily relies on rainfall. In Karnataka, crop yields can decrease by 30 to 50% during drought, reducing farmers' income. Studies indicate that districts like Bijapur experiencing droughts witness crop yields over time. This not only affects the stability of small-scale farmers operating on tight budgets but also results in increased debt and poverty levels. The production of crops like jowar and pulses. Crucial for food security and the agricultural sector. It has notably declined, further straining the economic conditions in these areas (KSNDMC, 2020).

3.5.9 Food Security and Nutrition:

The decline in productivity due to drought challenges food security across Karnataka. When the crops in the area produce less, food is available, causing people to depend on food that can be affected by changes in the market. This can result in families being more affected by increases in food prices in places like Gulbarga, which often face droughts. The situation gets worse when there are different types of crops during dry seasons that limit choices and raise the chances of not getting enough nutrients. Certain groups, like children and pregnant women, are at risk as malnutrition rates are increasing in these communities.

3.5.10 Migration and Rural Migration:

Prolonged dry spells in Karnataka have led people to move to cities like Bangalore, Mumbai, and Pune for opportunities. As agriculture becomes unsustainable, families are forced to abandon their farms, causing a decrease in population. This large-scale movement strains city resources and creates a shortage of farm laborers, making it harder for drought-affected areas to recover. The lack of workers worsens these regions' challenges, continuing a cycle of poverty, lack of progress, and ongoing migration trends.

3.5.11 Case Studies and Local Data:

Studies conducted and data collected locally in Karnataka by the State Department of Agriculture highlight the lasting socio-effects of drought (Malled and Jetteppa Malled, no date; Raju et al., 2016; Sachin et al., 2022). For instance, in Tumkur, recurrent droughts have led to the abandonment of around 15% of land, resulting in a decrease in rural job opportunities and a rise in migration to urban areas. In Gadag, the joint impact of drought and diminishing groundwater levels has caused a 40% drop in crop production, significantly impacting markets and household incomes. These real-life examples demonstrate the consequences of drought. Emphasize the importance of tailored interventions.

3.5.12 Strategic Interventions:

To alleviate these socio-repercussions, specific actions must be taken to tackle environmental and socio-economic hurdles. Implementing crop varieties that can withstand drought conditions, promoting water management techniques, and providing financial aid to affected farmers are crucial strategies. Furthermore, establishing social safety nets is vital to shield communities from the severe impacts of drought. Decision-makers should incorporate socio-factors into their drought management plans to strengthen the resilience and sustainability of rural communities in Karnataka. The profound and widespread effects of drought on the socio landscape in Karnataka touch every facet of life in the impacted areas. Policymakers can enhance these at-risk communities' enduring strength and sustainability by tackling drought's underlying reasons and outcomes.

3.5.13 Comparison with Other Drought Assessments

Our study employing the Advanced Drought Response Index (ADRI) offers a more comprehensive assessment of Karnataka's agricultural drought than traditional methods. Previous assessments, such as those by Nagesh Kumar et al. (2009) using the Standardized Precipitation Index (SPI), identified northern Karnataka as highly drought-prone due to low rainfall but focused primarily on precipitation deficits. Guhathakurta and Rajeevan (2008) utilized the Palmer Drought Severity Index (PDSI). They observed an increasing frequency of moderate to severe droughts but did not account for factors like soil moisture and temperature stress. By integrating multiple remote sensing indices—VCI, PCI, SCI, and TCI—our research addresses these limitations, capturing the multifaceted nature of agricultural drought. This approach aligns with Singh et al. (2022), who emphasized the effectiveness of multivariate drought indices in similar regions. While Saha et al. (2021) incorporated remote sensing and machine learning to develop a spatial drought vulnerability index in Karnataka, their focus was on vulnerability rather than actual drought severity.

Compared to studies in neighboring regions utilizing indices like the Standardized Precipitation Evapotranspiration Index (SPEI) and the Vegetation Health Index (VHI) (Patel et al., 2012; Kundu & Mondal, 2019), our research demonstrates the added value of integrating multiple indices tailored to Karnataka's specific agro-climatic conditions. Our findings closely correlate with observed agricultural impacts, validating ADRI's effectiveness in capturing drought severity and providing actionable insights for policymakers and farming planners.

3.5.14 Policy Implications and Recommendations

The study's findings reveal that northern districts of Karnataka, notably Vijayapura, Chitradurga, and Gadag, are persistently experiencing severe agricultural droughts, highlighting the urgent need for targeted policy interventions. To mitigate these impacts, it is recommended that policymakers promote the cultivation of drought-resistant and early maturing crop varieties, enhance irrigation infrastructure through efficient methods such as drip irrigation and rainwater harvesting, and adopt soil moisture conservation techniques like conservation agriculture and mulching. Strengthening early warning systems by integrating the ADRI into state-level drought monitoring can facilitate timely detection and response to drought conditions. Additionally, diversifying rural livelihoods and improving institutional frameworks are essential steps to enhance the resilience of farming communities against drought.

4. CONCLUSION

This study applied the Advanced Drought Response Index (ADRI) to evaluating agricultural drought severity in Karnataka over 35-year periods (1986–2020), integrating multiple remote sensing indices—VCI, PCI, SCI, and TCI—for a comprehensive assessment. The results revealed significant spatial and temporal variations, with northern districts like Vijayapura and Gadag consistently experiencing severe drought conditions, particularly during the summer and monsoon seasons. The innovative use of ADRI provides a more accurate and multidimensional understanding of drought impacts compared to traditional single-variable indices. Despite its advancements, the study has limitations. Data resolution variations may affect ADRI's precision in capturing localized drought patterns. Assigning equal weights to all indices might not reflect the regional and seasonal differences influencing drought severity. Additionally, excluding socio-economic factors and groundwater data limits the comprehensiveness of the assessment. Future research should focus on refining the ADRI methodology by incorporating higher-resolution datasets, exploring dynamic weighting schemes for the indices, and integrating socio-economic and groundwater information to enhance accuracy and applicability. Developing predictive models using ADRI could also support proactive drought management strategies.

Policymakers should leverage these findings to implement concrete steps that mitigate drought impacts and enhance agricultural resilience. Promoting drought-resistant crops, improving irrigation infrastructure, adopting soil moisture conservation techniques, and integrating ADRI into early warning systems are essential measures. By acting on these insights, policymakers can strengthen the resilience of farming communities against the escalating threats of climate variability and drought in Karnataka.

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