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Drought Monitoring with Multiple Indices and Management through Various Techniques: A Review†

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Abstract: Drought is a complex natural disaster with significant implications for agriculture, water resources, and socioeconomic development. Accurate and timely assessment of meteorological drought is crucial for effective management and mitigation strategies. Climate change has led to a rise in climatic anomalies, such as droughts, floods, heatwaves, and cold snaps, which have severe impacts on human well-being and societal patterns. Droughts, which are prolonged periods of limited or absent rainfall, pose significant challenges for sectors like agriculture, energy, and enterprises, especially in economically reliant countries with inadequate water management infrastructure. Drought indicators are essential in meteorology, agriculture, and hydrology for monitoring drought conditions. Accurate drought assessment relies on quantitative index-based comprehensive drought indices, such as India's Aridity Anomaly Index (AAI), Deciles Index, Percent of Normal Index, Reconnaissance Drought Index (RDI), and the Palmer Drought Severity Index (PDSI). Drought management involves analyzing risk components and using analytical tools for decision making. A decision support system includes institutional, methodological, public, and operational components. Long-term actions include demand reduction through economic incentives, while short-term actions include increasing water supply through wastewater reutilization, inter-basin water conveyance, reservoir construction, and agricultural ponds. Impact minimization is achieved through educational initiatives, reallocating water resources, early warning systems, and insurance programs. Challenges include developing technologies to integrate data sources and create unified indicators, and geospatial decision-support systems facilitate hazard mapping and strategic drought management plans.

Keywords: Drought; Meteorological drought indices; Management; Rainfall-based indices; Temperature-based indices; Combined indices; Climate change impacts

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1. Introduction

Climate change has significantly altered ecosystems, leading to anomalous climates such as more frequent droughts, floods, heatwaves, and cold snaps. This has resulted in increased harm to human life and habits, causing a significant shift in climatic cycles **[1].**

Drought is a disruption of the rainfall regime, characterized by no precipitation or below average rainfall lasting long enough to create hydrological and agricultural hazards. Drought, characterized by prolonged low precipitation, significantly impacts various ecosystems by causing water scarcity, influenced by factors like water demand, hydrological processes, and weather conditions.

A protracted period of below-average precipitation causes water deficits in the atmosphere and is the hallmark of a "meteorological drought". When there is not enough soil moisture to meet the needs of crops, an "agricultural drought" occurs, which lowers agricultural productivity. A "hydrological drought" affects the amount of water in rivers and aquifers by reducing streamflow, groundwater levels, or reservoir storage. The term "socioeconomic drought" refers to how water scarcity affects human endeavors including industry, urbanization, and water delivery. The term "ecological drought" describes how a lack of water affects ecosystem services, biodiversity, and habitats. [2,3].

Monitoring the drought is essential for determining the availability of water and efficiently managing water resources [4]. Farmers can better prepare for future water shortages and modify their agricultural operations by keeping an eye on drought conditions [5]. For the purpose of forecasting crop yields and guaranteeing food security in areas where water is scarce, drought monitoring is crucial [6]. Droughts can have detrimental effects on the economy; monitoring enables the evaluation of these effects and the creation of mitigation plans [7]. Early warning system development is aided by timely detection of drought conditions through monitoring, allowing for proactive measures [8]. Monitoring droughts helps to better understand how ecosystems are impacted by water scarcity, which supports conservation efforts [9]. Monitoring droughts helps with adaptation methods by shedding light on the trends and patterns of droughts in relation to climate change [10].

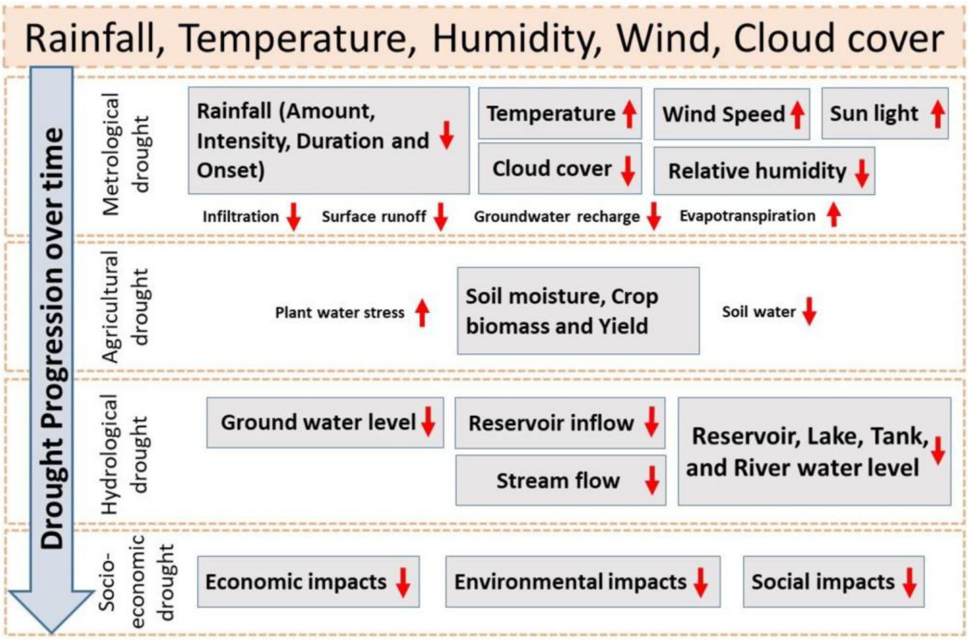

Figure 1. Schematic representation of drought process **[11].**

A review that highlights several drought indices is beneficial for hydrology, climatology, and water resource management in a number of ways. This kind of review advances the scientific knowledge of drought assessment techniques, assists practitioners and researchers in selecting suitable indices for particular applications, and supports the creation of efficient plans for drought management and monitoring.

Comparative Study of Drought Indices to assess the merits and demerits of several drought indices in evaluating droughts from meteorological, agricultural, & hydrological perspectives [12]. Application at All Scales and Areas: The aim of this study is to evaluate the effectiveness and suitability of drought indices across a range of geographical locations and at different temporal and spatial scales [13]. Technological Developments in Drought Monitoring is to investigate how new developments in remote sensing and satellite-based technology for drought monitoring interact with conventional drought indices [14]. The goal of this study is to examine how drought affects water resources, such as groundwater, reservoirs, and river flow, and to talk about how the selection of a drought index affects management choices [15]. The goal is to investigate the relationships between drought trends and climate change, as well as the ways in which various indicators reflect shifting trends and levels of drought intensity [16].

To effectively create ways to alleviate the effects of drought on water resources, agriculture, ecosystems, and communities, it is imperative to investigate drought management measures: To investigate methods for maximizing water usage in urban areas, industries, and agriculture in order to reduce water loss and raise total water use efficiency [17]. To investigate the creation and uptake of crop types that can withstand drought and are more resistant to water scarcity [18]. The aim of this study is to explore comprehensive strategies that take into account the whole water cycle and involve many sectors in order to improve drought resistance and water availability [19]. To investigate how early warning systems and cutting-edge monitoring technology can be used to detect drought conditions early and take proactive measures to combat them [20]. To investigate methods for collecting and storing rainfall in order to augment water supplies during dry spells, particularly in regions with erratic precipitation [21]. To investigate how local knowledge and community involvement may be utilized to create and execute grassroots drought adaptation plans [22].

2. Materials and Methods

2.1. Drought Indices Overview and Comparison

The tables present a list of drought indicators used in meteorology, agriculture, and hydrology to assess and monitor drought conditions. These indices use various input parameters and methodologies to measure drought severity. Preparatory research is needed to identify the right indicators for the period, location, and climate. These indices help sectors prepare for and mitigate drought impacts, ensuring the safety and sustainability of agricultural and other sectors. They are essential for monitoring drought conditions and ensuring a country's preparedness for potential drought impacts. Accurate drought assessment and decision-making rely on quantitative index-based comprehensive drought indices are given by Table 1 and 2.

The Aridity Anomaly Index (AAI) is a drought indicator for India, while the Deciles Index assesses precipitation frequency and distribution. The Percent of Normal Index (PNI) monitors drought-related impacts across geographical locations. The Standardized Precipitation Index (SPI) calculates precipitation likelihood using historical records. Other indicators include the Reconnaissance Drought Index (RDI), Palmer Drought Severity Index (PDSI), and Standardized Precipitation Evapotranspiration Index (SPEI) as described in Table 1.

Table 1. Comprehensive drought indices-based on meteorology.

Sr#	Indices	Input Parameters	Description	Methodology	Applications
1	Aridity Anomaly Index (AAI)	P, T, PET, ET	The Aridity Anomaly Index (AAI) is a drought indicator that compares actual aridity with the average, with positive numbers indicating moisture	UNEP (1992) defines AAI as the ratio of potential evapotranspiration (P) to average annual precipitation (PET). AAI = P/PET	Operationally accessible for India [23]

			stress and negative values indicating excess moisture.		
2	Deciles Index	P	The study assesses precipitation frequency and distribution by ranking the entire record of rainfall data for a specific area. The first decile represents the highest 10% of values, while the fifth decile represents the median.	Considers various temporal scales, including daily, weekly, monthly, seasonal, and annual values, allowing comparison of current data with historical records for a specific period.	Simple to compute; Australian examples are helpful.[24]
3	Percent of normal index (PNI)	P	This mathematical operation compares and contrasts different time periods across geographical locations, calculating on various timescales, divides actual precipitation by usual precipitation, and multiplies by 100.	To calculate, divide actual precipitation by typical precipitation for the time being considered and multiply by 100.	This tool can efficiently identify and monitor various drought-related impacts [25]
4	Standardized Precipitation Index (SPI)	P	SPI is a meteorological indicator that calculates precipitation likelihood using historical records, ranging from 1 month to 48 months. It indicates rainy and dry events, suitable for areas with limited data or unified datasets.	SPI can be calculated by probability of precipitation for any timescale. SPI $= X - Xm/\sigma$ Where X= Precipitation for station, Xm mean precipitation and σ is standard deviation. SPI can be calculated with missing data and recalculate output when more data is available.	SPI is a climate monitoring tool that measures drought, agricultural impacts, and hydrological impacts on gridded precipitation datasets.[26]
5	China Z Index (CZI)	P	The CZI and SPI are indices that use precipitation data to assess wet and dry periods. They follow a Pearson type III distribution and use monthly intervals ranging from 1 to 72 months to detect droughts of varying durations.	The monitoring approach, similar to the Standardized Precipitation Index (SPI), observes wet and dry events over different time periods, computing	Observes wet and dry events over different time periods, computing both moisture-related and non-moisture events over multiple time steps.[27]

6	Reconnaissance Drought Index (RDI)	P, T	The Drought Severity Index (RDI) is a comprehensive water balance equation that considers precipitation and evapotranspiration, offering three outputs: initial, normalized, and standardized.	(RDI) is based on the precipitation to potential evapotranspiration ratio (P/PET).	Potential evapotranspiration provides a more accurate water balance assessment than the Standardized Precipitation Index (SPI) [28]
7	Palmer Drought Severity Index (PDSI)	P, T and AWC	The calculation considers monthly temperature, precipitation data, soil water-holding capacity, and potential moisture loss due to temperature influences.	The Palmer Drought Severity Index (PDSI) is determined via the utilization of precipitation and temperature data, alongside the specific Available Water Content (AWC) of the soil in a certain locality.	PDSI is a global tool used to identify and monitor droughts affecting agriculture, with numerous examples of its use over the years. [29].
8	Standardized Precipitation Evapotranspiration Index (SPEI)	P, T	The SPEI is a drought index that uses temperature data to identify and characterize wet and dry conditions, with applicability for up to 48 months.	Thornthwaite's 1948 Standardized Precipitation Evapotranspiration Index (SPEI) is a water balance methodology used to calculate the difference between precipitation and potential evapotranspiration.	To track drought situations, providing a universally applicable tool for evaluating climate change impact in model output. [30]

Soil Moisture Anomaly (SMA) is a statistical tool used to detect anomalies in soil moisture levels over time, assessing soil conditions and tracking drought effects on agriculture and crop production. The Soil Moisture Deficit Index (SMDI) measures moisture loss by comparing actual soil moisture level and field capacity. SMI evaluates soil moisture conditions by comparing current soil moisture content with maximum and minimum values over a given period. The Normalized Soil Moisture Index (NSMI) standardizes soil moisture content, making it easier to compare results from different locations. SSMA assesses irregularities in the soil's top layer and offers information about transient changes in moisture content. These tools are useful for various applications, including drought monitoring, agricultural planning, water resource management, environmental studies, hydrological modeling, and climate change studies.

Table 2. Comprehensive drought indices-based on soil moisture.

Sr#	Indices	Input Parameters	Description	Methodology	Applications
1	Soil Moisture Anomaly (SMA)	P, T, and AWC	SMA helps detect anomalies from the norm by expressing the difference	SMA= Current Soil Moisture Content−Historical or Expected Soil Moisture Content / Historical	created and widely used to track the effects of drought on

			between the measured soil moisture as well as the long-term average.	or Expected Soil Moisture Content	global agriculture and crop production. [31]
2	Soil Moisture Deficit Index (SMDI)	Modeling approach	SMD measures the amount of moisture loss by quantifying the difference between the actual soil moisture level and the field capacity.	SMD=Field Capacity−Current Soil Moisture Content	Useful for identifying and monitoring drought affecting agriculture. [32]
3	Soil Moisture Index (SMI)	Current Soil Moisture Content Max. and Min. Soil Moisture Content Reference Period	By comparing the current soil moisture content with the maximum and minimum values over a given period, SMI evaluates the soil moisture conditions.	SMI= (Max SMC − Min SMC)/ Current Soil Moisture Content − Min SMC)×100 Researchers can modify SMI formulations based on factors like soil type, climate, and soil moisture sensitivity, ensuring varying results for different applications.	The Soil Moisture Index (SMI) is a statistical tool that compares soil moisture levels over time, assessing soil conditions, with its precise phrasing varying based on assessment objectives. [33]
4	Normalized Soil Moisture Index (NSMI)	Current Soil Moisture Con-tent Max. and Min. Soil Moisture Content	By standardizing the soil moisture content in relation to the range of variability, NSMI makes it easier to compare results from various places.	NSMI = Current Soil Moisture Content−Minimum Soil Moisture Content / Maximum Soil Moisture Content−Minimum Soil Moisture Content	drought monitoring, agricultural planning, water resource management, environmental studies, hydrological modeling, and climate change [34]
5	Surface soil moisture Anomaly (SSMA)	Current Surface Soil Moisture Content (SSM): Historical or Expected (SSMC): Temporal Period	SSMA assesses irregularities in the soil's top layer and offers information about transient changes in moisture content.	SSMA= Current Surface Soil Moisture Content−Historical or Expected Surface Soil Moisture Content / Historical or Expected Surface Soil Moisture Content	drought monitoring, agricultural planning, water resource management, environmental studies, hydrological modeling, and climate change studies [35]

3. Drought Management

Risk management for droughts involves understanding drought risk components and analyzing alternative strategies. This involves using analytical tools for decision making and developing strategies to manage uncertainty and risk perception. This work aims to present a planning process for preparing a decision support system for drought risk management. [36].

1. Institutional component – The institutional framework should include water, meteorology, agriculture, environment, and socioeconomic institutions to develop integrated drought risk management systems.

2. Methodological component – It is the framework for drought risk assessment and vulnerability assessment outlines procedures for assessing drought risks, analyzing climate trends and vulnerability factors, and mapping drought-prone areas for identification of risk elements and implementing mitigation measures.[37]

3. Public component- The Framework for Drought Prevention and Response outlines strategies for prompt responses, short-term readiness, and long-term resilience, requiring local institutions to develop and execute programs aimed at mitigating drought, similar to strategic planning.

4. The operational component offers guidance for developing a decision-support system for drought risk management, focusing on monitoring current conditions, predicting future droughts, and proactively implementing drought prevention. [38].

Table 3. Long and short-term drought management [39]:

Category	**Long term Actions**	**Short term Actions**
Demand reduction	Economic incentives aimed at encouraging water conservation encompass strategies such as the substitution of irrigated crops with drought-resistant alternatives and the promotion of water recycling practices within industrial sectors.	There is a current emphasis on promoting public awareness regarding water conservation, which includes the implementation of various measures such as restrictions on urban water usage, limitations on irrigation for crops, and the enforcement of forced rationing.
Water supply increase	The potential strategies encompass wastewater reutilization, inter-basin water conveyance, construction of additional reservoirs, augmentation of storage capacity, establishment of agricultural ponds, and implementation of measures to mitigate seepage & evaporation losses.	The suggested measures encompass enhancing water systems, employing low-quality, high-cost sources, tapping into groundwater reserves, and increasing diversion by loosening limits on ecological or recreational usage.
Impact minimization	The primary objectives of the educational initiatives are to enhance the state of preparedness for drought conditions, reallocate water resources in accordance with their quality, establish systems for early warning, and execute insurance programs.	Temporary water reallocation, allocation of resources, & public assistance programs is implemented as strategies to mitigate revenue losses, alleviate tax burdens, defer payments, and provide crop insurance coverage.

The inclusion of drought evaluation, tracking, future risk estimation, mitigation strategies, risk management, with drought records management within the decision support system is vital. This should be done while considering hydro-meteorological observational data and drought assessments.

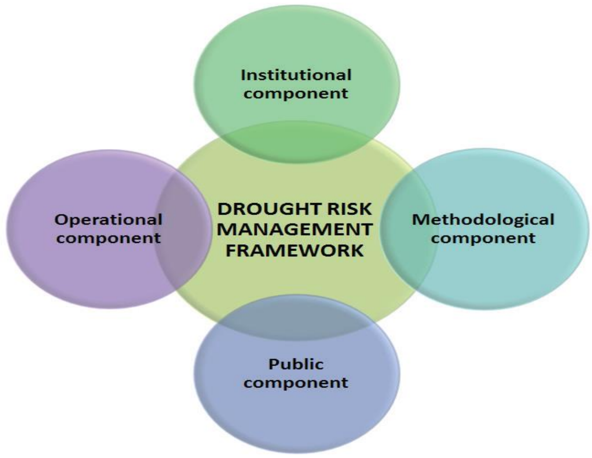

Figure 1. Framework for drought risk management [40].

Drought indicators utilize established monitoring networks to furnish practical information regarding drought danger. One of the challenges that researchers face is the development of technologies that can effectively integrate various sources of data and generate a unified drought indicator. Real-time apps facilitate the dissemination of readily available meteorological and hydrological data. [41].

• Application scope. Drought indicators utilize established monitoring networks to furnish practical information regarding drought danger. One of the challenges that researchers face is the development of technologies that can effectively integrate various sources of data and generate a unified drought indicator. Real-time apps facilitate the dissemination of readily available meteorological and hydrological data.

• Temporal scale. The assessment of drought hazards across different sectors necessitates varying temporal resolutions. However, drought indices have the capability to capture notable meteorological and hydrological fluctuations throughout a range of time periods.

• Spatial scale. The effective management of drought risk necessitates a concentrated approach at both regional and local levels, owing to the inherent unpredictability of hydrometeorological conditions. The utilization of standardized methodologies for assessing drought hazards facilitates the generation of maps that can be applied across various locations.

• Frequency analysis. The examination of time series data on drought indices can offer valuable insights on the susceptibility of a basin to the development, progression, and endurance of droughts, hence facilitating the prediction of droughts in real-time.

The primary objective is to create geospatial decision-support systems for the purpose of managing drought risk. This will be achieved through the utilization of remote sensing data as well as geoinformatics approaches. These tools facilitate the process of hazard mapping, the development of strategic drought management plans, and the efficient flow of information, especially in the context of climate change scenarios.

4. Conclusions and Future Directions

Climate change has increased climatic anomalies like droughts, floods, heatwaves, and cold snaps, affecting human well-being and social patterns. Droughts pose challenges for sectors like agriculture, energy, and enterprises, especially in economically reliant countries with inadequate water management infrastructure. Drought indicators are essential for meteorology, agriculture, and hydrology monitoring, using quantitative index-based comprehensive indices like India's Aridity Anomaly Index.

Drought management involves analyzing risk components and using analytical tools for decision making. A decision support system includes institutional, methodological, public, and operational components. Long-term actions include demand reduction through economic incentives, while short-term actions include increasing water supply through wastewater reutilization, inter-basin conveyance, reservoir construction, and agricultural ponds.

Climate change is altering precipitation distribution, necessitating the use of drought indices. Future research should integrate remote sensing technology, satellite data, and ground-based monitoring systems. Machine learning and artificial intelligence can improve drought prediction and risk assessment. Prioritizing agricultural practices, water resource management, and infrastructure upgrades is crucial for climate change adaptation.

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