Review Paper:

A Comprehensive Assessment of Agricultural Drought

Kadam Chandrakant Madhukar[1*], Bhosle Udhav V.[2] and Holambe Raghunath S.[3]
1. Shri Guru Gobind Singhji Institute of Engineering and Technology, Vishnupuri, Nanded, INDIA
2. Swami Ramanand Teerth Marathwada University, Nanded, INDIA
3. Shri Guru Gobind Singhji Institute of Engineering and Technology, Vishnupuri, Nanded, INDIA
*2019pin201@sggs.ac.in

Abstract
There are many disasters that are still a threat to the world. Tsunamis, volcanoes, earthquakes and droughts are well-known among the group. In fact, of all the hazards mentioned, drought is quite unpredictable and devastating. It directly affects the community at large. Droughts exist in almost all countries across the globe. Furthermore, its duration and frequency depend on and vary with different parameters. Surprisingly, droughts do not possess any formal, globally accepted definition which adds to its complexity. Meteorological, agricultural, hydrological and socioeconomic droughts are the most common forms of drought discussed in the literature. A mixture of factors including precipitation, temperature and soil moisture, among others, triggers drought.

According to the drought survey, researchers have examined drought, looking at the specific application along with geographical constraints, resulting in the formation of several drought indices. Drought indicators play an important role in quantitatively estimating drought intensities by integrating data from one or the other variable. Furthermore, these indices are derived in order to capture most of the characteristics of the specific drought incident. Therefore, it is necessary to strictly review established and emerging drought monitoring methods. In this work, we retrospectively analyzed various methods used to investigate drought, with special attention to agricultural drought.

Keywords: Agricultural Drought, Drought Indices, Remote sensing, Soil Moisture.

Introduction
Disasters have always been a challenge to the world for a long time. Tsunamis, volcanoes, earthquakes and droughts etc. are some specified disasters. Drought is one of the most prevalent natural disasters that inflict extensive damage and it has a huge impact on society at large[92]. Drought is a perilous hazard that influences not only economic but social as well as environmental sectors, which results in substantial damage. Drought is one of the most complex climatic occurrences, affecting both people and the environment[92]. Researchers ex-cogitated a range of assessment methodologies to deal with drought. Because satellite data is becoming more widely available and with the escalating technological advancement, many new opportunities are opening for researchers in the field of satellite remote sensing for the assessment of disasters. Environmental solutions defence and intelligence, land use and land cover survey, disaster observance etc. are some of the examples. The role of remote sensing is vital in the assessment as well as in observing these disasters due to its special attributes like large spatio-temporal coverage, repetitive coverage of the same area, accessibility, good resolution etc.

According to the researchers, drought should be considered as one of the most complex but least known natural threats affecting a comparatively large number of people than any other event[24]. Yevjevich[99] has clearly expressed that one of the biggest challenges in properly analyzing these events is the failure to define a succinct and objective definition of drought. In recent years, spectacular growth in losses and liabilities in economic, social and environmental aspects related to drought has also been observed.

Furthermore, due to a lack of comprehensive historical assessments of these losses, it is impossible to adequately evaluate this pattern[93]. To limit drought damage, timely identification of drought conditions is essential. Defining drought characteristics will help initiate preventive processes like drought early warning system[41] and drought hazard assessment[28].

Droughts are distinct from various further natural threats like floods, tropical cyclones and earthquakes in several ways. Furthermore, the impacts of drought are observed to compound over a long tenure. It also has a tendency to persist for years after the event has ended. Because of these reasons, drought is sometimes termed as the creeping phenomenon[97]. Droughts can also be difficult to anticipate in terms of space as well as time, as it is difficult to pinpoint the exact instant when a drought begins and terminates, as well as to estimate its continuance, size and geographic scope[93].

This study intended to explore the past as well as recent work in the field of drought assessment and present the issues and challenges in the evaluation as well as monitoring of agricultural drought with the help of conventional methods and satellite remote sensing based methods. Provided the rapid speed of technological advancement, it is critical to examine and reflect on past and recent achievements while also anticipating new prospects continuously[91]. In general, any scientific study starts the task by defining and specifying the elements of the problem clearly without any ambiguity. Obviously, before any proposed analysis is developed and used, it is essential to determine precisely the meaning of the term "drought"[17].

In contrast to this, there exists no universal definition of drought. Drought analysis is complicated because of non-existence of a defined and universally acknowledged definition of drought. As a result, the existence of a drought can be determined along with its intensity as well. Drought definitions should, in fact, be region-specific and application-specific. That is the reason why Wilhite[94] conducted a categorization analysis examined over 150 definitions.

In the previous works, numerous approaches have been projected for drought monitoring. The literature review shows that isolation and synthesis studies using meteorological, agricultural and hydrological drought indices have been performed in the past. Recent studies have examined the evolution of drought indices and evaluated their benefits and drawbacks[29,40,50].

According to the study's observations, drought phenomena are most frequently observed in the agricultural sector[45]. Agricultural drought has a significant impact on crop production and economic growth in the context of global climate change[98]. Agro-meteorological classes of drought are arguably the most important parts of drought evaluation from the standpoint of food security and societal requirements.

To assess the drought, scientists have formulated many application-specific indices. These indices are found to be very useful for adequately tracing the drought with the resources available at hand. The indices-based drought study was found to be very significant in the overall drought assessment. Furthermore, approaches like implementing artificial neural networks, fuzzy logic and various data mining methods are adapted for accuracy enhancement.

Zargar et al[102] discussed the indicators for different types of drought assessment in his review, emphasizing the significance of tracking the progress of drought indexes in each category.

The main objective of this study is to provide a comprehensive summary of the assessment of drought in general and agricultural type of drought in particular. In addition, the objective is to expand an understanding of the various methodologies used in agricultural drought studies.

Drought

Defining drought: Since drought influences, several economic, as well as social and environmental sections, scores of definitions, have been specifically evolved by a several disciplines. A universal definition of drought in almost any way is an unrealistic expectation. Definitions of drought can be grouped in two main classes as: conceptual and operational[95]. There are around 150 diverse definitions of drought in the literature[17,23,94].

Though there is no universal drought definition, few definitions of droughts are globally acknowledged and can be summarized as below in figure 1.

Drought monitoring: Obasi[56] and Kogan[44] found in their case study that extreme drought for several consecutive months can result in dangerous situation and harm to mankind. Droughts, for example, were responsible for approximately 37% of all deaths caused by natural catastrophes between 1967 and 1991.

The Intergovernmental Panel on Climate Change (IPCC) detailed the vulnerability to extreme events and their impact on human health, economic development and agricultural systems around the world in its fifth assessment report[57].

Moreover, it is predicted that the occurrence and severity of droughts may upsurge owing to global warming[75] and given that agricultural land plays important role in economic development, food security, local livelihood, etc., it is important to realize the relationships between drought and change in agricultural land use and how their interactions can be combined. Wilhite[93] reported that the severity, tenure and geographic range of drought occurrences and magnitude are very high compared to the associated impacts.

The various hazards were classified according to their characteristics and impacts. The case study has examined as good as thirty-one major hazards and compared them with the help of key hazard characteristics and their impacts. The outcome of the survey is that most of the times drought ranks at the top among all other hazards. Figure 2 shows the ranking of hazard events by characteristics and impacts.

Need for drought monitoring: The scope of drought studies can be as diverse as its definitions. The main objectives of drought analysis can be divided into the following few categories:

(1) Drought research explores the causes of drought and aspires to have a broader insight into the climate patterns linked to drought.
(2) Another goal is to get insight into the recurrence and intensity of droughts so as to investigate the likelihood of droughts of varied magnitudes occurring.
(3) The goal could be to depict and comprehend the effects of drought. In this study focus is on the expenses and losses involved due to drought. Damages can be characterized as monetary, societal, or environmental and then they can be direct or indirect.
(4) Drought responses, pertinent mitigation and preparedness initiatives are addressed in the final category, with an emphasis on minimizing the effects of drought[96].

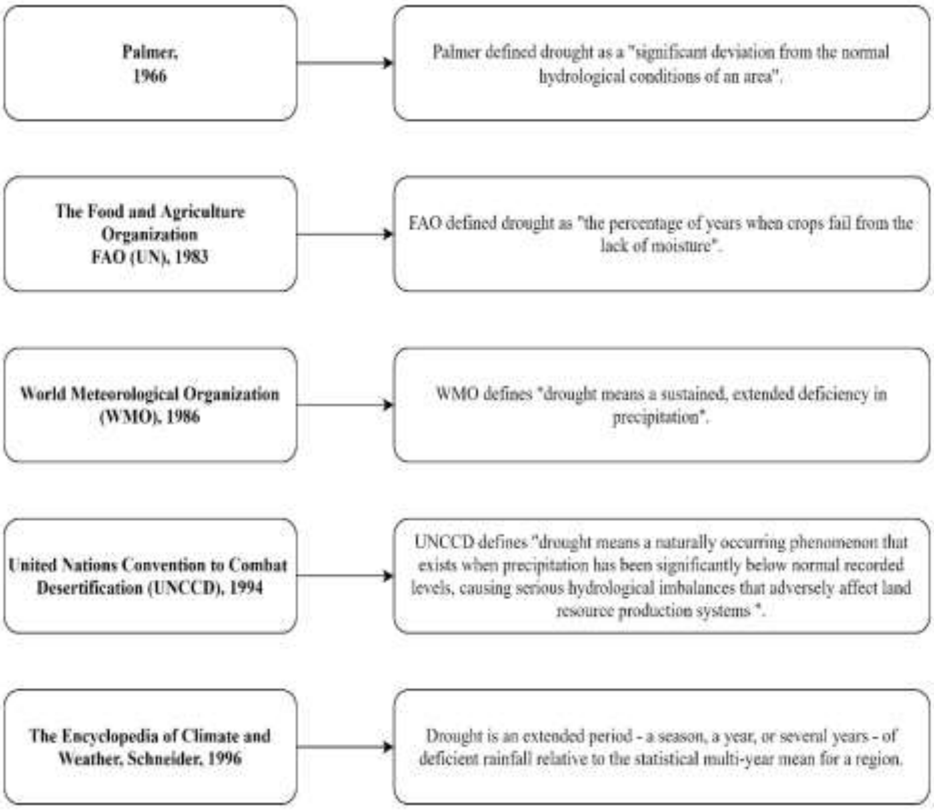

Fig. 1: Some key definitions of drought

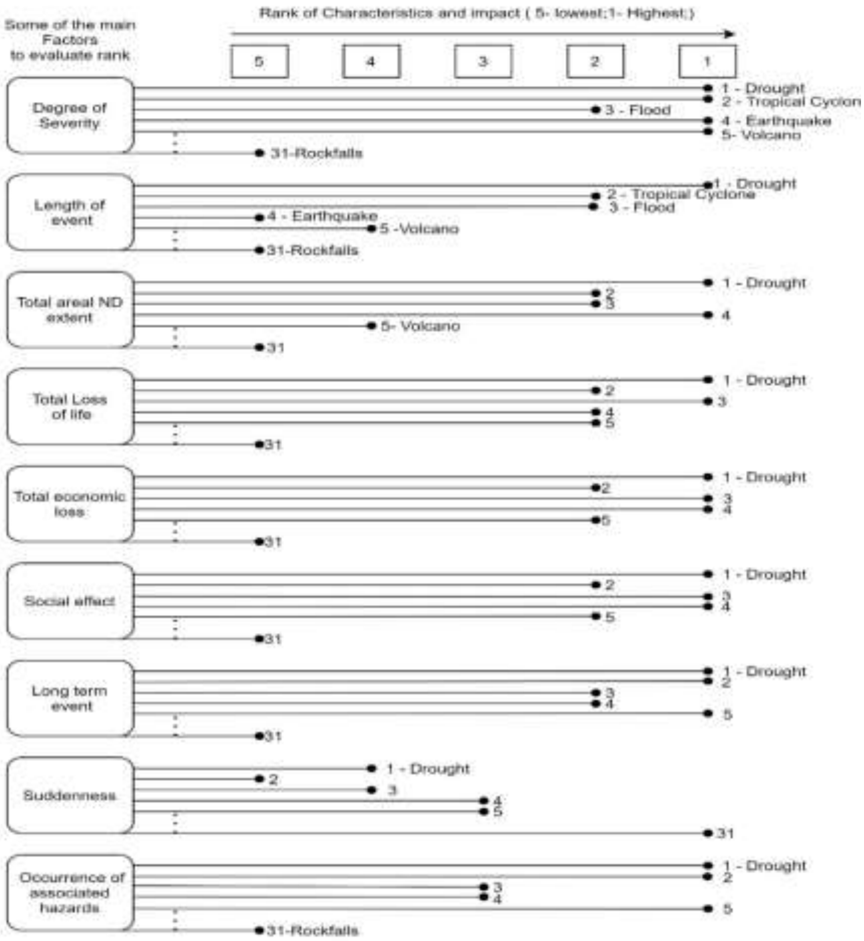

Fig. 2: Ranking of hazard events by characteristics and impacts

Drought classification: Apart from the number of definitions, droughts can be classified in a variety of ways including meteorological, agricultural, hydrological and socioeconomic droughts[95].

Moreover, meteorological, agricultural and hydrological drought characterized some of the other natural or environment-related impacts whereas impacts on human population and society can be seen through socioeconomic drought. In reality, all forms of drought begin with a lack of precipitation.

Meteorological drought: The drought can be referred to as the shortfall in the rainfall over the area or some considerable time span. It is solely determined by the degree of dryness (typically in contrast to a standard or average quantity) and the length of the dry spell[93]. A meteorological drought, unlike the other types of drought, has less severe impacts[73]. Region-specific precipitation is mostly useful in the analysis of meteorological drought[19,62,72].

Several researchers have investigated drought using monthly precipitation data, by interpreting drought as a precipitation shortfall relative to average values[23]. Other approaches have been used to estimate how long drought would endure and how severe it will be in response to aggregate rainfall deficits[11,21]. SPI -Standardized Precipitation Index, RD - Rainfall Deciles, PDSI - Palmer Drought Severity Index and RDI - Reconnaissance Drought Index are among the most prominent indices used for the assessment of this type of drought.

Agricultural: Agricultural drought, across most scenarios, refers to a period of diminishing soil moisture which further results in crop loss, without taking into account the sources of surface water. This can also be classified as a pronounced meteorological drought, which occurs whenever there is a deficit of precipitation at the time of crop developing season, this eventually limits the crop growth and its development[20]. Several factors, including climatic and hydrological droughts, influence soil moisture loss. To assess agricultural droughts, various drought indexes have been developed, generally these indexes are developed with single variable or with the combination of different variables like precipitation, temperature and soil moisture. Soil Moisture Deficit Index (SMDI), Soil Water Storage (SWS), Evapotranspiration Deficit Index (ETDI), Soil Moisture Anomaly Index (SMA) and other significant indices are employed.

(3) Hydrological: A hydrological drought occurs when there are inadequate surface and subsurface water resources for established water uses in a water resources management system. For hydrologic drought analysis, stream-flow data has been frequently used[17,51,73,103]. Hydrological drought is indeed the slowest moving of the major drought categories. Total water deficit, PHDI, Cumulative Streamflow Anomaly, Surface Water Supply Index etc. are the few prominent indexes used to define hydrological drought.

Socioeconomic: The supply-demand relationship and economic commodities in relation to agricultural, meteorological and hydrological droughts are referred to as socioeconomic drought. This occurs when the demand for economic entities exceeds the supply as a result of weather-related water scarcity. It can be distinguished from other drought types on the basis of its occurrence determined by the spatiotemporal supply and demand processes[94]. The impact of meteorological drought on the socioeconomic system is referred to as socioeconomic drought. The classification and the causes of different types of droughts are shown in figure 3 as follows:

Approaches for drought monitoring: Several factors contribute in characterizing drought. It is important to understand and assess numerous drought features like duration, spatial extent, severity or intensity, frequency or periodicity, initiation and termination[16]. Observing indices that measure changes in the region's hydrological cycle is part of drought monitoring. Drought indices are formulated by scientists to predict drought situations using drought variables such as soil moisture, precipitation, temperature, potential evapotranspiration, vegetation health, soil moisture, streamflow etc.

The ultimate goal is to evaluate the qualitative state of droughts on the terrain over a certain duration. Indices are also treated like technical indicators[78]. Not only are there various types of drought impacts, but a total of ninety-one such impacts have also been identified[54]. Historical drought studies reveal that the focus was on *in situ* observations. With the growing technological advancement, in the current scenario, satellite remote sensing with very explicit large data is becoming another strong source for designing drought indices. In addition, this data is available all season over the globe. In addition, various remote sensing indexes are designed and employed for drought assessment. Drought characterization can have a wide range of outcomes. Some specific goals are shown in figure 4.

Drought Indicators: Drought indicators are variables or factors that are used to describe the state of the drought. They may be defined as the variable which represents the magnitude, time span, intensity and areal extent of drought. Quantitative information on drought can be extracted from the indicators which makes the meaning of this information more obvious. Drought characterization can be expressed in a variety of ways, although the use of drought indices is perhaps the most common[82]. In addition, indicators should monitor and evaluate changes in the natural and social environment to establish a statistical basis for the development of disaster risk reduction policies and the evaluation of their effectiveness[52]. The majority of indexes are computed using meteorological or hydrological measurements[96].

Certain indicators are supposed to assess a single event or application, whereas others are customized to reflect varied impacts and hence different drought categories. As an example, the SPI- standardized precipitation index is primarily employed for the assessment of meteorological drought. However, it is found in the survey that SPI is also an inherent part of some of the agricultural drought assessment strategies.

On the other hand, few indices also help the research community to get insight into the historical reference. Historical study with the indices may help in understanding the probability of occurrence and drought severity along with recurrence of drought events. Furthermore, the indices have been found to be beneficial in validating drought indices that have already been simulated, integrated, or remotely sensed[77]. In the end, it can be concluded that the indicators that are data-rich and appropriate for regional conditions will be the best option.

It is relatively critical to select the indices for the assessment. In this context, Keyantash et al[40] proposed the evaluation criteria to evaluate the overall usefulness of the indexes. The desirable properties proposed for index are sophistication, robustness, tractability, dimensionality, extendibility and transparency. Further, they implemented the criterion on selective indices for each type of drought and compared the drought indices. As an outcome, rainfall deciles, computed soil moisture and total water deficit strongly adhere to the criterion among meteorological, agricultural and hydrological drought respectively under given circumstances.

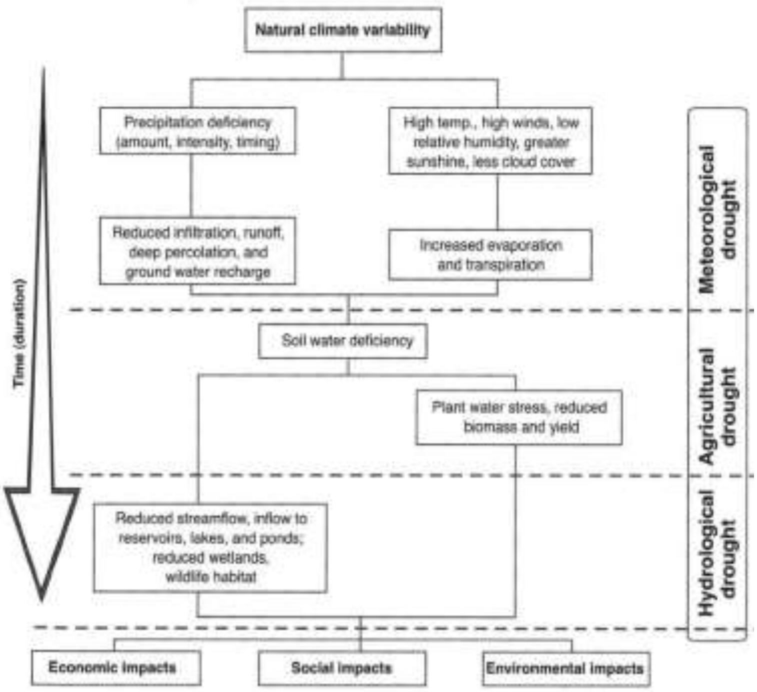

Fig. 3: Relationship among types of droughts and the duration of drought events (Source: National Drought Mitigation Center, University of Nebraska–Lincoln)

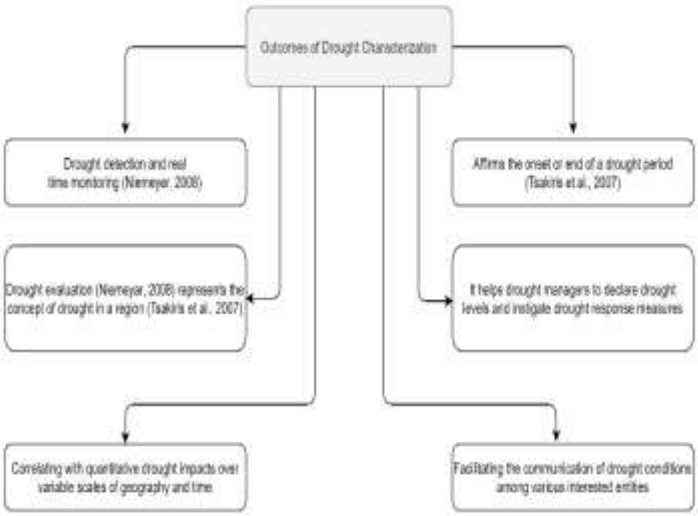

Fig. 4: Some of the outcomes of drought characterization

Drought index characteristics: The definitions of drought indicators are as varied as the indicators themselves. Given the substantial number of indicators, a few distinct characteristics can be identified. A drought indicator could have a variety of desired properties. Furthermore, some attributes are described briefly here for understanding:

(1) Drought indicators are expected to be globally acceptable.
(2) They should be interpretable and versatile enough to accommodate changing thresholds and severity scales.
(3) Most importantly, the input data required must be available readily.
(4) The index should be appropriate for further research.
(5) The indicator should predict the duration and intensity of the drought.
(6) They should be adequate for the early warning system to be activated.

Consequently, the ideal vegetation index, in theory, is "especially sensitive to vegetation canopies, unresponsive to soil brightness, unaffected to soil color, hardly impacted by atmospheric effects as well as environmental effects, solar illumination geometry and sensor viewing settings"[35,36]. Regardless of the fact that many indicators are available for use, certain indices are employed extensively. Many elements influence the indicator's selection. In addition, the availability of required input data is very important again.

A brief summary of a few key indicators used for the assessment of hydrological, meteorological and agricultural droughts is as shown in table 1.

Table 1
List of meteorological, agricultural and hydrological drought indices

Meteorological Indices	Agricultural Indices	Hydrological Indices
Standardized Precipitation Index (SPI)	Standardized Precipitation Index (SPI)	Reservoir Storage Index (RSI)
Palmer Drought Severity Index (PDSI)	Palmer Drought Severity Index (PDSI)	Surface Water Supply Index (SWSI)
Aridity Index (AI)	Crop Moisture Index (CMI)	Water Requirement Satisfaction Index (WRSI)
Reclamation Drought Index (RDI)	Soil Moisture Anomaly Index (SMA)	Total Water Deficit (TWD)
Bhalme & Mooley Index (BMDI)	Palmer Z-Index (Z index)	Cumulative Streamflow Anomaly (CSA)
Standardized Precipitation Evapotranspiration Index (SPEI)	Index of Moisture adequacy (IMA)	Palmer Hydrological Drought Index (PHDI)
Percent of Normal Precipitation (P)	Computed Soil Moisture (CSM)	Soil Water Storage (SWS)
Rainfall Anomaly Index (RAI)	Self-Calibrating PDSI (SC-PDSI)	Standardized Reservoir Supply Index (SRSI)
Keetch - Byram Drought Index (KBDI)	Dry Conditions & Excessive Moisture Index (DM Index)	Standardized Streamflow Index (SSFI)
Rainfall Deciles	Prescott (ratio) Index	Standardized Water Level Index (SWI)
Standardized Anomaly Index (SAI)	Plant Growth Index, (McDonald, 1994)	Streamflow Drought Index (SDI)

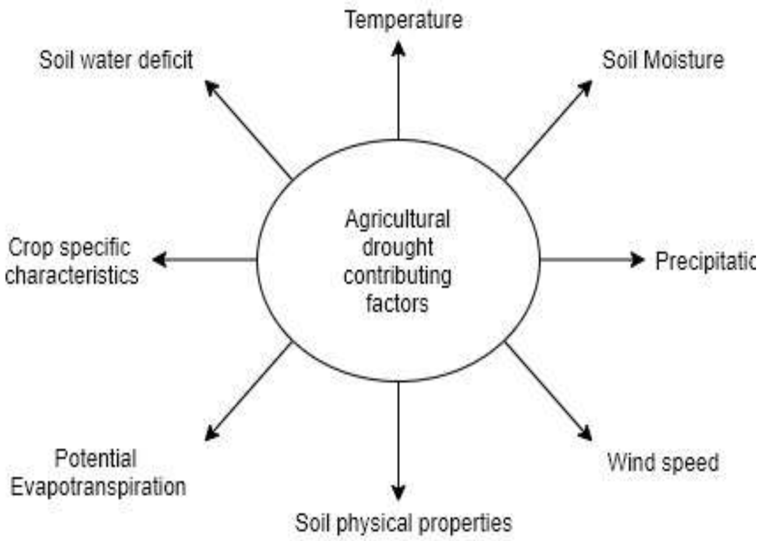

Fig. 5: Contributing parameters for agricultural drought

Agricultural Drought

Drought in agriculture is a complex process which involves the compounded effects of the soil, crops and atmosphere as shown in figure 5. Zargar et al[102], reviewed various indices for different types of drought assessment and emphasized the need to elaborate on the trends in the evolution of drought indexes in respective drought classes. Specifically, monitoring agricultural drought is necessary for laying the foundations for implementing appropriate strategies to avert potential disasters.

As discussed earlier, agricultural drought follows the meteorological drought and can be represented as the extended meteorological drought during the crop developing stage. Scarcity in precipitation in the crop growing season results in a deficit in soil moisture which puts a strain on crop growth and its development.

Drought in agriculture is termed as a shortage of soil moisture to replenish evapotranspiration losses owing to deficit in accessible water essential for crop growth[40]. Droughts in agriculture can affect much more than just the crop growing season[100]. Agricultural drought focuses on precipitation shortages, variations in between the actual and prospective evapotranspiration (ET), soil water shortages and other aspects of meteorological drought that have an impact on agriculture[93].

Various studies have reported that most of the time, agriculture is the first category that gets hampered owing to the inception of the drought. It is one such crucial natural calamity that impacts world food production[53]. Drought affects the agriculture sector the most.

Effective and timely monitoring of agricultural droughts with the development of an early warning system would reduce drought-related losses. Agriculture droughts and famines are monitored by international agencies like the Food and Agriculture Organization (FAO), World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP). Preventive planning such as real-time monitoring of drought conditions will certainly help in drought mitigation.

Every contribution to better understanding and forecasting drought conditions would go far towards mitigating drought's effects. Interpreting the consequences of extreme droughts on agriculture would help farmers more adequately predict and change their farming practices to maximize yield[63]. A decrease in crop yield leads to agricultural droughts. It becomes essential to study the factors which contribute to the preparation of crop yields. Droughts in agriculture will become more likely in the future, Droughts may cause a significant reduction in agricultural output, resulting in an imbalance between supply and demand for grains, it is also a critical issue that may hamper food security on a global scenario. As a result, a comprehensive monitoring of agricultural drought becomes critical.

Approaches in agricultural drought measurement: Drought in agriculture can be monitored using the three methods below:

1. Conventional approach
2. Remote sensing methods
3. Integrated indicator approach

1. Conventional methods: These methods use physical variables, which may be collected from the site. These variables actually play a major role in the formation of strategies for drought analysis and managing forewarning. Historical indices were mostly based on the *in situ* data. The beginning of the drought monitoring techniques started in the early 20th century. Precipitation data is the only input variable taken into consideration for the indices[87]. Moreover, these indices can be broadly subdivided into subgroups as follows:

a) Single index: Index based on a single data source as an input variable. The standardized precipitation index is one of the most recognized drought indices and uses precipitation as its only input. The other index in the category could be the Deciles, China Z Index (CZI), Drought Area Index (DAI), Rainfall Anomaly Index (RAI). Only time series precipitation data is used as an input source for all these indices. A literature study reveals that an index like SPI is greatly used in the assessment of not only meteorological drought but at the same time is extensively applied for the assessment of agricultural drought.

b) Multiple indices: Indices like the PDSI- Palmer Drought Severity Index, for example, which utilizes more than one input variable for the assessment, are categorized as multiple indices. In PDSI, precipitation and temperature along with available water content (AWC) are used. PDSI, developed is also one of the key drought indicators for meteorological as well as agricultural drought monitoring. VSMB- Versatile soil moisture budget is one in which precipitation and evapotranspiration are assimilated. In addition, another prominent example of multiple indexes is the Palmer Z index. Temperature, precipitation and available water content (AWC) are the basis of this indicator. The soil moisture anomaly index[8] (SMA), proposed in the mid1980s, incorporates monthly or weekly temperature and precipitation data along with date and latitude and is another indicator for assessment of agricultural drought and crop production estimation around the world.

2. Remote Sensing Methods for Agricultural Drought Monitoring: Traditional methods expect region-specific data which mostly do not exist for all the regions all the time. Remote sensing techniques help in providing information regarding quantitative information of crops instantaneously and above all non-destructively. There is difficulty in collecting physical data. In contrast to this, remote sensing data is persistently accessible and applied to determine the onset of drought, its span as well as magnitude[81]. Remote sensing data serves the purpose of gap filling. Moreover, crop harvests can be forecasted for 5 to 13 weeks preceding harvest, adopting remote sensing approaches[85].

Remote sensing data can be looked at as the source for the input information required for drought indicators for any part of the region in the world. It is best described as a collection of spectral bands that elaborates the qualities of the vegetation such that it stands out in comparison to other image features. It reflects the amount of vegetation (leaf area index, biomass, % coverage etc.). Along with this, it distinguishes between soil and vegetation. The indicators are a radiometric evaluation of vegetative state and dynamics using the distinct spectral signatures of canopy elements, particularly in the red and near-infrared (NIR) sections of the spectrum and are sensitive to the various parameters like type of vegetation, crop growth status, canopy cover and structure[79,80]. It is reported in various studies that in drought monitoring and early warning applications, remote sensing data outperforms traditional methods. From the beginning of the 1980s, various studies concentrated on the remote sensing data collected from the satellites for the analysis and monitoring of vegetation cover over large lands[37].

Furthermore, remote sensing systems monitor factors at the Earth's surface, such as vegetation health and water levels, resulting in a significant combination of contextual data for drought monitoring. As a result, satellite remote sensing in a true sense, has revolutionized and enables for the observation and monitoring of critical drought-related data at far broader temporal and geographical dimensions compared to what it was previously achievable with traditional approaches[91].

Evolution of remote sensing drought indices: There is an abundance of remote sensing data becoming available for assessment of a given purpose as a result of application-based satellite missions. Furthermore, technological advancements have led to the creation of several of the new remote sensing indices. This timeline describes the progress of remote sensing-based drought indicators over time. Bannari et al[5] presented the evolution of the index as the first and second generation indexes.

Despite the fact that there are several indexes to pick from, only a few are addressed here to get insight. Some details of the indicators shown in figure 6, figure 7 and figure 8 are summarized below:

(1) RVI: Ratio Vegetation Index was proposed by Pearson and Miller[5,59]. It is also described as a simple ratio. This ratio is maximum for the vegetation and minimum for water or soil. Further, this amount helps in judging vegetation status:

$$RVI = \frac{NIR}{Red}$$
$$= \frac{NIR}{VIS} \quad \text{if Red is not available}$$

(2) VIN: Vegetation Index Number is presented by Pearson and Miller[59]. It is given by the formula:

$$VIN = \frac{NIR}{R}$$

(3) NDVI: Normalized Difference Vegetation Index is presented by Rouse et al[68] and Kogan[43]. It is one of the most widely appreciated agricultural drought indicators. It is also the most extensively used drought index, as it reflects vegetative conditions[38]. The near-infrared (NIR) and visible bands of the electromagnetic spectrum are used in deriving NDVI.

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

Drought is being assessed using the Normalized Difference Vegetation Index with a variety of sensors at global, continental, regional and catchment scales[7,55].

(4) WDVI: Weighted Difference Vegetation Index was presented by Richardson and Wiegand[66].

(5) PVI: Perpendicular Vegetation Index (PVI) was proposed by Richardson and Wiegand[66]. The index outputs result in between -1.0 and 1.0.

(6) AVI: Ashburn presented the Ashburn Vegetation Index[3]. It is a measure of green growing vegetation.

(7) CWSI: Crop Water Stress Index[34]. It is more specifically used for irrigation scheduling.

(8) NDII: Normalized Difference Infrared Index is proposed by Hardisky et al[27]. It is greatly correlated with canopy and leaf water content. Further, it is employed for the estimation of water content of vegetation.

(9) TVI: Transformed Vegetation Index is proposed by Perry and Lautenschlager[60].

(10) LWCI: Leaf Water Content Index was formulated by Hunt et al[33].

(11) SAVI: The Soil-Adjusted Vegetation Index has the formula as:

$$SAVI = \frac{(\mathrm{NIR{-}R})}{(\mathrm{NIR{+}R{+}L})} * (1{+}\mathrm{L})$$

SAVI is anticipated to minimize the soil background effects on the vegetation signal by introducing soil factor L as constant[31].

(12) TSAVI: The basis for the index[6] is that the SAVI concept is exact only if the constants of the soil line are a = 1 and b = 0. On the second instant, TSAVI was reframed with an extra correction factor of 0.08 to decrease the effects due to background soil brightness. The new interpretation was named as TSAVI - 2.

(13) IPVI: Infrared Percentage Vegetation Index deals with the study that the red subtraction in NDVI is not needful[15].

(14) NDGI: Normalized Difference Greenness Index has formula[14]:

$$NDGI = \frac{G - R}{G + R}$$

(15) RI: Redness Index was observed that the noise due to soil is associated with soil colour. In order to remove this noise, the index is proposed. It is a correction factor for soil colour effect on vegetation indexes[5].

(16) ARVI: Atmospherically Resistant Vegetation Index (ARVI) was proposed by Kaufman and Tanre[39]. The ARVI is generally employed to nullify the impacts due to atmospheric aerosols.

(17) MSAVI: Modified Soil Adjusted Vegetation Index (MSAVI) and MSAVI-2 were presented by Qi et al[64] founded on the alteration of the L factor in the SAVI.

(18) WSVI: Water Supplying Vegetation Index is used to detect drought, it combines vegetative data with remotely detected temperature data[90].

(19) CRVI: Cubed Ratio Vegetation Index (CRVI) / (CVI) was proposed by Thenkabail, Ward and Lyon[79].

(20) TCI: Temperature Condition Index is proposed by Kogan[42]. TCI is applied to find stress on vegetation due to temperatures and excessive wetness. It is used in combination with NDVI and VCI for drought monitoring in the conditions where agricultural effects are the primary concern.

$$TCI = \frac{BTmax - BT}{BTmax - BTmin} \times 100$$

(21) VCI: Vegetation Condition Index was also proposed by Kogan. It is used for determining drought conditions and identify the onset[43].

$$VCI = \frac{NDVI - NDVImin}{NDVImax - NDVImin} \times 100$$

(22) NDWI: Normalized Difference Water Index and Land Surface Water Index (LSWI) were developed by Gao[22]. The strengths of the index are its good spatial coverage and high resolution.

(23) VHI: Vegetation Health Index was drafted by Kogan[44]. It provides a portrayal of vegetation conditions relative to long-term differences as compared to NDVI. Moreover, VHI is a weighted average of VCI and TCI. The VHI has been employed in drought management applications and in vegetation health and crop studies.

Other indices, such as the NDWI and Enhanced Vegetation Index (EVI), have been employed in conjunction with the VCI/VHI.

(24) EVI: Enhanced Vegetation Index was proposed by Huete[32]. It's NDVI with a soil adjustment factor L and two coefficients C1 and C2 that specify how the blue band is used to correct the red band for atmospheric aerosol scattering.

$$EVI = G * \left(\frac{(NIR - R)}{(NIR + C1*R - C2*B + L)} \right)$$

(25) SRWI: Simple Ratio Water Index was formulated by Zarco-Tejada and Ustin[101].

(26) VTCI: With the Vegetation temperature condition index, it is possible to monitor drought events in a specific period. Furthermore, it is also employed to verify the geographic spread of the drought over an area[89].

(27) TVDI: Temperature Vegetation Dryness Index was proposed by Sandholt, Rasmussen and Andersen[71].

(28) RDI: Reconnaissance Drought Index was proposed by Tsakiris and Vangelis. RDI is more comprehensive than Standardized Precipitation Index (SPI). Monthly precipitation input along with PET is used to calculate RDI[83].

(29) ESI: Evaporative Stress Index was formulated by a team led by Anderson et al. Potential evapotranspiration sensed by remote sensing is used as an input parameter[2].

(30) CWSI: Crop Water Stress Index is very recently proposed. Literature on CWSI describes how closely it relates with soil moisture content. CWSI can also be used to guide agricultural irrigation based on a combination of plant water status and soil moisture content[69].

As for the remote sensing index, it is basically a certain integration of the reflection characteristics measured by the sensor at two or more wavelengths, revealing the specific characteristics of the vegetation. In addition to the recognized NDVI and a few major indexes, there are at least hundreds of other indexes used for drought assessment.

3. Integrated indices: An approach in drought monitoring integrates conventional drought index data with remote sensing data. Literature study shows that the applicability of different indicators in a region is completely different. In addition to this, if a single index is combined, its performance will be better[47]. When a single drought indicator is paired with another, its limitations can be overcome. In addition, its performance has enhanced.

Table 2 summarizes some comprehensive indicators for monitoring agricultural drought.

Soil moisture measurement and agricultural drought: Soil moisture is an important determinant of agricultural drought conditions[4]. There exists a direct relationship in between the global climate and weather systems and soil moisture. Global Climate Observing System (GCOS) designates soil moisture content as an Essential Climate Variable[106], which shows its importance for various disciplines and practical applications[61]. In general, soil moisture can be measured with two broad approaches like *in situ* approach and remote sensing approach.

Soil moisture content assessments particularly ground based are limited to discrete measurements at specific places. It is found that point-based measurements cannot accurately reflect the highly variable spatial distribution of soil moisture[76]. The recent advancement of satellite-based remote sensing has sparked a lot of research on whether such systems can provide spatially precise measurements of surface soil moisture from space. The launch of new and more advanced satellites encourages the development of revolutionary research methodologies and scientific breakthroughs that will result in a number of ground-breaking innovations in soil moisture extraction from space.

Remote sensing technologies have been employed to evaluate soil moisture since the 1970s. This method has the potential to provide spatially explicit SM measurements. Using remote sensing methods to measure soil moisture can be divided into microwave, optical and thermal. Figure 9 shows an outline of the various remote sensing methods used to measure soil moisture.

Optical methods: In an optical method, three different bands of Visible, infrared and SWIR are used. It estimates soil moisture from the spectral reflectance information. Further, it is classified as multispectral and hyperspectral on the basis of the number of bands used. It has a wide spatial coverage and high spatial resolution. This approach has been discussed in many studies[70].

Thermal methods: Thermal Infra-Red remote sensing utilizes the electromagnetic wave range between 3500 and 14000 nm for extraction of soil moisture from land surface temperatures (LSTs) estimated by the thermal inertia method[88] or in combination with vegetation indices[13].

Microwave methods: Recent years have witnessed an enormous revolution in increasingly valuable resource and environmental information from sensors operating in the "microwave" part of the electromagnetic spectrum[48]. A variety of strategies have been offered to cater to this purpose. However, the microwave approaches have indeed made the most significant progress, especially in the low-frequency range (1-5 GHz). Moreover, microwave comes with some distinctive features that characterize microwave energy from a remote sensing standpoint. First, it is capable of penetrating through the atmosphere under virtually all conditions as well as provides day-night imaging capacity.

Literature reports that since 1978, microwave remote sensing is becoming instrumental in an assessment of the soil moisture. Agricultural droughts induced by a prolonged deficit of precipitation or enhanced evapotranspiration are also studied using satellite - derived soil moisture[86]. Figure 10 shows an overview of the main remote sensing instruments used to measure soil moisture. These instruments can generally be classified as assets or liabilities. In agricultural drought monitoring research, active and passive sensors are being used that obtain information in the microwave region of the electromagnetic spectrum.

Passive Microwave remote sensing: As being passive, these systems do not provide their own illumination, but instead, detect the microwave energy that is naturally available in their field of view. Passive microwave sensors are available in both radiometers and scanners[48]. The L (0.39–1.55 GHz), C (3.9–5.75 GHz) and X (5.75–10.9 GHz) frequencies are the most regularly used passive microwave soil moisture retrievals[47]. Also, so far, L band is acknowledged as the most promising for soil moisture measurement.

Active Microwave remote sensing: In contrast to passive microwaves, own source illumination is used in these systems. In addition, the change in energy between transmitted and received electromagnetic radiation, which is employed to correlate soil moisture is termed as the backscatter coefficient. L (0.39–1.55 GHz), C (3.9–5.75 GHz) and X (5.75–10.9 GHz) are the most popular wavelengths for active microwave SSM retrievals[47]. These systems are classified as imaging (Synthetic Aperture Radar – SAR) and non-imaging sensors (altimeters and scatterometers).

Many forthcoming missions will include devices which will help with soil moisture recovery. Although many reclamation processes have been developed that use multiple wavelength data to obtain soil moisture, only a few of the many remote sensing wavebands can be used to produce consistent products that meet the goals of the Earth system. Exploration of appropriate methodologies for obtaining consistent soil moisture database throughout an extended statistic from satellite data is crucial if remotely sensed soil moisture is to be used more widely in real-world applications.

Past Challenges and Future scope

Apart from the number of definitions and equally available relevant indexes, the biggest challenge in any type of drought assessment would be the selection of a suitable methodology. Conventional, remote sensing and synergistic methods are some of the strategies that can be used to assess the situation.

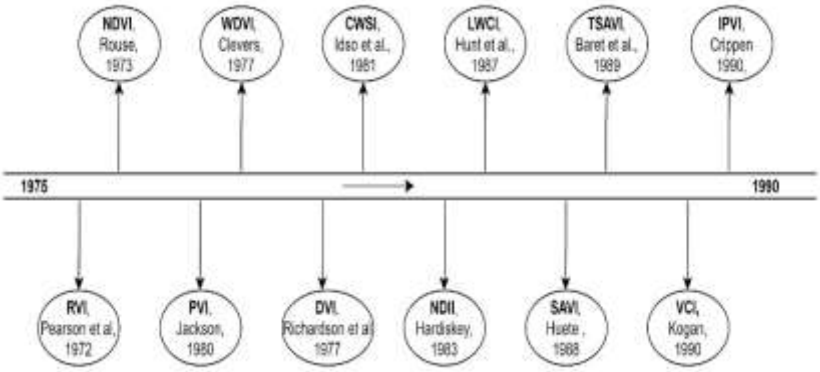

Fig. 6: Progression of key remote sensing indicators 1975-1990

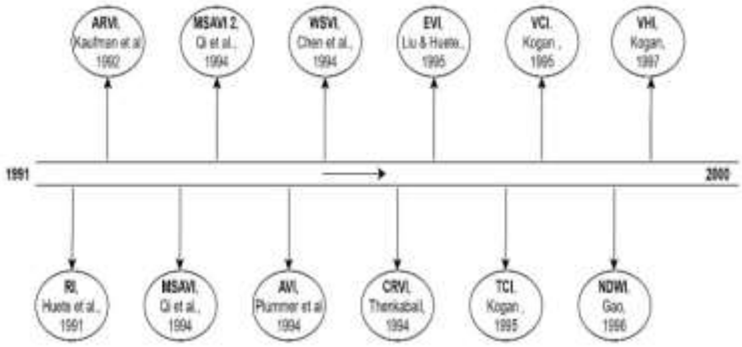

Fig. 7: Progression of key remote sensing indicators 1991 – 2000

Table 2
Composite drought indicators

Name of the index	Remark
CDI - Combined Drought Indicator (For Europe)	Inputs parameters required are fAPAR, SPI and Soil moisture anomaly[74].
MSDI - Multivariate Standardized Drought Index	Input data used are precipitation (monthly) and soil moisture obtained from the Modern Era Retrospective Analysis (MERRA)-Land systems[25].
VegDRI	Near real time 1km drought map is possible to retrieve with the index. The inputs used are satellite based vegetation index data and climate based parameters[9].
MIDI - Microwave Integrated Drought Index	The data used are in terms of TCI, SMCI and PCI[104].
SDI - Synthesized Drought Index	VCI, TCI as well as PCI are inputs used in the SDI[18].
TVMDI - Temperature Vegetation Soil Moisture Dryness Index	This index helps in monitoring soil moisture levels. Vegetation index (NDVI) and temperature (surface) are the inputs used[71].
SDCI - Scaled Drought Condition Index	Combines NDVI and LST with precipitation data. It is specially formulated for agricultural drought monitoring[65].
ISDI - Integrated Surface Drought Index	It is based on VegDRI. The inputs are vegetation growth status, land surface water and thermal environmental status data are integrated[105].
ICDI - Integrated Crop Drought Index	LST, PET, Soil Moisture, Enhanced Vegetation Index (EVI), Land cover type, Corn yield[46].

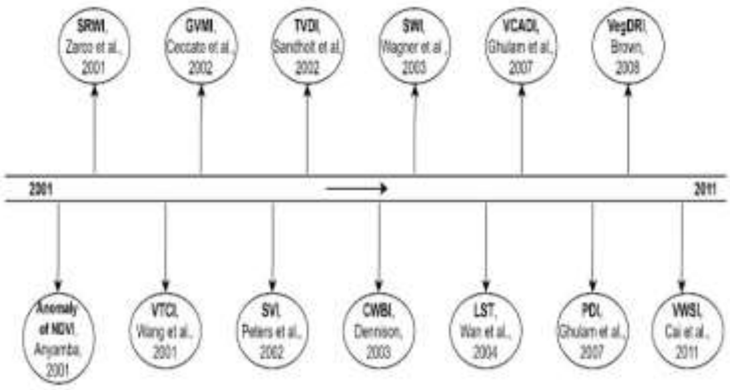

Fig. 8: Progression of key remote sensing indicators 2001 – onwards

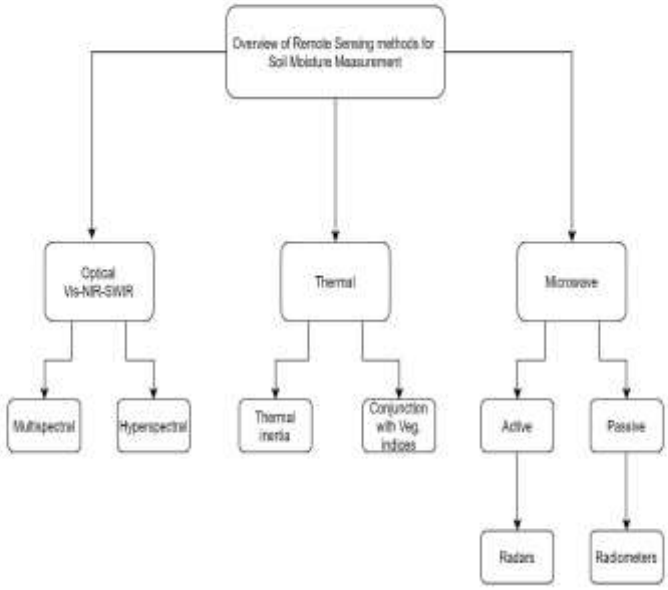

Fig. 9: Overview of the remote sensing methods for soil moisture measurement

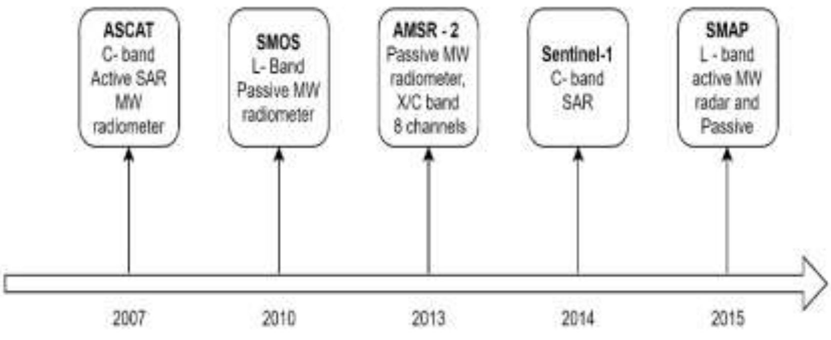

Fig. 10: Major remote sensing instruments for soil moisture measurement

The availability of data for the specific region under research as well as the data requirements for the specific study purpose, are always significant elements. The other biggest challenge has always been resolution (spatial, spectral and temporal). Understanding the resources of the region is essential and plays crucial role in effective monitoring. Moreover, every method has its own pros and cons.

Drought is determined by monitoring the indexes. There are a variety of drought indexes to choose from, each with its own set of advantages and disadvantages. The present indices still have a lot of flaws. According to the study, the current indexes are not self-sufficient to inform about initiation and termination of drought. They are also not considering the effects of evapotranspiration and runoff. These indexes have limitation to predict the ongoing drought because of time scale used. The current indices are not able to distinguish in between drought effects on surface and subsurface water supply[10].

The most frequently encountered challenges in the literature are difficulties in obtaining input data required for conventional methods such as precipitation data records, which are not available for many countries/regions. Further, for remote sensing information, the frequency of data, large image size and computational complexity need to be addressed.

Previous studies have shown that the drought index can only reflect drought conditions based on hydrological and meteorological variables and cannot quantify economic losses. Synergistic approaches help in getting more insight with the combination of indexes and proven very helpful in some of the regional studies.

Over the years since 1970s, many new satellites have been launched with some specific objective. Application specific data availability is also increasing with these missions. It is never ending process and many new missions will come in reality in coming few years.

Conclusion

The purpose of this assessment is to carry out a comprehensive and critical evaluation of the current drought monitoring systems with an emphasis on agricultural drought. The characterization of drought is essential for drought management and mitigation. The drought index is one of the practical ways to transform big data into quantitative information. Obviously, drought indices are an integral part in the assessment of any type of drought.

The significance of drought indicators in drought assessment would have resulted in the evolution of various drought indexes. These indexes are grouped among conventional, remote sensing based and synergistic methods in general. However, as the indices are not universal indicators, the knowledge extracted is always bound by the constraints set for the specific study or application. The survey highlights many revolutionary changes in the drought monitoring because of progression in the evolution of indices, mostly because of the growth in remote sensing technology.

This study presents a timely and systematic review of new concepts and algorithms proposed in recent years and the upcoming advancements in the field for agricultural drought assessment. However, there is always scope for further improvement of the drought index to obtain better information. Taking into account the needs of users in the region and classifying droughts according to their severity, the drought index can be further explored.

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