



Remote sensing and GIS techniques for assessment of drought vulnerability: Recent advances, challenges and future prospects

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Abstract

Drought is an environmental risk phenomenon that has impacts on vegetation cover, agriculture, soil moisture content, surface water, ground water and the entire ecosystem. The traditional drought analysis using only meteorological data sources gives useful time-based data; however, its limitations have been poor station coverage and inability to capture the spatial aspects of drought. The application of RS and GIS techniques has greatly contributed to effective drought monitoring through repetitive and continuous spatial observation of vegetation, temperature, rainfall, soil moisture and surface water parameters. The following review highlights some of the recent advances in the analysis of drought vulnerability using RS techniques as well as GIS. The use of optical, thermal, and microwave data provided by Landsat, MODIS, Sentinel, and SMAP satellites, along with precipitation data from remote sensing provided by CHIRPS, has facilitated monitoring of various aspects of drought. Some of the common drought indicators are the Normalized Difference Vegetation Index (NDVI), Vegetation Condition Index (VCI), Temperature Condition Index (TCI), Vegetation Health Index (VHI), Normalized Difference Water Index (NDWI), Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), and soil moisture anomalies. The GIS-based Multi-Criteria Decision Analysis facilitates the combination of these indicators with environmental and anthropogenic factors to identify drought vulnerability zones. The recent advancements in cloud computing, multi-sensor integration, and machine learning provide new avenues for drought assessment. Nonetheless, problems such as low spatial resolution, uncertainties in the weighting process, limited ground validation and regional variability still persist. Drought-vulnerability research that is conducted in the future should pay attention to the integrated approach of land, vegetation and water assessments and utilize multi-sensor data.

Keywords: Drought Vulnerability, GIS, Remote Sensing, NDVI, Soil moisture, Water Stress

Introduction

Drought is among the most common and complex hydrometeorological hazards since it develops slowly and may continue for many months or even years. Unlike other hazards that are fast and have clear starting and ending points, droughts do not have a clear starting or ending point. The effects of drought range from deficient rainfall to reduced soil moisture, vegetation, decreased agricultural productivity, reduced surface water and reduced groundwater levels. Drought can thus be described as an environmental response process rather than just a period of deficient rainfall (West *et al.*, 2019) ^[12]. The four common classifications of drought include meteorological, agricultural, hydrological, and socio-economic drought. The first phase of drought commences with below-normal rainfall levels. If the deficiency results in insufficient moisture content in the soil for plant growth, then agricultural drought will occur. Continued deficiency in rain levels will cause a decline in the amount of water flowing in rivers, dams, and groundwater sources, thereby causing hydrological drought. The transition among these drought types is influenced by vegetation, soils, geology, topography, climate and human water use (Van Loon, 2015; West *et al.*, 2019) ^[9, 12].

The conventional drought monitoring technique depends on rainfall and other meteorological information. While station-based information remains critical, its distribution is limited in many drought-prone and information-limited areas. The observation from a meteorological station describes the condition of the place but cannot always describe the spatial

variability of vegetation and soil water status. Remote sensing technology has revolutionized this scenario by enabling spatial continuity in regional to global levels. The satellite observation provides information about vegetation condition, surface temperature, soil moisture, evapotranspiration, precipitation, and surface water dynamics. In this way, remote sensing technology has made significant contributions to the shift from meteorological drought to an assessment of agricultural, ecological, and hydrological drought (West *et al.*, 2019; Jiao *et al.*, 2021) ^[3, 12].

GIS serves to supplement the satellite observations in the sense that various environmental datasets can be integrated, analyzed, and depicted using GIS. Information such as rainfall, vegetation, land surface temperature, soil moisture, LULC, groundwater, slope, soil, and socioeconomic data can be merged to determine the areas that are often affected by drought. Current research trends have been focusing more and more on the utilization of multi-indicators and multi-sensors rather than focusing on single indicators. Multi-sensor observations are very helpful because none of the satellite sensors gives the best spatial, temporal, and spectral data necessary for depicting all the aspects of droughts (Jiao *et al.*, 2021) ^[3]. The present review highlights the main datasets from satellites, remote sensing indices and GIS approaches adopted for drought vulnerability assessments. Moreover, this review also outlines the existing limitations in the methodology along with the scope for future research in this domain.

Remote Sensing and GIS in Drought

The use of remote sensing for assessing droughts comes with many benefits. Remote sensing satellite systems repeatedly image large areas, allow retrospective studies through archived data and provide data from areas where no ground-based data are available. Optical, thermal and microwave remote sensing are complementary approaches to environmental drought.

1. Optical Remote Sensing

Observations from optical satellites have been used widely to examine vegetation and surface water reactions to drought. One of the longest records of Earth observations by satellite, the Landsat archive, is especially useful in the study of changes in the environment through time due to their relatively high spatial resolution. Sentinel-2 provides better spatial and temporal resolutions for current vegetation, agriculture, and surface water assessments. MODIS, with its low spatial resolution, but high temporal resolution, is especially useful for assessing regional vegetation and drought.

The Normalized Difference Vegetation Index (NDVI) continues to be one of the most extensively used vegetation indices:

$$\text{NDVI} = (\text{NIR} - \text{Red}) / (\text{NIR} + \text{Red})$$

Healthy vegetation usually shows high NDVI since chlorophyll absorbs red light and plant structures reflect near infrared radiation. The decrease in water availability and photosynthetic action due to drought stress can lead to reduced NDVI. Unfortunately, it is not possible to discriminate between drought-induced stress and other effects due to vegetation types, phenology, agriculture, or changes in land cover with NDVI. It is more useful to compare the NDVI with the previous condition of vegetation.

2. Thermal Remote Sensing

The Land Surface Temperature (LST) is yet another essential component of drought assessment. A vegetated cover which has sufficient moisture supply regulates its

temperature by evapotranspiration. Under moisture stress, evapotranspiration is low, leading to increased canopy temperature. MODIS and Landsat thermal observations are therefore useful in assessing the thermal stress of crops. The combination of vegetation and temperature helps in better assessment of drought conditions.

3. Microwave Remote Sensing and Soil Moisture

Soil moisture links meteorological drought to its vegetation impacts directly. The value of microwave remote sensing lies in the fact that it is sensitive to surface moisture and is relatively unaffected by clouds. The Soil Moisture Active Passive (SMAP) mission collects repeated observations of soil moisture that have proven to be very helpful for agricultural drought analysis. However, coarse spatial resolution still poses a problem for local applications, which is why recent studies have been focused on downscaling techniques.

4. GIS Integration

GIS offers the environment needed for integrating remote sensing data with climatic, topographic, hydrological and socio-economic data. This allows drought vulnerability to be seen as a combination of various factors rather than one satellite indicator:

$$\text{Drought Vulnerability} = \text{Climatic Stress} + \text{Vegetation Stress} + \text{Thermal Stress} + \text{Soil Moisture Stress} + \text{Water Stress} + \text{Environmental Sensitivity}$$

The integration is especially critical for semi-arid farming areas where a given amount of lack of precipitation could have very different consequences depending on soil type, cultivation practices, water availability and environmental sensitivity.

Important Indicators of Drought

A wide range of drought indicators have been formulated because none of the indicators alone could be suitable for describing droughts.

Table 1: Important Indicators in Drought Assessment using Remote Sensing and GIS

Indicator	Major Variables	Applications	Major Limitations
SPI	Precipitation	Metrological Drought	Does not directly represent vegetation Response
SPEI	Precipitation and Evapotranspiration	Climate Related Drought	Sensitive to PET estimation
NDVI	Vegetation greenness	Vegetation/crop condition	Influenced by vegetation type and phenology
VCI	Relative vegetation condition	Agricultural drought	Requires historical NDVI
TCI	Thermal condition	Temperature stress	Requires historical temperature series
VHI	Vegetation + temperature	Agricultural drought	Weighting of VCI/TCI may vary
NDWI/ MNDWI	Surface water/moisture	Hydrological response	Sensitive to mixed pixels/clouds
Soil-Moisture Anomaly	Soil water availability	Agricultural drought	Satellite products can be spatially coarse
LST	Surface temperature	Thermal/water stress	Cloud contamination in thermal-optical data

1. Standardized Precipitation Index (SPI)

The SPI is amongst the most widely used drought indicators in the meteorology field. The SPI standardizes the precipitation deviations according to the historical climatic distribution and can be obtained on various time scales. Shorter time scales provide a basis for evaluation of meteorological/agricultural conditions that develop rapidly, while longer time scales could capture the hydrological responses. One of the main strengths of the SPI is the relatively low data requirements. Nonetheless, since it is based on precipitation, it does not capture any vegetation/soil moisture response directly.

2. Vegetation Condition Index

The Vegetation Condition Index was defined as follows to measure the status of vegetation in relation to its historic minimum:

$$\text{VCI} = [(\text{NDVI} - \text{NDVI}_{\text{min}}) / (\text{NDVI}_{\text{max}} - \text{NDVI}_{\text{min}})] \times 100$$

Small VCI values mean poor conditions of vegetation, while high values are indicative of better vegetation conditions.

The VCI is particularly valuable for agricultural drought because it normalizes the behavior of vegetation in terms of local historic conditions.

3. Temperature Condition Index

TCI considers the historical range of surface temperature to determine thermal stress conditions. High temperatures are often linked to vegetation and soil moisture stress. The TCI is useful as a complement to the VCI since vegetation greening does not always reflect immediate water shortage due to temperature sensitivity.

4. Vegetation Health Index

The Vegetation Health Index is a combination of vegetation and temperature, represented by the formula:

$$VHI = \alpha(VCI) + (1-\alpha)(TCI)$$

where α is the proportion of the effects of both the vegetation and the temperature conditions.

This index has found wide usage in the monitoring of agricultural drought since it takes into account both vegetation vigor and temperature stress. This is clearly indicated in recent reviews on the subject matter.

5. Indicators of Soil Moisture

Soil moisture is one of the critical physical connections between rainfall deficit and vegetational stress. Therefore,

the soil moisture anomaly is another method that can identify agriculture drought without being entirely captured by vegetation indicators.

The combination of indicators of rainfall, soil moisture, and vegetation offers a chance for drought propagation representation:

Rainfall Deficit → Soil Moisture Deficit → Vegetational Stress → Agricultural Drought

Multi-Sensor and Integrated Drought Vulnerability Assessment

The latest trend in remote-sensing-based drought vulnerability assessments is the shift in approach from individual-index-based monitoring to multi-sensor and integrated approaches. For example, while a rainfall index can help assess meteorological drought, it cannot establish if the plants have been impacted by the same. The NDVI method can help detect plant stress but cannot confirm if it was caused due to lack of rainfall, high temperature, diseases, harvesting or even land-cover change.

Table 2: Framework for assessment of drought vulnerability

Components	Suggested Parameters	Possible Sources
Metrological	Rainfall Anomaly, SPI/SPEI	IMD, CHIRPS
Vegetation	NDVI, VCI	Landsat, Sentinel-2, Modis
Thermal	LST, TCI	Landsat, Modis
Vegetation Health	VHI	NDVI+LST
Soil Moisture	Soil Moisture Anomaly	SMAP
Surface Water	NDWI/MNDWI, Water Extent	Landsat, Sentinel-2
Land Environment	LULC	Landsat, Sentinel-2
Terrain	Elevation, Slope	SRTM, ASTER
Water Resources	Groundwater trends	Observation wells/Grace at suitable Scale

GIS-based Multi-Criteria Decision Analysis (MCDA) may be used to incorporate these criteria within a composite drought vulnerability map. The use of Analytical Hierarchy Process (AHP), weighted overlay, fuzzy logic, and statistical weightings has all been used in vulnerability mapping. Nevertheless, the criteria and weights used must have scientific reasoning behind them. The arbitrary weightings of criteria may lead to uncertainty within the vulnerability map created. Sensitivity analysis is thus needed during composite vulnerability modeling due to the multi-dimensional aspect of drought vulnerability.

Recent Advances: Cloud Computing and Machine Learning

The huge amounts of Earth observation data have created computing problems for the evaluation of long-term drought. The development of cloud computing systems like Google Earth Engine (GEE) has addressed this problem by offering easy access to large amounts of satellite images and geospatial processing capability. Through GEE, long-term time series of NDVI, LST, rainfall, water, and LULC can be easily generated without having to download thousands of satellite images on local machines.

The use of machine-learning algorithms is also becoming a common trend in drought investigations. Nonlinear associations between the parameters such as precipitation, vegetation, soil moisture, temperature, etc. can be captured through methods such as Random Forest, Support Vector Machine, XGBoost and artificial neural networks. Modern

scientific works dedicated to the study of drought indicate the shift from traditional index-based approaches towards multi-sensor and AI-inclusive approaches. Still, having an advanced algorithm does not guarantee more scientifically valid outcomes.

Challenges and Research Gaps

Even with all the developments made, a number of challenges still persist in remote sensing-based drought assessments. The difference between spatial and temporal resolution of images poses as one of the challenges. For example, Sentinel-2 may have data about vegetation on 10–20 meters resolution, while Landsat has thermal information at even lower effective resolution and the SMAP soil moisture and precipitation at even lower kilometer-scale resolutions. The incorporation of these images needs proper resampling. There is the issue of cloud contamination in optical and thermal sensors, especially during the monsoon season. This is where microwave observations come into play.

Drought is scale-dependent. The index that is used for regional drought assessment might not be accurate when it comes to field-level agriculture.

The validation is insufficient in most cases. Drought maps could better be validated using independent observations, like meteorological drought data, yield, soil moisture, water table level, reservoir conditions, or field observations.

Composite vulnerability indices include weight uncertainty. Both AHP and Weighted Overlay offer an easy approach to

integrate them, but different weights could produce different vulnerability results.

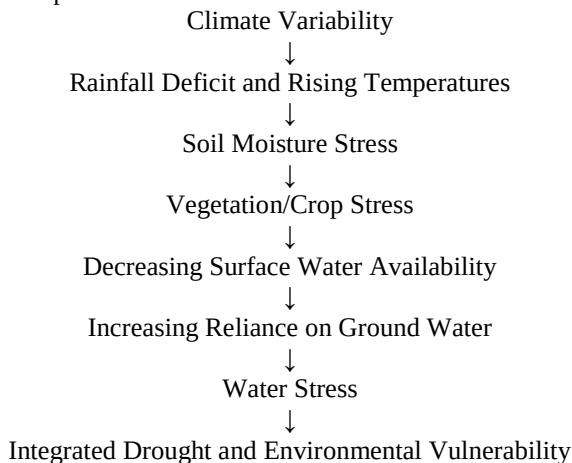
Another key gap is that of the poor integration of drought into environmental changes. Land use change, urbanization, deforestation, increased irrigation and water extraction from groundwater systems are some of the factors that can affect drought consequences.

Consequently, it would be important for future research to separate drought climatic hazards and vulnerability.

Future Perspectives

Drought studies in the future need to incorporate an integrated view of land-vegetation-water rather than consider droughts of the meteorological, agricultural, and hydrological nature in isolation.

A conceptual model can be:



Multi-sensor data will play an important role in this transition. Optical sensors can give vegetation and land cover information, thermal sensors can show surface temperature stress, microwave sensors can measure soil moisture, and climatic data can give rainfall anomaly data.

Drought frequency analysis would also merit some consideration. Mapping regions where drought occurs repeatedly might prove more helpful for environmental planning than making maps for each year of drought.

Another critical area includes the coupling of droughts with changes in land use. Urbanization, intensification of agriculture, degradation of vegetation, and extraction of groundwater can exacerbate the effects of climate on the availability of water.

Machine learning is expected to play an increasingly prominent role in drought prediction, although future work should focus on explainable and interpretable models. Multi-source data integration, regional model calibration, explainable AI and drought advisory systems have been highlighted recently as key future directions.

In the end, drought evaluation should move away from merely identifying “where is drought happening?” to asking the management-based questions:

Why is this place susceptible? How often do droughts reoccur here? What part of the environment is under stress? And what is the right management response?

Conclusion

The methods of Remote Sensing and GIS have significantly transformed the way of drought assessment since they allow conducting continuous spatial monitoring of the state of the vegetation, temperature, rainfall, soil moisture, and water

resources. The data collected via satellite imagery (Landsat, Sentinel, MODIS, and SMAP) along with rainfall datasets (CHIRPS) allow obtaining complementary information about the nature of the meteorological, agricultural and hydrological droughts. The use of traditional indices such as SPI, NDVI, VCI, TCI and VHI is important; however, none of them reflects all aspects of droughts.

The GIS-based approach constitutes an efficient way of integrating these indices with land use, topography, groundwater and other environmental factors. The cloud computing technologies and machine learning approaches offer even more opportunities for the large-scale and long-term assessment of drought. However, future research should be oriented towards scientific interpretation, independent verification, sensitivity analysis, and compatibility of datasets rather than mere methodological sophistication. Specific focus should be placed on the integration of drought with land use dynamics, vegetation changes, surface water availability and groundwater depletion. The integration of climate, land, vegetation, and water therefore constitutes a good way forward for the study of drought vulnerability and could contribute meaningfully to knowledge concerning drought mitigation, agriculture, environment conservation, and sustainable water resources management.

References

1. Gao BC. Ndw a normalized difference water index for remote sensing of vegetation liquid water from space. *Remote Sensing of Environment*. 1996;58(3):257-266.
2. Gorelick N, Hancher M, Dixon M, Ilyushchenko S, Thau D, Moore R. Google earth engine: planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment*. 2017;202:18-27.
3. Jiao W, Wang L, McCabe MF. Multi-sensor remote sensing for drought characterization: current status, opportunities and a roadmap for the future. *Remote Sensing of Environment*. 2021;256:112313. <https://doi.org/10.1016/j.rse.2021.112313>
4. Kogan FN. Application of vegetation index and brightness temperature for drought detection. *Advances in Space Research*. 1995;15(11):91-100.
5. McFeeters SK. The use of the normalized difference water index (NDWI) in the delineation of open water features. *International Journal of Remote Sensing*. 1996;17(7):1425-1432.
6. McKee TB, Doesken NJ, Kleist J. The relationship of drought frequency and duration to time scales. *Proceedings of the 8th Conference on Applied Climatology*. 1993;17(22):179-183.
7. Mu Q, Zhao M, Running SW. Improvements to a MODIS global terrestrial evapotranspiration algorithm. *Remote Sensing of Environment*. 2011;115(8):1781-1800.
8. Rouse JW, Haas RH, Schell JA, Deering DW. Monitoring vegetation systems in the Great Plains with ERTS. *Third Earth Resources Technology Satellite-1 Symposium*. 1974;30:9-317.
9. Van Loon AF. Hydrological drought explained. *Wiley Interdisciplinary Reviews: Water*. 2015;2(4):359-392. <https://doi.org/10.1002/wat2.1085>
10. Vicente-Serrano SM, Beguería S, López-Moreno JI. A multiscalar drought index sensitive to global warming:

- the standardized precipitation evapotranspiration index. *Journal of Climate*. 2010;23(7):1696-1718.
11. Weiss M, Jacob F, Duveiller G. Remote sensing for agricultural applications: a meta-review. *Remote Sensing of Environment*. 2020;236:111402. <https://doi.org/10.1016/j.rse.2019.111402>
 12. West H, Quinn N, Horswell M. Remote sensing for drought monitoring & impact assessment: progress, past challenges and future opportunities. *Remote Sensing of Environment*. 2019;232:111291. <https://doi.org/10.1016/j.rse.2019.111291>
 13. Xu H. Modification of normalised difference water index (NDWI) to enhance open water features in remotely sensed imagery. *International Journal of Remote Sensing*. 2006;27(14):3025-3033.