

Geospatial Techniques in Drought Vulnerability Assessment: Progress, Challenges, and Future Direction

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ABSTRACT

This paper presents an operational geospatial framework for watershed management and drought assessment, moving beyond a conventional review of existing methodologies. Increasing climate variability, extended dry periods, and irregular rainfall patterns have significantly impaired watershed functioning and associated ecosystem services. The proposed approach integrates vegetation, water, and terrain-based indicators—specifically NDVI, NDWI, and morphometric parameters—within a GIS environment to assess vegetation health, surface water availability, and drainage characteristics across multiple spatial scales. High-resolution satellite imagery and drone-based observations are employed to monitor land-use, land-cover, and moisture dynamics, while DEM-derived indices are utilized to prioritize sub-watersheds based on their susceptibility to flooding, erosion, and drought. By combining multispectral, radar, and field-based datasets into a unified decision-support workflow, the framework offers a practical and adaptable tool for local agencies and planners to support evidence-based watershed restoration and drought preparedness initiatives.

Keywords:- Morphometric Analysis, NDVI, NDWI, Watershed Management.

1. INTRODUCTION

Due to the ongoing sudden climate changes, followed by drought and occasionally heavy rainfall, put up a challenge to the ecosystem of watersheds globally (McFeeters, 2013). Such disruptions to nature's hydrological cycle leads to variability in the moisture of soil, groundwater recharge, and the patterns of surface runoffs. Over the period, these interferences worsen the degradation process of the land, increase in the erosion of soil, and the stress caused to the vegetation, hence, declining the productivity and ecological balance of the watersheds affected (Huang et al., 2021). The watershed systems, being an important part to the water resource accessibility and the services of the ecosystem, are open to progressive impacts of the stresses of climate and the anthropogenic activities, which includes deforestation, changes in the land use, and the improper watershed management. These components change the geomorphological and hydrological characteristics, of the drainage basins, which in turn, influence the flow regimes and the transportation of the sediments, further affecting the water quality and the downstream quantity. (S. S. Salvi et al., 2017) Land is the most important aspect of nature, which sustains the human species and the economic activities, through providing essential goods and ecosystem services. Land use is often referred to the human activities and the practices of management done on the land, such as agriculture, forestry, settlement, whereas land cover acts for the physical and the biological condition of the surface, such as the built-up areas, barren soil, the bodies of water, and vegetation. Over the period, Land Use and Land Cover (LULC) experiences remarkable transformations driven by several factors, such as the growth in population, urbanization, agricultural expansion, deforestation, and the changes in the environment (Lou et al., 2025). These factors sure cause several effects on the ecosystem health, biodiversity, regulation in climate, quality of soil, and the resources of water. Hence, it makes the surveillance of LULC changes important for understanding the interactions made between the human environment, also towards the long-term management for landscape. There are several effects caused in the analysis, like the introduction of modern technological approaches like remote sensing, satellite imaging, and the advanced GIS analytics, have completely changed the monitoring and management of the drought and rainfall-related problems (Bhatti et al., 2024). Remote sensing indices like NDVI and NDWI allow for a completely precise study of the quantification of vegetation and changes of the surface water, also with the support of early warning and adaptive resource management. Whereas conventional methods like the ground-based rain gauges, manual reading of moisture of soil sampling, and point-wise field surveys, provide some accurate measurements at the local scales, which can

be proved vital for the validation and calibration of the remote sensing technologies.(Sharma et al., 2025) Recently, the upcoming and latest trends in the watershed management have been drastically moulded through advancements in the remote sensing, technology mastery in satellite, surveys conducted by drones, and the networks created by sensors.(S. Salvi, Tiwari, et al., 2025) These tools gather data, which in turn, improve the precision, timelines, and the purview for monitoring and controlling the watershed economies. The high-resolutions satellite images, obtained via the missions like Sentinel-2, Landsat 8, PlanetScope, and Worldview help in the detailed mapping process for land use, health of vegetation, moisture quantity in soil, flood extent, and the dynamics of watershed. The multispectral data, which is of utmost importance for the indices of LULC, such as NDVI and NDWI, are sourced through the optical sensors provide in the satellite.(S. S. Salvi et al., 2025) The radar sensors, like the Synthetic Aperture Radar (SAR), help in procuring the all-weather, day and night imaging capabilities, essential for the flood inundation monitoring and the moisture levels of soil, even in the presence of cloud covers. Drone technologies are now widely used, as they offer flexible, affordable, data collection of high-resolution images done at local scales. It offers the same use case as that of the satellite, but the pollution sources tracking aspect is a unique factor of this technology. They also facilitate quick survey after a flood or drought events, which in turn can improve the collection of damage assessments and recovery planning. The data from the remote sensing data is fed to the hydrological and eco-hydrological models, which then are used for the watershed processes, forecasting flood and drought patterns, and also evaluating management scenarios. There are Decision Support Systems (DSS) in place, benefitting from the integrated datasets, which can further assist the Policymakers and stakeholders, for making informed, evidence-backed decisions towards sustainable use of watershed resources.

2. MORPHOMETRIC ANALYSIS OF RIVER DRAINAGE BASIN

The Morphometric Analysis is defined as the measurement and mathematical evaluation of the earth's surface, focusing on the shape and dimension of landforms within river drainage basins and watersheds. The area of catchment or the drainage basin represents hydrologic and geomorphic unit through which precipitation is collected and drained into larger bodies such as lakes, rivers, or the ocean.(Mani et al., 2022) The parameters of morphometric—such as stream order, drainage density, and bifurcation ratio—are important for assessing the watershed management, controlling silt erosion, analyzing flood frequency, and prioritizing development of natural resource. Recent studies emphasize the effectiveness of GIS and remote sensing approaches for geomorphological analysis, especially in inaccessible or ungauged basins, allowing for quantitative assessment of basin geometry, land use changes, and processes of erosion that are indispensable for the enduring watershed planning and management. There are various new geospatial analysis techniques, associated with Digital Elevation Model (DEM) such as ASTER, SRTM, and several multispectral sensors mounted on satellites. There are also aerial platforms, including Unmanned Aerial Systems (UAS), which not only provides robust and varied sources of data to be used for land and vegetation assessment, but also enables the option for availability of high-resolution satellite imagery, which in turn improves accuracy by tenfold. Because of these advancements in technology, it has also facilitated the increase in the spatial and temporal resolutions, which is facilitated by both the Government and Commercialized satellite missions. Integration of latest GIS software, like ArcGIS, Geomatica, ERDAS IMAGINE, open the doors for important digitization and spatial analysis, which can in turn support the automated stream ordering(S. Salvi et al., 2023). Because of the new algorithms and the analytical workflows enhances the processing of the DEMs and imagery of remote sensing, which enables the researchers to frequently do the calculations of complex morphometric parameters, landscape evolution's analysis, the quantification of soil erosion, and the potential zones for groundwater. Because of this Geospatial analysis, it significantly increases the inter-relations between hydrology, geomorphology, agriculture, ecology, and climate science, with the help of integrated remote sensing and the geoinformatics.(Shadoud et al., 2025) This interconnectivity enables the researchers to address the issues, such as, water security, and conservation of natural resources, with the help of a proper data-driven foundation. Despite the use case of this method, there are also the challenges it presents, such as the need for sensor adjustments, and the corrections for atmospheric data, which can hinder the reliability of other morphometric products. The ongoing researchers have aimed to improve these processes, for higher precision of morphometric analysis. Morphometric analysis, being a vast method, has several parameters under its name, like Linear Parameters, Areal (Aerial) Parameters, and Relief Parameters.

Linear Parameters defines the structural features for the drainage network. The main parameters included here are Stream Order (U), Stream Number (Nu), Stream Length (Lu), Mean Stream Length (Lsm), Stream Length Ratio (RL), and Bifurcation Ratio (Rb).(Pathare & Pathare, 2020) Areal or Aerial Parameters are used for assessing the surface characteristics for the basin.(Yegin et al., 2025) The main parameters related to Aerial are Drainage Density (Dd), Stream Frequency (Fs), Texture Ratio (T), Form Factor (Rf), Circulatory Ratio (Rc), Elongation Ratio (Re), Length of Overland Flow (Lof), Constant Channel Maintenance (C), and Infiltration

Number (In). Relief Parameters have reference to the vertical characteristics, which influence the hydrology and erosion.(Varouchakis et al., 2025)

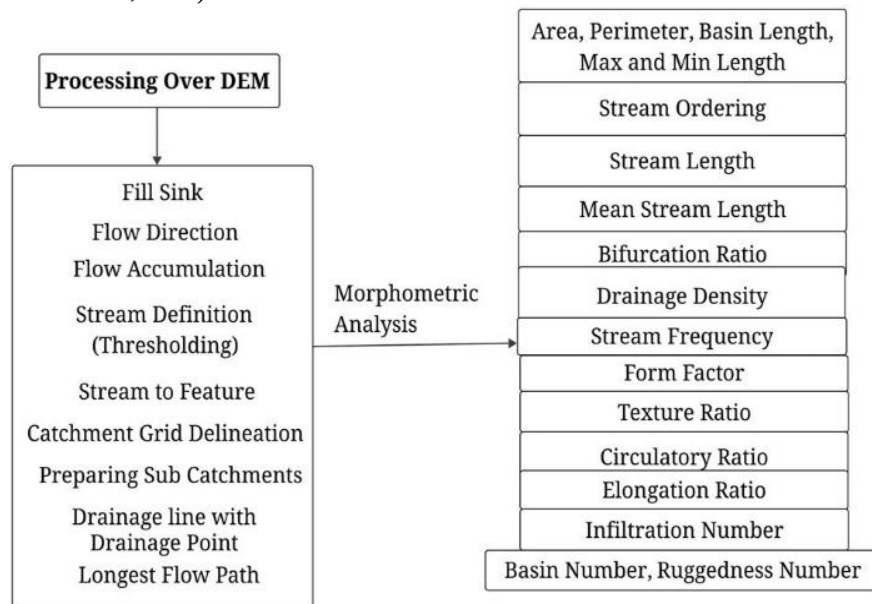


Fig -1: Steps for Morphological Analysis

There are 2 types of parameters in relation to Relief are Relief Ratio (Rh), and Ruggedness Number (Rn). All these morphometric parameters help to characterize the geometry of watershed, patterns for drainage, slope, and the potential of surface runoff.(Şimşek, 2025) These are also very much crucial for the prioritization of Watershed, assessment done for the flood, prediction of soil erosion, and sustainable water resource management.

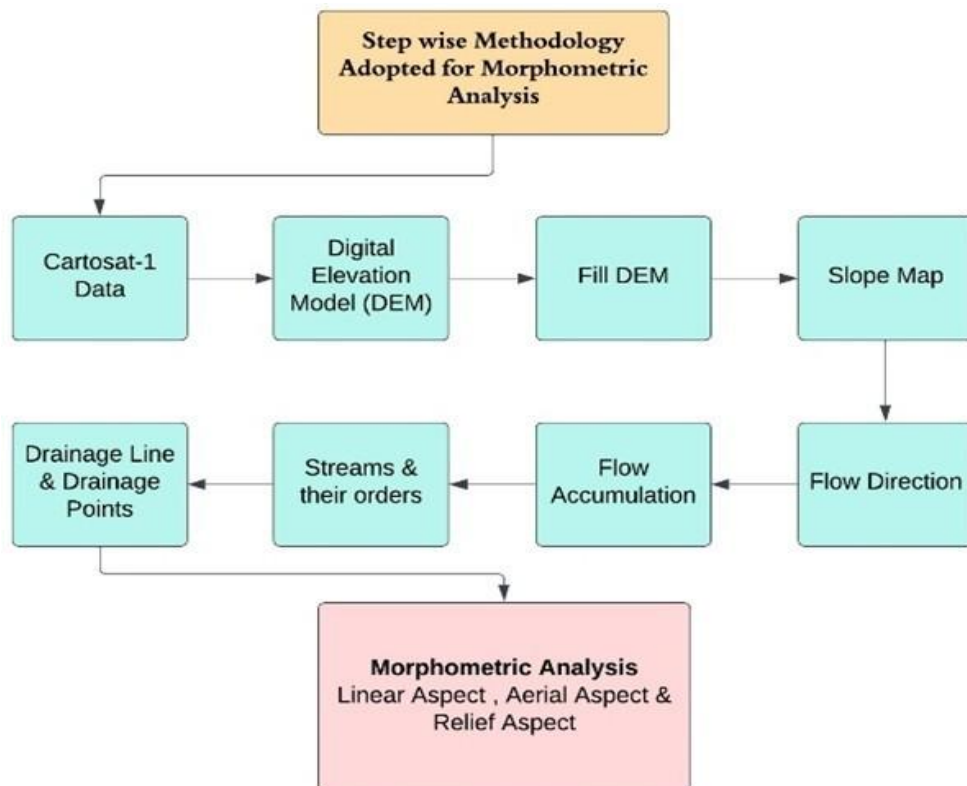


Fig -2: Methodology adopted for the Analysis

Table -1: Morphometric Types

Aspects	Morphometric Parameters	Formula	References
LINEAR	Stream Order (U)	Hierarchical Order	Strahler, 1964
	Stream Length (Lu)	Length of the Stream in km	Horton, 1945
	Mean Stream Length (Lsm)	$L_{sm} = L_u / N_u$ Where, L_u = Total stream length of order 'u'; N_u = Total no. of stream segments of order 'u'	Horton, 1945
	Stream Length Ratio (RL)	$RL = L_{sm} / L_{sm-1}$ Where, L_{sm} = Mean stream length of a given order ; L_{sm-1} = Mean stream length of next lower order $R_b = N_u / N_{u+1}$ Where, R_b = Bifurcation Ratio ; N_u = No. of stream segments of a given order ; N_{u+1} = No. of stream segments of next higher orde	Horton, 1945
AERIAL	Bifurcation Ratio (Rb)		Schumn, 1956
	Drainage Density (Dd)	$D_d = L_u / A$ Where, D_d = Drainage Density (1/km) ; L_u = Total stream length of all orders ; A = Area of the basin (km^2)	Horton, 1945
	Stream Frequency (Fs)	$F_s = N_u / A$ Where, F_s = Stream Frequency ; N_u = Total no. of streams of all orders and ; A = Area of the basin (km^2)	Horton, 1945
	Texture Ratio (T)	$T = N_u / P$ Where, N_u = No. of streams in a given order ; P = Perimeter of basin (km)	Horton, 1945
	Form Factor (Rf)	$R_f = A / L_b^2$ Where, A = Area of the basin ; L_b = Basin length	Horton, 1945
	Circulatory Ratio (Rc)	$R_c = 4\pi A / P^2$ Where, A = Basin area (km^2) ; P = Perimeter of the basin (km)	Miller, 1953
	Elongation Ratio (Re)	$R_e = \sqrt{A} / \pi / L_b$ Where, A = Area of the basin (km^2) ; L_b = Basin length (km)	Schumn, 1956
	Length of Overland Flow (Lof)	$L_{of} = 1 / 2 D_d$ Where, D_d = Drainage Density	Horton, 1945
	Constant Channel Maintanance (C)	$C = 1 / D_d$ Where, D_d = Drainage Density	Horton, 1945
RELIEF	Infiltration Number (In)	$I_n = D_d \times F_s$ Where, D_d = Drainage density ; F_s = Drainage frequency	Faniran, 1968
	Relief Ratio (Rh)	$R_r = H / L_b$ Where, H = Basin Relief (km) ; L_b = Basin length (km)	Schumn, 1956
	Ruggedness Number (Rn)	$R_n = H \times D_d$ Where, H = Basin Relief (km) ; D_d = Drainage Density	Patton & Baker, 1976

3. NORMALIZED DIFFERENCE VEGETATION INDEX (NDVI)

The Normalized Difference Vegetation Index (NDVI) is one of the most widely used remote sensing tools for vegetation assessment, benefiting from its simplicity and applicability across a wide range of multispectral sensors. NDVI simplifies the complexity inherent in multi-spectral imagery, providing an effective means for

quickly delineating vegetation health and stress, making it attractive to users in agricultural, ecological, and climate studies. (et al., 2020) The surge in NDVI-based research correlates with the growing availability of free high-resolution satellite data (such as MODIS, Landsat, and Sentinel) and advances in UAV/drone platforms—a trend that empowers both broad and local-scale vegetation analysis. (Pande et al., 2021) The method is being widely used in the assessment of how the vegetation responds to the variability in the climate, such as the fluctuations in temperature and the patterns in precipitation. (Thakkar, 2012) Some of the studies done show strong correspondence between the changes in NDVI and the levels of rainfall, which in turn, can make it useful for the examining of drought conditions and the evaluation of ecosystem health. The assessment for land degradation, desertification, and the recovery processes spearheaded by climate factors. (Suthar, 2022) NDVI time series analysis is done for the values collected routinely at some of the specific locations to detect patterns, trends, and seasonal variations occurring in the vegetation health and biomass. Complex methods, along with Machine Learning methods are being incorporated into the analysis of time series-related data. (S. S. Salvi et al., 2025) Recently conducted research integrates prognostic modelling techniques, which includes the Long Short-Term Memory (LSTM) networks, with Support Vector Regression (SVR), both of which helps in the forecasting of the NDVI temporal behaviour providing expectant understanding for the vegetation health and productivity. These models can learn the historical NDVI-related data, essential for capturing the seasonal cycles, which can aid in the early warning systems for drought or the failure of crop. (Anand et al., 2025) While NDVI method is a widely adopted and robust vegetation index compared to other indexes like EVI, SAVI, NDRE, etc., (Zareie et al., 2025) it also comes with its challenges addressed by the community. (Walsh et al., 2001) It's sensitivity to the environmental and the factors related to atmosphere like cloud cover, shadows, and aerosols, comprehends that the data quality relies on the preprocessing and rectification techniques. To give expected results, NDVI has certain datasets needed to better perform for the area. The required datasets include Satellite imagery which has at least a Red Reflectance band (at around 0.66 μm) and a Near-Infrared (NIR) reflectance band (in range of 0.86 μm), Common satellite systems like Landsat, MODIS, AVHRR, Sentinel-2 among few, (N. Tiwari et al., 2025) and last being the data from single-date or multi-date (part of time-series) for the analysis of seasonal or temporal. The expected outcome to from NDVI can be the raster maps produced, with their values usually in the range from -1 to +1 for each pixel, the higher values present (e.g., 0.6-0.9) which usually indicate the dense healthy vegetation, moderate values (0.2-0.5) show the sparsely or stressed vegetation, and then the values near 0 or directly negative correspond to water, barren soil, or the built-up areas, and at last, these maps can then be used for plant biomass estimation, assessment of the vegetation health, classification of land cover, monitoring of crop, and the detection in the change of time (drought impact, cropping cycles). (S. S. Salvi et al., 2025)

(1)

$$N_{DVI} = \frac{N_{IR} - R_{red}}{N_{IR} + R_{red}}$$

Where N_{DVI} = Normalized difference Vegetation Index, R_{red} and N_{IR} are the spectral radiance measurements, which are recorded with the sensors in red(visible) and NIR regions.

4. NORMALIZED DIFFERENCE WATER INDEX (NDWI)

NDWI can be defined as an index of remote sensing which is developed to supervise the vegetation liquid water content from outer space. It utilizes the reflectivity measurements in the near-infrared spectral bands, around the range of 0.86 μm and 1.24 μm , both of which are located in the high reflectance plateau canopies of vegetation, which in turn can make it sensitive to the changes done towards the status of vegetation water. (Mani et al., 2022) This index captures the content of liquid water in vegetation through exploiting the less-strong absorption features nearby these bands, which is enhanced by the scattering effects done by leaf and canopy. (A. K. Tiwari & Kanchan, 2024) It exhibits some resilient sensitivity towards the moisture levels of vegetations, which can be assumed critical for the assessment of plant health, stress of drought, and the dynamics of ecosystems. This method is strong against atmospheric interference, like aerosol scattering and water vapour absorption, which in turn, produces a more stable and reliable vegetation water content results, under some variable atmospheric conditions, as compared against some of the traditional indices. (Perivolioti et al., 2025) The main factor, being its stability towards the atmospheric characteristics and the spectral sensitivity, which in turn, makes it a most powerful tool for understanding and managing the plant-water relations from the space and airborne sensors. (Kanjin & Alam, 2024) NDWI works perfectly with its required datasets, which are the remote sensing imagery which have 2 specific NIR bands: Band at 0.86 μm (Near-Infrared), and Band at 1.24 μm (shortwave-infrared, SWIR, and sometimes NIR2), and the sources being the MODIS, Landsat, AVIRIS or other imaging spectrometers offering the required bands. (Hamrell, 2014) We can expect the outcomes can be to yield a raster map having values for each pixel, wherein the positive values indicate high vegetation liquid water content, typically associated with the fresh and healthy vegetation or sometimes even the waterbodies, can be used for assessing the plant water stress, surveying the drought effects,

irrigation, and distinguishing the water features from the soil and vegetation, and also NDWI being less sensitive to noise from atmospheric scattering than NDVI, can provide a complementary view of the landscape hydrology and the water status of the vegetation. (Sumeet, 2020)

(2)

$$NDWI = \frac{NIR - SWIR}{NIR + SWIR}$$

Where NIR = Reflectance in the near-infrared band and SWIR = Reflectance in the shortwave infrared band

5. LAND USE LAND COVER

Land Use and Land Cover (LULC) classification is the foundation for environmental monitoring, which enables the production of information from the images obtained through remote sensing, which can be a tool used for decision- making in management of resource, agriculture, urban development planning, and the conservation of the ecosystem. The technology advancements being made, like the hyperspectral imaging to the analysis of time-series, through sensors like Moderate Resolution Imaging Spectroradiometer (MODIS), have increased the capability to characterize the dynamics and patterns associated with Landscape.(et al., 2020) For LULC analysis, there are 2 widely used sensors, being the Cartosat and LISS III, both of which are popularly used for LULC mapping. Although both provide with the required data, there strengths differ. Like Cartosat offers a high-spatial resolution, up to 2.5 meters for the Cartosat-2 series, which can be termed as ideal for detailed mapping, urban studies, and extraction of the features from the heterogeneous landscapes.(Thenkabail et al., 2005) LISS III also doesn't lag behind. Being part of the Indian IRS series, it can provide a spatial resolution of

23.5 meters, covering a wider swath, and the provision of multispectral information across the four bands. It can be more useful a broad-scale mapping, the occasionally monitoring, and the studies related to agriculture.(S. Salvi et al., 2024) But according to the community, Cartosat can provide better imaging resolution compared to LISS III, when the detailed land information is required for the study. There are some resolutions which are used for the data retrieval, all of which offer their strength. Like the Cartosat-2 series offer up to 2.5 meters resolution (panchromatic), LISS III provides 23.5 meters of spectral type, MODIS is mostly being used for time-series and broad-scale analysis, providing 250m-500m spatial resolution, but the cost of very high temporal (8-16 days) repeat cycles.(S. Salvi, Bobade, et al., 2025) But among these resolutions, Cartosat's resolution is the best available panchromatic data for advanced LULC mapping among the others. When it comes to the data collection for LULC, there are various types from where the data can be collected, such as Satellite Data (Cartosat, LISS III, MODIS, AVHRR, Landsat, etc),(Mohammed et al., 2025) Time Series analysis, Hyperspectral Image Analysis, Ground Truthing (Field Visits), and Hybrid classification.(Tefaye et al., 2024) From this pool of data collections, the most accurate and recommended datasets are used for the study area. In LULC, there are 2 main spectral indices, which have their own unique use case. They are Normalized Difference Vegetation Index (NDVI) and Normalized Difference Water Index (NDWI), both of which are used as analytical tools in LULC.(Mangan et al., 2019)

6. COMPARISONS

Table -2: Comparison Table

ASPECT	DATA REQUIREMENTS	STRENGTHS	LIMITATIONS	APPLICATION DOMAIN
NDVI	Satellite imagery with red and near-infrared bands (e.g., Landsat, Sentinel-2)	Effective for vegetation health assessment, drought monitoring	Sensitive to atmospheric conditions, soil background can affect accuracy	Vegetation monitoring, drought vulnerability assessment
NDWI	Satellite imagery with green and near-infrared bands	Useful for water content estimation in vegetation and soil	Influenced by soil moisture variability and cloud cover	Surface water mapping, drought assessment
Morphometric Parameters	Digital Elevation Model (DEM), topographic maps	Quantitative analysis of watershed shape and drainage patterns	Dependent on DEM resolution; may not capture temporal changes	Watershed management, flood risk analysis, erosion studies

7. CONCLUSIONS

This work shows that merging satellite indices, morphometric descriptors, and GIS layers into one workflow can substantially strengthen how watersheds are analyzed under changing climate conditions. The combination of LULC mapping with NDVI/NDWI and DEM-derived parameters makes it possible to delineate priority sub-watersheds, locate erosion-prone and drought-sensitive zones, and suggest where conservation measures will have the greatest impact. By proving that freely available high-resolution imagery and drone data can be organized into a decision-support system, the study offers a template that agencies can replicate for routine drought tracking and adaptive planning. Although ground surveys are still required for calibration and local details, the proposed geospatial approach provides a scalable way to move from ad-hoc assessment towards proactive, resilient watershed management.

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