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# A Comprehensive Review of Geospatial Techniques in Drought Vulnerability Assessment

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***Abstract:*** ***This study presents an integrated geospatial framework for watershed management and drought vulnerability assessment, moving beyond traditional review-based approaches. Climate variability and irregular rainfall patterns are increasingly affecting watershed stability and ecosystem functions. To address this, NDVI, NDWI, and morphometric parameters are combined within a GIS environment to assess vegetation health, water availability, and drainage characteristics. Clear-resolution satellite and drone data are used to monitor land use and moisture variations, while DEM-based indices support prioritization of sub-watersheds based on erosion, flood, drought risks. The integration of spectral indices with morphometric analysis enhances the accuracy watershed evaluation compared to standalone methods. The framework demonstrates a scalable and cost-effective decision-support approach using accessible geospatial data. It provides a practical and replicable model for improving drought preparedness and promoting resilient watershed management under changing climatic conditions***
***Keywords: Morphometric Analysis, NDVI, NDWI, Watershed Management.***

## I. INTRODUCTION

In recent years, rapid and unpredictable climatic variations, including prolonged droughts and sudden intense rainfall events, have created significant challenges for watershed ecosystems worldwide. Such variations disturb the natural hydrological cycle, leading to fluctuations in soil moisture, groundwater recharge, and surface runoff patterns. Over time, these disturbances accelerate land degradation, increase soil erosion, and impose stress on vegetation, ultimately reducing land productivity and disrupting the ecological balance of watershed regions (Huang et al., 2021).

Watersheds are critical components of the environment, as they regulate water availability and support various ecosystem services. However, these systems are increasingly affected by both climatic stress and human activities, including deforestation, land-use changes, and improper management practices. These factors modify the geomorphological and hydrological characteristics of drainage basins, influencing flow behaviour, sediment transport, and water quality, which in turn affects downstream water availability (S. S. Salvi et al., 2025).

Land plays a fundamental role in sustaining human life and economic development by providing essential resources and ecosystem services. Land use characterizes the extent of human interventions on land, such as agricultural practices, forestry operations, and urbanization, during land cover reflects physical composition of Earth's surface, encompassing vegetation, hydrological features, barren landscapes, and built environments. Over time, Land Use and Land Cover (LULC) patterns undergo significant changes caused by factors like population growth, urbanization, agricultural expansion, deforestation, environmental variations (Lou et al., 2025). These changes directly influence biodiversity, soil quality, climate regulation, and water resources. Consequently, continuous observation of LULC changes plays a key role in studying the relationship between human actions and the environment, while facilitating implementation of sustainable land management frameworks.

Advances in geospatial technologies, particularly remote sensing, satellite data acquisition, Geographic Information Systems (GIS), have considerably improved capability to monitor and analyze drought and precipitation-related processes. Remote sensing indices such as NDVI and NDWI enable accurate assessment of vegetation conditions and surface water changes, supporting early warning systems and efficient resource management. At the same time, conventional techniques, including rain gauge measurements, soil moisture sampling, and field surveys, provide reliable ground-based data that are crucial for validating remote sensing outputs (Sharma et al., 2025).

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Recent developments in watershed management have been strongly influenced by emerging technologies such as high-resolution satellite systems, drone surveys, and sensor-based monitoring networks (S. Salvi, Tiwari, et al., 2025). Satellite missions like Sentinel-2, Landsat 8, PlanetScope, and WorldView provide detailed spatial information on land use, vegetation health, soil moisture, and flood extent. Multispectral data obtained from these platforms are particularly useful for generating indices such as NDVI and NDWI (S. S. Salvi et al., 2025).

In addition, radar-based technologies including Synthetic Aperture Radar (SAR), provide offer the advantage of uninterrupted under all atmospheric and temporal conditions data acquisition, thereby rendering them highly effective for the assessment of flood inundation as well as soil moisture even under cloud cover. Drone technology has also gained importance owing to its operational flexibility, cost-effectiveness, along with its capability to capture high-resolution geospatial data at local scales. It is especially useful for rapid assessment following extreme events like floods and droughts, as well as for identifying pollution sources.

Furthermore, remotely sensed data are increasingly integrated with hydrological and eco-hydrological models to simulate watershed processes, predict flood and drought conditions, and evaluate different management strategies. Decision Support Systems (DSS), developed using these integrated datasets, assist policymakers and stakeholders in making informed decisions for the sustainable management of watershed resources.

## II. MORPHOMETRIC ANALYSIS Of RIVER DRAINAGE BASIN

Morphometric analysis refers to numerical assessment and mathematical evaluation of terrestrial surfaces, with particular focus on the overall shape as well as dimensions of landforms within river basins and watershed systems. A drainage basin or

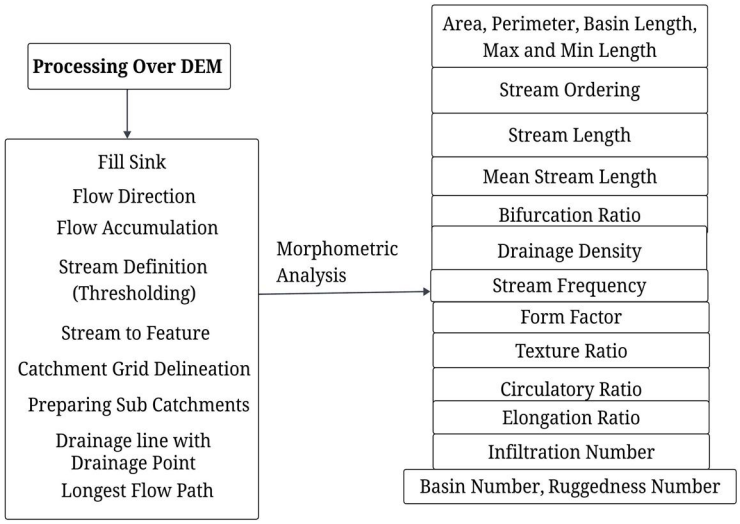



Figure I: Steps for Morphological Analysis

catchment area functions as a hydrological and geomorphological unit where precipitation is collected and ultimately drained into larger water bodies such as rivers, lakes, or oceans.(Mani et al., 2022) Morphometric parameters, stream order, drainage density, bifurcation ratio, play vital role in watershed management, sediment control, flood frequency analysis, and prioritization of natural resource development.

Recent studies highlight the effectiveness of Geographic Information Systems (GIS) and integrated with remote sensing techniques in geomorphological analysis, especially in ungauged or difficult-to-access basins. These approaches enable accurate quantitative evaluation of basin geometry, land use variations, and erosion processes, which play main role in sustainable watershed planning and sustainable management practices. Modern geospatial techniques utilize Digital Elevation Models (DEM) such as ASTER and SRTM platforms, along side multispectral remote sensing, to improve data accuracy and analysis. In addition, aerial platforms like Unmanned Aerial Systems (UAS) generate high-resolution spatial data,, further thereby improving the precision of land and vegetation assessment.

Advancements in satellite technologies, including both government and commercial missions, have significantly improved spatial and temporal resolution of data. The integration of advanced GIS software such as ArcGIS, Geomatical, and ERDAS IMAGINE supports efficient digitization and spatial analysis, including automated stream ordering.(S. Salvi et al., 2023) Furthermore, improved algorithms and analytical workflows have enhanced the processing of DEM and remote sensing imagery, enabling researchers to compute complex morphometric parameters, analyze landscape evolution, estimate soil erosion, and identify groundwater potential zones.

Geospatial analysis has strengthened the interconnection between hydrology, geomorphology, agriculture, ecology, and climate science through the integration of remote sensing and geoinformatics. (Shadoud et al., 2025) This multidisciplinary approach helps in addressing critical challenges such as water resource management and environmental conservation using data-driven methods. However, certain limitations still exist, including the need for sensor calibration and atmospheric corrections, which may affect the accuracy of morphometric outputs. Ongoing research is focused on improving these techniques to achieve higher precision in analysis.

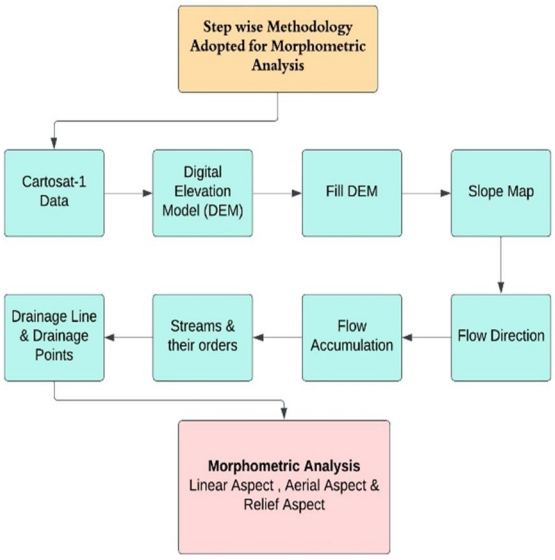
Morphometric analysis includes several categories of parameters, namely Linear, Areal (Aerial), and Relief parameters. Linear parameters describe structural characteristics of the drainage network and include Stream Order (U), Stream Number (Nu), Stream Length (Lu), Mean Stream Length (Lsm), Stream Length Ratio (RL), Bifurcation Ratio (Rb).(Pathare & Pathare, 2020) Areal parameters are used to check surface characteristics of the basin,(Yegin et al., 2025) and include 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 represent the vertical characteristics influencing hydrology and erosion processes, (Varouchakis et al., 2025) and include Relief Ratio (Rh) and Ruggedness Number (Rn).

Table I: 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) | Lsm = Lu / Nu | Horton, 1945 |
| | Stream Length Ratio (RL) | RL = Lsm / Lsm−1 | Horton, 1945 |
| | Bifurcation Ratio (Rb) | Rb = Nu / Nu+1 | Schumn, 1956 |
| | Drainage Density (Dd) | Dd = Lu / A | Horton, 1945 |
| | Stream Frequency (Fs) | Fs = Nu / A | Horton, 1945 |
| | Texture Ratio (T) | T = Nu / P | Horton, 1945 |
| **AERIAL** | Form Factor (Rf) | $Rf = A / Lb^2$ | Horton, 1945 |

| | | | |
|---|---|---|---|
| | Circulatory Ratio (Rc) | $Rc = 4\pi A / P^2$ | Miller, 1953 |
| | Elongation Ratio (Re) | $Re = \sqrt{(A/\pi)} / Lb$ | Schumn, 1956 |
| | Length of Overland Flow (Lof) | $Lof = 1 / (2Dd)$ | Horton, 1945 |
| | Constant Channel Maintenance (C) | $C = 1 / Dd$ | Horton, 1945 |
| | Infiltration Number (In) | $In = Dd \times Fs$ | Faniran, 1968 |
| **RELIEF** | Relief Ratio (Rh) | $Rh = H / Lb$ | Schumn, 1956 |
| | Ruggedness Number (Rn) | $Rn = H \times Dd$ | Patton & Baker, 1976 |

All these morphometric parameters collectively help in understanding watershed geometry, drainage patterns, slope characteristics, and surface runoff potential.(Şimşek, 2025) They are also essential for watershed prioritization, flood assessment, soil erosion prediction, and sustainable water resource management




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Figure 2: Methodology adopted for the Analysis

## III. NORMALIZED DIFFERENCE VEGETATION INDEX (NDVI)

The Normalized Difference Vegetation Index (NDVI) is among the frequently utilized remote sensing methods to vegetation assessment, owing to its computational simplicity and compatibility with multiple multispectral sensors.. It reduces the complexity of multispectral data and provides an efficient approach for identifying vegetation health and stress conditions, making it highly useful in agricultural, ecological, and climate-related studies.( et al., 2020) The increasing use of NDVI-based research is largely associated with the easy access to free clear-resolution satellite records like MODIS, Landsat, and Sentinel, along with advancements in UAV and drone technologies, which support both large-scale and localized vegetation analysis.(Pande et al., 2021)

NDVI is extensively used to evaluate vegetation response to climatic variability, including changes in temperature and precipitation patterns. (Thakkar, 2012) Several studies have demonstrated a strong relationship between NDVI variations and rainfall levels, making it an effective tool for drought assessment and ecosystem health evaluation. It is also applied in studying land degradation, desertification processes, and vegetation recovery influenced by climatic factors. (Suthar, 2022)

Time-series analysis of NDVI involves the use of regularly collected data at specific locations to identify trends, patterns, and seasonal variations in vegetation condition and biomass. Advanced analytical approaches, including Machine Learning techniques, are increasingly being used for analyzing NDVI time-series data.(S. S. Salvi et al., 2025) Recent studies incorporate predictive modeling approaches such as Long Short-Term Memory (LSTM)-based network combined with Support Vector Regression (SVR), which help in forecasting NDVI temporal behavior and provide insights into vegetation health and productivity. These models utilize historical NDVI datasets to capture seasonal cycles, thereby supporting early warning systems for drought conditions and potential crop failure. (Anand et al., 2025)

Although NDVI is a widely accepted and reliable vegetation index compared to others such as EVI, SAVI, and NDRE, (Zareie et al., 2025) it also has certain limitations. Its sensitivity to environmental and atmospheric conditions such as cloud cover, shadows, and aerosols indicates that data accuracy depends on proper preprocessing and correction techniques.(Walsh et al., 2001) To achieve reliable results, NDVI requires specific datasets, including

Satellite imagery with at least Red reflectance band (approximately 0.66 µm), along with near-infrared (NIR) spectral reflectance band (0.86 µm). Common satellite platforms providing such data include Landsat, MODIS, AVHRR, and Sentinel-2 (N. Tiwari et al., 2025), along with single-date or multi-date datasets for seasonal and temporal analysis. The output of NDVI analysis is typically in the form of raster maps, where pixel values vary between −1 and +1 for each pixel. Higher values (e.g., 0.6–0.9) signify dense and vigorous vegetation cover, moderate value ranges (0.2–0.5) indicate sparse or stressed vegetation conditions, and values approaching zero and negative are associated with water bodies and barren land, as well as built-up regions. These maps are widely used for biomass estimation, vegetation health assessment, land cover classification, crop monitoring, and detection of temporal changes such as drought impacts and cropping patterns. (S. S. Salvi et al., 2025)

$$N_{DVI} = \frac{N_{IR} - R_{Red}}{N_{IR} + R_{Red}} \quad (1)$$

Where NDVI denotes Normalized Difference Vegetation Index, and Red and NIR represent spectral reflectance values, which are acquired using sensors operating in the red (visible) near-infrared (NIR) spectral bands.

## IV. NORMALIZED DIFFERENCE WATER INDEX (NDWI)

The Normalized Difference Water Index (NDWI) is commonly applied remote sensing indicator designed to effectively assess moisture content in vegetation using satellite observations. It is based on reflectance characteristics derived from near-infrared spectral bands, typically around wavelengths of approximately 0.86 µm and 1.24 µm. These spectral wavelengths lie within the high reflectance region of vegetation canopies, making the index highly responsive to variations in plant water content (Mani et al., 2022).

NDWI estimates vegetation water content by utilizing weak absorption features in these spectral bands, which are further influenced by scattering effects within leaves and canopy structures (A. K. Tiwari & Kanchan, 2024). Due to this property, the index is highly responsive to variations in vegetation moisture levels, thereby making it an important parameter for evaluating vegetation health and drought stress, and ecosystem dynamics.

One of the key advantages of NDWI is its relative resistance to atmospheric disturbances such as aerosol scattering and water vapor absorption. This characteristic allows it to produce more consistent and reliable results under varying atmospheric conditions when compared to many conventional vegetation indices (Perivolioti et al., 2025). NDWI values also enable clear differentiation between vegetation conditions, where positive values generally indicate healthy, water-rich vegetation, while negative values represent dry or sparse vegetation. This capability supports accurate spatial mapping of vegetation water status.

Experimental studies, including laboratory spectral analysis and hyperspectral remote sensing observations, have demonstrated a strong linear relationship between NDWI values and vegetation liquid water thickness. In particular, studies using Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) data have shown that NDWI is effective in detecting spatial variations in vegetation water content, even in cases where other indices may not perform adequately.

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Due to these advantages, NDWI has become an important tool in applications such as agricultural monitoring, forest management, drought assessment, and ecological analysis (Ramkar & Yadav, 2021). Overall, NDWI serves as a robust and reliable index for evaluating vegetation water content, enhancing the capabilities of remote sensing in environmental monitoring. Its sensitivity to spectral variations and stability under different atmospheric conditions make it a valuable tool for effective watershed and ecosystem management.. (Sumeet, 2020)

$$NDWI = \frac{NIR-SWIR}{NIR+SWIR} \quad (2)$$

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

## V. LAND USE LAND COVER

Land Use and Land Cover (LULC) classification forms basis of environmental monitoring, as it helps in extracting meaningful information from remotely sensed images. This information supports decision-making in areas such as resource management, agriculture, urban planning, and ecosystem conservation. Recent technological developments, including hyperspectral imaging and time-series analysis using sensors such as Moderate Resolution Imaging Spectroradiometer (MODIS), have significantly improved ability to analyze landscape patterns and dynamics. (et al., 2020)

For LULC analysis, two commonly used sensors are Cartosat and LISS III, both widely applied in land use mapping. Although both sensors provide useful data, their capabilities differ in terms of resolution and application. Cartosat, particularly the Cartosat-2 series, offers very high spatial resolution of up to 2.5 meters, making it suitable for detailed mapping, urban analysis, and feature extraction in complex landscapes. (Thenkabail et al., 2005)

On the other hand, LISS III, which is part of the Indian IRS satellite series, provides a spatial resolution of 23.5 meters along with multispectral data across four bands. It is more appropriate for large-scale mapping, periodic monitoring, and agricultural studies. (S. Salvi et al., 2024) However, for applications requiring detailed land information, Cartosat is generally considered superior due to its higher image resolution.

Different satellite datasets offer varying spatial and temporal resolutions, each with its own advantages. For example, Cartosat-2 provides high-resolution panchromatic data at 2.5 meters, while LISS III offers 23.5-meter multispectral data. MODIS is mainly used for time-series and large-scale analysis, providing spatial resolution between 250 m to 500 m alongside high temporal frequency (8–16 days).(S. Salvi, Bobade, et al., 2025) Among these, Cartosat provides the most suitable high-resolution panchromatic data for advanced and detailed LULC mapping.

Data for LULC studies can be collected from multiple sources, including satellite datasets such as Cartosat, LISS III, MODIS, AVHRR, and Landsat,(Mohammed et al., 2025) along with methods like time-series analysis, hyperspectral image processing, ground truthing through field surveys, and hybrid classification techniques.(Tesfaye et al., 2024) From these available sources, the most appropriate and accurate datasets are selected based on the study area requirements.

In LULC analysis, two important spectral indices are widely used due to their specific applications: Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Water Index (NDWI). Such things serve as essential analytical tools for assessing vegetation health and water presence within research area. (Mangan et al., 2019)

## VI. COMPARISONS AND DISCUSSIONS

NDVI uses satellite data with red and near-infrared bands (e.g., Landsat, Sentinel-2) and is effective for vegetation health and drought monitoring, though it is sensitive to atmospheric effects. NDWI relies on green and near-infrared bands to estimate water content, making it useful for surface water mapping and drought analysis, but it can be affected by soil moisture and cloud cover. Morphometric parameters use DEM and topographic data to analyze watershed characteristics like drainage and shape, though their accuracy depends on data resolution. These methods are widely applied in vegetation monitoring, water assessment, and watershed management.

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Table II: 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 and drought monitoring | Sensitive to atmospheric conditions; soil background may 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 |

## VII. CONCLUSIONS

This work shows that merging satellite indices, morphometric descriptors, and GIS layers into one workflow can substantially strengthen how watersheds are analysed 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.

The comparative analysis further highlights that while NDVI is highly effective for vegetation health assessment, NDWI provides better insight into water content, and morphometric parameters offer structural understanding of watershed characteristics, making their integration more powerful than using any single method independently.

By proving that freely available high-resolution imagery and drone data can be organised 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.

## VIII. ACKNOWLEDGEMENTS

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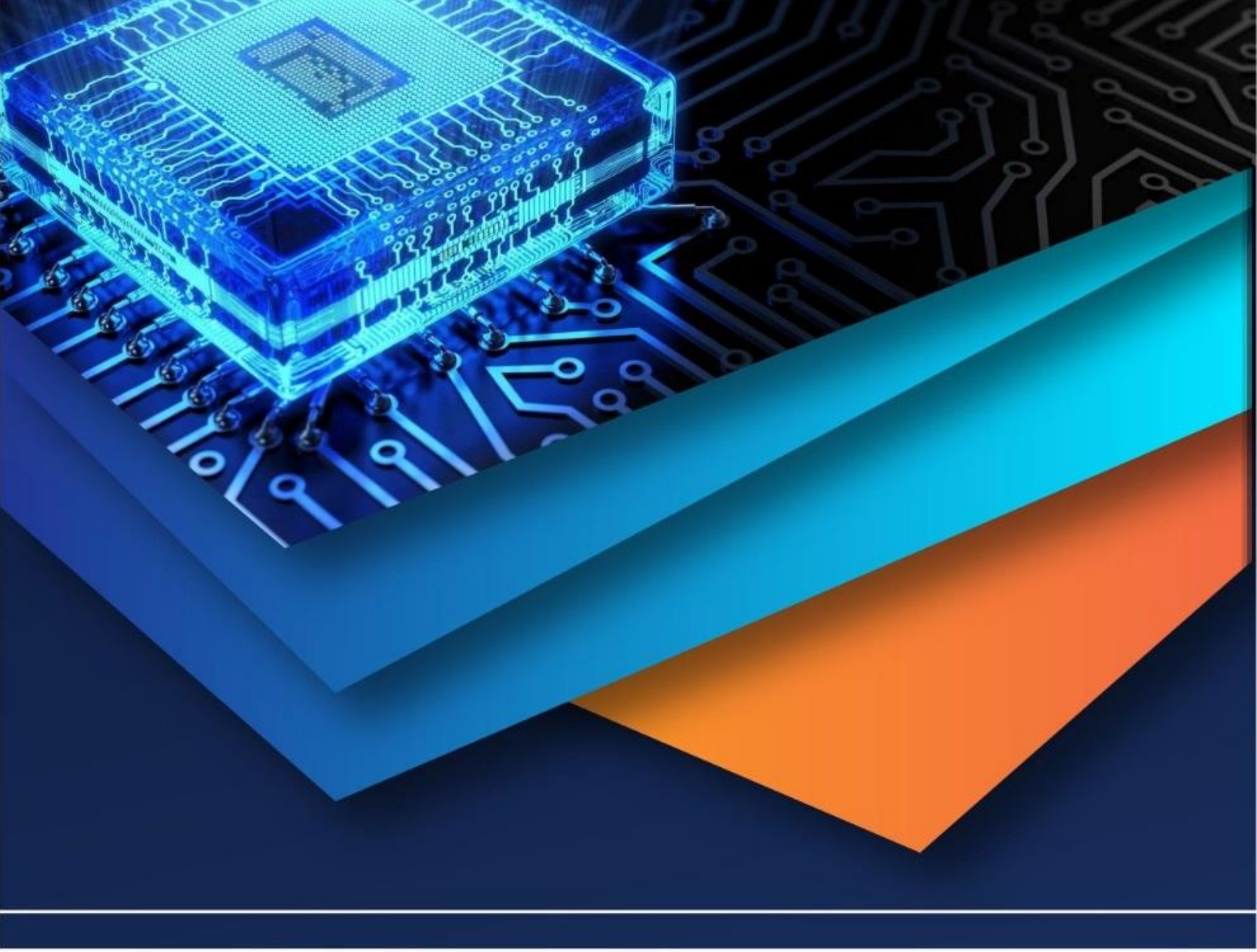
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