iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 13 **Issue:** VII **Month of publication:** July 2025

DOI: https://doi.org/10.22214/ijraset.2025.73135

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue VII July 2025- Available at www.ijraset.com

A Comparative Review of Soil Erosion Models: From Empirical Equations to Process-Based Simulations

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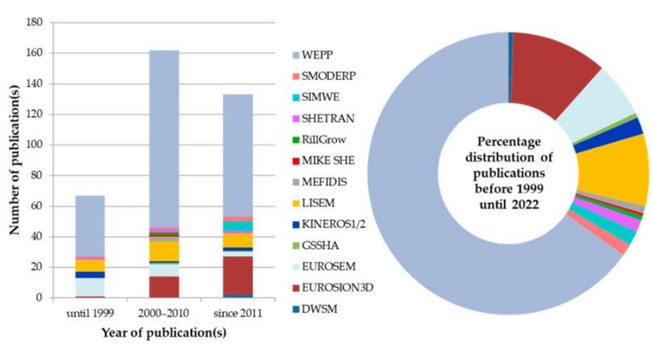
Abstract: Soil erosion remains a major environmental and agricultural challenge, particularly in India's diverse agro-climatic regions. This review examines the strengths and limitations of widely used soil erosion models—USLE, RUSLE, and process-based models such as WEPP. Empirical models like USLE and RUSLE are simple, require minimal input data, and are effective for broad-scale assessments, but they lack the ability to simulate dynamic processes. In contrast, process-based models offer detailed insights into erosion mechanisms and watershed responses but demand high-resolution data and extensive calibration. Based on recent studies across Indian watersheds, this paper compares these models in terms of accuracy, data requirements, and field applicability. The review concludes that while empirical models are useful for rapid evaluations, process-based models are more suitable for site-specific planning and conservation interventions. An integrated approach combining both model types with geospatial tools is recommended for effective watershed management.

Keywords: Soil erosion modelling; USLE; RUSLE; WEPP; process-based models; empirical models; hydrological response; sediment yield; watershed prioritization; runoff simulation; GIS-based modelling; remote sensing; watershed management; soil conservation; erosion prediction; model calibration; India; Agro-climatic zones; rainfall-runoff modelling; sustainable land management

I. INTRODUCTION

Soil erosion is a leading cause of land degradation worldwide, significantly impacting agricultural productivity, water quality, and ecosystem stability. In India, nearly 120 million hectares—over a third of the country's land area—are affected by land degradation, with water-induced erosion accounting for the majority. This widespread erosion leads to the loss of fertile topsoil, increased sedimentation in reservoirs, reduced crop yields, and disruption of hydrological processes. To address these challenges, accurate prediction and assessment of soil erosion are essential for implementing effective conservation and watershed management strategies.



Over the years, several models have been developed to estimate soil erosion, ranging from simple empirical equations to complex process-based simulations. The Universal Soil Loss Equation (USLE) and its revised form, RUSLE, remain widely used for their simplicity and ease of application. However, they are limited in capturing the spatial and temporal variability of erosion processes. In contrast, process-based models such as the Water Erosion Prediction Project (WEPP) simulate the physical mechanisms of runoff, sediment detachment, and deposition, providing more detailed and site-specific outputs. These models have gained prominence in recent decades, especially in regions with diverse topography and intensive land use, such as India.

This review critically examines the key soil erosion models used globally and in India, with a particular focus on USLE, RUSLE, and process-based models like WEPP. It compares their structure, data requirements, advantages, and limitations, and highlights model applications across various Indian watersheds. The objective is to provide a comprehensive understanding of model suitability for different contexts and to guide future soil conservation planning and watershed development initiatives.

II. EMPIRICAL MODELS: USLE AND RUSLE

The Universal Soil Loss Equation (USLE) and its revised form RUSLE are widely used empirical models for estimating long-term average soil loss due to sheet and rill erosion. These models are simple, require minimal data (rainfall, soil, slope, land use, conservation practices), and are easy to apply across large areas. However, they do not simulate the physical processes of erosion.

In India, these models have been applied extensively—for example, in the Gumti River Basin (Tripura) using USLE and in the Pambar River Basin (Kerala) using RUSLE to identify erosion-prone zones and guide conservation strategies.

A. Process-Based Models: WEPP, EUROSEM, and ANSWERS

Process-based models such as WEPP, EUROSEM, and ANSWERS simulate erosion mechanisms by accounting for runoff, infiltration, sediment transport, and deposition. These models are data-intensive but offer more accurate and dynamic predictions, especially under varying land use and climatic conditions.

In India, WEPP has been successfully used in the Karso watershed (Jharkhand) and Sitlarao watershed (Uttarakhand) to assess runoff and sediment yield. These models are particularly effective in complex terrains like the Himalayan region, though their application is limited by data availability and calibration requirements.

Table 1. Soil erosion models used in India

Model	Region	Purpose	Climate	Data source	Remarks
USLE[29]	Gumti River Basin (Tripura), area 2492 km^2	To assess the amount of soil loss[30].	Humid sub-tropical (rainfall 335.27 mm)	Rainfall data (IMD), soil data (NBSSLUP), ASTER DEM (30 m resolution) and LISS III	LULC has a greater influence on soil erosion compared to rainfall. The field-measured soil-loss data should be used to validate the predicted soil loss.
RUSLE[31] and TLSD[32]	Pambar River Basin (Idukki district, Kerala), area 288.53 km^2	To predict average annual soil erosion and deposition, and identify critical erosion or deposition areas[33].	Tropical mountainous river basin (rainfall 1533 mm (U/S) to 852 mm (D/S))	Rainfall data (meteorological stations), soil properties (field sampling), elevation data (Survey of India toposheet, 1 : 50,000 scale), and vegetation characteristics (IRS-P6 LISS-III)	Loamy sand and sandy loam texture soil have relatively low 'K' values compared to silt loam textured soil. Semiarid sub-basins having less vegetative cover show higher soil erosion compared to humid regions. So climate-specific management plans should be formulated.
USLE and MUSLE[34]	Sarada River basin (Andhra Pradesh), area 1252.99 km^2	To find vulnerable soil erosion-prone regions, computation of sediment yield and to suggest best management practices[35].	Rainfall 1105 mm	ASTER DEM (30 m), LISS III, Survey of India toposheets (1 : 50,000), Suspended-sediment concentration (for 28 storm events by DH-48), discharge (1 yr data)	In MUSLE, the sediment yield produced from the MNRCS-CN model outperforms the NRSC-CN model.
MUSLE[34]	Karso watershed of Hazaribagh (Jharkhand), area 28 km^2	To estimate sediment yield[36].	Sub-humid, tropical (rainfall 1300 mm)	Daily rainfall (automatic rain-gauge station), run-off and sediment yield data (gauging station), IRS-1C LISS-III	This model does not predict well the sediment yield for small and large rainfall events, but is good for intermediate events.
MMF[37]	Shiwalk hills region (Saharanpur district, Uttar Pradesh), area 205.95 km^2	To evaluate soil erosion risk and land capability categorization for watershed management[26].	Sub-tropical, semi-arid climate (rainfall 1170 mm)	ResourceSat LISS IV (5.8 m resolution), soil map (1 : 50,000), SRTM DEM	Soil erosion database can be effectively classified into different land-use systems and conservation measures suggested accordingly.
MMF and USLE	Sitla Rao sub-watershed (Dehradun district, Uttarakhand), area 52 km^2	To estimate soil erosion[10].	Western part of the Doon Valley	Toposheet (1 : 50,000), rainfall data and IRS-IC, LISS III	MMF model predicts well the soil erosion compared to USLE in hilly terrains like the Himalaya.
RUSLE-3D[38]	Pathri Rao sub-watershed (Haridwar district, Uttarakhand), area 44 km^2	To predict soil loss and spatial distribution of soil erosion hazards for soil conservation planning[39].	Sub-tropical, semi-arid climate (rainfall 1044 mm)	ResourceSat-1 LISS-IV (5.8 m resolution), IKONOS (1 m resolution) and toposheet (1 : 25,000), field survey of farmers and rainfall data	Topographic factor (LS) is dominant in controlling soil erosion.

USLE, Universal soil loss equation; RUSLE, Revised universal soil loss equation; TLSD, Transport limited sediment delivery; MUSLE, Modified universal soil loss equation; MMF, Morgan, Morgan and Finney; K, Hydraulic conductivity of soil.

Table 3. Process-based models used in India

Model	Region	Objective	Remarks
WEPP watershed model[52]	Umroi watershed (Eastern Himalayan region, Ribhoi, Meghalaya), area 239.44 ha, climate humid subtropical, rainfall 2842.5 mm, elevation 900 to 1240 m, data of two years were used	To simulate run-off and sediment yield, and sensitivity analysis of watershed characteristics with high rainfall and steep slope[5]. To develop integrated crop, tillage and structural management practices in order to reduce sediment yield[5].	Results of the WEPP model have been improved using the climate input files generated by the Break Point Climatic Data Generator (BPCDG). It underpredicts the high run-off events and sediment yield.
WEPP watershed model	Karso watershed (Damodar Barakar catchment), area 2793 ha, climate sub-humid tropical, rainfall 1300 mm, elevation 390–650 m amsl	To evaluate the WEPP model for estimation of run-off and sediment yield, and its sensitivity analysis[64].	Run-off is sensitive to changes in the physical environment, i.e. effective hydraulic conductivity value, whereas interrill erodibility and effective hydraulic conductivity affect sediment yield.
WEPP watershed model	Karso watershed (Damodar Barakar catchment), area 2793 ha, climate sub-humid tropical, rainfall 1300 mm, elevation 390–650 m	To classify and prioritize vulnerable sub-watersheds based on erosion and assessment of optimal management practices[63].	This model was found suitable for use as a decision-making tool to assess erosion hazards and prioritization purposes.
WEPP watershed model	Kaneli watershed (middle Himalayan region, Uttarakhand), area 0.67 km^2, elevation 1220–1540 m, rainfall 2840 mm	To validate and evaluate the WEPP model for estimating run-off and sediment in data-scarce areas[62].	The model failed to account for less severe rainfall events with less than 1 mm discharge and sediment yields of less than 0.02 t/ha.
WEPP, MUSLE and unit sediment graph (USG)[65]	Kozhy Thodu watershed, area 37.49 km^2, Valiya Thodu watershed (area 41.15 km^2) and Kiri Thodu watershed (area 36.55 km^2) in the Pamba River basin, Central Kerala	To evaluate the soil erosion models (WEPP, MUSLE and USG) for sediment yield prediction with the help of measured rainfall, run-off and sediment yield data[27].	The USG model predicts better than WEPP in data-scarce conditions.
WEPP hillslope model	Sub-catchment of Sitlarao (Dehradun), area 0.57 km^2, rainfall 1753 mm, elevation 920–1200 m	To study the impact of soil hydrological properties on spatial variation of run-off and soil loss[66].	The WEPP model is used to understand the relationship between infiltration, surface run-off and soil erosion process along the hillslope.
WEPP watershed model	Sitlarao watershed (Doon Valley, Dehradun), area 5300 ha, rainfall 1753 mm, elevation 960–1480 m	To evaluate the simulated surface run-off and soil loss data using the WEPP watershed model with the observed data[67].	The surface run-off produced from higher intensity rainfall events (>50 mm/h) is poorly simulated, but surface run-off from low to medium intensity rainfall (<50 mm/h) is well simulated.
WEPP watershed model	Experimental farm (ICAR-NEH, Meghalaya), area 2.19 ha, rainfall 2232 mm, elevation 952–1082 m	To simulate run-off and soil loss from three different conservation practices using the WEPP model[45].	The model overpredicts small run-off values and under-predicts large run-off values. Run-off is highly sensitive to Manning's roughness coefficient, initial saturation level and effective hydraulic conductivity.
WEPP watershed model	Patiala-Ki-Rao (Ropar, Punjab, Shivalik foothills), area 15.55 ha, rainfall 910 mm	To simulate run-off from a small watershed using the WEPP model[68].	Run-off is sensitive effective hydraulic conductivity followed by slope.
ANSWERS model	Three small agricultural watersheds (Bandi river basin), area 326.82 km^2, 450.33 km^2 and 1024.02 km^2, rainfall 300–600 mm, arid climate	To assess the significance of the ANSWERS model in predicting run-off and soil loss in agricultural watersheds[69].	Total soil loss is under-predicted by this model. It gives better run-off prediction on sloping watersheds than on level watersheds.
ANSWERS model	Banha (Upper Damodar Valley, Hazaribagh, Jharkhand), area 1613 ha, rainfall 1255 mm, humid subtropical climate elevation 450–406 m	To simulate run-off, peak flow and sediment yield under various soil moisture and rainfall conditions[70].	Run-off and peak flow are most sensitive to antecedent soil moisture, followed by control zone depth and Manning's roughness coefficient. Run-off, peak flow and sediment yield are under predicted for small storms (25–50 mm) of medium intensity rainfall (30–45 mm/h).

III. COMPARISON OF MODELS

A direct comparison of commonly used soil erosion models helps determine their suitability for specific regions, datasets, and applications. The table below compares the USLE, RUSLE, and WEPP models based on key parameters relevant to watershed studies and soil conservation planning, particularly in the Indian context.

Criteria	USLE	RUSLE	WEPP
Model Type	Empirical	Empirical (updated version of USLE)	Physically-based (process-based)
Data Requirement	Low (rainfall, soil, slope, land cover, practices)	Moderate (more accurate inputs for slope, C & P factors)	High (climate, soil, slope, vegetation, management)
Scale	Field to regional	Field to regional	Hillslope to watershed
Output	Soil loss (average annual)	Soil loss (improved accuracy over USLE)	Runoff, soil loss, sediment yield (spatially and temporally detailed)
Temporal Resolution	Long-term average	Long-term average	Daily, event-based, seasonal
Applicability in India	Widely applied due to simplicity and GIS support	Improved applicability with RS/GIS integration	Used in research for Himalayan and data-rich regions
Strengths	Simple, widely accepted	More flexible and precise than USLE	Captures erosion dynamics; suitable for scenario analysis
Limitations	Ignores dynamic processes	Still empirical; limited to sheet/rill erosion	High input demand; complex calibration required

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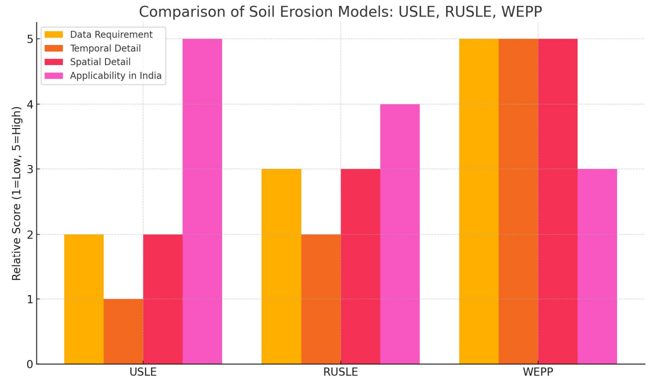

This comparison highlights that USLE and RUSLE are best suited for rapid assessments and large-scale mapping, especially where data is limited. In contrast, WEPP is ideal for detailed erosion analysis in data-rich or high-priority watersheds, such as those in hilly or Himalayan regions.

IV. APPLICATIONS AND CASE STUDIES IN INDIA

Soil erosion modeling has been actively applied across India's varied agro-climatic zones to assess erosion risk, prioritize watersheds, and guide conservation planning. The following summarizes notable case studies using USLE, RUSLE, and WEPP based on applications compiled in [9] (1..pdf), particularly from Table 1 and Table 3.

A. WEPP in the Eastern Himalayas and Other Hilly Regions

The WEPP (Water Erosion Prediction Project) model has been applied in several hilly watersheds to simulate runoff and sediment yield with high spatial and temporal resolution:

- Umroi watershed, Meghalaya (Eastern Himalayas): WEPP was used to simulate runoff and sediment dynamics under steep slopes and heavy rainfall (2842 mm). It aided in identifying critical erosion zones and evaluating conservation practices.
- Karso watershed, Jharkhand: WEPP effectively classified sub-watersheds based on erosion risk, demonstrating sensitivity to factors like hydraulic conductivity and interrill erodibility.
- Sitlarao sub-watershed, Uttarakhand: WEPP showed better performance than USLE in hilly terrain, especially in predicting erosion in small-scale catchments.

B. RUSLE in Kerala and the Shivalik Foothills

The RUSLE model has been widely used in tropical and sub-tropical mountainous areas, often in combination with GIS and remote sensing:

- Pambar River Basin, Kerala: RUSLE, along with the TLSD model, was used to map erosion-prone areas in a tropical mountainous basin. Results indicated that vegetation cover and soil texture significantly influenced erosion risk.
- Pathri Rao, Uttarakhand (Shivalik foothills): The RUSLE-3D model helped map erosion hazards, showing that topographic factors were dominant drivers of erosion in semi-arid sub-watersheds.

C. Comparative Analysis: USLE vs. WEPP in Small Watersheds

- In the Karso watershed (Jharkhand), WEPP outperformed MUSLE/USLE in identifying spatial variability in erosion and sediment deposition. USLE provided a general overview, while WEPP enabled prioritization of erosion control interventions.
- In Sitlarao, WEPP's hillslope simulation capability offered better prediction accuracy than USLE in steep, heterogeneous terrains.

These comparisons highlight that empirical models are useful for large-scale screening, but process-based models like WEPP are more appropriate for site-specific planning, especially in hilly and erosion-prone regions.

V. ADVANTAGES AND LIMITATIONS OF COMMON SOIL EROSION MODELS

Understanding the strengths and limitations of soil erosion models is crucial for selecting the appropriate tool based on data availability, terrain complexity, and project objectives. The following summarizes the advantages and constraints of USLE, RUSLE, and WEPP.

A. USLE (Universal Soil Loss Equation)

Advantages:

- Simple and easy to apply.
- Requires minimal input data.
- Widely used and supported by GIS tools.
- Suitable for broad-scale and preliminary assessments.

Limitations:

- Empirical in nature; does not simulate physical processes.
- Limited to estimating sheet and rill erosion.
- Lacks temporal variability—only gives long-term averages.
- Not suitable for scenario analysis or event-based predictions.

B. RUSLE (Revised Universal Soil Loss Equation)

Advantages:

- Builds on USLE with updated databases and algorithms.
- More accurate estimation of slope and cover factors.
- Compatible with remote sensing and GIS platforms.
- Widely used in India for regional erosion mapping.

Limitations:

- Still empirical; cannot model runoff or sediment transport processes.
- Requires more detailed input (e.g., slope length, vegetation cover).
- Limited for use in complex terrains or dynamic conditions.

C. WEPP (Water Erosion Prediction Project)

Advantages:

- Fully process-based; simulates runoff, soil detachment, transport, and deposition.
- Provides spatially and temporally distributed outputs.
- Suitable for event-based and continuous simulations.
- Useful for scenario analysis, conservation planning, and prioritization.

Limitations:

- High data demand (climate, soil, land use, topography, management).
- Requires climate generators like CLIGEN or BPCDG.
- Model calibration and validation can be complex.
- Less practical in data-scarce regions without institutional support.

VI. SCOPE FOR FUTURE WORK

Despite the extensive use of soil erosion models in India, several critical gaps remain that need to be addressed to improve prediction accuracy and policy relevance.

ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
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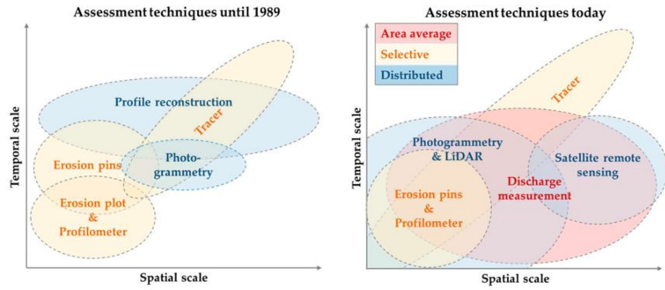
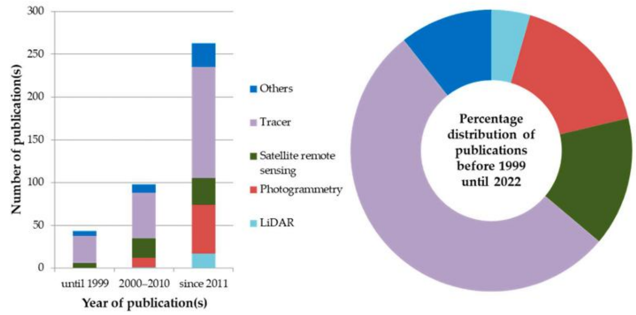


Evolution of soil erosion assessment techniques in terms of temporal and spatial scale, from traditional methods (pre-1989) to modern approaches using remote sensing and distributed modeling (post-2000). Adapted from Ghosh et al. (2022).



Global publication trends for soil erosion assessment techniques from 1999 to 2022, showing increased emphasis on remote sensing, LiDAR, and tracer-based methods. Source: Ghosh et al. (2022).

1) Need for Validation Data: A major limitation in model application across Indian watersheds is the lack of long-term, high-resolution field data for model calibration and validation. This restricts the reliability of model outputs and their use in decision-making.
2) Hybrid Modeling Approaches: Emerging technologies like remote sensing, machine learning, and AI offer promising opportunities for improving model efficiency and spatial coverage. Integrating traditional models like RUSLE or WEPP with real-time satellite data and AI-driven parameter tuning can enhance predictive accuracy, especially in data-scarce regions. Some studies (as seen in [10] 2.pdf) are beginning to explore such integrations, though they remain in early stages.
3) Modeling Climate Change Impacts: There is an urgent need to simulate how changing rainfall intensity, temperature, and land-use dynamics—driven by climate change—affect soil erosion patterns. Future models must incorporate dynamic climate scenarios to assess long-term erosion risks and support adaptive watershed planning.

VII. CONCLUSION

1) Soil erosion modeling remains a critical component of sustainable watershed management in India and globally. This review highlights the distinct roles and applicability of **empirical** and **process-based** models.
2) Empirical models like **USLE** and **RUSLE** continue to be widely used for **rapid, large-scale assessments** due to their simplicity and compatibility with GIS tools. However, their inability to simulate physical processes limits their use in dynamic or complex environments.
3) In contrast, process-based models such as WEPP offer greater spatial and temporal resolution, making them suitable for detailed planning, conservation scenario analysis, and erosion prioritization in data-rich, small to medium-scale watersheds.
4) The growing body of India-specific research demonstrates increasing awareness and capability in erosion modeling, yet further progress depends on improving data availability, enhancing model calibration, and embracing newer technologies such as remote sensing and AI.
5) Ultimately, the selection of an appropriate soil erosion model must be guided by project objectives, terrain complexity, data availability, and desired output detail—ensuring that both scientific rigor and practical utility are achieved.

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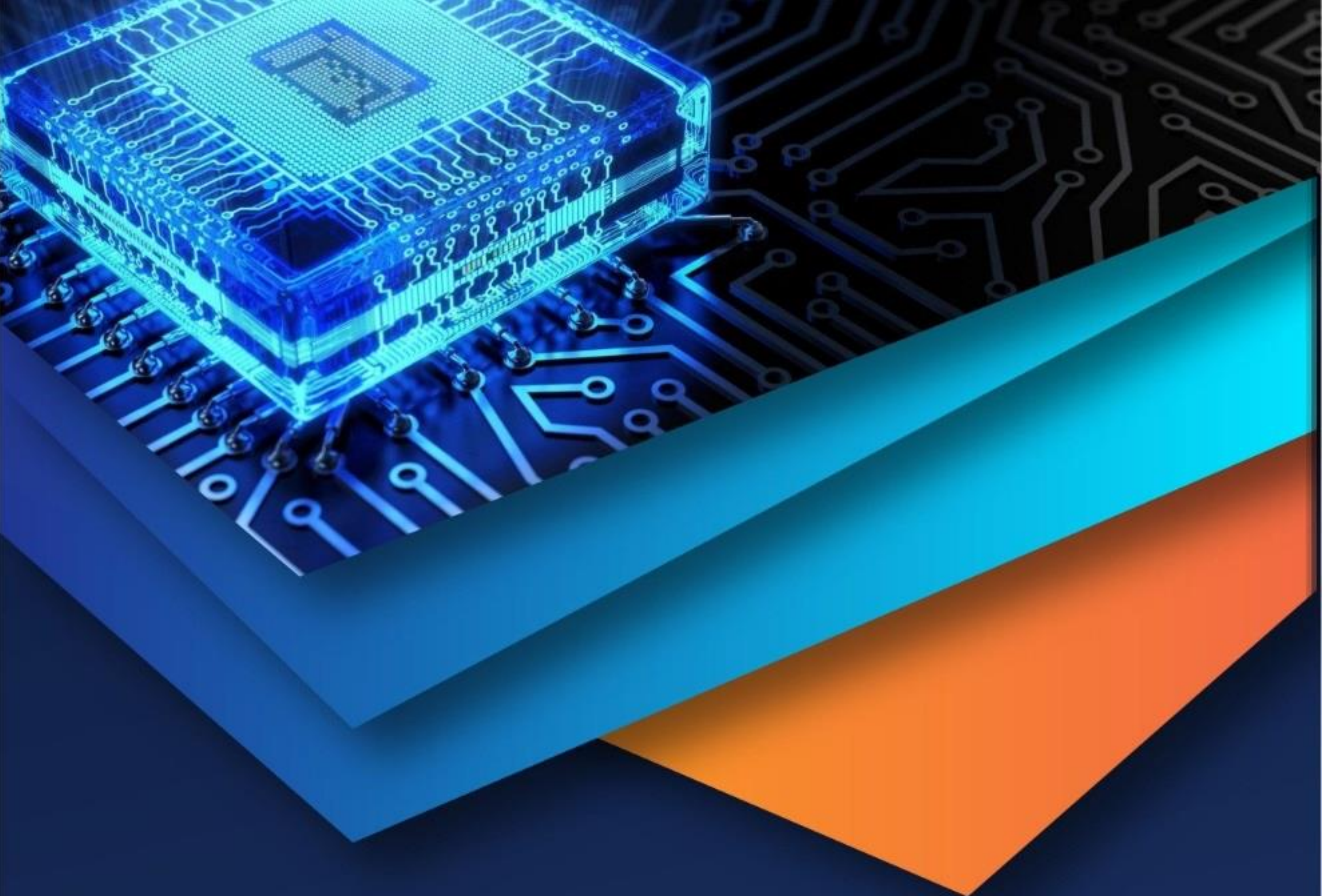

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