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Analyzing Inundation Impacts on Transportation Network - The Case Study of Vadodara City

Kruti Patel[1], L.B. Zala[2], Pinakin Patel[3]
[1]*Student at Birla Vishvakarma Mahavidyalaya, Anand, Gujarat*
[2]*HOD of Civil Engineering, BVM, Anand, Gujarat*
[3]*Asst Prof in Civil Engineering at BVM, Anand, Gujarat*

Abstract: Inundation and related problems have become more uncontrollable all over the world leading to unexpected deaths, severe damage to infrastructure, and epidemics like conditions every year. A great number of cities in India have reported a series of heavy hazardous precipitation events during past few years. The immediate effects observed of floods specifically in urban areas are on the transportation network leading to its disruption. Most of the studies on transportation susceptibility including immediate and shortly after inundation events consider topographic properties along with supply and demand side of transportation system to access the disruption caused. In response to such events, this study aims to provide framework to access the susceptibility to urban road network due to inundation events. An integrated framework between meteorological information, land use functions, and hydrodynamic model simulated in HEC-RAS with rainfall event with 1-in-100 year is used for the analysis of the impacts being generated on the transportation infrastructure by such event. A critical map and index is developed to identify affected road length susceptible to flood. It has been observed that more than 40 percent of road length across the network has been affected by such unpredictable events. Also, there is a significant decrease in average speed of movement as compared to average normal speed observed on the normal days.
Keywords: Road network infrastructure susceptibility assessment, urban flood, HEC-RAS, Gumbel extreme value Distribution, Flood inundation Mapping

I. INTRODUCTION

The world’s leading climate scientists have quoted that because of increasing global warming there’s high spike in the climate system. Such spike will carry with it a host of consequences for the global community. Floods are directly related to the heavy precipitation events and along with it heavy urbanization and unplanned development of cities have added to the disrupt behavior of the catchment. Changed climate has direct impact on the rainfall patterns. Several studies on the rainfall patterns in India have concluded that during the past recent decades there is an observed increased in the severe rainfall events with high frequency as well as high duration intensity. Thus, such situations are near future to such cities.

There is an increase in the percentage of urbanization in the country from 27.81% in 2001 to 31.16% in 2011(census 2011). To accommodate such rapid increase of populations various wet lands, barren plots, and other available resources have been converted to built-up areas. Therefore, decrease in impervious surfaces leads to frequent flooding in the cities because of poor infiltration rate and reduction in flow resistance of the rain water. Because of this there is an observed increase in peak discharge rate, decrease in the time of concentration and increase in the volume of runoff. For predicting potentiality of flooding and mitigation in case of such hazards we can impose our studies to better understanding of land use pattern changes over years and its impact on the hydrologic processes. Certain studies reveal that loss of pervious layer to impervious layer leads to increase in the flashiness of storm water runoff and relative to its peak flow; careful measures need to be implicated while designing the mitigation measures

Presently, the predesigned drainage system is unable to cope up with the increase in the rainfall events and increase in runoff volume. Heavy precipitation events have resulted in several damaging situations in the urban areas around the nation. Consecutive heavy floods in the three major cities of India i.e. Mumbai, Chennai, and Bangalore cause heavy damage to economy, loss of lives, and disturbance to the transport infrastructure. Transportation roads have the most immediate effects of floods as they become the preferential path to flow after heavy floods. Inadequate and poorly maintained drainage system is unable to carry such heavy floods and leads to inundation of low-lying areas of the city as well as road links making movement of vehicles difficult. Flooding of roads has major setbacks casing movement of vehicles difficult, damage to transport infrastructure and also associated economic losses to regain it back. In response to such conditions is it necessary to study the impacts of storm water for further planning of mitigation as well as planning in terms of transportation infrastructure.

II. STUDY AREA

Vadodara urban area is selected for the study. The city vadodara located at western part of the country in the state of Gujarat with (Latitude: 22 deg 17' 59'' North Longitude: 73 deg 15' 18'' East) emerged as one of the main city of the Gujarat state. The city comprises an area of 108.22 sq.km situated at an Altitude of: 35.5m, above mean sea level, with winter temperature min 11˚C and summer temperature max 45˚C. According to the 2011 India census, Vadodara city had a population of 1,822,221. An approximate growth of 22.2% was observed from the year 2001 to 2011.

Study area for assessment of impact on road transport due to flood covers the vadodara urban district extended from 22° 18' 38.5056" N and 73° 11' 33.4860" E covering a watershed of around 20.04864 sq.km.

Transport infrastructure of the vadodara city is being constantly put under stress due to rapid increase in urbanization and increasing rapidly in number of vehicles because of modern lifestyle. The existing network of the city in certain areas has surpassed the carrying capacity which results in heavy traffic congestion during the peak hours during week days and certain holidays. There is obviously limited scope for the expansion of transport infrastructure in certain parts of the city. Therefore, just development in the terms of technology alone cannot help to meet the needs of increasing number of vehicles.

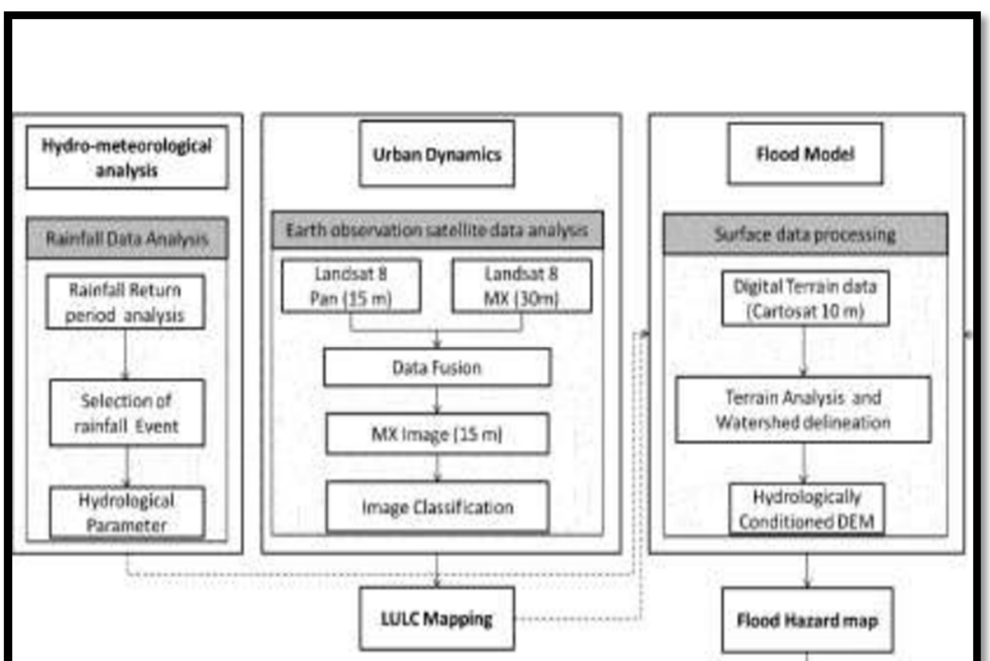
A. Impacts Of Weather Extremes On The Transport Infrastructure

Transport infrastructure is considered as one of the basic requirement in today's fast growing scenario. Extreme climatic conditions may lead to disruption to the road network and regular operations on the same may get disturbed resulting in related losses like loss of life, physical injuries and increase in vehicle operating cost. There are lots of studies available that link climate studies to the weather extreme damage to the transport network.

Studies reveal that impact on the transportation infrastructure will increase with the increase in magnitude and frequency of climate change. Studies analysed the impact of climate change and flood risk and concluded that they are increasing in parts of the country frequently. It also shows that there is direct relationship between climatic changes and its financial impacts on transportation and maintenance cost, service distortions, effect of climate on the age of road pavement, failure of the transportation structure, disturbance due to potholes and rut, and after looking at all we need to counter this climatic changes in the design of road and the mitigation measures.

III. METHODOLOGY AND APPROACH

With respect to all the discussion made above to undergo the study we need to follow certain analysis to access the impacts on the road infrastructure of the potential rainfall events for the overall functioning of the network. The steps included in the same are hydro-metrological analysis, land function with flood mapping, and later followed by the analysis of flood exposure to know the water depth on roads and relative speed of the vehicle during floods with relation equation.



A. Hydro-metrological Analysis

Rainfall is the main responsible parameter of the urban floods in vadodara. Since, rainfall intensity, duration, and frequency determine the extent and severity of inundation, it is important to analyze the rainfall for the selection of extreme of floods for the mapping purpose. Various methods are available for the same. In this study we use the data that are provided by the Indian Meteorological Department (IMD) from the year (1990-2020) for the rainfall analysis purpose.

$$X_T = \bar{x} + K\sigma_{n-1} \qquad \sigma_{n-1} = \sqrt{\frac{\Sigma(x-\bar{x})^2}{N-1}}$$

Gumbel's probability distribution function (extreme value type-1 distribution) is being used for the calculation of return period and analysis for frequency (table-1). The Gumbel method of frequency analysis is based on extreme value distribution and is the most widely used function for the rainfall analysis.

Extreme value type-I distribution (EV-I) or Gumbel's distribution

Maximum rainfall expected for the single day is being calculated using Gumbel extreme value distribution

$$y_t = -\left[ln.\,ln\frac{T}{T-1}\right]$$

Where X_T = maximum expected rainfall for single day, $\bar{X}$ mean of the observed data, K is the frequency factor for the equation and σ_{n-1} = standard deviation of the data, N is equal to number of observations considered

$$K = \frac{(Y_T - \bar{y}_n)}{S_n}$$

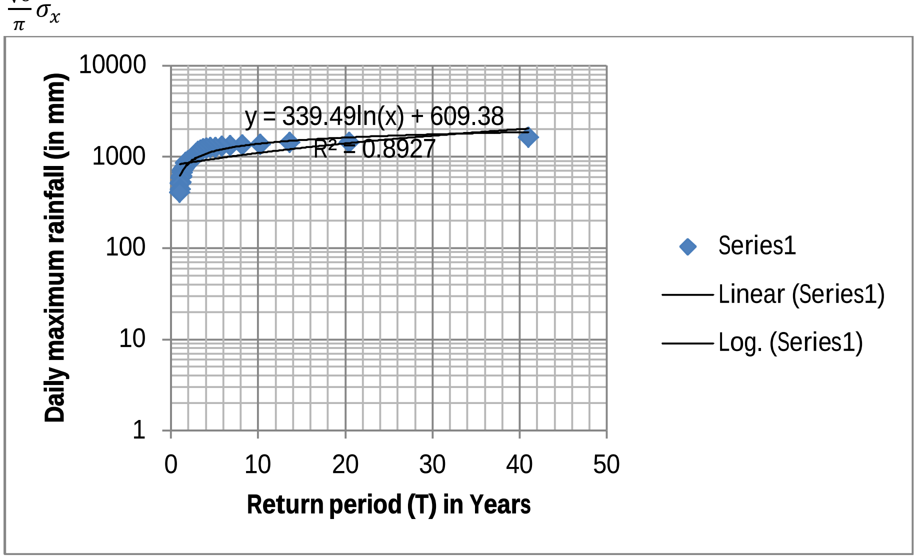
The frequency factor K is the relationship between expected rainfall and standard deviation of the data observed.

Where,

$$f(x) = \frac{1}{\alpha} e^{\frac{-(a+x)}{\alpha - e^{-\frac{(a+x)}{\alpha}}}}, (\alpha \leq x \leq \infty)$$

Where, x is the variate, a and α are:

$$a = y\alpha - \bar{x} \; and \; \alpha = \frac{\sqrt{6}}{\pi}\sigma_x$$



Graph shows the overall observed data

Table 1 calculated rainfall for the return period using Gumbel extreme value distribution for vadodara

Return period for the expected rainfall	yt	K	Xt(m3/s) Daily maximum for single day in (mm)
5	1.49994	1.091471	136.4865
10	2.250367	1.947934	193.9268
20	2.970195	2.769473	249.0248
50	3.901939	3.832872	320.3436
100	4.600149	4.62974	373.787
150	5.007293	5.094412	404.9512
200	5.295812	5.4237	427.0354
500	6.213607	6.471179	497.2866

Hydro-dynamic overland 2D model HEC-RAS is used for flooding mapping. It requires the time-series discharge data for the drainage system to calculate the flood affected areas and the intensity or depth of water in an around area for mapping.

B. Urban Dynamics: Land Use Land Cover Analysis

The spatial and temporal changes of the land use change can be assessed by comparing the previous land use data and present land use cover analysis. For land use cover analysis initially we need to have satellite imagery of Landsat 8-OLI sensor having 30m spatial resolution which is being downloaded from the USGS earth explorer. The following imagery is then processed further for land use classification in the QGIS platform. Steps followed for the same are as follows:

1) Download satellite imagery of Landsat 8-OLI sensor having 30m spatial resolution from the USGS earth explorer.
2) Data preparation/data pre-processing: once the QGIS is being downloaded import the TIFF files with raster data input option. Then install SCP plugin from the install and manage plugins option. With the help SCP plugin toolbar preprocessing of the data can be initiated i.e. creating a Landsat and clipping of the Landsat files.
3) Adding pixel information for each band to have imaginary land use classification idea.
4) Then we proceed with the supervised classification with the SCP Dock platform.
5) We add classification groups in the training inputs form with the help of ROI's and run classification.
6) We obtain 6 broad classes after classification including built-up areas, forest areas, water bodies, roads, and barren land.

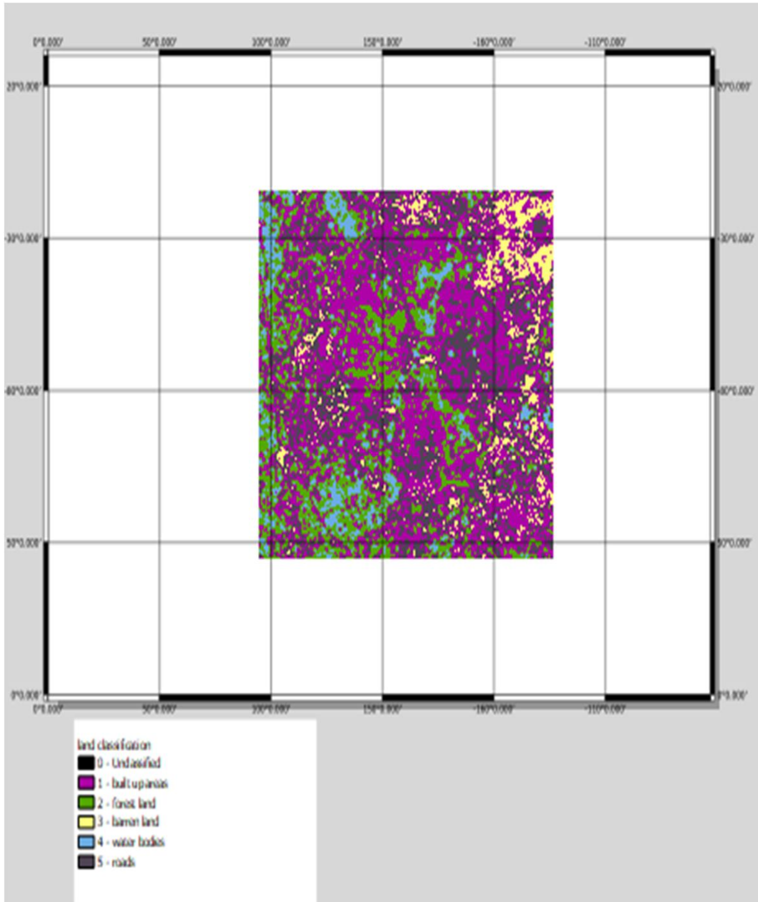
These five classes represent the vadodara urban land use forms and they are used as roughness coefficient in the form of manning's number in this model as input parameter.

$$V = \frac{R^{2/3} + S^{1/2}}{n}$$

Where, V is the average velocity measured in (m/s), R is the hydraulic radius (m), and S is energy slope for the same (m/m), n is Manning's roughness coefficient

Table: Manning's roughness coefficient used for the calibration of land use model

Land use class	Manning's n	Manning's number M=(1/n), [m^(1/3)/s]
Built-up	0.083	12.0
Forest/trees	0.100	10.0
Roads	0.016	62.5
Water bodies	0.045	22.2
Barren land	0.030	33.3



C. Hydrodynamic Modelling for Flood Mapping

One rainfall event with certain intensity, duration of rainfall, and return period of that particular event is being simulated and analysed for the given land use and boundary conditions for the same in 2-D hydrodynamic model HEC-RAS. HEC-RAS is general numerical model that analysis terrain for the flood mapping giving water depth for particular water delineated area. It simulates the unsteady flow of water and the software has been in number of analysis for the study purpose.

D. Processing Of Surface Data: Topographical Analysis

Orthorectified cartosat-1 driven digital elevation model (DEM) with 10 m spatial resolution is used for the topographical analysis. The DEM data is being obtained from the National Remote Sensing Center (NRSC) Hyderabad. The following DEM data so obtained is being analysed in the QGIS platform for obtaining the watershed delineation and channels which can be further incorporated into HEC-RAS software for 2D unsteady flow analysis for obtaining of water depth on the roads and further analysis of the change in speed observed for the than the normal average speed.

Following steps need to be followed for the terrain analysis in QGIS software:

1) Initially input raster file i.e. DEM tiff into QGIS using raster input dialog box.
2) Wrap the DEM to create reprojected DEM data file to change the projection of the DEM file.
3) Then the reprojected file is further processed in fill voids processing tool bar to fill the raster regions with no data values by interpolation from the edges.
4) Then we use the strahler order processing for the numerical measuring of the branching complexity of the drainage design. With the help of raster calculation we obtain just the potential branches into consideration.
5) After that we obtain the channels for the filled DEM for the further calculation of the upslope area.
6) Then with processing tool upslope area we obtain the catchment basin or watershed delineated area for which we need to do the simulation to obtain water depth for the region.

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The obtained watershed Delineated tiff file is being incorporated in the HEC-RAS software for further analysis of the data obtained. Further steps followed are as follows:

a) The watershed delineated file is incorporated as terrain input in the software. After obtained terrain we did add geometric features to the terrain which includes main river, boundary conditions, flow lines, bank lines and cross-sections for unsteady flow analysis.

b) After addition of geometry we add unsteady flow details for the further simulation i.e. manning's value, time-series for simulation rate, rate of discharge and undergo unsteady flow analysis to obtain flood water depth on the road links within the delineated areas.

The obtained results of the HEC-RAS simulation is being further processed to obtain the areas that are flooded and upto what level? With further digitization we can have the actual water flooded roads with accurate kms

Flood stage is classified into three subclasses:

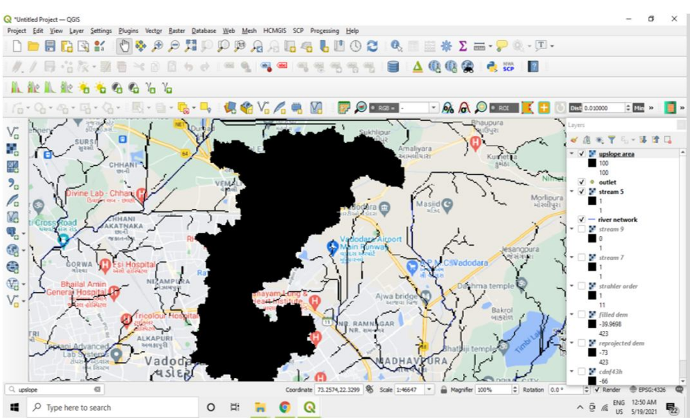
- Minor flooding (water level between 0.1m to 0.5m)
- Moderate flooding (water level between 0.5m to 1m), and
- Major flooding (water level 1m and above).

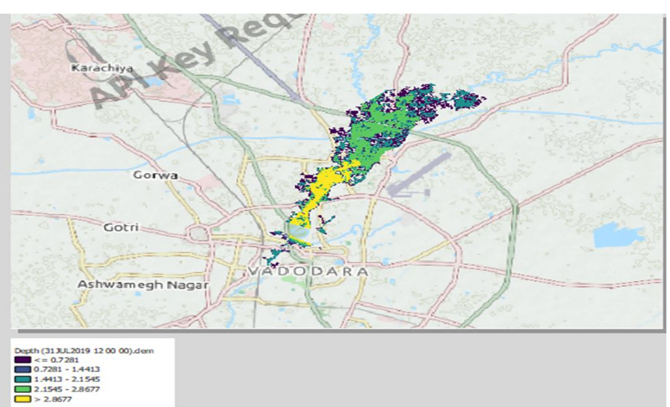
IV. RESULTS

Flood stage distribution in terms of percentage of flooded area obtained from the simulation

Flood level (meter)	Percentage of flooded area	Flood stage
<=0.7281	12.652	no flooding
0.7281-1.4413	3.654	minor flooding
1.4413-2.1545	10.256	moderate flooding
2.1545-2.8677	51.962	major flooding
>2.8677	21.476	hazardous flooding

Flood exposure for studying the impact of water depth on the average speed reduction:





Watershed delineated area obtained from the processing of Cartosat-1 driven digital elevation model (DEM)

Flood-water-depth obtained from the hydro-dynamic simulation of watershed delineation obtained

Exposure to the floods is taken as the most important factor for studying the impact of floods on road network. In research observations, there is a linkage obtained wherein, there is direct relationship between developed between flood depth and flow velocity with the speed of the vehicle. Chen et al. (2016) average speed of the vehicle as one of the impact and is directly impacted by the depth of the flood on the road. The susceptibility curve developed which Is developed by Pregnolato et al (2016) and is used to assess the impact of water depth on the roads. The curve function was developed for bitumen road using experimental data and certain expert's judgment for European Union, Canada, and Australia and is modified for the Indian roads accordingly for assessment. The road susceptibility curve for safety speed to flood water depth is expressed by second-order polynomial function.

$$y = 0.0006x^2 - 0.4780x + c$$

Where,
Y = flood safety speed in KMPH
X=water level on road in mm
C=speed constant (82.615)

V. CONCLUSIONS

Such high climatic variability is the near future for the Indian cities in the future. Cities will experience more such events with high frequency and high intensity and along with it longer duration of floods. High resolution hydro-meteorological data-sets are the pre-required data sets necessary to carry out such analysis to study the impacts of flooding on the road network links. Here, in the studies above it shows how to carry out hydro-dynamic analysis to understand the impacts to certain extend. Further this analysis can also be used to calculate the increase in the vehicle-operating cost because of reduction in speed and increased time of travel during floods. From the studies we can also conclude that the drainage system of the city needs to be repaired and maintained periodically so that there is reduction in the stagnant time of floods on the roads which will direct have positive impact on the road infrastructure damage as roads will be immersed less. Along with this Vishwamitri River have high quantity of siltation due to which the natural discharge flow rate has reduced which also needs to be put check on.

VI. ACKNOWLEDGMENT

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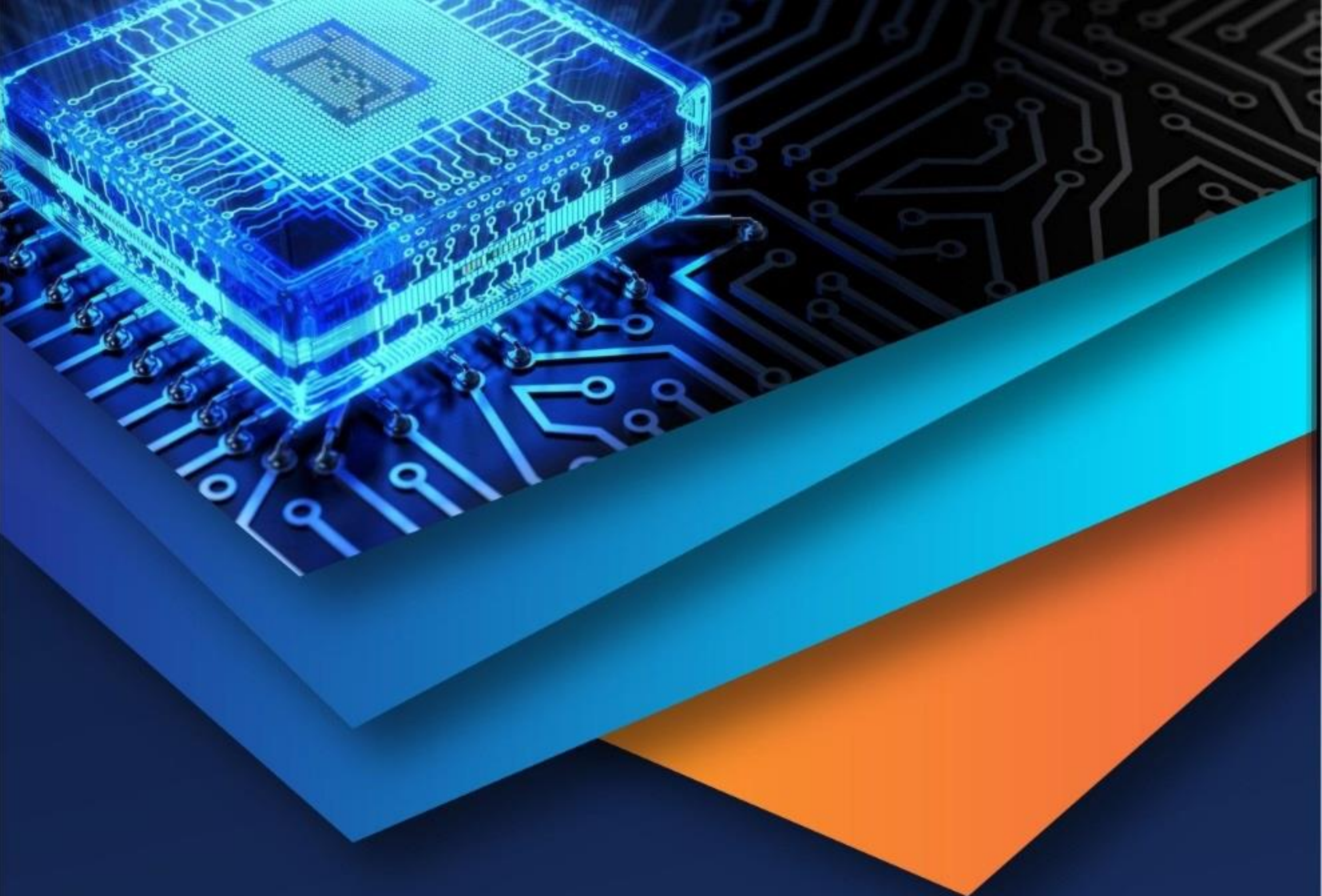

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