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Model of Lightning Strike Risk to Humans Based on Spatial Analysis and Environmental Factors

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ABSTRACT

Lightning strikes pose significant threats to human safety and infrastructure, particularly in tropical regions like Indonesia with high lightning activity. This study aims to develop a predictive model of lightning strike risk to humans based on spatial analysis and environmental factors, utilizing data on lightning distribution, land use, population density, and meteorological parameters. Using probabilistic decision trees and tropical lightning formulas, the model identifies key predictors, including rainfall, land use patterns, and humidity, which influence lightning density. The results reveal that densely populated areas with high lightning activity, such as parts of Java and Sumatra, are particularly vulnerable. Spatial risk maps generated from the model highlight high-risk zones, providing critical insights for disaster mitigation planning and infrastructure protection. Furthermore, the study emphasizes the significant correlation between lightning density, land use, and population exposure, offering a comprehensive framework for understanding lightning risks. This predictive model not only serves as a tool for early warning systems and sustainable spatial planning but also underscores the importance of integrating environmental and spatial data for effective lightning risk mitigation. Future research should incorporate temporal lightning variations and field validation to refine the model and enhance its applicability.

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1. INTRODUCTION

Thunderstorms aren't only dangerous because they may damage property; they can also kill people. In Indonesia, particularly in areas with high human density and distinct land uses, the risk of lightning effects is becoming evident, given its tropical location characterised by intense lightning activity [1][2]. Not only is lightning intensity a contributing component in this danger, but environmental variables such as population density and land use patterns also affect it. These factors control soil conductivity and the amount of time humans are exposed to lightning strikes [3].

The likelihood of lightning strikes affecting people increases with rising population density in metropolitan regions. Jakarta and Surabaya, being extensive urban centers with complex infrastructure, are especially vulnerable to this hazard [4]. The transformation of agricultural land into residential or industrial zones, together with changes in land use, might affect lightning striking patterns. Unobstructed terrain is more vulnerable to direct assaults, whilst regions with elevated edifices may act as focal locations for attacks. Thus, land use factor analysis is essential for understanding the comprehensive risk of lightning effects [5][6].

The geographical distribution of electrical activity is a crucial component, alongside human density and land use [7]. Lightning activity in Indonesia is markedly varied, with several areas, such central Sumatra and West Java, demonstrating elevated rates of lightning strikes compared to others. Geographic and climatic variables, such as mountainous terrain, humidity levels, and prevailing wind patterns, affect this fluctuation.

The amalgamation of geographical distribution data of lightning with other environmental variables may provide a more thorough comprehension of high-risk zones and provide a basis for the formulation of efficient mitigation methods [8][9].

Research in Indonesia that integrates spatial elements such as lightning distribution, land use patterns, and population density to assess risk remains scarce, despite the acknowledged threat of lightning strikes to human safety. The efficacy of evidence-based mitigation measures might be hindered by a lack of understanding of the interplay of these three components. A predictive strategy using spatial analysis is necessary to map and identify areas with a high probability of lightning strikes [10][11]

This study aims to develop a prediction model of the risk of lightning strikes to people in Indonesia using geographical analysis. This will be accomplished by combining information on the distribution of lightning, land use, and population density. To protect the community from lightning risks, this model is expected to provide an accurate lightning strike risk map that can be used as a tool for mitigation planning and decision-making.

This analysis used three main data sources: lightning distribution maps, land use maps, and population density maps of Indonesia. The research aims to develop a predictive model for lightning strike risk to people by analyzing the interplay between the geographical distribution of lightning strikes, environmental factors, and population density via data integration. Consequently, it is expected that the model would provide an accurate risk map to enhance Indonesia's lightning hazard mitigation efforts.

This study advances geographical data-driven risk analysis approaches and offers practical recommendations to the government and stakeholders for developing more effective mitigation plans to protect the community from lightning risks.

2. LITERATURE REVIEW

2.1 Relationship Between Spatial Distribution of Lightning and Strike Risk

The geographical distribution of lightning strikes is profoundly affected by local meteorological conditions and area terrain, as shown by research on this phenomenon [1][2]. In tropical areas such as Indonesia, lightning intensity is often greater in zones characterized by elevated humidity and vigorous convection activity. Prior studies have shown that lightning concentrations are often found in areas with steep slopes or mountains due to orographic processes. Numerous studies further substantiate that regional topography may provide certain meteorological conditions favorable for the development of lightning clouds, including increased local humidity and convective activity in mountainous areas [8][9]. This data is essential for analyzing the geographical distribution of lightning strike risk, especially for identifying danger zones in certain locations. The dispersion of lightning is affected by a confluence of meteorological and geographical parameters, as shown by pertinent research [12].

Researchers indicate that the temporal and geographical distribution of lightning activity may be affected by fluctuations in climatic patterns. For example, lightning intensity in several tropical locations, including Indonesia, may increase due to increasing global temperatures [13]. When developing a lightning risk forecasting model that adapts to climate change, it is essential to include this occurrence. This model can provide a dynamic danger map based on current atmospheric conditions and lightning dispersion data.

Integrating lightning distribution data with other environmental factors, such as population density and land use, provides a more comprehensive understanding of lightning strike risk. The formulation of evidence-based risk mitigation strategies depends on identifying locations with significant vulnerability, a process aided by this study.

2.2 The Influence of Land Use Patterns on the Risk of Lightning Strikes

Prior studies have shown that the allocation of lightning strike risk is markedly affected by land use patterns. These structures elevate the probability of a hit, which is why lightning commonly targets metropolitan areas with multiple tall buildings. The lack of natural or manmade lightning rods makes open regions, such rice fields or grasslands, more vulnerable to direct strikes [14]. The correlation between land usage and strike risk in Indonesia may be examined based on these data [15].

The distribution of lightning strike currents on the surface is determined by soil conductivity, which affects land usage. Collisions may be exacerbated by ground with elevated water content, such as wetlands, requiring specific attention in risk reduction strategies [16]. Regions with heightened risk levels due to certain environmental conditions may be discerned via the amalgamation of land use data.

Lightning striking patterns are impacted by land transitions in Indonesia, including the conversion of forests to agricultural land and urbanization. These alterations provide new challenges to the accurate assessment of hit risk. Further investigation is necessary to understand the long-term impacts of land use changes on the distribution of lightning danger [16].

2.3 The Role of Artificial Intelligence in Lightning Research

Vulnerability to Lightning and Population Density Population density is a crucial determinant of the danger of lightning strikes affecting people [4][9]. This danger is particularly common in areas with high population densities, such as Jakarta. The likelihood of lightning strikes often increases in areas with significant human activity, especially if adequate lightning protection measures are absent, as shown by previous studies. Thus, population density maps are crucial data for risk assessment [17].

Researchers have shown that human contact with the environment, including activities in open spaces or near towering buildings, increases the probability of lightning strikes. This understanding is essential for formulating mitigation strategies, such as the placement of lightning rods in areas often visited by the public. Moreover, efficient self-defence methods and education about lightning risks are essential elements in reducing population susceptibility [18].

Communities most vulnerable to lightning effects may be determined by integrating population density data with other environmental elements. This analysis's conclusions may inform the prioritization of mitigation activities, including enhanced design of lightning protection infrastructure in heavily populated regions.

2.4 Technology and Analysis Methods for Lightning Risk Modelling

Technological improvements have enabled the use of diverse analytical methodologies, allowing for more accurate mapping of lightning strike risk. Spatial data-driven modelling is a prevalent methodology that utilizes spatial information to discern risk trends. Prior studies have shown that including diverse environmental factors, such as population density, land use, and air humidity, may improve the precision of risk prediction using machine learning algorithms [19].

Furthermore, spatial analytic techniques have been used to accurately identify high-risk areas. Researchers may create risk maps that depict the geographical distribution of lightning strikes using GIS (Geographic Information System) software. These results significantly enhance decision-making in the planning of risk reduction at both local and national levels [20].

The research emphasized the need of corroborating the model with empirical data to improve the trustworthiness of the findings. The precision of prediction models may be assessed by examining lightning distribution data acquired from direct observations or lightning sensors. This step ensures that the created model is both theoretical and practical in mitigating the danger of lightning strikes in Indonesia [9][14].

3. RESEARCH METHOD

3.1 Data Collection

Fig. 1. Cloud-to-Ground type Indonesian lightning density map

The 2021 Indonesian cloud-to-ground (CG) lightning strike distribution map showed concentrations in Java and Kalimantan. Topography, vegetation, land use, and human activities affect CG lightning, which may destroy infrastructure and kill people. Hilly or steeply sloping places like West Java have more cloud-to-ground lightning due to air convection. Season and climatic change affect temperature and humidity, affecting lightning strikes. CG lightning strikes may increase when metropolitan areas with strong infrastructure grow owing to structures that may be impacted directly. Thus, a complete prediction model must integrate these factors to generate an accurate risk map. This model might improve early warning, spatial planning, and disaster mitigation to decrease CG lightning strike losses for people and infrastructure.

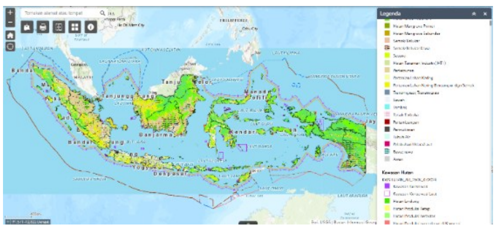

Fig. 2. map of land use in Indonesia

The likelihood of lightning strikes is considerably influenced by the diverse land cover of Indonesia, which includes metropolitan regions and tropical rainforests. The urban heat island effect intensifies convection in metropolitan regions, while woods, serving as microclimate regulators, elevate air humidity and trigger atmospheric convection. The distinctive lightning strike risk patterns in each location arise from the intricate interplay between land cover and several climatic parameters, including surface temperature and terrain. By integrating land cover data into prediction models, we can pinpoint regions vulnerable to lightning strikes across many spatial dimensions and types of lightning events. The results of this research may be used to create more accurate lightning strike risk maps and formulate effective mitigation techniques, such as the placement of lightning rods on essential buildings and the distribution of early warning information to the public.

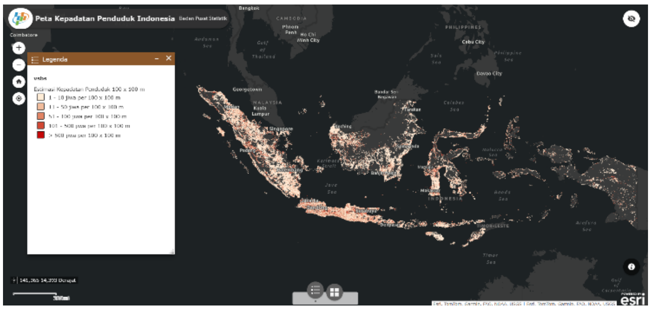

Fig. 3. Indonesian population density map

The susceptibility of Java Island to lightning strikes is enhanced by its high population density, as seen by the population density chart. The danger is enhanced by variables like the existence of tall buildings, extensive electrical infrastructure, and high levels of human activity in metropolitan environments. Agricultural practices and the existence of scattered communities persist in making rural regions susceptible, although their diminished population density. In addition to population density, social vulnerability variables such as public awareness and access to information must be considered. Thus, assessing population density is an essential first step in identifying areas that need enhanced lightning strike risk mitigation measures.

3.2 Risk Scale-Based Data Processing

An investigation was conducted to establish a predictive model for lightning density in Indonesia, examining the correlation between predictor variables—land use, topography, and rainfall—and the response variable, which is lightning density (frequency of lightning strikes). This model employs a multiple linear regression methodology, represented by the following mathematical equation:

$$y=\beta 0+\beta 1X1+\beta 2X2+\beta 3X3+\epsilon \qquad (1)$$

Where y represents lightning density, $X1$ represents land use, $X2$ represents topography (elevation or slope gradient), and $X3$ represents rainfall. The regression coefficients ($\beta 1$, $\beta 2$, $\beta 3$) are estimated using historical data, which measures the effect of each factor on the frequency of lightning strikes. The process begins with the collection of lightning, land use, rainfall, and topography data. This data is then processed to handle missing values and standardize the necessary variables. Afterward, the linear regression model is constructed to link the predictor variables with lightning density. Coefficient estimation is performed through regression analysis, which is then evaluated using test data to assess the model's accuracy and validity. The results of this model are used to predict lightning density in unobserved areas, which are then mapped to generate a lightning strike risk map. This map displays areas with high, medium, and low lightning strike risks, which can be used as a tool for mitigation planning and early warning systems based on spatial analysis.

3.3 Prediction Model

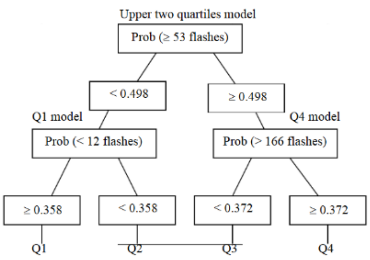

Fig. 4. Probability decision tree used to determine the predicted lightning quartile

This tree diagram depicts the quartile model, an effective tool for predicting lightning frequency. The model functions by categorizing the data into four quartiles based on the probability of lightning strikes. Every node in the tree represents a choice about the allocation of data based on a certain probability threshold. The quartile that best corresponds with the given data may be identified by following the trajectory from the tree's root to its leaves. The probability linked to each branch indicates the likelihood that the data is categorized inside that quartile. The model may be used to ascertain climatic circumstances or intervals with a high probability of lightning occurrence.

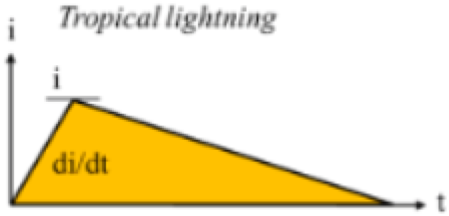

Fig. 5. Tropical lightning current waveforms in general

This graph depicts the standard waveform of a tropical lightning current. The chart illustrates that the electrical current rises exponentially at the onset of the stroke, attains a maximum in a short duration, and then diminishes gradually. The curve's initial slope is quite steep, indicating a present rate of change that is very high. This waveform has considerable ramifications for the design of lightning protection systems, since the system must endure very huge current surges in a short duration.

4. RESULT AND DISCUSSION

4.1 Lightning Strike Risk Analysis Results

Table 1. Level of threat of lightning strikes per province

Threat level	Province	Strike density (d)
medium	Aceh, North Sumatra, West Sumatra, Bangka Belitung, Lampung, Riau, Jambi, South Sumatra, Riau Islands, Banten, Jakarta, West Java, East Java, West Kalimantan, Central Kalimantan, East Kalimantan, East Nusa Tenggara, Maluku	d > 14
height	Riau, West Sumatra, South Sumatra, Bengkulu, West Kalimantan, Central Kalimantan, East Kalimantan, South Kalimantan, North Kalimantan, Central java, East Java, Bali, West Nusa Tenggara, East Nusa Tenggara, Gorontalo, Southeast Sulawesi, Maluku, East Nusa Tenggara.	8 < d < 14
light	Riau, South Sumatra, West Kalimantan, Central Kalimantan, Central Java, East Java, Bali, West Nusa Tenggara, East Nusa Tenggara, South Sulawesi, Central Sulawesi, West Sulawesi, North Maluku, Maluku, Papua	1 < d < 7

This paper develops a predictive analysis of human lightning strike risk by integrating geographical data and environmental parameters, including lightning strike distribution, population density, land use, and meteorological conditions such as rainfall and humidity. This research employs a lightning strike distribution map of Indonesia, providing an extensive overview of the nation's lightning dispersion pattern. Additionally, a land use map is used to examine the possible effects of land use alterations on the likelihood of lightning occurrences. The extent of human exposure to lightning dangers is dictated by population density statistics, but meteorological circumstances, like precipitation and humidity, provide insights into atmospheric components that affect lightning production. The lightning strike risk map is produced by integrating all previously stated variables into a prediction algorithm. This map offers insights into regions with elevated and reduced potential dangers of lightning strikes. Thus, the aim of this model is to provide a comprehensive knowledge of lightning strike risk distribution in Indonesia and to aid in the formulation of more effective risk reduction techniques.

4.2 Correlation Analysis

The objective of the correlation study among lightning, population density, and land use is to investigate the relationship between the frequency of lightning occurrences in a certain region and the impact of environmental elements and human activities.

In densely populated metropolitan regions, population density may affect vulnerability to lightning strikes. In densely populated areas, there is often a proliferation of infrastructure, particularly tall buildings that are vulnerable to lightning strikes. Thus, a potential positive association exists between the frequency of lightning strikes in the area and population density. The likelihood of lightning strikes may be heightened by intensified human activity, especially in densely populated regions, particularly if the infrastructure is deficient in adequate protective mechanisms.

The susceptibility of a region to lightning strikes is substantially affected by land use. Regions characterized by extensive open ground, such as rice paddies or grasslands, are more vulnerable to direct lightning strikes owing to the lack of natural or manmade obstructions that might reduce the probability of a hit. Conversely, places with a dense aggregation of tall edifices, such as urban centers or industrial zones, may be classified as high-risk owing to the elevated likelihood of lightning strikes. There exists a strong association between the incidence of lightning strikes and the kind of land usage.

The correlation between population density and land use is apparent, since places with high population density often transform into industrial or urban zones. The susceptibility of green spaces to electrical risks may be increased by urbanization, which transforms them into residential and commercial zones. Urban environments characterized by a high density of tall buildings and intricate infrastructure are more susceptible to lightning strikes, since these structures may act as focal sites for such occurrences.

The correlation analysis of the three variables—lightning, population density, and land use—indicates their interdependence and influence on the probability of lightning strikes. Lightning strikes are more probable in densely populated areas that see changes in land use, such as residential or industrial zones. Therefore, a comprehensive, data-driven strategy is necessary to successfully map and manage lightning strike hazards.

4.3 Predictive Model Development Using Decision Trees

This study used a probabilistic decision tree to predict quartiles of lightning strike frequency based on current environmental factors. The algorithm produces a probability distribution for each quartile, classifying regions into low, medium low, medium high, and high quartiles according to the likelihood of lightning strikes. The modelling approach accounts for the interplay of climatic factors, land use, and population density.

The results of the modelling reveal that areas that are characterized by high population density, urban land use, and tropical climatic conditions, such as high humidity, are likely to be in the high quartile, which indicates that there is an increased risk of lightning strikes. However, locations that are characterized by low human density, natural land use, and dry climatic conditions often dwell in the lowest quartile, indicating a decreased risk of lightning strikes. This is because these regions have a lower risk of lightning strikes.

Verification of the predictions that are produced by the model is accomplished by comparing the model's accuracy to both historical and empirical data. A high degree of prediction accuracy has been shown by the decision tree model that was constructed, as demonstrated by the evaluation criteria, which include the area under the curve (AUC).

5. CONCLUSION

This research effectively created a prediction model for the danger of lightning strikes to people by using data on lightning strike distribution, population density, land use, and meteorological variables. The model is based on geographical analysis and environmental variables. The study indicates that the danger of lightning strikes is considerably influenced by climatic elements such as humidity and rainfall, alongside population density and land use patterns, which dictate the level of human exposure to the hazard. In highly populated areas with significant lightning activity, such as Java and Sumatra, the generated risk map delineates locations with elevated danger potential. This approach has the capacity to underpin more focused and evidence-driven lightning hazard reduction, while also advancing sustainable spatial planning.

To improve the flexibility of prediction models to atmospheric dynamics and climate change, more study is recommended to include temporal data on lightning activity. Moreover, the precision of predictions and their application across various geographical scales will be improved by validating the model via comprehensive field data collecting. The findings of this study can assist the government and stakeholders in formulating mitigation policies that encompass the implementation of lightning protection systems in high-risk zones and educational initiatives that raise public awareness regarding the dangers and self-protective strategies related to lightning strikes.

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