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Investigating Lightning Stroke Variability and Ground Stroke Density in Peninsular Malaysia: A Statewise Comparative Study of Fatality Trends

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Abstract

This study investigates the spatial variability of lightning stroke occurrences and their associated fatality rates across the 12 states of Peninsular Malaysia from 2019 to 2023. A total of 8,427,391 cloud -to-ground strokes were analyzed using data obtained from the Vaisala GLD360 network and processed by ArcGIS Pro with total of 130 fatalities. The western region demonstrated the highest lightning fatalities with Selangor and Kuala Lumpur / Putrajaya with the maximum GSD value 3,470,455 strokes km-2 yr-1 with 16.7 fatalities per million strokes. Despite recording the largest stroke total with 1,212,345 strokes, Johor had a comparatively low risk with 28.3 deaths per million strokes with the maximum GSD value 1,360 strokes km-2 yr-1 due to higher population preparedness and infrastructure resilience. However, smaller northern states such as Perlis the maximum GSD value 22,294 strokes km-2 yr-1 with 200 fatalities per million strokes and Pulau Pinang the maximum GSD value 13,003 strokes km-2 yr-1 with 100 fatalities per million strokes faced disproportionate risks and highlight the impact of demographic exposure and limited protective measures. The correlation findings which is lightning strokes count versus land area, R2 =0.7545; lightning strokes count versus fatalities, R2 = 0.3631 explain that the lightning

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occurrence is driven by the geographical scale while fatality rates governed by socio environmental vulnerabilities.These findings provide a detailed statewise comparative assessment and highlight the need for targeted mitigation strategies to improve lightning safety awareness in high risk regions.

1. Introduction

Peninsular Malaysia is in Mainland Southeast Asia on the southern part of the Malay Peninsula and separated from East Malaysia on the island of Borneo by the South China Sea. Peninsular Malaysia is recognized as one of the most lightning-prone areas globally, where lightning activity represents a significant geophysical hazard in tropical regions. [1] The frequency of lightning strokes has implications for public safety, infrastructure resilience and economic activities particularly in sectors such as power transmission, aviation and agriculture. [2]Although prior research has extensively characterized lightning climatology and ground flash density (GSD) and ground stroke density (GSD) for instance, GIS-based mapping or yearly data identifying seasonal and regional hotspots [3] There remains a lack of empirical, state wise analyses that directly link the lightning strokes patterns to actual fatality outcomes. In Peninsular Malaysia, lightning is a significant atmospheric danger, and high ground stroke density has been connected to power disruptions, property damage and fatalities.

The GLD360 network provides near real-time stroke monitoring by integrating data from a wide range of worldwide sensors, as shown in Fig. 1 (XWeather Interactive). For hazard monitoring, one of the most reliable long-range lightning detection systems is the Vaisala Global Lightning Dataset (GLD360). The network can triangulate lightning discharges with high spatial precision using a hybrid approach that combines Time of Arrival (TOA) and Magnetic Direction Finding (MDF). GLD360 offers reliable data coverage in both land and water regions, with a median location precision of 2–5 km and a reported detection efficiency of over 70% [4], [5] A more thorough understanding of lightning dispersion is made possible by this global-scale dataset, which overcomes the drawbacks of localized networks, especially in areas with a dearth of ground-based sensors. In addition to its technological advantages, the dataset is being used more in early warning systems, climatological research, severe weather forecasting, and disaster risk assessments. GLD360 provides vital input for mapping lightning hazards in Malaysia, where dense populations and frequent thunderstorms coexist. This supports not only scientific research but also policy development and infrastructure protection [6], [7], [8].

Despite this, state-level analyses that relate lightning stroke variability to trends in fatalities still have gaps. Little research has looked at comparative risk patterns throughout Malaysia's states; most previous studies have concentrated on lightning climatology, spatial distribution, or case-specific occurrence reports. Because of variations in population exposure, awareness, and infrastructural resilience, smaller states with lower stroke numbers may nevertheless have disproportionately high death rates, making such assessments crucial. Closing this gap is essential to creating lightning mitigation plans tailored to each state. In order to correlate these findings with state-level mortality records, this study examines the ground stroke density and lightning stroke variability in Peninsular Malaysia between 2019 and 2023. The analysis measures stroke density, fatality rates per million strokes, and correlation trends with demographic and geographic parameters using GLD360 stroke data combined with ArcGIS Pro. The results are intended to improve knowledge of lightning-related hazards in Malaysia and offer practical advice for risk control, power system dependability, and community safety planning.



Fig. 1 *Vaisala XWeather interactive*

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2. Methodology

Fig. 2 shows the flow chart of state-wise analysis in Peninsular Malaysia based on lightning data and fatality data. The lightning data is recorded by the data collection of lightning strokes from Vaisala GLD360 and the data must be filter out from 2019 to 2023 for 5 years studies to demonstrate the behavior of the lightning strokes densities with another parameter. Then, clip the latitude and longitude for the Peninsular Malaysia together with 12 states. Then the fatalities data is the collection cases and the limitation time from 2019 to 2023 and categorized from each state in Peninsular Malaysia. For the analysis, split into six part to get the correlation between lightning stokes and fatalities which is GSD mapping, Lightning strokes (count), Fatalities, Area, Fatality rate and correlation.

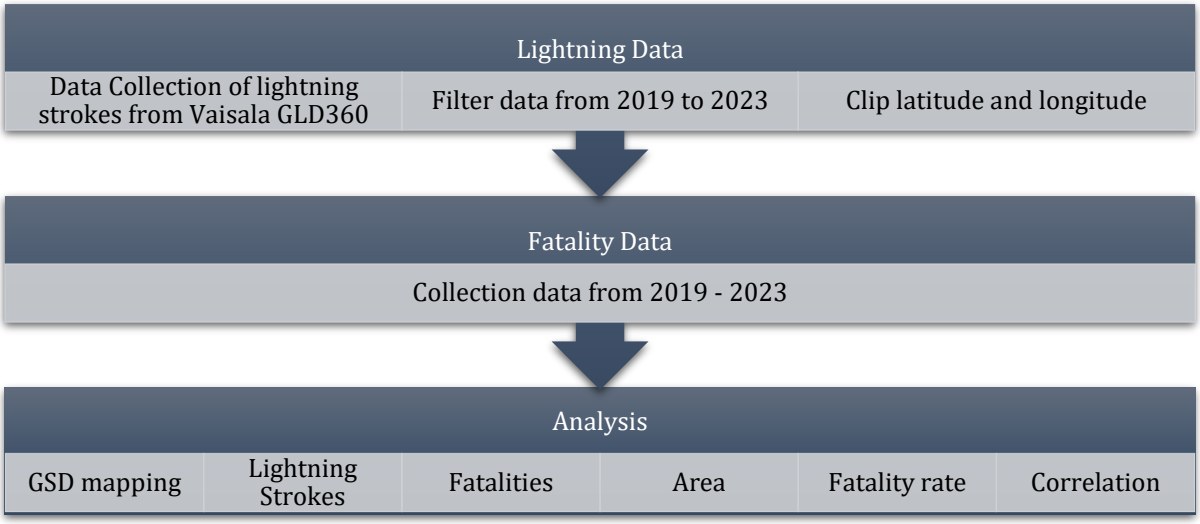


Fig. 2 *Flow chart of statewise analysis in Peninsular Malaysia*

Ground stroke density, which is typically expressed in strokes per square kilometer annually and the quantity of lightning strikes that contact the ground in a particular location over a specified time period. The following formula can be used to comprehend the connection between lightning counts and the area of interest [1]:

$$D = \frac{N}{A \times T} \quad (1)$$

Note :

D is the lightning density (strokes/ km2/year)

A is the area in square kilometres (km2)

N is the total number of lightning counts

T is the time in years over which the counts were recorded.

Several factors must be considered when calculating ground stroke density, such as the distribution of muzzle velocity, departure angle dispersion, and linear coefficient dispersion. Additionally, depending on the annual number of lightning days, the ground flash density and the number of lightning strikes to the ground per square kilometer can be computed using the relationships that are now in place [1]. Fig 3 shows the flowchart of visualization GSD maps analysis in Peninsular Malaysia. The dataset comprising of time, latitude, longitude, and stroke attributes was processed using ArcGIS Pro. All spatial data were projected into Kertau RSO Malaya (meters) coordinate system to ensure consistency with local basemaps. Data filtering was conducted to exclude records outside the study period and region of interest. JUPEM (Department of Survey and Mapping Malaysia) provided the state administrative boundaries and lightning strike locations, which were then stored in a geodatabase. Coordinates for latitude and longitude were trimmed to include Peninsular Malaysia. The aggregation of stroke counts by state was then made possible by integrating lightning stroke locations with state-level basemap data using the spatial join tool. Ground Stroke Density (GSD) maps were created with a grid cell size of 1 km^2 to measure

lightning activity. Spatial differences in stroke density were visualized using ArcGIS Pro's point density and symbology capabilities. To evaluate lightning distribution patterns, the resulting GSD maps were examined state-by-state. These findings were then compared with secondary source fatality figures[9], [10].

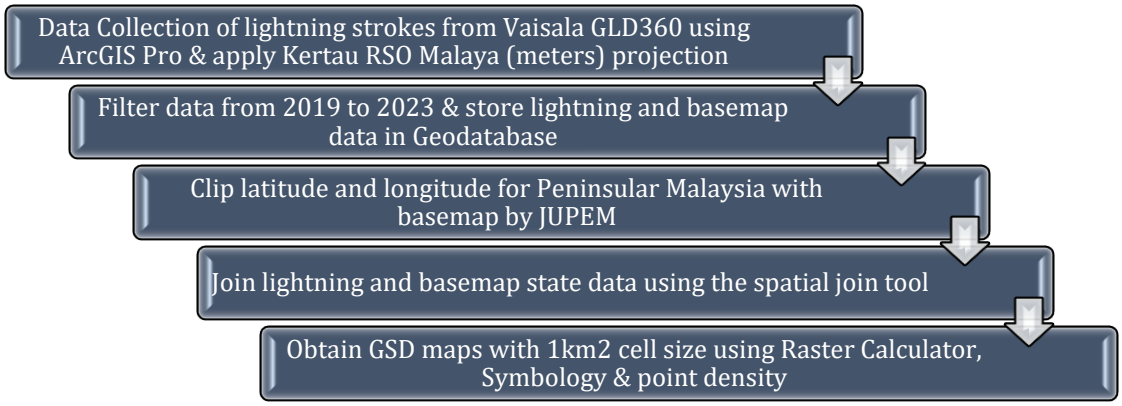


Fig. 3 *Flowchart of visualization GSD maps analysis in Peninsular Malaysia*

2.1 Study Area

Southeast Asia's Peninsular Malaysia is situated between latitudes 10 and 70 N and longitudes 990 and 1050 E with population is approximately 21 million, as Fig. 4 illustrates. The total area of Peninsular Malaysia is 131,802 km2, of which the largest state (Pahang) is 35,944 km2 (27.3%) and the smallest state (Putrajaya) is 49 km2 (0.04%). This data was added to the ArcGIS base map data collection by the Department of Survey and Mapping Malaysia (JUPEM). Malaysia's peninsula is well situated between the Straits of Malacca to the west and the South China Sea to the east. The local monsoon climate is greatly influenced by the watery surroundings. Because of its precise location in the equatorial zone of the Earth's surface, it experiences unique meteorological patterns, including the monsoon season.



Fig. 4 *Study area in Peninsular Malaysia*

At the highest level of modern lightning detection technology, the Vaisala Global Lightning Dataset GLD360 offers incredibly important insights into the geographic and temporal dynamics of lightning events. To detect and locate lightning discharges that happen both in-cloud and cloud-to-ground, GLD360 makes use of a vast global

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network of sensors [11], [12], [13]. The database offers a comprehensive picture of lightning activity in Peninsular Malaysia throughout the monsoon season with impressively accurate real-time data. Table 1 shows a sample of the original data from January to December 2019 till 2023. It includes all pertinent data, such as the date, time, latitude and longitude in decimal degrees, the peak current signal in kA, and the capacity to discriminate between clouds and the ground. The GLD360 data was used to determine the date, time, latitude (in UTC), longitude (in decimal degrees), and peak current (in kiloAmperes, with the polarity of either positive (+) or negative (-)). Lightning in cloud (C) and cloud-to-ground (G) localization was filtered and used G as part of this study for land in Peninsular Malaysia. The GLD360dataset was used to determine the date, time, and latitude (in UTC), longitude (in decimal degrees), and peak current (in kiloAmperes, with polarity of either positive (+) or negative (-)) [1], [14].

Table 1 *Sample of original lightning strokes data from Vaisala GLD360*

Date	Time	Latitude	Longitude	Current	C/G
01/12/2023	00:25.5	2.9348	100.0423	-17.5	G
01/12/2023	00:25.5	2.933	100.0294	-32.2	G
01/12/2023	00:41.5	4.4048	102.9751	-100.6	G
01/12/2023	00:41.6	4.3182	103.0624	-10.7	G
01/12/2023	00:41.6	4.3966	102.9022	-24.6	G
01/12/2023	00:41.6	4.3834	103.0649	-17	G
01/12/2023	00:41.6	4.4001	102.9839	-35.6	G
01/12/2023	00:41.7	4.3852	102.999	-49	G
01/12/2023	00:41.7	4.4166	103.059	-21.3	G
01/12/2023	02:52.4	4.3511	103.0585	-20.4	G

3. Results & Discussion

This section analyzes the lightning occurrence of Peninsular Malaysia from 2019 to 2023 as provided by Vaisala GLD360 with the fatalities data from 2008 to 2024. The analysis focuses on the 2019–2023 timeframe to establish a uniform comparison period for the two datasets. While historical fatality data covers the broader 2008–2024 period, it lacks continuous annual records. In contrast, highly frequent and continuous lightning stroke data are available for 2019–2023. Restricting both datasets to this shared five-year window ensures chronological alignment, data completeness, and statistical consistency across the variables analyzed. The result and discussion consist of GSD mapping analysis, lightning strokes analysis, fatalities analysis, fatalities rate and correlation analysis using Microsoft Power Bi, Microsoft Excel and ArcGIS Pro. There are spatial variations in the distribution of lightning strokes throughout state of Peninsular Malaysia from 2019 to 2023 as shown in Fig 5. The analysis with filled map and bar chart is using Microsoft Power Bi to see the variations of analysis with the lightning strokes in Peninsular Malaysia. Johor had the highest lightning strokes count with 0.99 million, followed by Pahang with 0.90 million and Perak 0.78 million. While states like Kuala Lumpur/ Putrajaya with 0.03 million together with Pulau Pinang and Perlis with 0.01 million recorded the lowest lightning count. This demonstrates the convective weather systems have a geographical impact with higher lightning strokes densities occurring in coastal and bigger landmass states [15], [16], [17], [18].

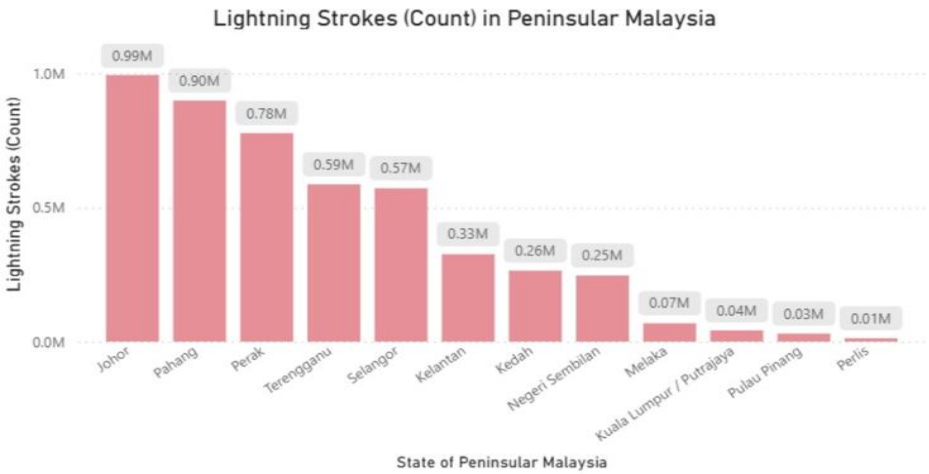


Fig. 5 *Analysis of lightning strokes (count)*

However, the fatalities trend different with the number of lightning strokes in Peninsular Malaysia as shown in Fig. 6. The analysis with filled map and bar chart is using Microsoft Power Bi to see the variations of analysis with the fatalities cases in Peninsular Malaysia. Johor had the highest fatalities with 28 cases recorded followed by Terengganu with 12 cases, Kedah with 15 cases and Selangor with 20 cases. Perlis had the fewest fatalities with 2 cases while other states including Melaka, Negeri Sembilan and Perak each reported 9 incidents. It's interesting to discuss that Pahang only recorded 6 fatalities while having 0.90 million lightning strokes that indicating weaker relationship between lightning occurrence and the likelihood of fatalities. This highlights the importance of preparedness, exposure and population density in determining the fatality outcomes [10], [19]

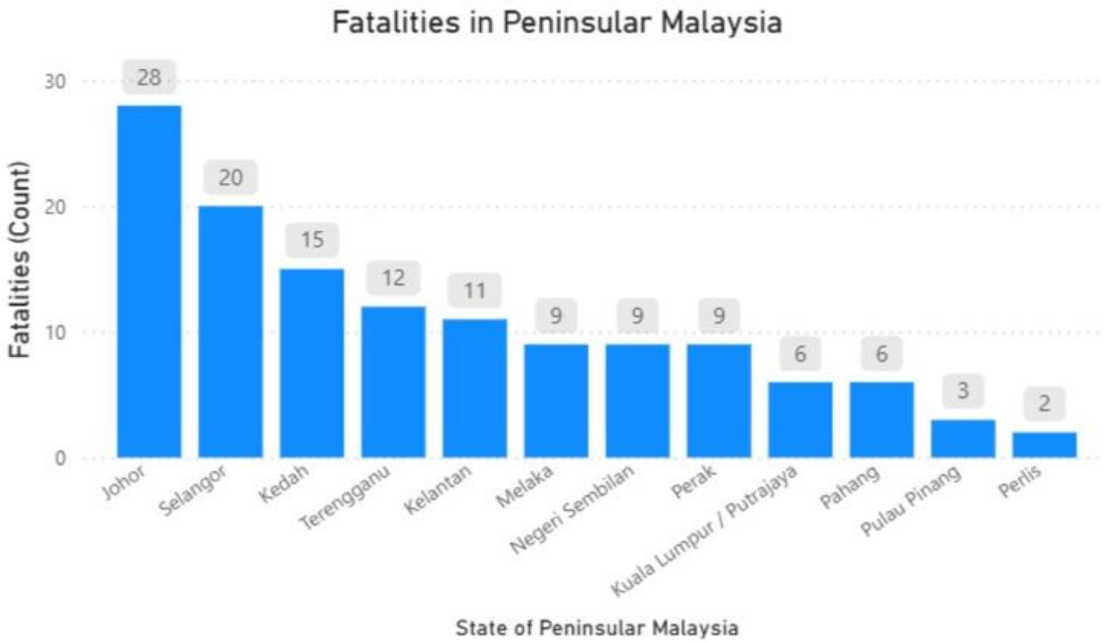
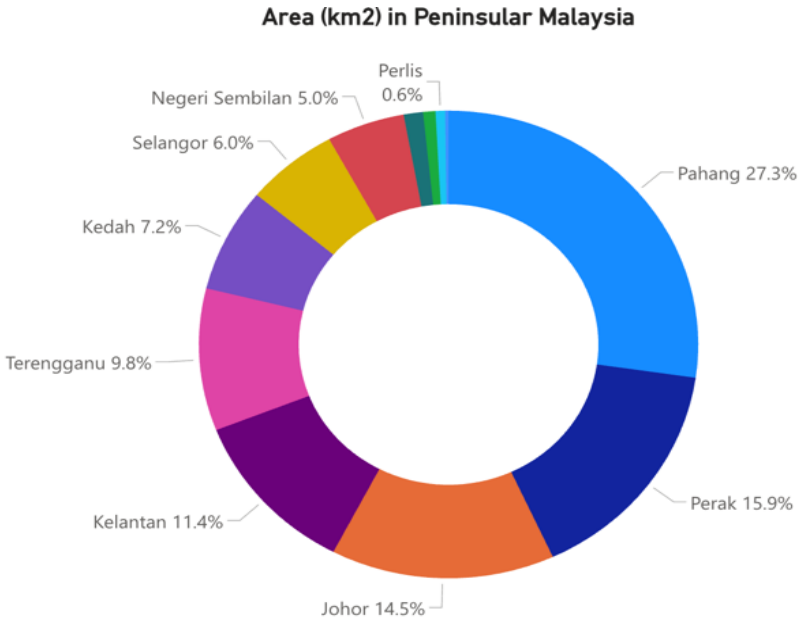


Fig. 6 *Analysis of fatalities in Peninsular Malaysia*

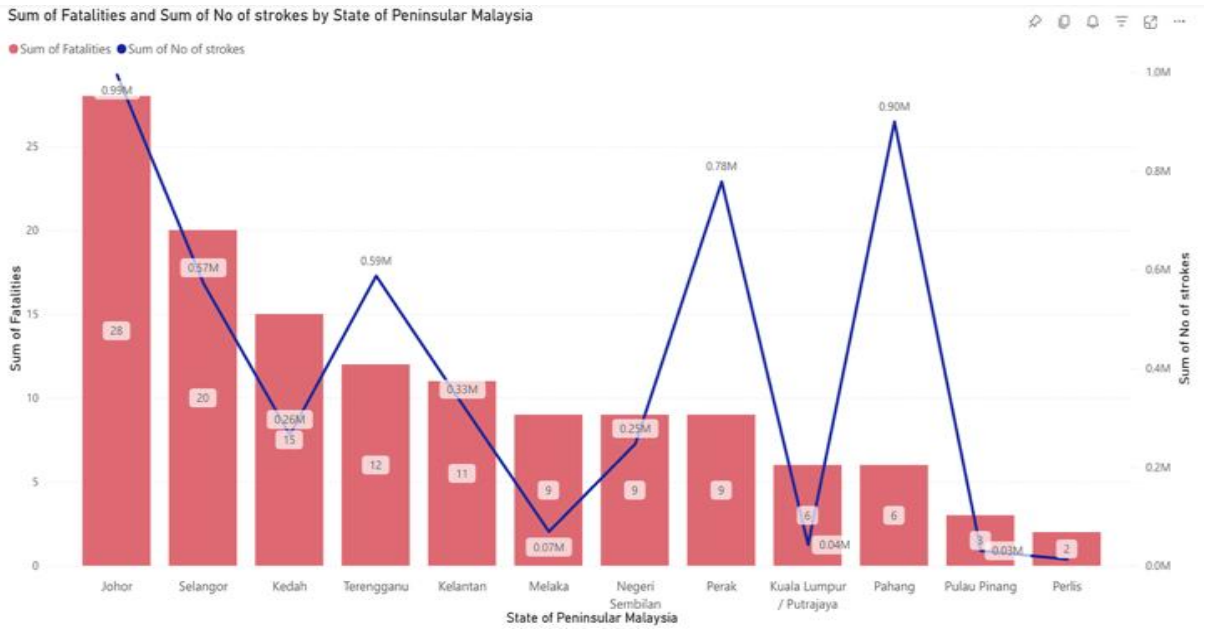
Fig. 7 (a) shows that Pahang is the largest state in terms of land coverage in Peninsular Malaysia with an area of 35.9km^2 (27.3%) and followed by Perak with an area 20.9km^2 (15.9%) and Johor 19.1km^2(14.5%), Pulau Pinang, Perlis and Kuala Lumpur/Putrajaya are the smallest state with area 1.1km^2(0.6%), 0.8km^2 (0.16%) and 0.3km^2 (0.06%). Due to their greater exposure to convective systems, larger states like Johor and Pahang had report more in lightning strokes occurrence. However, the urbanised states like Selangor exhibit higher mortality risks when fatalities are normalised against land area and lightning stroke counts. This implies that human outdoor activities, urbanisation and socioeconomic characteristics are more reliable indicators of lightning related fatalities than land size [9], [20], [21] Fig. 7(b) shows both proportional and correlations can be seen in

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the correlation between lightning strokes and fatalities. Johor had a fatality rate of 28.3 deaths per million strokes with 0.99 million strokes and 28 fatalities. Selangor had the greatest fatality rate at 35.1 deaths per million strokes although having fewer strokes in 0.57 million. In comparison, Pahang had 6.7 deaths per million strokes a lower rate with 0.90 million strokes but only 6 fatalities. Similarly, Perak reported 11.5 stroke deaths per million compared to 20.3 detahs per million in Terengganu. These results highlight the fact that human susceptibility elements such as population density, safety knowledge and infrastructure resilience ultimately decide casualty outcomes even when the lightning stroke density signals the intensity of environmental hazards [22], [23], [24]



(a)



(b)

Fig. 7 *(a) Area; (b) Lightning strokes versus fatalities in Peninsular Malaysia*

Table 2 show the fatality rate per million lightning strokes by state in Peninsular Malaysia. There is a different trend when states are ranked by the number of fatalities per million lightning strokes as opposed to the number of fatalities or raw stroke counts. Perlis and Kuala Lumpur/Putrajaya recorded only 0.03 million and 0.01 million strokes respectively but reported the highest fatality rates with 16.7 fatalities per million strokes. The dangers are also excessively high in relation in their lightning density in Melaka with 10.7 fatalities per million strokes and Pulau Pinang with 8.3 fatalities per million strokes. Larger states like Johor with 2.4 fatalities per million strokes

and Pahang with 0.6 fatalities per million strokes are lower than Kedah which has 4.8 fatalities per million strokes. These results highlight the significance of localised lightning safety methods and urban focused awareness campaigns as states with larger population densities and smaller land areas are more likely to experience fatalities per lightning occurrence [16], [18]. The fatalities rate or the normalized fatality risk (NFR) was calculated to account for state level differences in lightning stroke exposure. Expressing fatalities per million strokes in Eqn 2 was divided into 12 months to get annual value enable comparison across states of varying lightning exposure, ensuring a standardized risk representation. This metric was obtained using the formula:

$$NFR= \frac{F}{S} \; x\ 10\text{^}6 \tag{2}$$

Note :

F is the total number of fatalities in a state during 2019 to 2023

S is the total lightning strokes count during 2019 to 2023

Table 2 *Fatality rate per million lightning strokes by state in Peninsular Malaysia*

Rank	State	S : Lightning strokes (million)	F: Fatalities	NFR/ annual (per million strokes)
1	Kuala Lumpur/Putrajaya	0.03	6	16.7
2	Perlis	0.01	2	16.7
3	Melaka	0.07	9	10.7
4	Pulau Pinang	0.03	3	8.3
5	Kedah	0.26	15	4.8
6	Selangor	0.57	20	2.9
7	Johor	0.99	28	2.4
8	Terengganu	0.59	12	1.7
9	Perak	0.78	9	0.9
10	Negeri Sembilan	0.25	9	3.0
11	Kelantan	0.33	11	2.8
12	Pahang	0.9	6	0.6

The relationship between lightning strokes and state land areas in Peninsular Malysia is depicted in Fig. 8. It shows a comparatively high positive correlation with R^2 value of 0.7545. This suggests that because of their greater exposure to convective systems, states with greater geographic coverage land area like Pahang with 35.9 km^2 and Johor with 19.1km^2 are more likely to record higher numbers of lightning strokes. However, despite their lower land area, smaller states like Selangor and Kuala Lumpur/Putrajaya record disproportionately high casualty risks, therefore this link is unable to fully explain the disparities in fatality rates. This implies that although area is an important indicator of lightning density, human vulnerability cannot be explained exclusively by area [1], [2].

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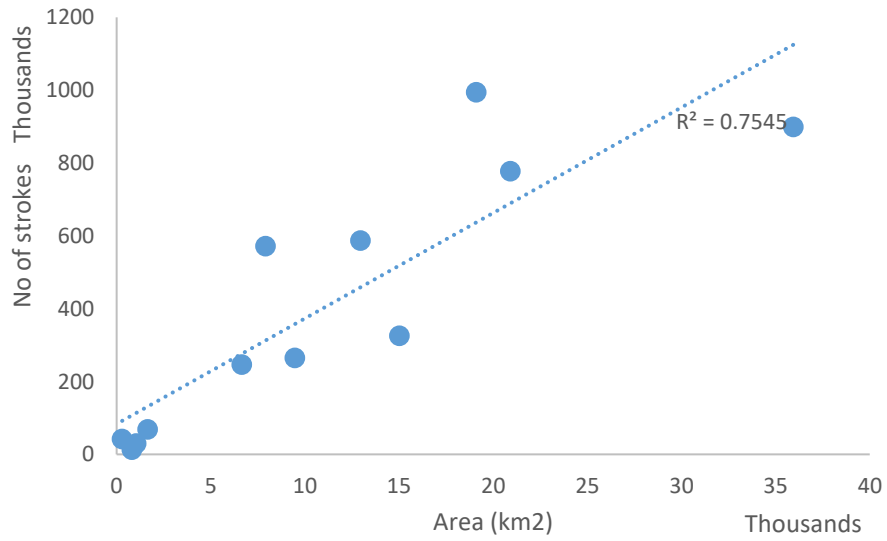


Fig. 8 *Correlation between lightning strokes and area (km2)*

The link between lightning strokes and fatalities on the other hand is relatively weak to moderate as seen in Fig.9 where the R^2 value falls to 0.3631. Some states including Selangor with 0.57 million of lightning strokes and 20 fatalities together with Pahang for 0.90 million of lightning strokes and 6 fatalities exhibit notable departures from the proportionate results of states with high lightning activity such as Johor with 0.99 million of lightning strokes with 28 fatalities. This disparity emphasizes the environmental and sociodemographic elements including urbanisation, population density, infrastructure resilience and awareness campaigns, influence the likelihood of lethal consequences from lightning strokes [1], [25] The significance of ground stroke density study in combination with sociodemographic exposure is highlighted by the discrepancy between the fatality outcomes and stroke density. State like Kuala Lumpur/Putrajaya with 200 fatalities per millions stroke which have fewer lightning strokes but the higher fatality rates, demonstrate that population susceptibility and natural hazard intensity are not only factors that affect lightning risk. Given that exposure risk per stroke increased in urbanized and highly inhabited areas, these findings highlight the necessity of focused lightning risk control techniques [26], [27], [28] According to this state wise comparison, Peninsular Malaysia's lightning risk is a result of both sociodemographic susceptibility and physical hazard variation. While smaller but densely populated states like Selangor and Kuala Lumpur / Putrajaya require tailored mitigation plans because to their disproportionately high fatality risk high stroke states like Johor and Pahang require ongoing monitoring due to their extensive geographic exposure. These results offer vital information for early warning systems, infrastructure design and risk management frameworks that need to be adjusted for community vulnerability and stroke density.

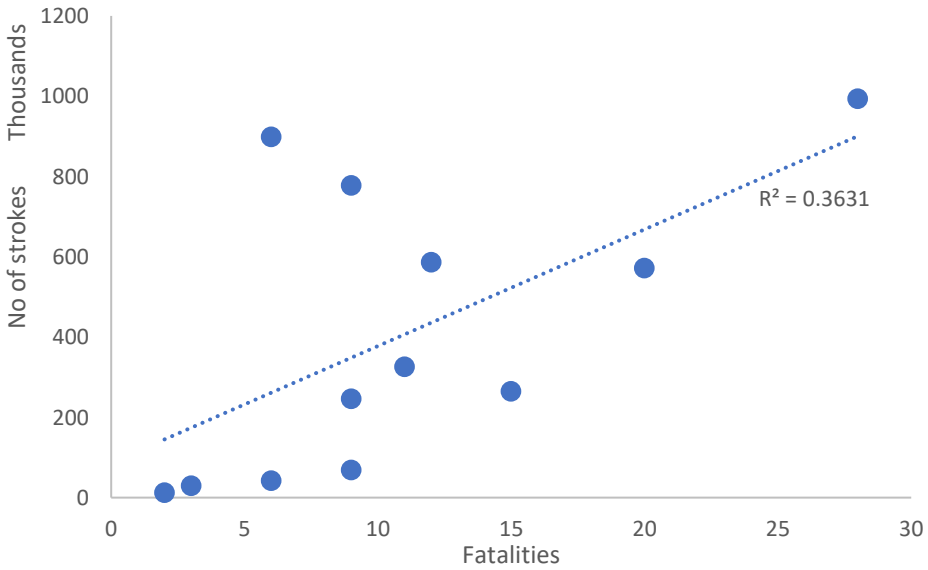


Fig. 9 *Correlation between lightning strokes and fatalities*

GSD Mapping demonstrate the analysis of lightning stroke activity in Peninsular Malaysia from 2019 to 2023 reveals distinct spatial variability in Ground Stroke Density (GSD) and fatality outcomes across different regions. Based on the Vaisala GLD360 dataset, more than 8.4 million strokes were detected over the study period. Johor, Selangor, and Pahang recorded the highest stroke counts, yet normalized fatality rates were notably higher in smaller and urbanized states such as Perlis, Pulau Pinang, Kuala Lumpur, and Putrajaya, where values exceeded 190–210 deaths per million strokes. These findings align with prior research that identified disproportionate lightning fatality risks in high-density urban regions despite moderate stroke frequencies [29], [30]. The Northern states demonstrate a significant GSD map in lightning risk. As seen in Fig.10 (a) to (d) clustering in northern states which is states of Perlis, Pulau Pinang, Kedah and Perak. The maximum GSD value in range from 1,135 to 22,994 strokes km-2 yr-1 with average of 92 fatalities per million strokes amplified by its small geographic size. Pulau Pinang displays similarity high lightning exposure with average of 5,599 strokes km-2 yr-1 with disproportionate fatalities linked to the urban industrial concentrating and coastal convergence zones. Widespread lightning hotspots with the maximum 1,445 strokes km-2 yr-1 are reported in Kedah but Perak especially in central area recorded intense density with the maximum 1,135 strokes km-2 yr-1. These findings support the previous evidence of regional scale lightning risk [1], [3] by showing the northern states, even though their smaller geographic size have higher chances of lightning fatalities due to concentrated population exposure in lightning prone locations.

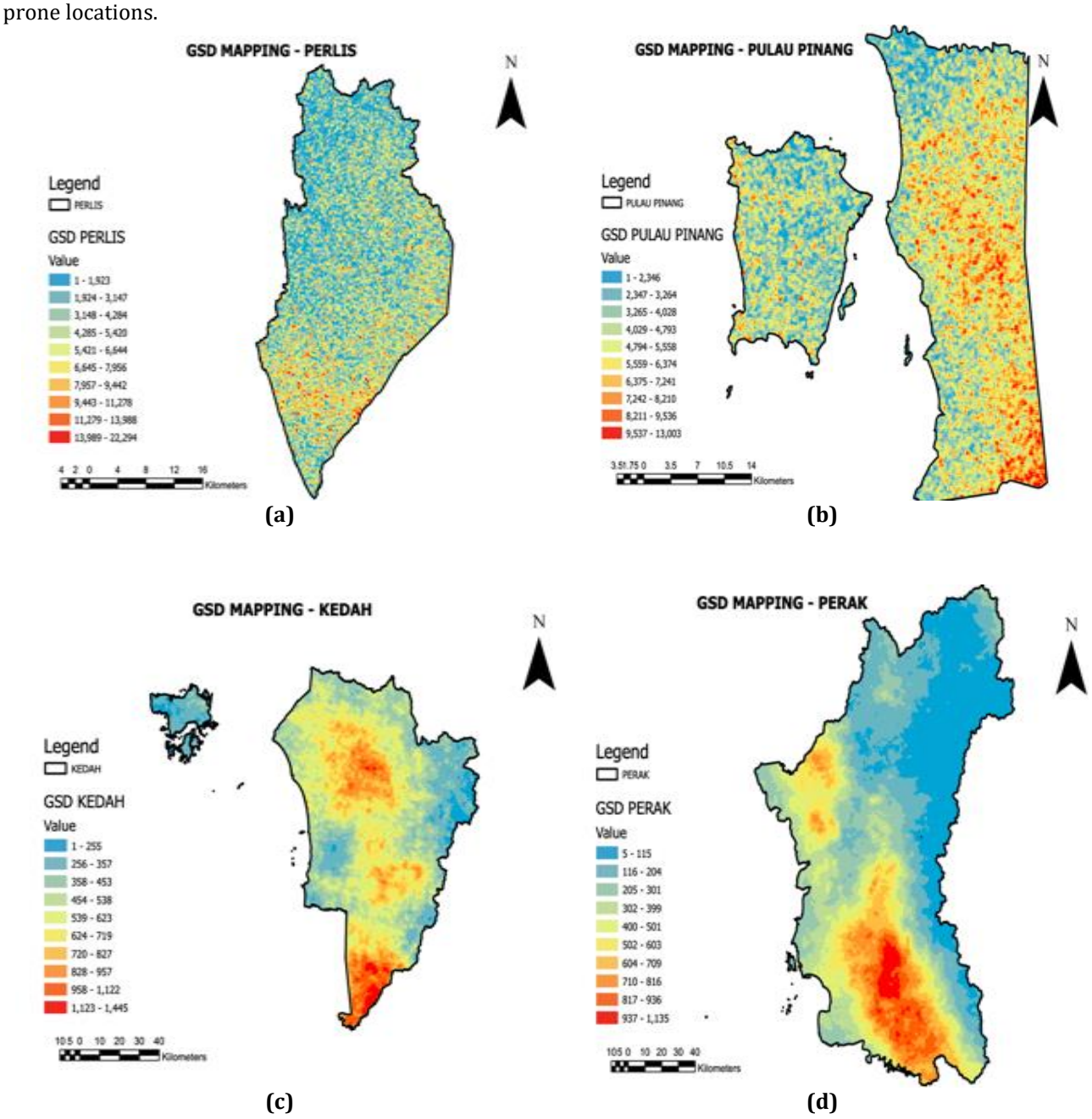


Fig. 10 *GSD mapping in Northern states of Peninsular Malaysia (a) Perlis; (b) Pulau Pinang; (c) Kedah; (d) Perak*

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The Eastern states exhibit the high lightning activity linked to Northeast Monsoon season as shown in Fig. 11 (a) to (c). Pahang recorded widespread GSD value with the maximum 399 strokes km^{-2} yr^{-1} particularly in central and southern area, while Kelantan reported dense clusters of GSD value with the maximum 816 strokes km^{-2} yr^{-1} in southern zones and Terengganu reported widespread in central zones with the maximum 1,568 strokes km^{-2} yr^{-1}. Despite these high stroke densities, the Eastern states records moderate fatality rates with average 10 fatalities per million strokes which can be attributed to larger land areas, lower population densities and reduced exposure similar with observation in other tropical regions [22], [23], [24].

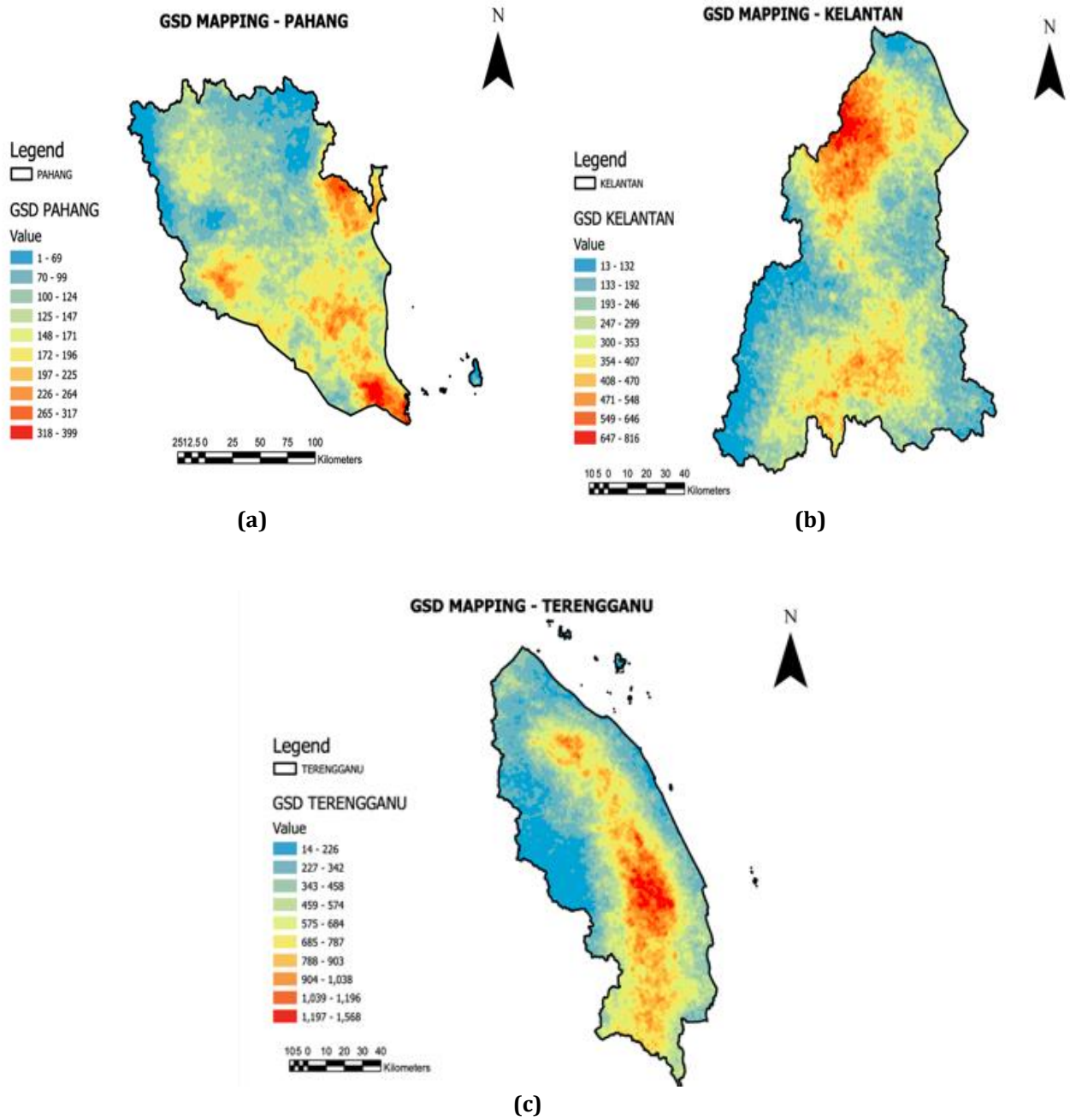


Fig. 11 *GSD mapping in eastern states of peninsular Malaysia (a) Pahang; (b) Kelantan; (c) Terengganu*

In the Southern states, Johor is the most lightning active state with stroke densities with the maximum 1,360 strokes km^{-2} yr^{-1} and the highest fatalities reported which is 28 cases and GSD mapping as shown in Fig.12. However, its normalised fatality rate remained comparatively low with 28 deaths per million strokes, explaining the denominator effect of high stroke counts on relative fatality ratios. Although Melaka and Negeri Sembilan reported moderate GSD intensities with the maximum 10210 and 3,517 strokes km^{-2} yr^{-1} but elevated relative

risks. This finding highlights the role of population density land use and socio-economic factor in shaping lightning fatality outcomes as similarly reported in prior lightning vulnerability studies [21], [22].

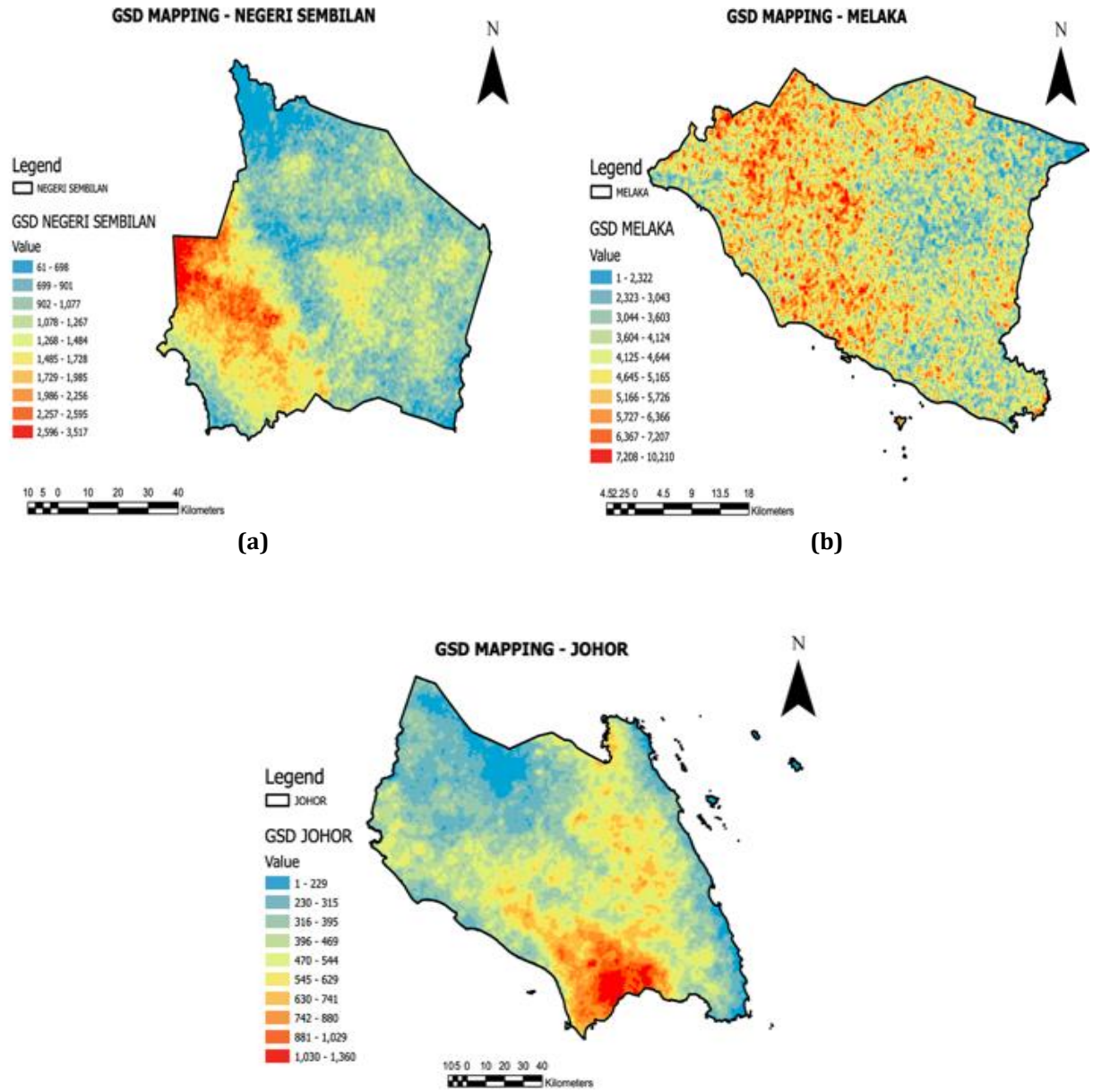


Fig. 12 *GSD mapping in southern states of peninsular Malaysia (a) Negeri Sembilan; (b) Melaka; (c) Johor*

Finally, the Western states such as Kuala Lumpur, Putrajaya and Selangor the highest GSD with range maximum from 5,488 to 3,470,455 strokes km-2 yr-1and higher fatality ratio within 57.7 into 200 in urban centre and GSD mapping as shown in Fig. 13. Kuala Lumpur and Putrajaya recorded normalized fatality rates exceeding to 200 deaths per millions strokes despite lower stroke counts compared to the larger states. However, Selangor reported one of the highest lightning strokes (count) with 0.55 million of lightning strokes exhibited a relatively lower normalized fatality rate. This suggests that the presence of urban lightning protection measures such as grounding systems, surge protection can be significantly reducing lightning casualties, consistent with earlier findings in urbanized Southeast Asia regions [9], [22], [31], [32], [33].

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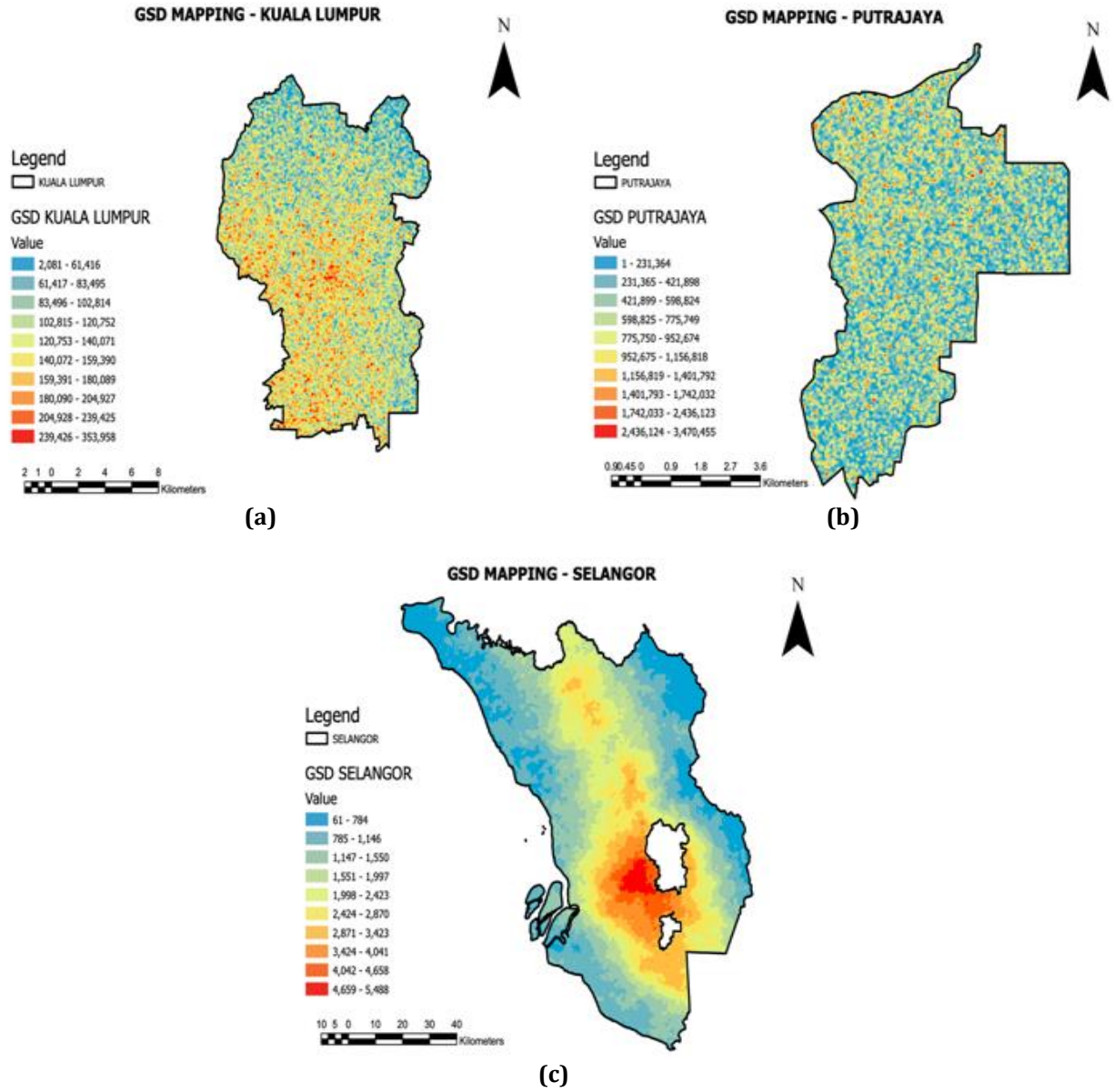


Fig. 13 *GSD mapping in western states of peninsular Malaysia (a) Kuala Lumpur; (b) Putrajaya; (c) Selangor*

Table 3 shows the list of states in Peninsular Malaysia with the spatial distribution of fatalities categorized into high, moderate and low risk areas. States as Johor in Southern states and Kuala Lumpur / Putrajaya in Western states are identified as high-risk areas with a recorded 10 risk index respectively. Moderate-risk regions with range 5 to 9 risk index, including Kedah, Selangor, Melaka, Kelantan, Terengganu, Negeri Sembilan, Perlis, Pulau Pinang account for 53% of fatalities with individual state counts ranging from 3 to 20. The low-risk zones of Perak and Pahang each recorded between 2 to 4 risk index with below 1 fatalities per million strokes. This quantification underscores the similar distribution of lightning-induced fatalities across Peninsular Malaysia reflecting both environmental exposure and population density affects with area [34] [35], [36].

Table 3 *Table of risk matrix per state wise*

State	Fatalities	NFR/annual (per million strokes)	Likelihood	Severity	Risk Index	Risk Level
KL+Putrajaya	6	16.7	5	2	10	High
Johor	28	2.4	2	5	10	High
Kedah	15	4.8	3	3	9	Moderate
Selangor	20	2.9	2	4	8	Moderate
Melaka	9	10.7	4	2	8	Moderate
Kelantan	11	2.8	2	3	6	Moderate
Terengganu	12	1.7	2	3	6	Moderate
Negeri Sembilan	9	3.0	3	2	6	Moderate
Perlis	2	16.7	5	1	5	Moderate
Pulau Pinang	3	8.3	5	1	5	Moderate
Perak	9	0.9	2	2	4	Low
Pahang	6	0.6	1	2	2	Low

Fig. 14 shows the lightning fatality risk matrix from 2019 to 2023 in Peninsular Malaysia and expresses fatality rate (per million strokes) using MATLAB with data in Table 3. Kuala Lumpur / Putrajaya and Johor classes under high absolute due to larger population exposure, urbanized states indicate diverse high vulnerability per stroke. This emphasizes that lightning safety management should not be uniform but tailored such as urban states require infrastructure-based protection for instance automated warning systems while rural or agricultural states (Perak and Pahang with low-risk states in green coloured) need behavioural interventions for instance awareness campaigns and safe work practices in different sectors. Such a matrix bridges the gap between meteorological hazard quantification risk management strategies, making the study more impactful for policy and disaster risk reduction planning same as previous studies[22], [37], [38], [39], [40], [41], [42]. By quantifying the risk matrix, this framework allows policymakers to prioritize state-specific interventions and resource allocation to mitigate and adapt Peninsular Malaysia's lightning related fatalities.

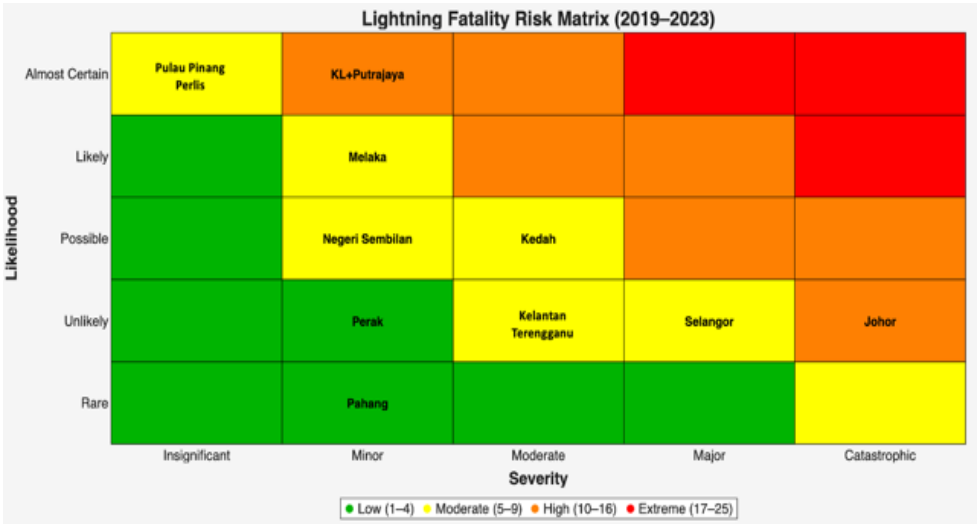


Fig. 13 *Risk matrix for lightning fatality in Peninsular Malaysia (2019 – 2023)*

Table 4 show that the summary for lightning strokes versus fatalities in Peninsular Malaysia based on this study. The state wise research demonstrates how land extent has a major impact on the distribution of lightning strikes. Two of the largest states, Perak (20,912 km^2, 16%) and Pahang (35,944 km^2, 27%), reported 777,617 (16%) and 898,917 (19%) lightning strikes, respectively. Larger states typically amass more lightning activity because of their wider spatial coverage, as evidenced by the positive association between area and stroke count (R^2 = 0.7545). Though smaller than Pahang and Perak, Johor (19,106 km^2, 14%) outperformed them with 994,225

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strokes (21%), demonstrating that climate and geography, notably coastal convection, are significant factors of lightning occurrence. Statistics on fatalities show that human vulnerability is not determined exclusively by the frequency of strokes. The largest number of fatalities (28 deaths; 22%) was observed in Johor, followed by Selangor (20 deaths; 15%) and Kedah (15 deaths; 12%). This indicates that exposure and population density have a significant impact on mortality results. The lesser connection (R^2 = 0.3831) between fatalities and stroke counts in contrast to the significantly stronger strokes area link supports this. Compared to more urbanised states, states with high stroke counts but comparatively low fatalities like Pahang (6 deaths) and Perak (9 deaths) suggest greater resilience or lower exposure density. Smaller and more urbanised states have excessive risks when normalised by total strokes. Despite having significantly fewer lightning strikes than larger jurisdictions, Kuala Lumpur/Putrajaya and Perlis stand out with extremely high fatality rates of 16.7 deaths per million strokes each (23%). Despite making a negligible contribution to the national stroke statistics, Melaka also shown increased risk, with 10.7 deaths per million strokes (12%). These findings show that lightning is a more serious threat in urban and semi-urban settings, and that states with compact, dense populations are more likely to experience per-stroke fatalities. Mapping the ground stroke density (GSD) provides additional information on the concentration of lightning in a given area. Due to their restricted geographical size, which magnifies stroke-per-unit-km^2 estimates, Putrajaya (3.47 million strokes km^{-2} yr^{-1}) and Kuala Lumpur (353,958 strokes km^{-2} yr^{-1}) have the greatest densities, significantly exceeding that of other states. In addition, Pulau Pinang has significant stroke intensity in relation to its tight topography, with 13,003 strokes/km^2/year. These findings support the interaction between lightning concentration, human exposure, and vulnerability and are consistent with high normalised fatality rates seen in small states. Overall, the results point to Peninsular Malaysia having two risk profiles. Compact urban states like Kuala Lumpur, Putrajaya, Perlis, and Melaka suffer the highest chances of stroke deaths, whereas large states like Johor, Pahang, and Perak lead in absolute stroke counts. This dichotomy highlights the necessity of state-specific mitigation measures, such as enhanced lightning protection systems in areas with large population densities and community education initiatives in states with high stroke rates. Reducing lightning-related deaths in Malaysia will require integrating GLD360-based monitoring with early warning and urban planning systems.

Table 4 *Summary of analysis for lightning strokes versus fatalities in Peninsular Malaysia*

Analysis	Statewise	Value	Percentage
Area (km^2)	Pahang	35,944	27
	Perak	20,912	16
	Johor	19,106	14
Lightning strokes (Count)	Johor	994,225	21
	Pahang	898,917	19
	Perak	777,617	16
Fatalities (cases)	Johor	28	22
	Selangor	20	15
	Kedah	15	12
Fatalities rate / annual (per millions stroke)	Kuala Lumpur / Putrajaya	16.7	23
	Perlis	16.7	23
	Melaka	10.7	12
Correlation (R^2)	Lightning Strokes Vs Area	0.7545	75
	Lightning Strokes Vs Fatalities	0.3831	38
GSD Mapping (strokes km^{-2} yr^{-1})	Putrajaya	3,470,455	NIL
	Kuala Lumpur	353,958	NIL
	Pulau Pinang	13,003	NIL

4. Conclusion

This study quantified lightning variability across Peninsular Malaysia from 2019 to 2023, identifying the spatial disparities in both GSD mapping and fatality outcomes. The western region demonstrated the highest lightning fatalities, with Selangor and Kuala Lumpur / Putrajaya with the maximum GSD value of 3,470,455 strokes km-2 yr-1, with 16.7 fatalities per million strokes. Despite recording the largest stroke total with 1,212,345 strokes, Johor had a comparatively low risk with 2.4 deaths per million strokes with the maximum GSD value 1,360 strokes km^{-2} yr^{-1} due to higher population preparedness and infrastructure resilience. However, smaller northern states such as Perlis the maximum GSD value 22,294 strokes km^{-2} yr^{-1} with 16.7 fatalities per million strokes and Pulau Pinang the maximum GSD value 13,003 strokes km^{-2} yr^{-1} with 8.3 fatalities per million strokes faced disproportionate risks and highlight the impact of demographic exposure and limited protective measures.

The correlation findings which is lightning strokes count versus land area, R^2 =0.7545; lightning strokes count versus fatalities, R^2 = 0.3631 explain that the lightning occurrence is driven by the geographical scale while fatality rates governed by socio environmental vulnerabilities. These quantified findings highlight two risk dimensions, first is western states such as Kuala Lumpur/Putrajaya and Selangor as lightning strokes density hotspots demanding the stronger protective standards, second is northern states such as Perlis, Pulau Pinang and urbanized states as fatality prone zones requiring focused public awareness campaigns and lightning safety education. The critical 130 fatalities in Peninsular Malaysia over five-year study period will be reducing by integrating Vaisala GLD360 detection data into national early warning systems together with enforcement of lightning protection infrastructure in Peninsular Malaysia.

Future recommendation for this study will enhance on the fatality data collection based on type of fatalities inclusive the likelihood and severity to model the risk assessment against with lightning event with the exact number of populations for each state in Peninsular Malaysia. Correlation analysis such as Poisson regression will be introduced to get more details on parameters lightning event with fatalities cases.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design****: Nur Azliza Ahmad, Mohd Zainal Abidin Ab. Kadir, Ungku Anisa Ungku Amiruldin, Nik Norasma Che Ya, Helmi Zulhaidi Mohd Shafri, Mohd Faris Ariffin, Nurul Husniyah Abas;* ***data collection****: Nur Azliza Ahmad, Mohd Zainal Abidin Ab. Kadir;* ***analysis and interpretation of results****: Nur Azliza Ahmad, Mohd Zainal Abidin Ab. Kadir;* ***draft manuscript preparation****: Nur Azliza Ahmad. All authors reviewed the results and approved the final version of the manuscript.*

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