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Spatiotemporal Variability of Lightning Activity over the Railway Network in Sri Lanka with Special Attention to the Proposed Suburban Railway Electrification Network

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Abstract: This study is oriented towards the investigation of the spatiotemporal variability of the lightning activity over the railway network in Sri Lanka using -lightning data from 1998 to 2014 that were downloaded from the database of Lightning Imaging Sensor (LIS) onboard NASA's Tropical Rainfall Measuring Mission (TRMM). The study has also been extended to study the lightning activity over the proposed suburban railway electrification network. GIS was used to conduct an annual and seasonal analysis of the railway network, which consists of nine major railway lines, to identify vulnerable stations and segments. The average annual lightning flash density over a 1447 km-long railway network of Sri Lanka varies between 5.08–16.58 flashes/(km^2 year). The railway lines run across the western and southern regions of the country have been identified as being in areas with higher lightning activity. In comparison to other railway lines, the Kelani Valley line in the Colombo district and Colombo-Maradana to Polgahawela segment of the Mainline are particularly vulnerable to lightning activity. These areas have also been recognized as regions with higher population density. The proposed 102 km long railway electrification network in Sri Lanka is also within higher population density segments, with higher lightning flash density values between 10.55–16.53 flashes/(km^2·year). As a result, to improve the operational efficiency of the proposed electrification network, a fully coordinated lightning protection system in accordance with the findings of this study is strongly suggested.

Keywords: lightning; lightning safety; railway network; railway safety; transportation safety

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1. Introduction

Lightning is a dangerous, strong, amazing, and well-known naturally occurring phenomenon on the earth [1]. In 1752, Benjamin Franklin was pioneered in observing the nature of lightning activities, simply by using a kite and string. At that time, he had proved the lightning phenomenon with a simple experiment explaining that thunderstorms are capable of forming electricity and the lower side of the cloud possesses a negative charge. Currently, satellites play a crucial role in collecting and recording lightning flashes all over the world. These satellites have the potential of recording about 3 million flashes around the world in one day [2].

Lightning activities are producing influential vulnerabilities to the entire world. Mainly, lightning can cause severe damages to properties, can generate hazardous impacts on power and communication lines, and sometimes leads to conflagrations over the country. These imply the necessity of studying and analyzing lightning activities over the country to mitigate the lightning hazard and to alter the existing lightning protection system in an apposite way for a particular region as a key solution to reduce the lightning impacts [3]. Furthermore, community awareness about the hazardous influences of lightning, precautionary measures, and highly active periods of lightning is critically important to minimize the influences of lightning.

When considering cloud to ground lightning, besides negative lightning, positive lightning is intensively hazardous as it frequently strikes away from the rain core, either ahead or behind the thunderstorm, as far as 5 to 10 miles (8–16 km) from the storm. Damages due to surge voltages can occur over a radius of up to 2 km from the location of the lightning strike [4].

Other than the general influential lightning hazards, lightning activities may have posed greater threats to the communication signal system and the contact network of the railway. Therefore, economical and rational lightning protection methods are highly demanded. Comprehensive awareness of the distribution of lightning activities is one of the apposite ways to design and introduce lightning protection systems to the railways.

The railway network in Sri Lanka is designed to join the main population centers, tourist destinations, and commuter rail servings to Colombo commuters. The railway network of Sri Lanka consists of nine major lines: the Batticaloa line, Coastal line, Kelani Valley line, Northern line, Mannar line, Matale line, Puttalam line, Trincomalee line, and the Mainline. The Sri Lankan Railway (SLR) network extends to a 1447 km distance and is a 1676 mm broad gauge. SLR has divided the railway network into three functional centers at Colombo-Maradana, Nawalapitya, and Anuradhapura. The majority of lines account for single railway lines, while some have a double railway line. In Sri Lanka, railway transportation facilitates the transportation of about 360,000 passengers daily by 366 trains between 320 railway stations all over the country [5]. This mode of transportation has become the most popular and convenient mode of transportation among the general public in Sri Lanka. From a general point of view, the rail transportation system in Sri Lanka is not solely a mode of passenger transportation. It is also a mode of essential good transportation such as oil and other required materials for the industrial zones. Currently, the railway network comprises diesel locomotives, electronic signal networks controlled by centralized traffic control, and is monitored by an interlocking colored light signaling system.

A previous study extensively emphasizes that lightning has had a hazardous influence on equipment on the railway network, such as track circuit systems with rectifiers and relays, booster transformers, wayside telephone systems, cables, communication equipment, signal circuits, overhead conductor systems, etc. [6–11]. As both the overhead conductors and railway tracks can be addressed as Multi-conductor Transmission Lines (MTL) above the ground, electromagnetic induction due to lightning activities could cause to damage the railway network and reduces the effectiveness of the railway transportation.

Conversely, air pollutants from railroad diesel locomotives arise as one of the most critical air polluting sources. These pollutants account for both direct and indirect effects on weather and the atmosphere [4]. Long-term aerosol pollution is a major influential factor, which affects cloud formation processes as well as rainfall. Aerosol loading in the atmosphere tends to increase lightning flashes [12,13]. The literature emphasizes that for the incremental trend of lightning flash rate, the high surface pollution near the storm environment, mainly due to increased NOx and also surface ozone accumulation over the Kolkata station in India, is highly affected [14].

The space-based Lightning Imaging Sensor (LIS) instrument effectively detects the distribution of lightning activity in the Tropical Rainfall Measurement Mission (TRMM) by NASA [15–17]. Furthermore, data can specifically be exploited to study storm convection, dynamics, and microphysics, which can be addressed as mesoscale phenomena [16]. This study is oriented toward the investigation of the total lightning over the railway network in Sri Lanka in the aforementioned period using the TRMM data. Furthermore, at present, the Sri Lankan government is fulfilling and authenticating major requirements to launch a project to construct the potentially electrifying suburban railway network by centering the

Colombo-Fort and Colombo-Maradana railway stations. Therefore, consideration of the spatiotemporal variability of lightning activities and variation trends over the country is a critical matter of concern, which can assist to build up the construction plans [18–21].

2. Materials and Methods

2.1. Study Area

Geographically, Sri Lanka is bordered between latitudes 5° and 10° N and longitudes 79° and 82° E (Figure 1). The total area of the country expands over a landmass of 65,610 km^2. According to the estimation of the Department of Census and Statistics in Sri Lanka, the Sri Lankan population in 2019 is approximately 21.8 million [22]. However, Sri Lanka's transport network is highly dense, with the railways being the most important, as they significantly contribute to freight and passenger transport. Although the total length of the railway line is 1447 km, it supports the daily travel of millions of people, especially in the Western Province. The administrative hierarchy of the country diverges as Provinces, Districts, Divisional Secretariat Division (DSD), and Grama-Niladari Divisions (GND). The railway network is spread over all the districts of Sri Lanka except Moneragala, Ampara, and Ratnapura. Lightning occurrence in Sri Lanka coincides primarily with monsoon rainfall; during this time, disturbances of railway signals in Sri Lanka may probably increase. There are four major monsoon seasons in Sri Lanka, i.e., First Inter-Monsoon (FIM-March to April), South Western Monsoon (SWM-May to September), Second Inter-Monsoon (SIM-October to November), and North Eastern Monsoon (NEM-December to February). However, the railway network is more effective in connecting administrative regions as well as economic hubs of Sri Lanka, especially as the railway network extends across different geographies (from plains to high slopes) and climatic zones (Wet, Dry, and Intermediate zones). These climate zones are categorized based on the annual rainfall received in the respective geographic area.

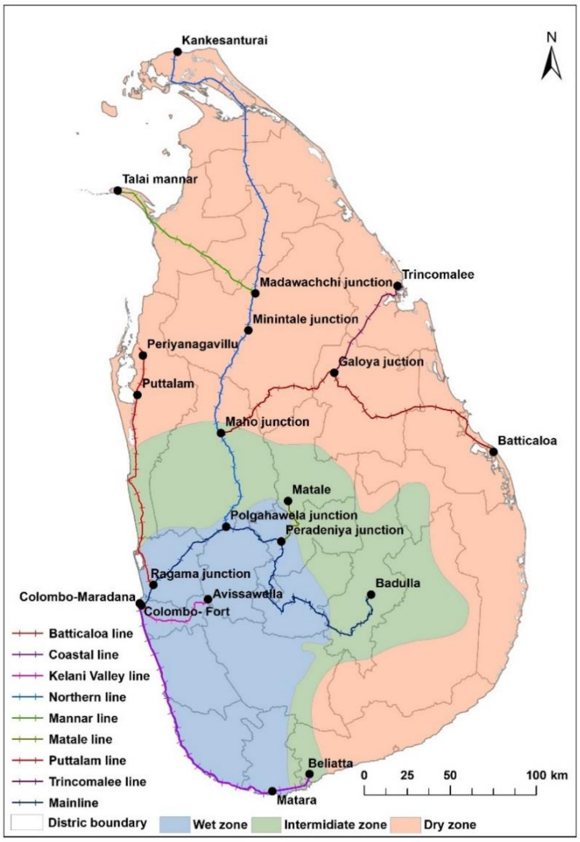

Figure 1. Study area with the railway network of Sri Lanka.

2.2. Lightning Data and Population Data

Remotely sensed lightning data recording in NASA are mainly accomplished by the space-based instrument of Lightning Imaging Sensor (LIS) on the TRMM. The LIS instrument was discovered in 1990 and the use of the instrument dates back 17 years from November 1997 to April 2015. The LIS on TRMM lightning data from 1998 to 2014 were used to analyse the spatial variability of the lightning flash density over the railway network of Sri Lanka. The satellite data collection procedure for lightning data were in accordance with the previously reported studies [19–21]. According to the previous study, the aforementioned satellite data have a 3 km to 6 km resolution and the detection efficiency lies within the range of 69% to 88% [16]. The LIS instrument is capable of detecting the time of occurrence, measuring the radiant energy, and determining the lightning events with the location within the field of view of the satellite. These data can be precisely used to obtain the lightning flash density, which is a profound parameter to study the spatiotemporal variation and lightning risk over a particular area. Further information about the rail transportation network in Sri Lanka was obtained from Railway Department, Sri Lanka [23].

The WorldProp data were used as the population data source in this study that was developed by the WorldProp project (https://www.worldpop.org (accessed on 1 June 2022)). The WorldProp datasets provide annual gridded population and demographic data for 2000–2020, with a spatial resolution of 100 m. WorldPop's input variables also use the latest official census population data from countries and a wide range of other spatial support databases.

2.3. Methodology

Lightning flash density raster maps were generated based on the aforementioned lightning satellite data. Figure 2 shows the descriptive overview of the methodology used in the study. Equation (1) has been utilized to calculate the annual average lightning flash density and seasonal lightning flash density using LIS data, which were associated with $0.2^0 \times 0.2^0$ latitude and longitude grids in accordance with the previous studies [21,24,25].

$$\mathit{Flash\ density}\left(\text{flashes}/\left(\text{km}^2\cdot\text{year}\right)\right) = \frac{\sum \text{flashes}}{22\text{ km}\times 22\text{ km}} \times \frac{24\times 3600}{2\times 80} \times \frac{1}{\text{years}} \quad (1)$$

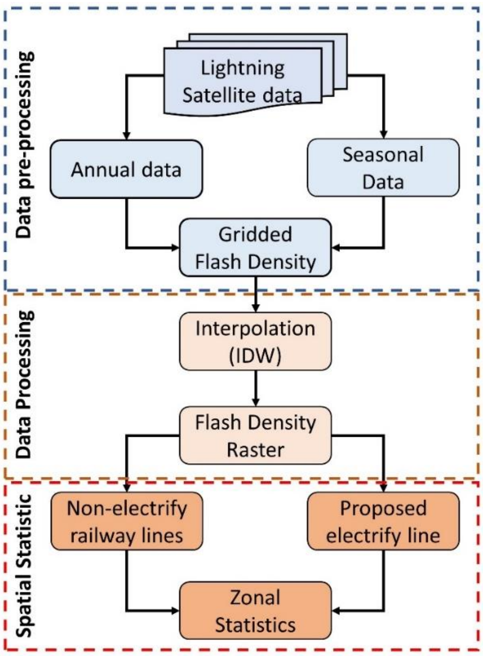

Figure 2. Methodology flowchart of the study.

Then, calculated lightning flash density values were interpolated by utilizing Inverse Distance Weighting (IDW) in the Geographic Information System (GIS). The lightning activities over the railroads were visualized and analysed at a 5 km horizontal distance from the road using 5 km buffers for both sides of the road. Areas high in lightning activity were identified and the variation of lightning flash density among the roads in these high-lightning activity locations in the country was analysed annually and seasonally by using GIS. GIS was used to generate the relevant buffers for the railway network to analyse the spatial variation and to obtain descriptive statistics such as maximum, minimum, average, and standard deviation (STD) using zonal statistics.

3. Results

The spatial variability of lightning over the railway network of Sri Lanka is presented in this section. Moreover, the variability of lightning activities over the nine railway lines were considered separately for a period of 17 years from 1998 to 2014.

3.1. Spatial Variability of Annual Lightning Flash Density over the Existed Railway Network

Figure 3 presents the spatial variation trend of the lightning flash density along with the railway network and the disparity of lightning flash density along the railway line at each point of 1 km distance from 1998 to 2014. Table 1 shows the extracted information of recorded maximum flash density on each railway line. According to the spatial variability of lightning flash density over the railway network, Kelani Valley is more vulnerable to lightning activities than the other railway lines. It extends from Colombo to Maradana East to Avissawella, which extends up to 30 km from Colombo. According to Figure 3 and Table 1, along this railway line, the maximum lightning flash density of 24.13 flashes/(km^2·year) was near the Avissawella railway station (6°56′41″ N/80°12′00″ E). Operations at Seethawaka Export Processing Zone and power stations installed within the region may be significantly influenced by a rise in lightning activities over the region.

Table 1. Distribution of the maximum annual lightning flash density (flashes/(km^2·year)) on each line of the railway network of Sri Lanka.

Railway Line	Maximum Flash Density *	Location (N/E)	Nearest Station
Batticaloa line	10.82	7°49′41″/80°17′52″	Maho junction
Coastal line	12.19	8°56′01″/79°51′01″	Colombo-Fort
Kelani Valley line	24.13	6°56′41″80°12′00″	Avissawella
Northern line	17.32	7°20′24″/80°18′01″	Polgahawela
Mannar line	7.85	8°40′15″/80°18′17″	Cheddikulam
Matale line	8.80	7°26′26″/80°37′44″	Matale
Puttalam line	22.82	7°02′09″/79°54′43″	Ragama
Trincomalee line	8.80	8°09′55″/80°53′12″	Galoya
Mainline	22.27	7°02′06″/79°55′12″	Ragama

Units: * flashes/(km^2·year).

Moreover, significantly, more lightning activities had been recorded over the Coastal line, Puttalam line, and Mainline. Starting from Colombo-Fort station, the coastal line runs towards the Southern end. It extends by connecting the regional centres of Moratuwa, Panadura, Kalutara South, Aluthgama, Ambalangoda, and Hikkaduwa towards Galle before the termination at Beliatta. Along this railway line, the maximum lightning flash density of 12.19 flashes/(km^2·year) was recorded near the Colombo-Fort railway station (8°56′01″ N/79°51′01″ E), and Minimum flash density values are recorded from close proximity to the Matara district. In the Puttalam line, which extends from Ragama to Periyangavillu, the highest lightning activities had been recorded at close proximity to Ragama railway station (7°02′09″ N/79°54′43″ E) in the Gampaha district with a maximum lightning flash density of 22.82 flashes/(km^2·year). Results suggest that with the increase in the latitude values, there is a decreasing trend in the lightning flash density in a specific region. On the other hand, Mainline runs from Colombo to Badulla, and it reaches its summit at Pattipola, which is 6226 feet (1898 m) above sea level, before continuing its descending to Badulla through Bandarawela. As stated in Figure 3 and Table 1, along the railway line, the maximum lightning flash density of 22.27 flashes/(km^2·year) was recorded near the Ragama railway station (7°02′06″ N/79°55′12″ E).

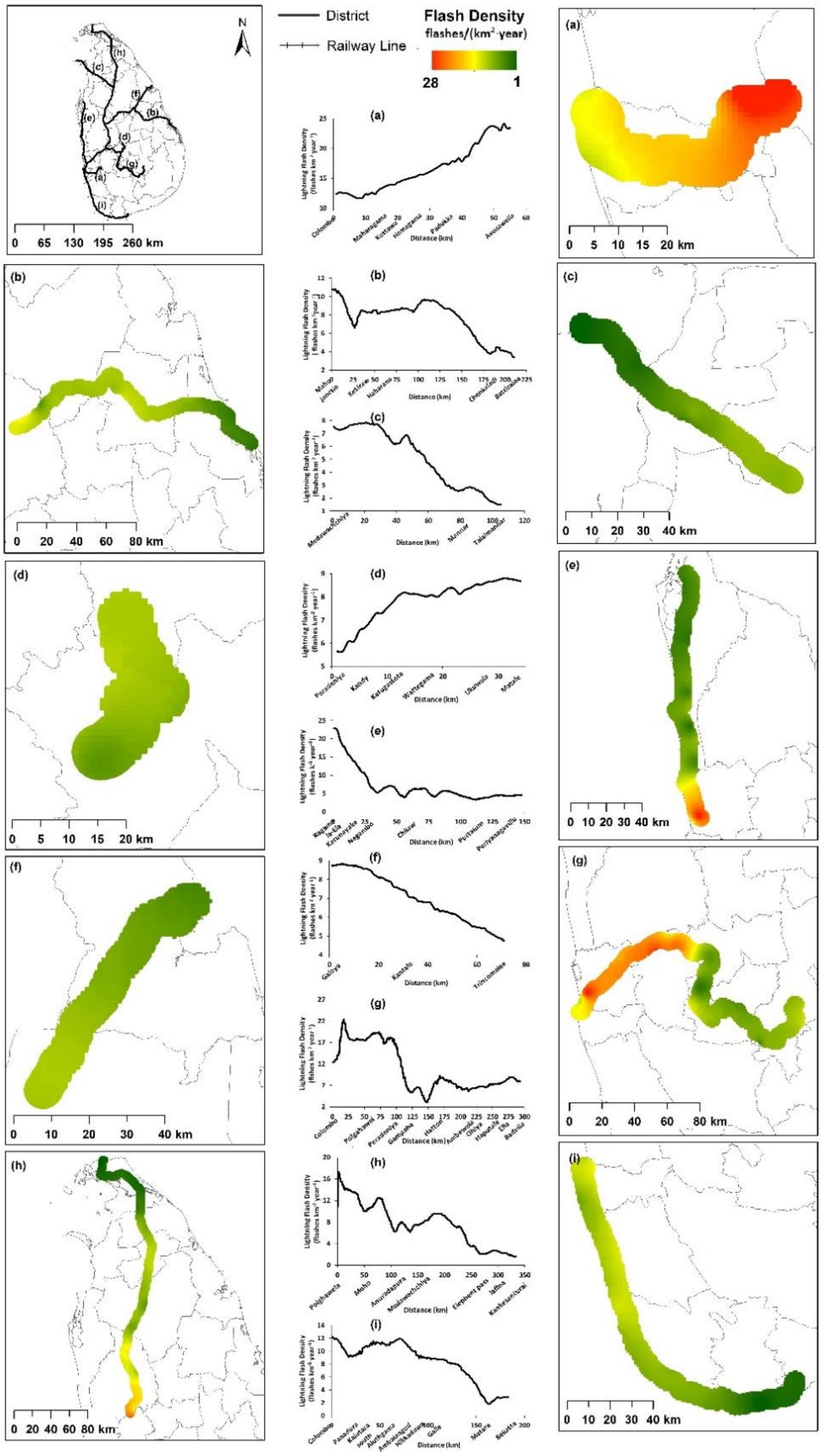

Figure 3. Spatial variability of the lightning flash density over the existed railway lines and distribution of lightning flash density along the railway line at each point of 1 km distance in the period from 1998 to 2014 (**a**) Kelani Valley line (**b**) Batticaloa line (**c**) Mannar line (**d**) Matale line (**e**) Puttalam line (**f**) Trincomalee line (**g**) Mainline (**h**) Northern line (**i**) Coastal line.

High aerosol emission and variation of surface temperature in a particular area may be the causative influential factors to the incremental trends in lightning activities in the study area. The above-indicated paths are bound to relatively high populated districts (Gampaha, Colombo, Kalutara, and Galle). Therefore, the highest population density may rigorously influence to increase in the traffic on public road networks, which will eventually pave the path to make a direct influence to enhance the atmospheric pollution by releasing aerosols generating air pollutants.

On the other hand, low lightning flash density is shown over the Mannar, Trincomalee, and Matale lines. Lightning activities over the railway network show a clear decrement in lightning activities near the coastal line of the country. Observed results suggest that the lightning activities are low over the Northern line at higher latitudes relative to the lower latitudes. Furthermore, over the Trincomalee line, the lightning flash density is decreasing with the rise of latitude.

Railway lines in the wet zone such as the Kelani Valley line, part of the Mainline (Colombo-Fort to Peradeniya junction), part of the Coastal line (Colombo-Fort to Matara), and part of the Puttalam line are highly susceptible to lightning activates relative to the other climate zones. Furthermore, lower lightning activities account over the railway lines in the intermediate zone and dry zone. The wet zone accounts for the highest annual rainfall and the dry zone and semi-arid zone receive the lower annual rainfall. Variations in the climate and inclined geographical features towards lightning hits featured, manmade structures prone to lightning in the wet zone can assume to be accounted for this variation.

Figure 4a presents the spatial variability of the annual lightning flash density, which was obtained by LIS satellite data in the period of 1998 to 2014 over the railway network of Sri Lanka. Satellites have observed about 3316 lightning flashes from the total lightning flash counts over the railway network from 1998 to 2014; as a percentage, it is 18.29%. According to Figure 4a, the Kelani Valley line is highly susceptible to lightning in the considered duration. Furthermore, one of the main controlling centers at the railway network–the Maradana–and its surrounded area account for higher lightning flash density values. Moreover, the lightning flash density and lightning activities over the railway network in the southern part of the country are comparatively higher than that of the north part of the country. In particular, railways running across the high populated areas were recorded with more lightning activities. Established industrial zones, implemented major thermal power plants, elevated buildings and towers, and other manmade climbing structures may be the influential factors to raise the lightning activities in those highly populated areas. Furthermore, aerosol emissions have been increasing over this area during the considered period due to excessive burning of huge amounts of carbon by diesel locomotive engines. This eventually makes a critical impact on aerosol pollution, which harshly affects cloud formation processes and precipitations. The statistical representation of the annual lightning flash density distribution and population density over the considered buffer area of each railway line from 1998 to 2014 is indicated in Table 2. The maximum average of the 16.58 flashes/(km^2·year) is shown over the Kelani Valley railway line (maximum = 28.05 flashes/(km^2·year), minimum = 10.13 flashes/(km^2·year), and standard deviation = 4.34 flashes/(km^2·year)). The minimum average of the 5.08 flashes/(km^2·year) is shown over the Mannar line (maximum = 8.27 flashes/(km^2·year), minimum = 1.37 flashes/(km^2·year), and standard deviation = 2.29 flashes/(km^2·year)).

Figure 4b depicts the variability of the population density within the 5 km buffer zone in 2020 by centering each railway line. The maximum population density had been recorded in the vicinity of Colombo-Fort (32,657 people km^{-2}), Colombo-Maradana (30,240 people km^{-2}), and Ragama (8241 people km^{-2}) railway stations. On the other hand, lightning flash density is higher over the aforementioned area. Furthermore, both population density and lightning flash density over the vicinity of the coastal line are greater than over the other railway lines in the network. Although the population density accounts for a higher value in areas such as Kankasanturai, Batticaloa, and Peradeniya junction relative to the other mentioned areas in the railway network, recorded lightning flash density values are relatively low. According to Table 2, the maximum population density (32,657 people km^{-2}) is associated with the Mainline. In general, throughout the globe, the use of rail transportation as a mode of public transportation is more popular among the public in areas with a high population density. Therefore, high attention should be drawn towards the aforementioned areas to mitigate the hazardous influences due to lightning.

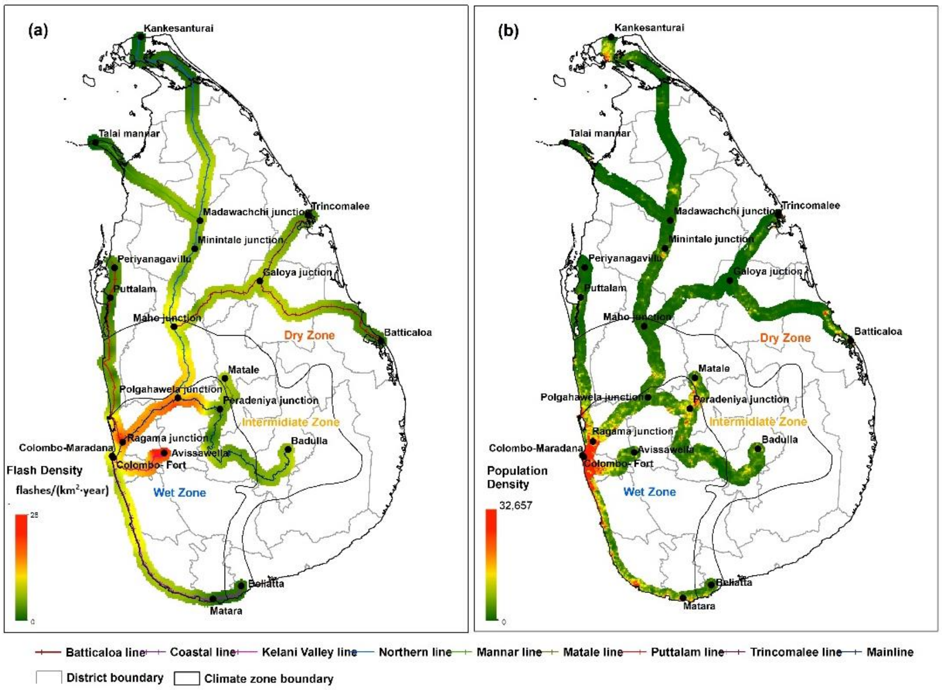

Figure 4. Spatial variability of the (**a**) annual lightning flash density (1998–2014) and (**b**) population density (2020) over the railway network of Sri Lanka.

Table 2. Statistical overview of the annual lightning flash density (flashes/(km^2·year)) distribution and population density variation over the considered buffer area of the railway line from 1998 to 2014.

Railway Line	Average Density		Maximum Density		Minimum Density		STD	
	Flash *	Population **	Flash *	Population **	Flash *	Population **	Flash *	Population **
Batticaloa line	7.59	326	12.02	15,342	2.89	0	2.13	831
Coastal line	8.24	2369	12.82	18,111	1.81	24	3.13	2453
Kelani Valley line	16.58	731	28.05	9245	10.13	4	4.34	828
Northern line	7.66	324	20.11	13,997	1.31	0	4.09	725
Mannar line	5.08	134	8.27	7886	1.37	0	2.29	358
Matale line	7.80	1805	9.26	8128	5.31	29	1.04	1522
Puttalam line	7.23	830	22.85	10,504	3.09	0	4.61	1259
Trincomalee line	7.02	360	8.94	11,521	4.23	1	1.36	385
Mainline	11.03	1548	22.94	32,657	3.30	72	5.18	2828

Units: * flashes/(km^2·year) and ** people km$^{-2.}$

As described in the previous study, the average annual lightning flash density of Sri Lanka from 1998 to 2014 was 8.26 flashes/(km^2·year) [21]. Lightning flash density disparity along with the railway network of Sri Lanka in the aforementioned period at each point of 1 km distance and the percentage deviation of the lightning flash density along with the railway network relative to the average annual lightning flash density of Sri Lanka is illustrated in Figure 5. Figure 5 emphasizes that the maximum lightning flash density has been recorded in the vicinity of the Avissawella railway station in the Kelani Valley line, and relatively, a broad area of the Mainline is vulnerable to lightning activities. On the other hand, low lightning flash density is shown over the Mannar and Matale lines. Analysis of lightning activity disparity over the railway network of Sri Lanka is important for the electrifying process of the Sri Lanka railway network.

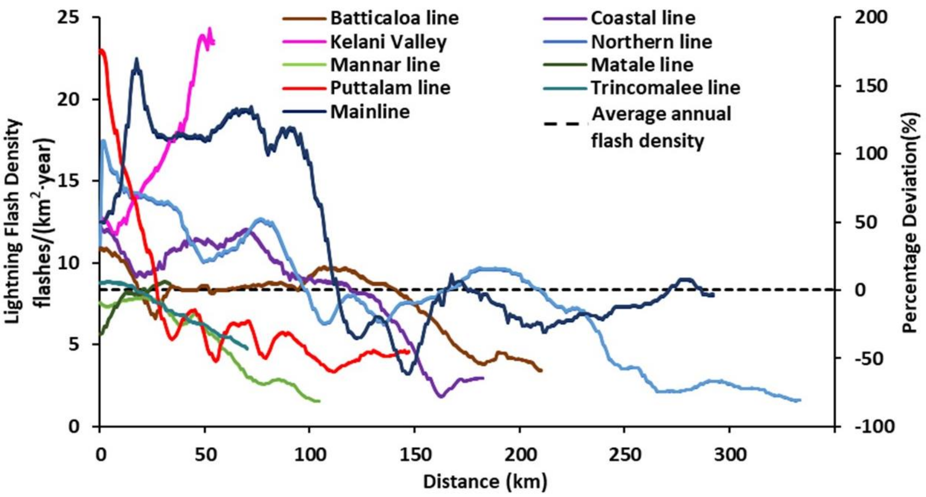

Figure 5. Variability of lightning flash density along with the railway network at each point of 1 km distance and percentage deviation of lightning flash density relative to the annual average flash density of Sri Lanka along with the railway network of Sri Lanka during the period of 1998–2014.

Moreover, over the Kelani Valley railway line, a maximum percentage deviation of 192.10% has been reported near the Avissawella railway station and it is gradually decreasing by reporting a 42.04% of percentage deviation as a minimum, near the Colombo-Fort railway station. The maximum percentage deviation of 176.22% has been reported at the Ragama railway station in the Puttalam line, and 27 km from the Ragama railway station, the recorded lightning flash density over the Puttalam line is lower than the average annual lightning flash density of Sri Lanka. Moreover, the maximum percentage deviation of 169.72% has been reported 16 km from Colombo-Fort railway station in Mainline, and the lightning flash density over this railway line is higher than 50% of the annual average flash density of Sri Lanka– in between 0 km (Colombo-Fort railway station) and 100 km. On the other hand, all the recorded values of the flash density over the Mannar line are lower than the annual average flash density of Sri Lanka (maximum percentage deviation = −4.98%, minimum percentage deviation = −81.62%). However, lightning flash density over the Coastal line from 0 km (Colombo-Fort railway station) to 120 km (near the Galle railway station) is higher than the annual average flash density of Sri Lanka; after more than 120 km, lightning flash density values are relatively lower than the annual average flash density of Sri Lanka (maximum percentage deviation = 47.58%, minimum percentage deviation = −77.96%). Furthermore, over the Northern line, lightning flash density values have fluctuated around the value of the annual average flash density of Sri Lanka (maximum percentage deviation = 109.74%, minimum percentage deviation = −80.96%). Lightning flash density over the Batticaloa line, Trincomalee line, and Matale line express minor variations relative to the annual average flash density of Sri Lanka.

Table 3 shows the percentage distribution of lightning flash density within five different ranges, relative to the annual average flash density of Sri Lanka over the railway network, from 1998 to 2014. According to the reported details of Table 3, all recorded lightning flash density values along the Mannar line are lower than the average annual flash density of Sri Lanka, and 39.05% of lightning flash density points are below 50% of the average annual flash density of Sri Lanka. As per the reported details of the study, over the area of the Kelani Valley line accounts for the maximum average lightning flash density. Along the full length of the line, 14.55% of lightning flash density values are in between the annual average flash density and 150% of the annual average flash density of Sri Lanka, 41.82% of lightning flash density values are in between 150% of the annual average flash density and 200% of the annual average flash density of Sri Lanka, and 43.64% of lightning flash density values are greater than 200% of the annual average flash density of Sri Lanka. Furthermore, 43.67% of lightning flash density values over the Kelani Valley line, 29.69% of lightning flash density values over the Mainline, 6.76% of lightning flash density values over the Puttalam line, and 0.90% of lightning flash density values over the Northern line are more than 200% of the annual average flash density of Sri Lanka. This information implies that the aforementioned fragments of the railway line are more vulnerable to lightning accidents. Therefore, responsible authorities of the Sri Lankan railway should be attentive in enhancing the precautionary measures by conforming to the safety of passengers, the working crew of the railway, and the properties of the railway.

Table 3. Percentage distribution of lightning flash density relative to the annual average flash density of Sri Lanka over the railway network.

Railway Line	Relative Percentage Distribution to the Annual Average Flash Density of Sri Lanka (8.26 flashes/(km^2·Year))				
	≤50%	50–100%	100–150%	150–200%	>200%
Batticaloa line	11.37	29.86	58.77	0.00	0.00
Coastal line	16.94	17.49	65.57	0.00	0.00
Kelani Valley line	0.00	0.00	14.55	41.82	43.64
Northern line	27.54	29.04	30.24	12.28	0.90
Mannar line	39.05	60.95	0.00	0.00	0.00
Matale line	0.00	61.76	38.24	0.00	0.00
Puttalam line	16.22	65.54	5.41	6.08	6.76
Trincomalee line	0.00	76.06	23.94	0.00	0.00
Mainline	3.07	48.81	11.60	6.83	29.69

3.2. Spatial Variability of Lightning Flash Density over the Railway Network in Climate Seasons

The distribution of lightning activities in all climatic seasons over the country varies in different geographical regions. Moreover, an average flash density of 22.25 flashes/(km^2·year) was reported in the FIM in the country whereas, in the SWM it was 5.67 flashes/(km^2·year) [21]. As mentioned in [21], an average lightning flash density of 9.29 flashes/(km^2·year) was recorded in the SIM in the country; for the NEM, it was 2.99 flashes/(km^2·year).

The spatial variation pattern of the lightning flash density over the railway network of Sri Lanka in FIM from 1998 to 2014 is depicted in Figure 6a. According to Figure 6a, in this monsoon season, the railway lines of Colombo-Fort to Peradeniya junction and Colombo-Maradana to Avissawella (Kelani Valley line) have been highly susceptible to lightning activities. Furthermore, the vicinity of the railway stations of Talai Mannar, Kankesanturai, Trincomalee, and Batticaloa have shown lower lightning activities. Previous studies show that the FIM is the highest lightning active monsoon season in Sri Lanka [18,20,21], and Figure 6a also depicts the same behavior for the railway network of Sri Lanka.

Figure 6b depicts the spatial variation of the lightning flash density over the railway network of Sri Lanka in the SWM from 1998 to 2014. During this seasonal period, the railway road between Galoya junction and Batticaloa is more vulnerable to lightning activities than other railway roads in the network. Figure 6c illustrates the spatial disparity of the flash density over the railway network of Sri Lanka in the SIM from 1998 to 2014. In this seasonal period, the railway road of Colombo-Fort to Moho junction and Kelani Valley line is more vulnerable to lightning activities than other railway roads in the network. The vicinity of Polgahawela junction has recorded more lightning activities in the SIM. Figure 6d presents the spatial variability of the lightning flash density over the railway network of Sri Lanka in the NEM from 1998 to 2014. The coastal line is more highly vulnerable to lightning activities than other railway lines in the network during this monsoon season. Moreover, previous studies show that the NEM is the active monsoon season in Sri Lanka with the lowest amount of lightning [18,20,21], which shows similar behavior for the railway network of Sri Lanka. Table 4 presents the statistical description of the annual and seasonal lightning flash density variation over the considered buffer area of the railway network from 1998 to 2014.

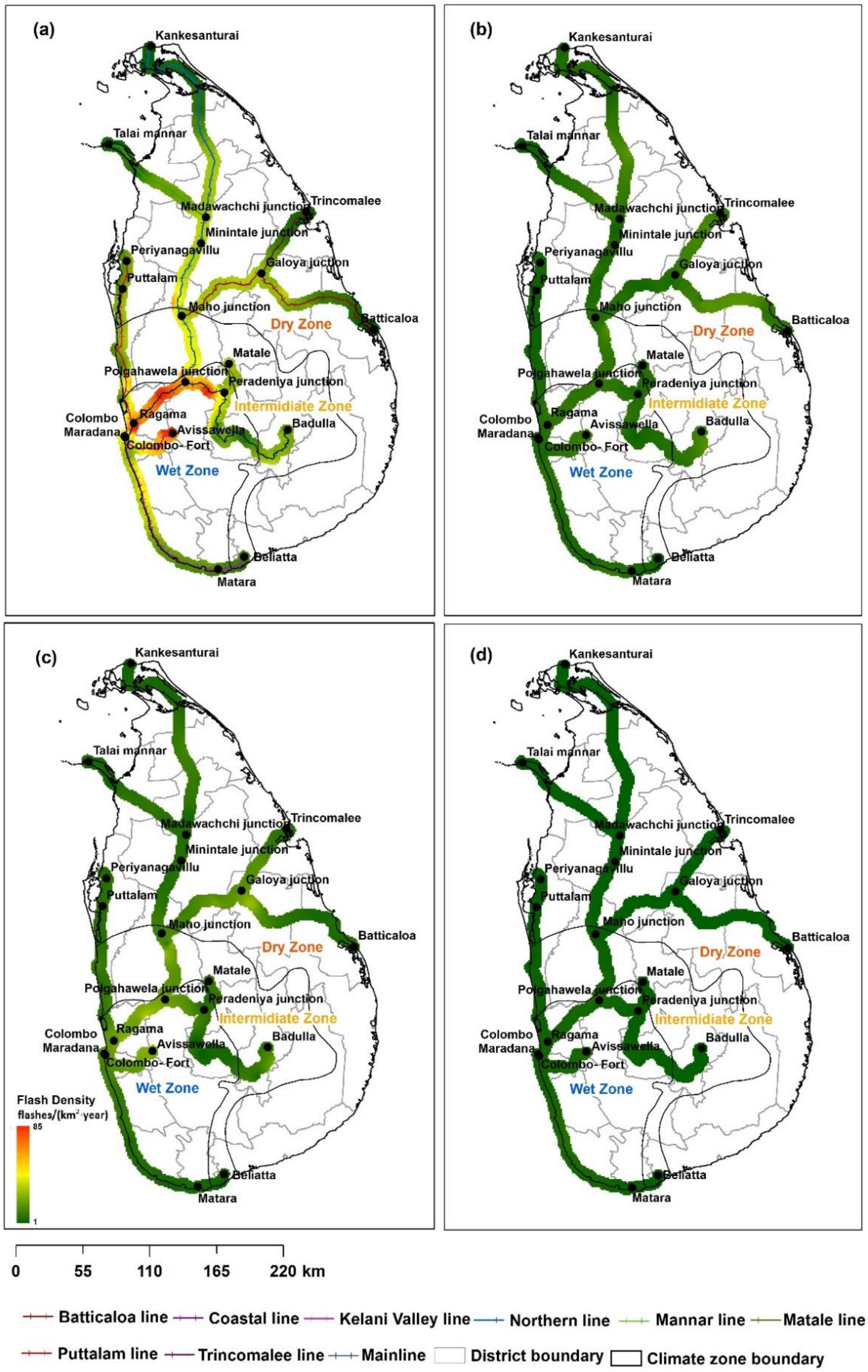

Figure 6. Spatial variability of the lightning flash density over the railway network of Sri Lanka in the four climate seasons from 1998 to 2014 (**a**) FIM, (**b**) SWM, (**c**) SIM, (**d**) NEM.

Table 4. Statistical overview of the seasonal variation of lightning flash density (flashes/(km^2·year)) over the considered buffer zone of the railway network from 1998 to 2014.

	Flash Density *			
	Average	**Maximum**	**Minimum**	**STD**
Annual	8.23	28.04	1.26	4.33
FIM	24.80	85.88	0.79	16.00
SWM	4.46	12.48	0.39	2.58
SIM	8.94	32.58	0.40	6.12
NEM	3.23	26.27	0.26	3.72

Units: * flashes/(km^2·year).

The FIM season accounts for high lightning activities in the railway network of Sri Lanka covering all the climatic zones, relative to the other seasons. Moreover, the Kelani Valley line and part of the Mainline (Colombo-Fort to Peradeniya junction) running across the wet zone are extremely vulnerable to lightning activities during this season. Thunderstorms with dense convections are pronounced in the afternoon hours over the southern part of the country in the FIM season. In the SIM season, more lightning activities was recorded over the railway lines in the dry zone. Within this seasonal period, thunder clouds are drawn towards the northwest of the country by southwest winds. This leads to an intense occurrence of lightning activities over the dry zone. In the SIM season, the Kelani Valley line and part of the Mainline (Colombo-Fort to Polgahawela junction) in the wet zone have more lightning activities. During this seasonal period, in the afternoon hours, thunderstorms are occurring over the wet zone of the country. Significant lightning activities have been observed over the proximity of the Aluthgama and Ambalangada railway stations in the Coastal line and Avissawella railway station in the Kelani Valley line in the wet zone during the NEM. It seems that the above-mentioned railway lines in the wet zone are highly susceptible to lightning during the FIM, SIM, and NEM seasons, but the vulnerability towards lightning is considerably low in the SWM.

3.3. Spatial Variability of Lightning Flash Density over the Proposed Railway Electrification System

As a future masterly proceeding of the Sri Lankan railway, they plan to electrify a 102 km distance of the existing railway network by including the 15 electric multiple units and a signaling system [26]. Direct lightning flashes and the induced surges due to cloud–cloud and cloud–air lightning can harshly influence the overhead transmission line of the electrified railway network or compromise the telecommunication system and interrupt the transmission of the railway signal via temporary malfunction, degradation, or permanent damages [27–33]. Therefore, a study on the spatial variability of lightning activities over the existing railway system is an essential requirement for the Sri Lanka railway as a part of the feasibility study on the proposed railway electrification network. Figure 7 shows the spatial disparity of lightning flash density over the railway lines that are expected to be electrified. Railway lines of Colombo-Maradana to Veyangoda (36 km), which is part of the Mainline, Ragama to Negombo (23 km), which is part of the Puttalam line, and Colombo-Maradana to Kalutara (43 km), which is part of the Coastal line, are expected to be electrified in the near future by the railway department of Sri Lanka. According to the results of the study, lightning flash density over the expected electrified railway lines is higher than the other lines of the railway network. Table 5 shows the descriptive statistics of the variability of the annual lightning flash density over the railway lines expected for electrification. The maximum annual flash density of 22.85 flashes/(km^2·year) was recorded at the Ragama railway station. Accordingly, for the study period from 1998 to 2014, the maximum average annual lightning flash density of 16.53 flashes/(km^2·year) was recorded over the Colombo-Maradana to Veyangoda railway line (Maximum = 22.85 flashes/(km^2·year), Minimum = flashes/(km^2·year), and Standard deviation = 2.94 flashes/(km^2·year)). Considering the information in Table 5, a high population density can be detected in the selected area, which is proposed to launch the electrification. This implies the inevitability of implementing a strong lightning protection system for the proposed electrified railway network by the Sri Lanka Railway Department in order to achieve sustainable development in the railway network in Sri Lanka, through proper minimization of lightning hazards. Otherwise, lightning accidents may act as a booster to reduce the operational efficiency of the proposed electrified railway network.

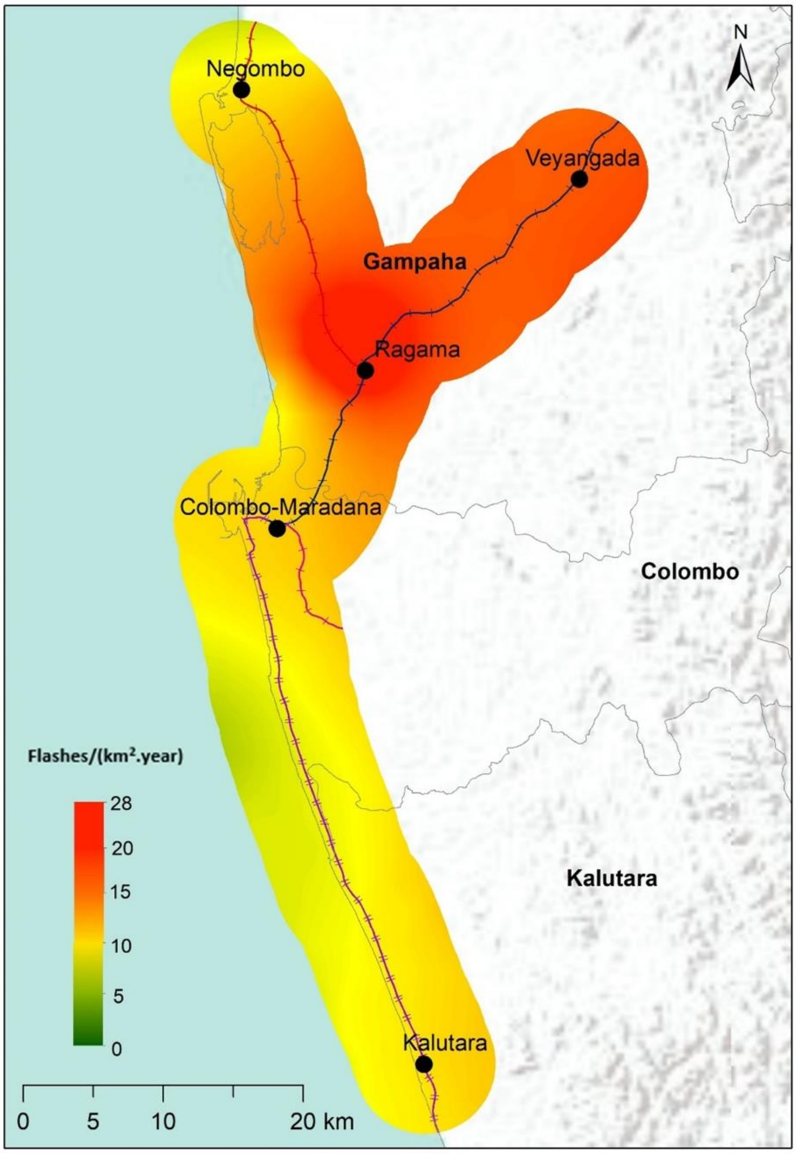

Figure 7. Spatial variability of the lightning flash density over the railway lines that are expected to be electrified.

Table 5. Descriptive statistics of the variability of the annual lightning flash density (flashes/(km^2·year)) over the expected electrified railway lines.

Railway Line	Average Density		Maximum Density		Minimum Density		STD	
	Flash *	Flash *	Flash *	Flash *	Flash *	Population **	Flash *	Population **
Colombo to Veyangoda	16.53	22.85	9.69	2.94	2.94	4,704	2.94	3107
Ragama to Negombo	15.58	22.84	8.65	3.55	3.55	2,712	3.55	1767
Colombo to Kalutara	10.55	13.48	7.28	1.24	1.24	4,142	1.24	4425

Units: * flashes/(km^2·year) and ** people km^{-2}.

4. Discussion

A comprehensive analysis of spatial variability of the lightning flash density over the railway network of Sri Lanka has been conducted in this study to reach a comprehensive awareness of intense lightning active segments of the respective railway lines. It is an essential requirement of improving the currently existing lightning protection systems and procedures for the railway network by enhancing the safety of the passengers and property. This will eventually increase the operational efficiency of the service supplied by the railway department, without any delay. Therefore, the consideration of the dissemination of lightning over the railway network is critically important for electrifying the existing railway network.

According to the performance report of the Sri Lanka railway, in 2015, an average number of 360,000 passengers have daily used rail transportation [34]. Furthermore, the report indicates that 398 trains have been operated per day by the Sri Lanka Railway. Among those trains, 366 trains have been used for passenger transportation and 32 trains have been used for goods transportation within a day [34]. Accordingly, Table 6 shows the detailed information on the number of trains operated on weekdays on nine railway lines in 2015 and the number of railway stations located in the railway network of Sri Lanka, together with their flash density and population density [34]. According to Table 6, 148 trains were operated in the Matale and Mainline. Furthermore, 113 trains were operated on the coastal line within a day. According to the study, on average, the railway line of Colombo-Fort to Peradeniya junction is the part of the Mainline that is more vulnerable to lightning activities, and the railway line of Colombo-Fort to Galle is the part of the Coastal line that is also more susceptible to lightning activities. Therefore, authorized parties of the Sri Lanka railway should turn their attention to developing the existing lightning protection system by enhancing the lightning safety of both passengers, workers, and properties of the railway network, with special attention paid to identified susceptible regions as reported in this study.

Table 6. Descriptive information on trains operated on weekdays, railway stations of the railway network, and descriptive statistics of flash density and population density over the railway network of Sri Lanka.

Railway Line	Number of Trains	Number of Stations, Main Stations, Substations	Flash Density *			Population Density **
			Average	Maximum	Minimum	Average
Batticaloa line	10	28	7.59	12.02	2.89	326
Coastal line	113	67	8.24	12.82	1.81	2369
Kelani Valley line	20	30	16.58	28.05	10.13	731
Northern line	40	56	7.66	20.11	1.31	324
Mannar line	4	12	5.08	8.27	1.37	134
Puttalam line	42	45	7.80	9.26	5.31	1805
Trincomalee	6	6	7.23	22.85	3.09	830
Matale line & Mainline	148	12	7.02	8.94	4.23	360
		78	11.03	22.94	3.30	1548

Units: * flashes/(km^2·year) and ** people km^{-2}.

The percentage deviation of the lightning flash density along with the railway network relative to the average annual lightning flash density shows that over the Kelani Valley railway line, a maximum percentage deviation of 192.10% has been reported near the Avissawella railway station; it is gradually decreasing, reporting 42.04% of percentage deviation as a minimum, near the Colombo-Fort railway station. When compared with the annual average lightning flash density of Sri Lanka, all recorded lightning flash density values along the Mannar line are lower than the average annual flash density of Sri Lanka, and 39.05% of lightning flash density points are below 50% of the average annual flash density of Sri Lanka. The maximum average lightning flash density has been recorded over the Kelani Valley line. Along the full length of this line, 14.55% of lightning flash density values are in between the annual average flash density and 150% of the annual average flash density of Sri Lanka, 41.82% of lightning flash density values are in between 150% of the annual average flash density and 200% of the annual average flash density of Sri Lanka, and 43.64% of lightning flash density values are greater than 200% of the annual average flash density of Sri Lanka.

Furthermore, if the used mode of transportation has a lesser tendency towards accidents, passengers can ensure the safety of that particular mode of transportation. In some instances, railway transportation can make passengers more vulnerable to direct lightning flashes. Most of the railway stations in Sri Lanka consist of long outdoor platforms, and when thunderstorms are stirring, passengers who are waiting for the trains on outdoor platforms have a higher risk of being victims of accidents due to lightning. Moreover, passengers waiting under unprotected metal shelters available in some of the railway stations are highly susceptible to striking lightning flashes.

Direct lightning flashes are more dangerous toward railway signal towers [35,36]. On the other hand, signal operators and other outdoor workers on railways may also be victims of lightning accidents. Furthermore, electrical transients and surges due to indirect lightning, side flashes, ground potential rise, and lightning-induced voltages due to inductive and capacitive coupling on low voltage power systems of the rail network could also affect its uninterrupted operation [27,28,30,31,33]. These suggest the necessity of developing and enhancing the efficiency of the existing lightning protection system for both structural and low voltage power systems–including the signaling and telecommunication network of the railway–with proper maintenance, together with an effective earthing system as a major requirement to mitigate the lightning accidents for working crew, passengers, and the property of the railway. Implementation of an automated lightning warning system in railway stations is an apposite action as a safety precaution to minimize lightning accidents among outdoor workers and passengers.

Moreover, the railway department of Sri Lanka has installed fully electronically controlled crossing safety systems, which are operated with efficient control technology in some of the crossings. This is capable of enhancing the efficiency of rail transportation by minimizing the accidents that are happening in the railway crossing [37,38]. Disastrously, the disruption of the regulating systems by lightning strikes is generally a serious matter of concern [37]. Therefore, it is recommended to integrate safety systems appositely with protective circuit components, which remain intact even in concurrence with lightning currents.

As a novel implementation of governing authorities in Sri Lanka, the proposed electrified railway network can be addressed as a major lending hand to reduce railway traffic with the increasing population by connecting the railway stations with a high mobility of passengers and trains [39]. On the other hand, the reduction of greenhouse gas emissions through reducing the usage of diesel locomotive engines is one of the major aims of the proposed electrification project [39]. This may be a prodigious solution to reduce the contamination of unburnt carbon particles, which cause long-term aerosol pollution and will ultimately affect the thunder cloud formation processes. According to the study, however, the area of the proposed railway electrification network accounts for higher lightning flash density over the railway lines than other existing railway lines; the railway line of Colombo-Maradana to Kalutara has a lower lightning flash density than the other two railway lines in the proposed area. This emphasizes the necessity of initiating the project on electrification focusing on the Colombo-Maradana to Kalutara line. Moreover, the height, gradient, and length of the slope of the railway line are the major influential factors that ensure energy-saving [40,41]. Therefore, by considering energy-saving requirements and low lightning vulnerability, a segment of the railway lines such as the Negombo to Puttalam line (part of the Puttalam line), Kalutara to Beliatta line (part of the Coastal line), and the northern part of the Northern railway line can be utilized to launch the proposed electrification network as a secondary approach of this project in the future.

Lightning data from 1998 to 2014, which were obtained from one of the Lightning Imaging Sensors (LIS) of NASA's Tropical Rainfall Measuring Mission (TRMM), were utilized for this study because this mission was terminated on in April 2015, due to the crash of the TRMM satellite [1,2]. Nevertheless, another LIS instrument was established on the International Space Station (ISS) in February 2017 [42,43]. Henceforth, we could only access a complete four-year LIS data (on ISS) set from 2018 to 2021. However, the authors believe that the available short-period data set (LIS on ISS) is not enough to conduct a long-term analysis of the variation patterns of lightning activities over the country monthly, seasonally, and annually. On the other hand, those two missions (LIS on TRMM & LIS on ISS) have different characteristics [1,2,42,43]. Therefore, due to the inconsistency in both data sets (from TRMM & ISS), a combine-study of both two LIS data sets for lightning distribution analysis would not be applicable. Therefore, in this study, even though LIS data are available until 2021, we cannot extend the study period to recent years. Moreover, in Sri Lanka, there are no ground-based Lightning Detection Systems (LDS) to obtain lightning data. Thus, NASA LIS is a reliable source for obtaining lightning flash data. Henceforth, the authors believe analysis conducted in this study using LIS data on TRMM for the period 1998–2014 is a good scientific option to propose current lightning warning and protection systems for the Sri Lanka railway network. However, in the real scenario, there can be a change in lightning climatology in recent years due to changes in the urban landscape and respective infrastructure. Nonetheless, since Sri Lanka's climate is of tropical island nature, there cannot be a significant recent change in lightning climatology. As such, the conclusions of the analysis of this study can still be applied to enhance current lightning warning and protection systems for the Sri Lanka railway network.

5. Conclusions

The study on the spatial variability of lightning over the railway network of Sri Lanka from 1998 to 2014 concluded that the LIS data could be used to study the spatiotemporal variation of lightning activities over the railway roads in Sri Lanka.

The study reveals that one of the main controlling centers at the railway network, the Maradana, and its surrounded area account for higher lightning flash density values. The lightning flash density and lightning activities over the railway network in the southern part of the country are comparatively higher than that of the north part of the country. On the other hand, lightning flash density over the Batticaloa line, Trincomalee line, and Matale line express minor variations relative to the annual average flash density of Sri Lanka. Railway lines in the wet zone namely, the Kelani Valley line, part of the Mainline (Colombo-Fort to Peradeniya junction), Part of the coastal line (Colombo-Fort to Matara), and part of the Puttalam line are highly susceptible to lightning activates relative to the other climate zones. On the other hand, a high population density had been recorded in the vicinity of Colombo-Fort, Colombo-Maradana, and Ragama railway stations with higher lightning flash density.

The railway lines of Colombo-Fort to Peradeniya junction and Colombo-Maradana to Avissawella (Kelani Valley line) have been highly susceptible to lightning activities in FIM. Furthermore, the vicinity of the railway stations of Talai Mannar, Kankesanturai, Trincomalee, and Batticaloa have lower lightning activities in this season. In the SWM, the railway road between Galoya junction and Batticaloa is more vulnerable to lightning activities than other railway roads in the network. The railway road of Colombo-Fort to Moho junction, Kelani Valley line, and the vicinity of Polgahawela junction are more vulnerable to lightning activities than other railway roads in the network during the SIM. Further, the coastal line is highly vulnerable to lightning activities than other railway lines in the network, within the NEM.

Unprotected outdoor platforms, buildings, communication signal towers, and electronic railway crossings are the areas of the Sri Lankan railway identified as being vulnerable to lightning. It is an urgent requirement to implement lightning warning systems in the pre-recognized lightning active areas for the safety of the outdoor workers and passengers in order to mitigate lightning accidents by enhancing the reliability of the railway transportation mode. Train delays, cancelations, interruption of the usual train timetable, and train accidents due to signal failure are the major issues arising due to the disruption of the railway signaling network caused by lightning flashes. This may cause a reduction in the operational efficiency of the railway transportation mode. Henceforth, maintaining a proper earthing system for the lightning protection of the railway signal towers can be addressed as a demanding solution to overcome the above barriers.

According to the analysis of spatial variability of the lightning flash density over the proposed electrified railway network of Sri Lanka, the implementation of a strong lightning protection system for the proposed electrification railway network due to the high lightning flash density over the proposed area is highly recommended. As an initial approach, the Sri Lankan railway should implement measures to initiate the project on electrification focusing on the Colombo-Maradana to Kalutara line, which has a lower lightning flash density than the other two railway lines in the proposed area. Moreover, the spatial variability of the lightning flash density is a significant factor to study the variation of the regular lightning activities over a particular area. Therefore, the study is vital to identify the high-risk lightning locations that are situated in the current railway network system of Sri Lanka. It is important to take action to install a properly coordinated effective lightning protection system for railway stations and develop the existing lightning protection systems for the Sri Lanka railway department. This may be a well-restored project to enhance the reliability of the rail transport method. Furthermore, this study also emphasizes the utilization of LIS on TRMM data for investigating lightning risk for a railway network in any country successfully by following the procedure followed in the paper.

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