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Lightning Climatology and Human Vulnerability to Lightning Hazards in a School Community: A Case Study in Sri Lanka using LIS Data from TRMM Satellite

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Abstract

This study reported lightning climatology and human vulnerability to lightning in a 20 km × 20 km high-density school area in Colombo city in Sri Lanka from 1998 to 2014 using Lightning Imaging Sensor (LIS) flash data of NASA's Tropical Rainfall Measuring Mission (TRMM). An average annual flash density recorded over the study area was 9.43 flashes km^{-2} $year^{-1}$. A maximum of 49% lightning flashes happened during the first inter-monsoon season. There were only 4% lightning flashes that occurred during 06.00-12.00 LT and during 18.00-24.00 LT, it was 67%, whereas 94% of lightning flashes within a day had occurred after 14.00 LT. It is recommended that, without having proper lightning hazard preventive measures, schools in the study area should avoid or minimalize scheduling their outdoor activities in high lightning risk months of April and November. Especially, after-school outdoor activities should be planned with proper safety measures during the aforementioned months as per the diurnal analysis. Moreover, May to September and December to February were the months with the least lightning risk levels. It is recommended to follow the proposed five-level lightning safety guideline which includes, schedule outdoor activities by considering the variation of lightning activities, follow the 30-30 rule whenever required, avoid staying at the most hazardous locations which are vulnerable to lightning accidents, crouching action if required and providing first-aid whenever necessary. Not only for the Sri Lankan context but also the study is crucial and highly applicable for all schools and other institutes especially in other tropical countries.

Keywords: lightning flash density; lightning safety; lightning risk; 30-30 rule; LIS data; lightning vulnerability.

Introduction

Natural disasters have a significant influence on different sectors in both developed and developing countries. Both direct and indirect impacts of natural disasters are devastating the wellbeing of many communities, infrastructures, and the economic sector of the country. In Sri Lanka, the most frequent natural hazards are droughts, floods, landslides, cyclones, vector-borne epidemics (malaria and dengue), and coastal erosion (Edirisooriya, 2019). Developing the management and policies for natural hazards of the country is an essential requirement to mitigate the impact of the natural hazards without compromising the development and poverty reduction priorities of Sri Lanka. Disaster Management Centre (DMC) of Sri Lanka is the government-authorized institute to prepare and implement the national disaster management plan and the national emergency operation plan. Meanwhile, lightning can be categorized as a natural disaster that could cause injuries to both humans and animals, including fatal accidents and structural damage (Maduranga et al., 2019; Yadava et al., 2020). It can also be categorized as a severe weather hazard. Deaths due to thunderstorms in the United States are higher than tornadoes or hurricanes (Curran et al., 1997). According to the global context, infrequent, 0.2-0.8 people per million per year die from lightning accidents in different geographic areas (Aslar et al., 2001). Moreover, lightning fatality rates differ country-wise, and developed countries such as Australia, Canada, Europe, Japan, USA, etc. show low lightning fatality rates than developing Asian and African countries (Holle, 1997). Therefore, governments and other authorized parties in any country should interfere to take action to mitigate lightning hazards, by considering this as a serious matter of concern.

Furthermore, investigating the lightning activities of a particular area is significant to minimize the lightning hazards and to design a lightning protection system in that particular location (Maduranga et al., 2019; Tong, 2008). The lightning flash density of a particular area is a significant factor to identify the hazard risk level in that location. Moreover, it is important to make the general public aware of the ways of lightning hazards that could occur together with its respective intense periods in the year (Maduranga et al., 2019). Thus that they can take preventive actions to reduce the damage (Maduranga et al., 2019). Henceforth, installing and maintaining an early warning system to locate and map the lightning activities can be utilized as a preventive action (Maduranga et al., 2019; Schmitt et al., 2016). Statistics of these activities are important in generating a vulnerable map at a particular location and can take hazard preventive actions if required. On the other hand, reported hazards due to lightning have emphasized a coordinated lightning protection system by identifying the respective risk levels (Edirisinghe et al., 2015). In the Sri Lankan context, a spatiotemporal variation of lightning distribution has been analyzed in terms of different aspects (Edirisinghe et al., 2021; Maduranga et al., 2019; Jeyanthiran et al., 2008).

Furthermore, previous studies also suggest that lightning activities over Sri Lanka are having an incremental trend over time (Maduranga et al., 2018). It is also important to mention that, in Sri Lanka, reported lightning accidents including deaths, injuries, and property damage had been significantly increased over the last two decades (Edirisinghe et al., 2021). Most of the lightning accidents over humans reported in Sri Lanka during 2003 were due to their outdoor activities in an open field or staying under unprotected shelters or trees (Gomes et al., 2006). Moreover, in the USA, a higher number of lightning fatalities have occurred in open fields (Curran et al., 1997). In the Sri Lankan context, according to reported incidents from 2000 to 2019, on average, there could be 18.40 deaths and 16.50 injuries that may account for in a year (Edirisinghe et al., 2021). Moreover, 0.86 and 0.77 Sri Lankans per million may die and get injured respectively due to lightning accidents (Edirisinghe et al., 2021). Henceforth, in general, Sri Lanka as a country in the tropics, it is very significant to know the nature of the lightning activity at a particular place of interest and to estimate respective lightning risk level analysis. Moreover, these information are substantially significant for a school, since parents or guardians sending their children to the school by anticipating that the school will raise their children's education level with more than 100% safety. On the other hand, there are different types of schools in Sri Lanka including, government-controlled national, provincial & piriven (monastic) schools, semi-government schools, private schools, international schools, etc.(Statistics Branch of Ministry of Education of Sri Lanka, 2018). Altogether, it can estimate that approximately 4.4 million students perusing their school education all over the country (Statistics Branch of Ministry of Education of Sri Lanka, 2018). Henceforth, it can be further estimated based on the lightning death rate in 2019 that there could be a possibility of 3.8 number of students may die and 3.4 number of students may get injured in a year in the school community of Sri Lanka due to lightning accidents. Therefore, knowing the lightning risk level at each and every school is very vital to reduce the vulnerability at the school. On the other hand, due to the lack of awareness about lightning hazards and lightning active periods, even at a very lower risk level, sometimes particular school management will spend a lot of money for establishing preventive actions and sometimes cancellation or postpone of scheduled events which will eventually affect to the productivity of the school.

On the other hand, enhancing lightning safety explorations in the school community are of the current global interest of researchers (Jensenius et al., 2010; Groszek, 2004). According to the reported details, annual school activities of schools in Orange County, Florida were scheduled by considering the lightning climatology over the school area and past lightning accidents as a preventive measure to enhance the safety of the school community (Groszek, 2004). A study about the lightning casualties at schools outside the United States in 14 years shows that most of the lightning accidents have happed during outdoor activities in the schoolyard, playground, under trees, and verandas than in the classroom (Groszek, 2004). Furthermore, lack of proper lightning protection at most rural schools and clustered closely together in the school setting are generally rigorous to susceptible the school community for severe injuries and deaths by lightning (Groszek, 2004). Therefore, the implementation of standard guidelines for lightning safety and the installation of reliable weather warnings are important to mitigate the lightning hazard in the school area (Walsh et al., 1997; Holle et al., 1999; Pedeboy, 2018). Moreover, particular school management and other authorized parties such as coaches and teachers are responsible to introduce, implement, and follow the recommended lightning safety guidelines for recreational activities and athletic events in schools (Walsh et al., 2013; Spengler et al., 2002). As well as, schools should get the concern and assistance of the governing authorities to initiate deep education and training workshops on lightning safety to minimize lightning accidents in schools (Walsh et al., 2013; Spengler et al., 2002; Holle, 2016). As per the reported details in the Ministry of Education of Sri Lanka, in the recent past, incidents and evidence have been recorded that Sri Lankan school children are highly vulnerable to all these types of natural hazards (Ministry of Education of Sri Lanka, 2008). Therefore, the government has taken their attention to developing a school disaster safety plan by proposing the seven-step safety plan in 2008 (Ministry of Education of Sri Lanka, 2008). Mainly, the establishment and training a disaster safety team, create the awareness among the school community, analysis the vulnerability, hazards, and risks in the school environment, mapping school and village by identifying safer locations, and provide practical exercises how to face the real situation are the major objectives to act adequately to save lives in case of an emergency for the school community (Ministry of Education of Sri Lanka, 2008).

However, as of now, in Sri Lanka, minimal information is available on the lightning risk level at the respective location of interest for a specific period during the year. Henceforth, no prediction can be made on the respective hazard level. This is mainly because Sri Lanka doesn't have a lightning detection and locating system (Edirisinghe et al., 2021). Nevertheless, previous studies reported that satellite-based data can be used to analyze lightning risk levels at a particular place of interest in Sri Lanka (Aslar et al., 2001; Maduranga et al., 2018).

On the other hand, in Sri Lanka, most of the schools are with a common educational culture that consists of routine classroom activities together with many outdoor activities. Sometimes these outdoor activities are in open fields such as in the playground. Moreover, Sri Lankan school administrators plan to do a large number of indoor and outdoor activities during school time. In most of the schools, students are involved in lots of activities such as sports training sessions, band practices, etc., before the school starts its academic work (from 7:30 a.m.) and after the school schedule time (from 1:30 p.m.). Generally, schools schedule respective year plans, including key annual events such as sports-meet, astronomy camp, examinations, etc. Moreover, organizers and leaders of the respective field activities should ensure to follow appropriate lightning safety, and hence keep the school students safe from lightning hazards. Furthermore, in Sri Lanka, school children are learning about lightning safety and protection to some extent as a part of the curriculum. Moreover, reading materials such as books, guidelines on disaster risk reduction in school curriculum should be integrated with subjects such as Geography, Environmental Studies, and through extracurricular activities such as Scouting and Girl Guiding and Environmental Pioneer Societies. This may be a great helping hand to enhance the physical health, mental health, and educational attainment, and achievement of children those who had become victims of a particular disaster. A previous study shows that the lightning education programs conducted by expertise in the field of lightning for school children and teachers are important to enhance the awareness among the school community (Jayaratne et al., 2012).

This case study was carried out to identify the possible use of the aforementioned satellite data to explore lightning climatology and human vulnerability to lightning hazards in the school community in Sri Lanka. Henceforth, it can be emphasized the importance of having a properly coordinated lightning protection system and specific safety guidelines for the said community. In this study, the Colombo Zonal Education region and its surroundings located in Colombo District in Western Province of Sri Lanka has been selected as the study area which is one of the highest school density areas of the country. In the Sri Lankan context, it is reported that the administrative districts in Western Province are with a higher lightning flash density and higher vulnerability level for lightning accidents in Sri Lanka (Maduranga et al., 2018). In the administrative district of Colombo, according to reported incidents from 1974 to 2019, an average number of 0.39 deaths and 0.13 injuries per year had been recorded (Edirisinghe et al., 2021). Moreover, in 2012 the population of Colombo was 2.32 million and with a 0.3% growth rate, the population had reached 2.37 million in 2019 (United Nations Population Fund (UNPFPA), 2014). Therefore, 0.16 people per million may die and 0.05 people per million may get injured respectively due to lightning accidents. Students in the school community of the Colombo administrative district are approximately 0.45 million as per the reported literature (Uman, 1987). Henceforth, it can be convinced that 0.07 students might susceptible to deaths and 0.02 students might be injured and might become severe victims of lightning accidents. This implies the necessity of analyzing the lightning vulnerability for the selected area with a high school density as a prompt and apposite precautionary measure. Moreover, most of the schools in the study area are controlled by the central government of Sri Lanka, which provides primary and secondary level education. There are few leading private schools and the majority of the international schools of the country are also located in the study area.

Most of these schools are with more than 2000 students and some of these schools even with more than 5000 students along with a staff of about 200 or more including administrators, teachers, and supportive employees. Inside of these schools' premises, there are multi-story buildings, big trees, playgrounds for cricket, soccer, hockey, etc., an outdoor swimming pool, indoor stadium, etc. It is also important to mention that around the vicinity of some of the schools, there are no high-rise buildings. Hence, in terms of lightning risk level, it is important to identify the possibility of a direct lightning hit to unprotected structures, side flashes, and the possibility of having direct hit injuries. Assessing the hazard risk level due to the step potential which could be occurred as a result of earth potential rise which normally initialized due to a close-by ground flash. On the other hand, the destruction of education infrastructures due to these types of natural hazards can make a severe interruption on the education system. Therefore, this study is more imperative to launch prominent actions to develop a well-accredited disaster safety plan for the school community in the country by identifying risk areas in the schools together with highly vulnerable time periods.

Henceforth, the main intention of this study is to investigate the lightning activities over the study area in Colombo by keeping the study location ($6^0$53'51" N, $79^0$51'43" E) at its center. The study area consists of approximately covering 20 km × 20 km surrounding square area and it is an area with high school density. It is also important to mention that the average thunder cloud in the tropics which includes Sri Lanka is on an approximately 10 km base which justifies the selected dimensions of the study area (Uman, 1987). This is the first exploratory study on reporting about the spatiotemporal variation of lightning activities over a school area in Sri Lanka. The objective of the study is to identify suitable periods in a calendar year to plan the school annual events and other activities for minimizing the lightning hazard risk level by mapping lightning activities over the study area. Also, the study is vital to make necessary amendments to existing lightning safety protocols which have been introduced by governing authorities to schools as well as other institutes in the country. Moreover, the study is highly applicable for other countries specially experiencing a tropical climate throughout the year.

Methodology

The data collection procedure was more or less the same as described in previous studies (Maduranga et al., 2019; Maduranga et al., 2018; Edirisinghe et al., 2021). The aforementioned data were collected by the Lightning Imaging Sensor (LIS) of the NASA Earth Observing System having a spatial resolution in the range of 3 km to 6 km (Maduranga et al., 2019; Maduranga et al., 2018; Graves et al., 2009). The LIS-based measuring system was produced to estimate the lightning data together with a detection efficiency variation in the range of 69% to 88% (Maduranga et al., 2019; Maduranga et al., 2018; Graves et al., 2009). The study was conducted by studying the extracted LIS data for the study area for 17 years, from 1998 to 2014. The extracted data over the study area was separated into 5 km × 5 km grids annually, monthly, and seasonally. Gridded data were projected by using the Geographic Information System (GIS) separately. This satellite had monitored the individual storm and storm system for 80 s period and it had observed the storm activities over Sri Lanka twice per day (Maduranga et al., 2019; Maduranga et al., 2018; Edirisinghe et al., 2021). By considering the above information, flash density in considered 5 km × 5 km grid can be calculated as Eq. (1) (Maduranga et al., 2019).

$$\text{Flash density (flashes km}^{-2}\text{year}^{-1}) = \frac{\sum Flashes}{5\,km\ \times 5\,km} \times \frac{24 \times 3600}{2\ \times 80} \times \frac{1}{Years} \tag{1}$$

Lightning flash density raster maps were generated for analysis of spatial and temporal variation over the study area by using the interpolation method of Invers Distance Weight (IDW) in GIS and the total number of stricken lightning flashes during the considered time period was estimated by using average lightning flash density which was obtained from zonal statistics using generated raster maps. Relevant thunder data from 1998 to 2014 was obtained from the Metrological Department of Sri Lanka.

Data Analysis

This study was oriented towards the identification of hazardous locations in the study area together with having a thorough understanding of the hazardous vulnerability situations. This was achieved by investigating the lightning activity over the aforementioned area. Fig. 1 depicts the study area ($6^0$52'48" N- $6^0$54'00" N and $79^0$51'00" E-$79^0$52'12" E). On the other hand, as per the annual precipitation profile of the country, Sri Lanka is with two monsoon seasons (southwest and northeast) and two inter-monsoon seasons (first and second), covering May to September, December to February, March to April, and October to November respectively. Relevant calculations related to this study were essentially based on the aforementioned four seasons carried out by using GIS. Respective results were analyzed to detect the highly dynamic lightning seasons in a calendar year around the study area. Moreover, corresponding results were analyzed to investigate the lightning hazard areas and to detect the highly dynamic lightning seasons around the study area. To ensure the validity of the above process, the results were compared with the thunder data observed at the Colombo 07 weather station located at the Metrological Department of Sri Lanka ($6^0$55'38" N, $79^0$51'40" E) which is 0.92 km aerial distance away from the study location which is the center of the study area.

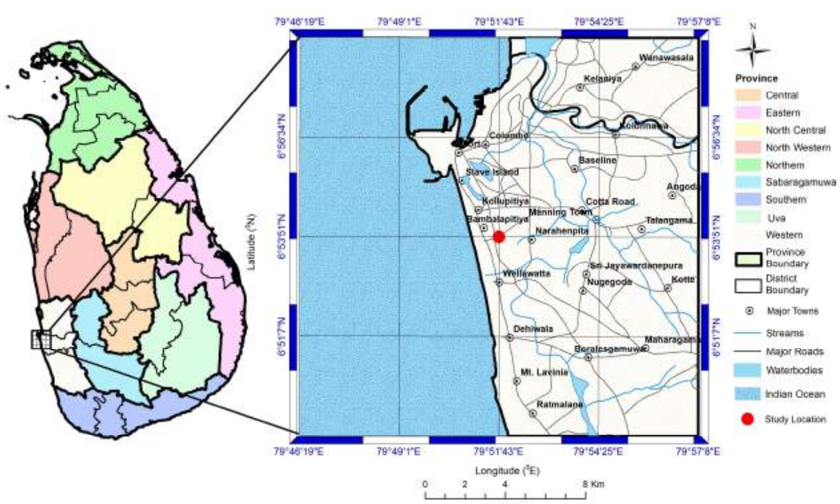

Figure 1. Expanded view of the study area in Colombo 07, Sri Lanka, by keeping the study location ($6^0$53'51" N, $79^0$51'43" E) in the center.

Results

Spatiotemporal analysis of lightning flash distribution using satellite observation over the study area is presented in this section. The analysis was done seasonally and annually to identify the respective variations of lightning activities by considering the 17 years data.

Statistical Analysis of Temporal Variation of Lightning Flash Density

A comprehensive statistical analysis was carried out to present a general overview of the temporal distribution of the lightning flash density over the study area from 1998 to 2014. Table 1 shows the statistical overview of seasonal and annual variation of lightning flash density over the study area during the study period. The maximum flash density had been recorded in the first inter-monsoon (FIM) with an average of 29.19 flashes km^{-2} $year^{-1}$ and the second maxima of flash density had been recorded in the second inter-monsoon (SIM) with an average of 23.00 flashes km^{-2} $year^{-1}$. Furthermore, low flash density values had been recorded in southwest monsoon (SWM) and northeast monsoon (NEM) seasons with an average of 3.36 flashes km^{-2} $year^{-1}$ and 5.09 flashes km^{-2} $year^{-1}$ respectively. According to Table 1, the average annual flash density of the study period was 9.43 flashes km^{-2} $year^{-1}$.

Table 1. Descriptive statistics of seasonal and annual variations of lightning flash density (flashes km^{-2} $year^{-1}$) over the study area from 1998 to 2014.

	FIM	SWM	SIM	NEM	ANNUAL
Average	29.19	3.36	23.00	5.09	9.43
Maximum	83.86	9.15	68.61	10.16	20.33
Minimum	3.52	0.16	3.63	0.60	1.27
Standard Deviation	12.73	1.20	10.12	1.10	3.95

Table 2 represents the statistical summarization of monthly variation lightning flash density over the study area from 1998 to 2014. As per reported information in Table 2, the maximum lightning flash density, 167.69 flashes km^{-2} $year^{-1}$ had been recorded in April with an average of 52.72 flashes km^{-2} $year^{-1}$ and second maxima of flash density, 121.98 flashes km^{-2} $year^{-1}$ had been recorded in November with an average of 28.85 flashes km^{-2} $year^{-1}$ over the study area during the considered period. Moreover, it seems that, in June, July, August, and September, the average flash density is less than 0.50 flashes km^{-2} $year^{-1}$.

Table 2. Descriptive statistics of monthly variations of lightning flash density (flashes km^{-2} $year^{-1}$) over the study area from 1998 to 2014.

Month	Average	Maximum	Minimum	Standard Deviation
January	4.49	15.25	0.00	3.98
February	1.37	15.25	0.00	2.36
March	11.44	45.74	0.00	8.93
April	52.72	167.69	0.00	31.25
May	5.18	30.49	0.00	5.72
June	0.49	15.25	0.00	1.55
July	0.00	0.00	0.00	0.00
August	0.00	0.00	0.00	0.00
September	0.49	15.25	0.00	1.55
October	14.35	45.73	0.00	9.55
November	28.85	121.98	0.00	18.22
December	2.93	15.25	0.00	3.09

The statistical overview of the annual variation of lightning flash density over the study area from 1998 to 2014 is summarized in Table 3. According to indicated information in Table 3, the maximum flash density had been recorded in 2012 with an average of 65.92 flashes km^{-2} $year^{-1}$ over the study area during the considered study period. Moreover, comparatively, in the years 2002 and 2009, low lightning flash density values had been recorded over the study area.

Table 3. Descriptive statistics of annual variations of lightning flash density (flashes km^{-2} year^{-1}) over study area from 1998 to 2014.

Year	Average	Maximum	Minimum	Standard Deviation
1998	1.25	21.60	0.00	2.83
1999	13.58	43.20	0.00	7.18
2000	21.22	151.20	0.00	19.79
2001	2.49	21.60	0.00	3.70
2002	0.00	0.00	0.00	0.00
2003	2.91	21.60	0.00	3.93
2004	13.56	43.20	0.00	10.99
2005	3.19	43.20	0.00	6.48
2006	9.53	43.19	0.00	7.80
2007	6.10	21.60	0.00	5.13
2008	12.46	64.80	0.00	13.66
2009	0.70	21.60	0.00	2.20
2010	5.40	21.60	0.00	4.92
2011	3.74	21.60	0.00	4.67
2012	65.92	215.96	0.00	47.48
2013	7.90	64.80	0.00	7.28
2014	3.34	43.20	0.00	5.19

Seasonal Variation over the Study Area

Fig. 2 exemplifies the spatial variation of the recorded lightning data covering the study area over the considered period during the FIM season. For the study area considered, an average flash density of 29.19 flashes km^{-2} year^{-1} had been recorded in the FIM (maximum = 83.86 flashes km^{-2} year^{-1}, minimum = 3.52 flashes km^{-2} year^{-1}, and standard deviation = 12.73 flashes km^{-2} year^{-1}). This is in tally with the Sri Lankan context as well that according to the previous studies, the maximum number of lightning activity over Sri Lanka had been recorded in FIM than the other seasons (Edirisinghe et al., 2021; Maduranga et al., 2019; Jeyanthiran et al., 2008). According to the reported details, an average flash density of 22.25 flashes km^{-2} year^{-1} had been recorded in the FIM over Sri Lanka (Edirisinghe et al., 2021). Fig. 3 presents a graphical indication of the number of estimated total lightning flashes which had been recorded during the period from 1998 to 2014 over the study area. This estimation was done by considering the average flash density over the study area in respective years during the FIM by using zonal statistics generated by the raster map. The maximum number of lightning flashes of 19,120, during the study period, had been recorded over the study area in 2012.

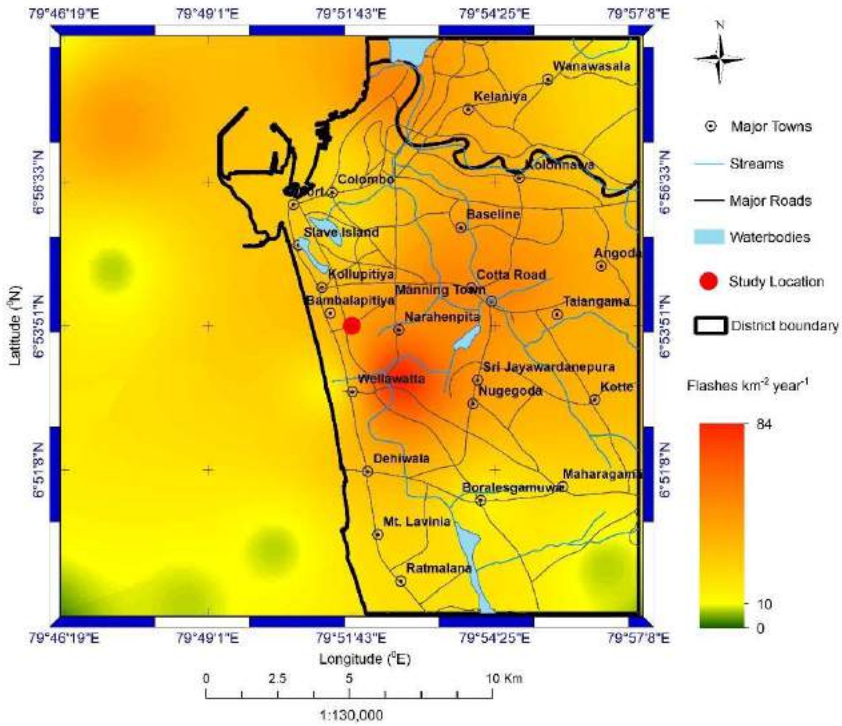

Figure 2. Spatial variation of lightning activities during the FIM season over the study area from 1998 to 2014.

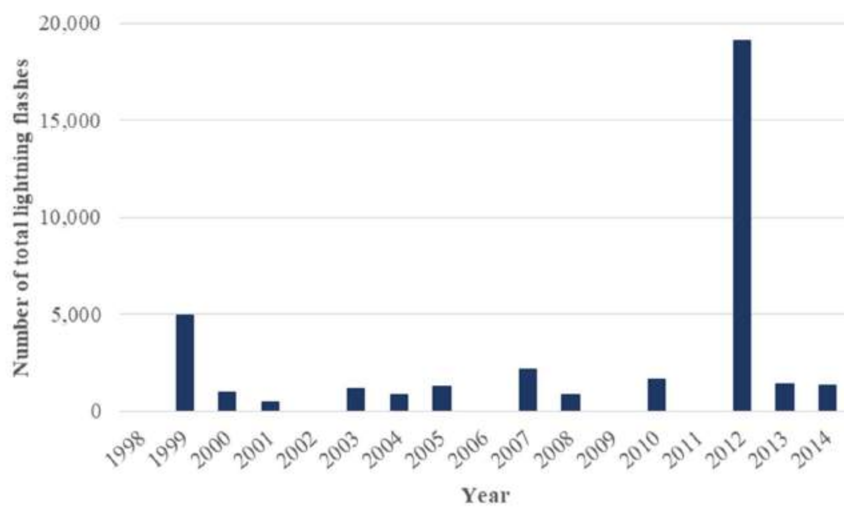

Figure 3. Estimated total lightning activities during the FIM season over the study area from 1998 to 2014.

Fig. 4 illustrates the spatial variation over the study area during the study period in the SWM season. Fig. 5 depicts the estimated total number of lightning flashes which had been occurred in the SWM season from 1998 to 2014. This estimation was done by considering the average flash density over the study area in respective years during SWM by using zonal statistics generated by the raster map. Furthermore, it can be observed that a fewer number of lightning flashes had been recorded during the SWM season than in the other seasons. For the study area considered, an average flash density of 3.36 flashes km^{-2} year^{-1} had been recorded in the SWM (maximum = 9.15 flashes km^{-2} year^{-1}, minimum = 0.16 flashes km^{-2} year^{-1}, and standard deviation = 1.20 flashes km^{-2} year^{-1}). In accordance to the reported details, an average flash density of 5.67 flashes km^{-2} year^{-1} had been recorded in the SWM over Sri Lanka (Edirisinghe et al., 2021).

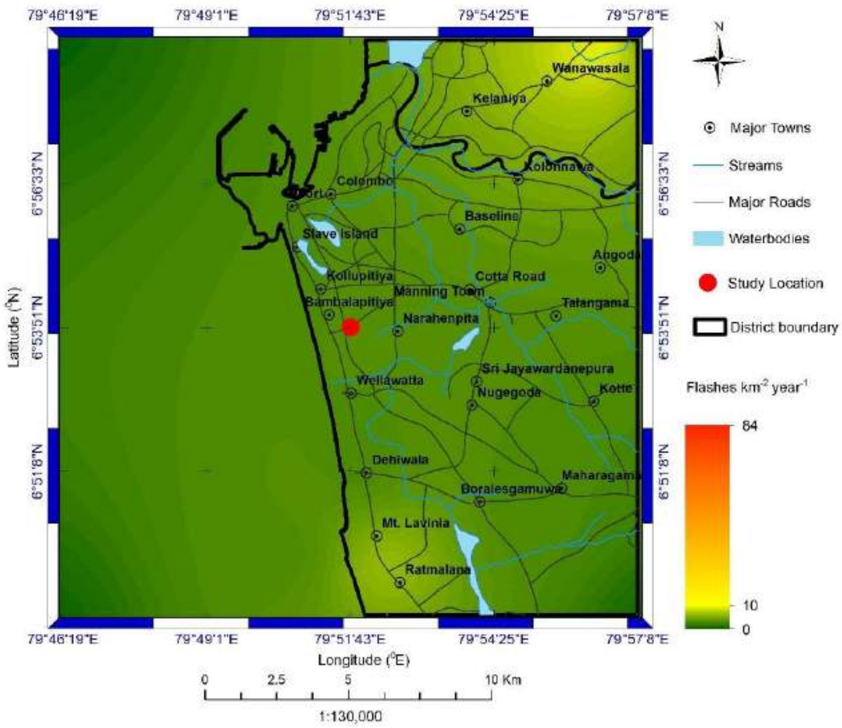

Figure 4. Spatial variation during the SWM season over the study area from 1998 to 2014.

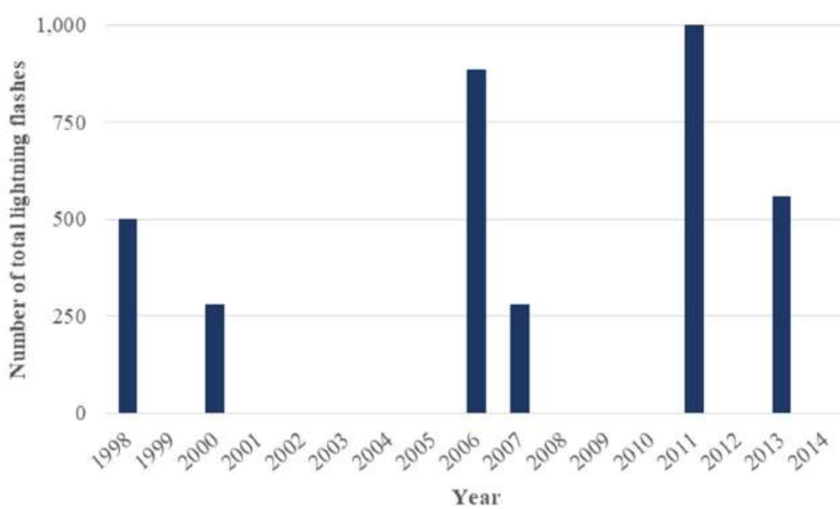

Figure 5. Estimated total lightning activities during the SWM season over the study area from 1998 to 2014.

The spatial variation of lightning activities over the study area for the SIM season during the period from 1998 to 2014 is depicted in Fig. 6. An average lightning flash density of 23.00 flashes km^{-2} year^{-1} had occurred in the SIM season (maximum = 68.61 flashes km^{-2} year^{-1}, minimum = 3.63 flashes km^{-2} year^{-1}, and standard deviation = 10.12 flashes km^{-2} year^{-1}). According to the reported details, an average flash density of 9.29 flashes km^{-2} year^{-1}

had been recorded in the SIM over Sri Lanka (Edirisinghe et al., 2021). Fig. 7 depicts the estimated total number of lightning flashes that had been recorded during the SIM season from 1998 to 2014. This estimation was done by considering the average flash density over the study area in respective years during the SIM by using zonal statistics generated by the raster map. Furthermore, the maximum number of lightning flashes had been recorded in the year 2000 with 3,657 total lightning flashes in this season.

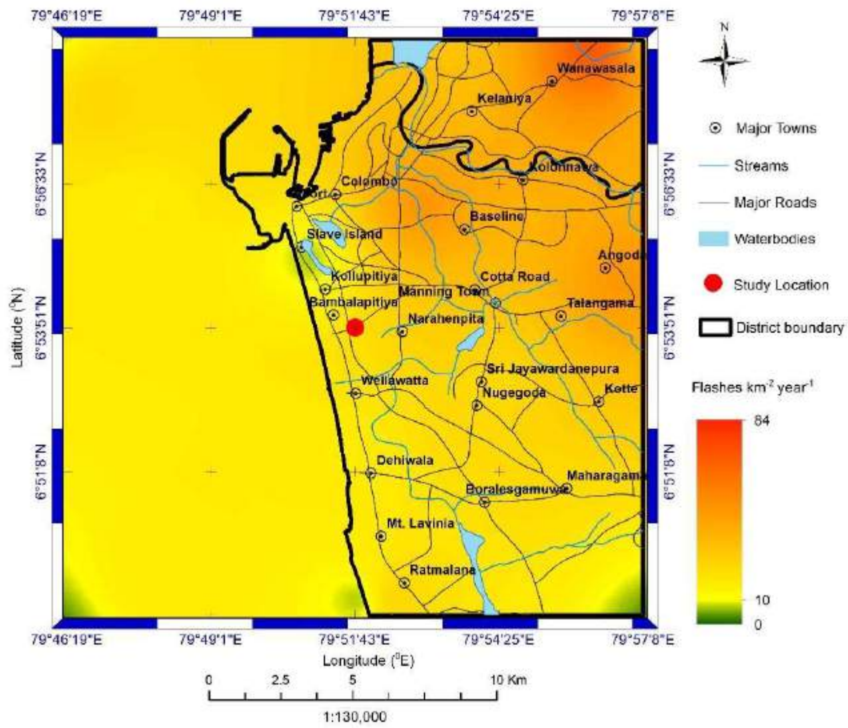

Figure 6. Spatial variation during the SIM season over the study area from 1998 to 2014.

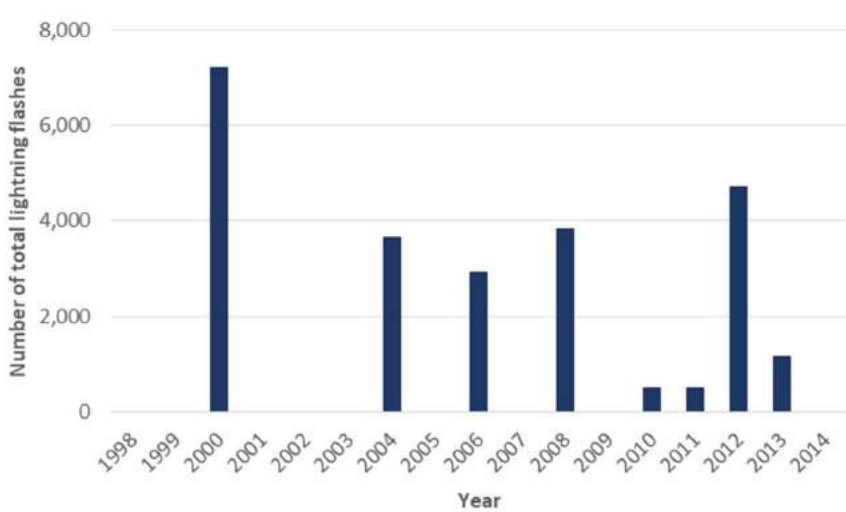

Figure 7. Estimated total lightning activities during the SIM season over the study area from 1998 to 2014.

Fig. 8 shows the spatial variation of lightning activities over the study area for the study period during the NEM season. According to Fig. 8, an average flash density of 5.09 flashes km^{-2} year^{-1} had been recorded during this season (maximum = 10.16 flashes km^{-2} year^{-1}, minimum = 0.60 flashes km^{-2} year^{-1}, and standard deviation = 1.10 flashes km^{-2} year^{-1}). According to the reported details, an average flash density of 2.99 flashes km^{-2} year^{-1} had been recorded in the NEM over Sri Lanka (Edirisinghe et al., 2021). Fig. 9 depicts the estimated total number of lightning flashes which had been occurred in the NEM season from 1998 to 2014. This estimation was done by considering the average flash density over the study area in respective years during the NEM by using zonal statistics generated by the raster map. Furthermore, a fewer number of lightning flashes had been recorded during this seasonal period as the same as in the SWM season.

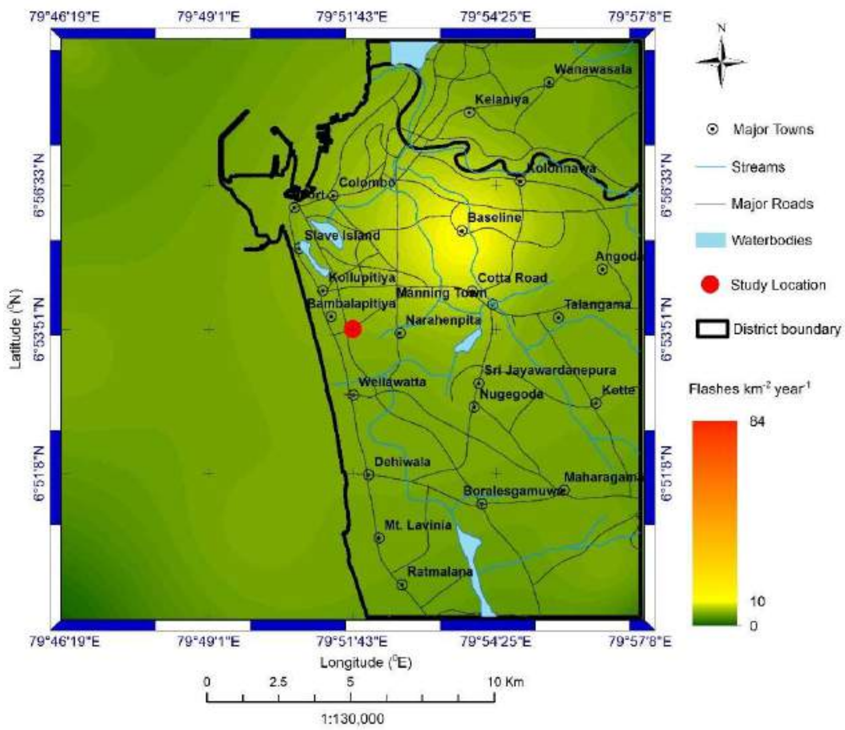

Figure 8. Spatial variation during the NEM season over the study area from 1998 to 2014.

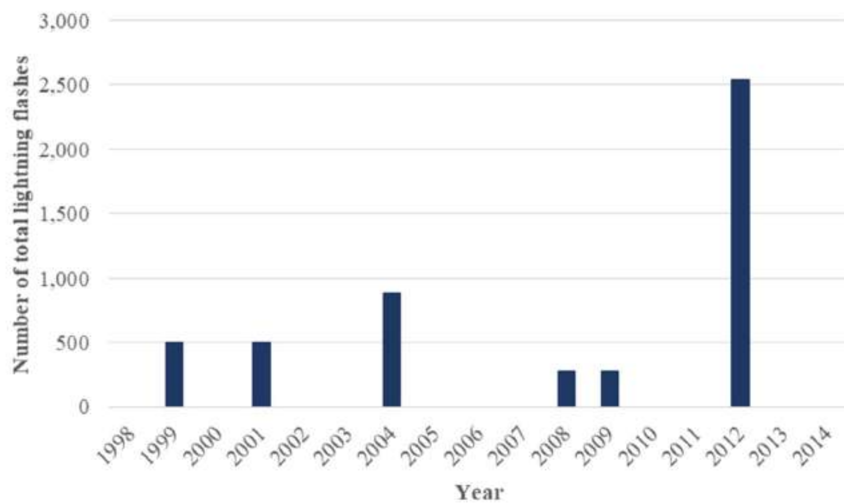

Figure 9. Estimated total lightning activities during the NEM season over the study area from 1998 to 2014.

Annual Variation of Lightning over the Study Area

Fig. 10 depicts the annual variations of lightning flash density over the study area by considering the lightning data from 1998 to 2014. An average flash density of 9.43 flashes km^{-2} year^{-1} had been recorded over the study area (maximum = 20.33 flashes km^{-2} year^{-1}, minimum = 1.27 flashes km^{-2} year^{-1}, and standard deviation = 3.95 flashes km^{-2} year^{-1}). According to the reported details, an average flash density of 8.26 flashes km^{-2} year^{-1} had been recorded over Sri Lanka (Edirisinghe et al., 2021). Fig. 11a shows the estimated average number of lightning flashes in each month that had been recorded over the study area by considering the lightning data from 1998 to 2014.

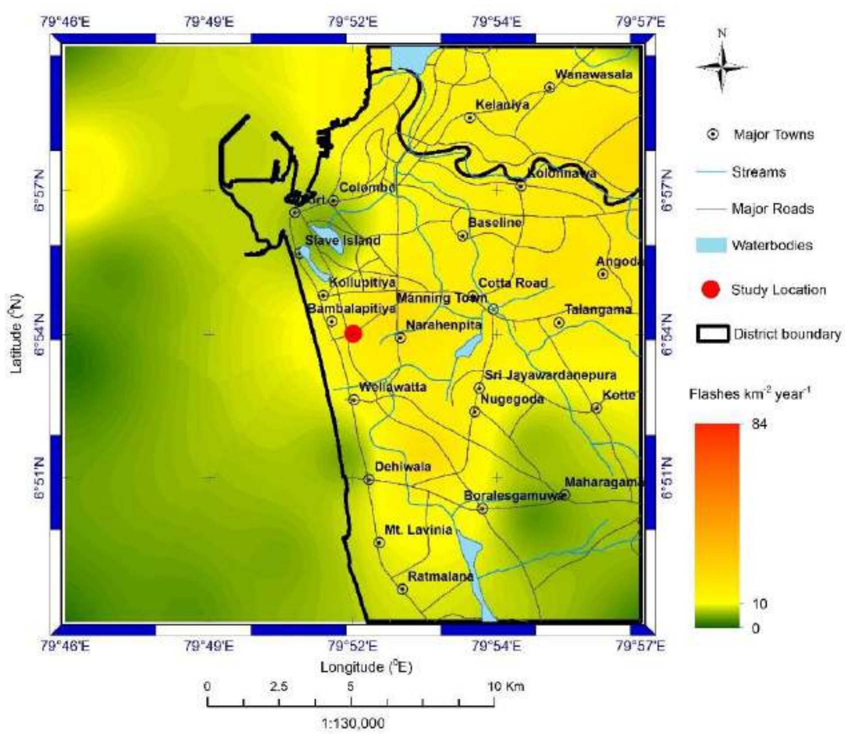

Figure 10. Annual spatial variation over the study area from 1998 to 2014.

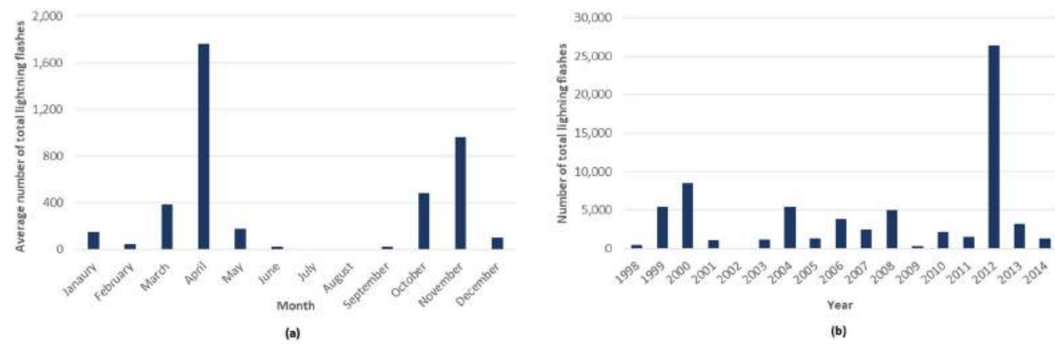

Figure 11. Estimated number of lightning flashes over the study area from 1998 to 2014: (a) Average monthly variation; (b) Annual variation.

As shown in Fig. 11a, the maximum number of activities had been recorded in April with an average of 1,757 number of lightning flashes. However, June, July, August, and September, show a less number of lightning activities relative to the other months of the year. Fig. 11b shows the annual variation of estimated total lightning flashes over the study area from 1998 to 2014. Over the study area, the maximum number of lightning flashes had been recorded in 2012.

Discussion

The investigation and analysis of lightning activities over the study location and its surroundings provide significant outcomes. Those are vital to identify suitable periods in a calendar year to plan the respective schools' outdoor and indoor events. As such, it can bring down the lightning hazard risk level to the lowest possible level and design an appropriate lightning safety scheme. In this study, covering approximately 20 km × 20 km square area by placing its center as the study location was considered for the analysis. This was mainly done by considering the accuracy level of the data and the average dimensions of the thunder cloud. Recorded data were placed into respective 5 km × 5 km grids to analyze the lightning flash density.

Fig. 12 depicts the distribution of the schools in the study area which is described in Fig. 1. Fig. 12 conveys that the selected high-density school area is highly vulnerable to lightning activities within the considered time period. Therefore, it implies the applicability of this study to propose appropriate safety precautions to the respective school community. The study area is with a high school density and the locations of most of the schools in the study area are highly vulnerable hotspots to lightning activities. When considering the seasonal variations, as can be seen in Fig. 13a, the maximum number of lightning flashes of 49% had been recorded over the study area during the FIM season and the second maximum of occurrence of 37% was during the SIM season. Moreover, previous studies reported that the maximum number of lightning activities had occurred in the same seasonal period (Edirisinghe et al., 2021; Maduranga et al., 2019; Jeranthiran et al., 2008). A minimum number of lightning flashes (7%) had occurred in both SWM and NEM seasons in May to September and December to February. Fig. 13b depicts the monthly variation of lightning activities over the study area. As per indicated information in Fig. 13b, the maximum number of lightning flashes of 43% had occurred in April and the second maximum of occurrence (24%) of lightning flashes was in November. Months of February, June, July, August, and September, had low lightning activities (less than or equal to 1%) over the study area from 1998 to 2014.

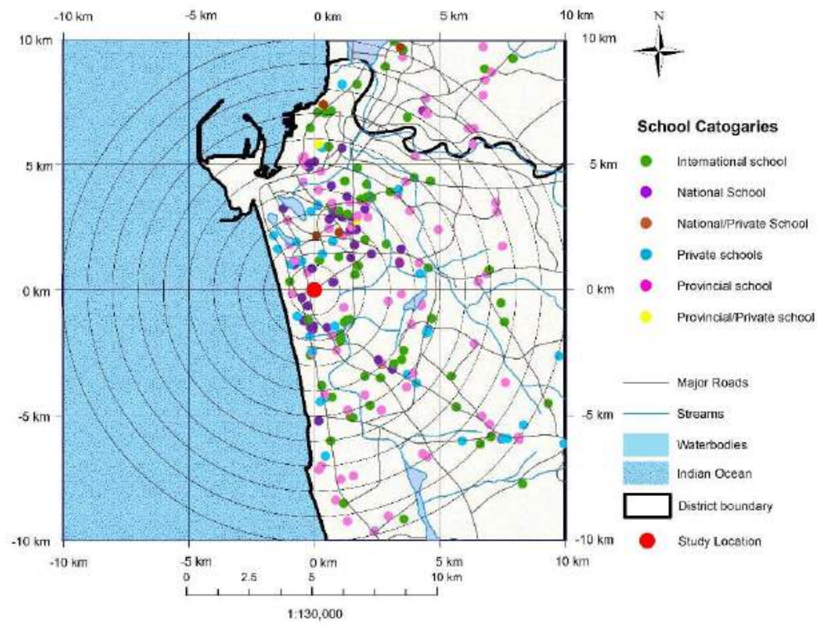

Figure 12. Distribution of different types of schools in the study area.

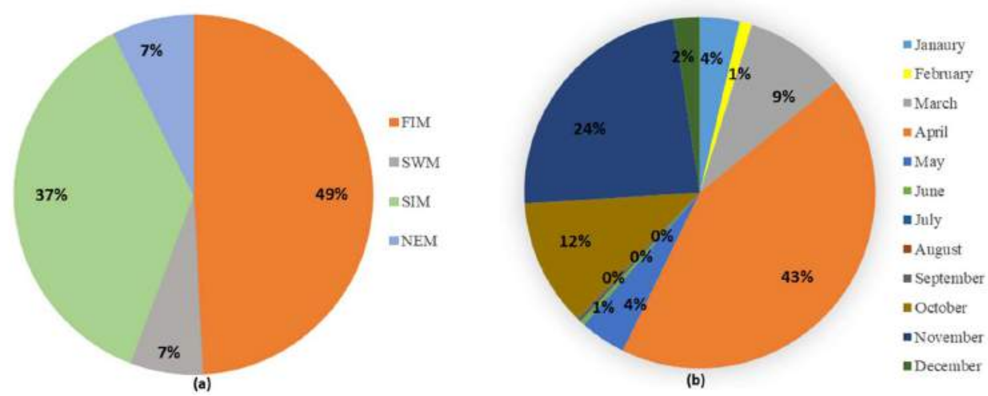

Figure 13. Temporal variation of lightning activities over the study area from 1998 to 2014: (a) Seasonal variation; (b) Monthly variation.

In general, all government and private schools in Sri Lanka have planned their studies in the morning hours (from 7:30 a.m. to 1:30 p.m.) and after-school activities have been planned in the afternoon hours (from 1:30 p.m. onwards). On the other hand, most of the lightning flashes had been recorded after 14.00 local time (LT) over the study area as illustrated in Fig. 14a that shows the percentage of diurnal variation. Fig. 14b shows the percentage of diurnal variation for each month over the study area. According to Fig. 14b, afternoon lightning activities are higher than the other time periods of every month. The maximum number of afternoon lightning flashes over the study area had been recorded in April and November. Furthermore, Fig. 15 depicts the percentage variation of lightning flashes categorized into four quarter-day time periods divided within a day. It shows that 27% of the total lightning flashes had been occurred in the afternoon hours (12.00 to 18.00 LT) over the study area. These results justify that a safety plan is essential for schools in the study area to propose a well-implemented plan to conduct afterschool activities to reduce the vulnerability level due to lightning among students and other stakeholders. In the morning hours (06.00-12.00 LT), 4% of lightning flashes had been recorded over the study area.

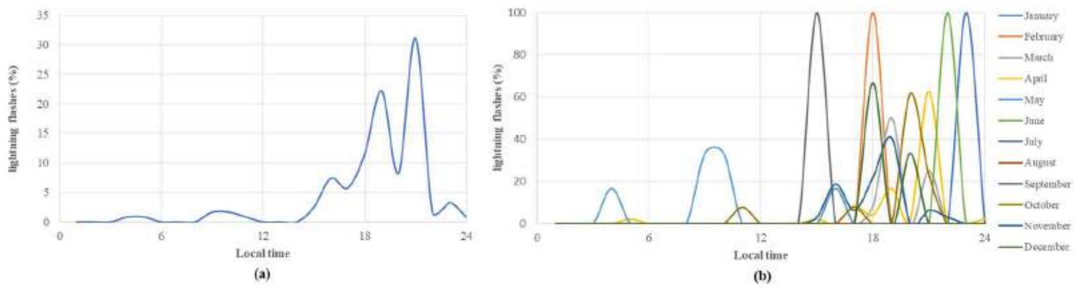

Figure 14. Diurnal variation over the study area: (a) Average variation; (b) Diurnal variation in each month.

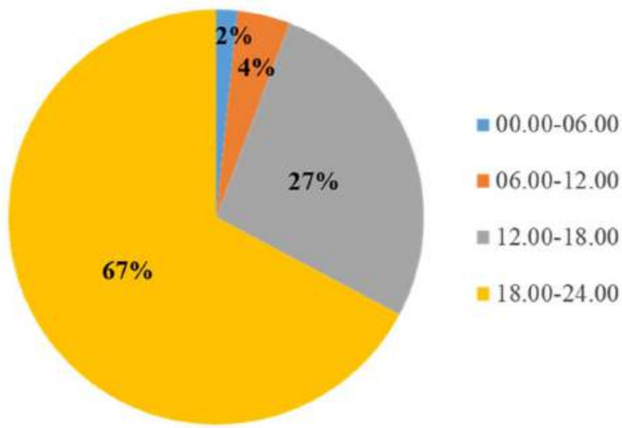

Figure 15. Percentage of lightning flashes in four quarter-day periods of a day over the study area.

Fig. 16 shows the spatial variation of lightning activities categorized into four quarter-day time periods (00.00 -06.00 LT, 06.00 -12.00 LT, 12.00 -18.00 LT, 18.00 -24.00 LT) divided within a day over the study area from 1998 to 2014. An average flash density of 2.88 flashes km^{-2} $year^{-1}$, 4.08 flashes km^{-2} $year^{-1}$,10.86 flashes km^{-2} $year^{-1}$, and 25.76 flashes km^{-2} $year^{-1}$ had been recorded in the period of 00.00 -06.00 LT, 06.00 -12.00 LT, 12.00 -18.00 LT and 18.00 -24.00 LT respectively during the considered period. As indicated in Fig. 16, the spatial variation of the lightning activities in the afternoon hours is much higher than the lightning activities in the morning hours. Therefore, engaging in outdoor activities in the afternoon hours is highly vulnerable to the safety of students. As well as, when organizing the afterschool activities, authorized parties in schools should pay attention to reduce lightning risk by implementing appropriate precautions.

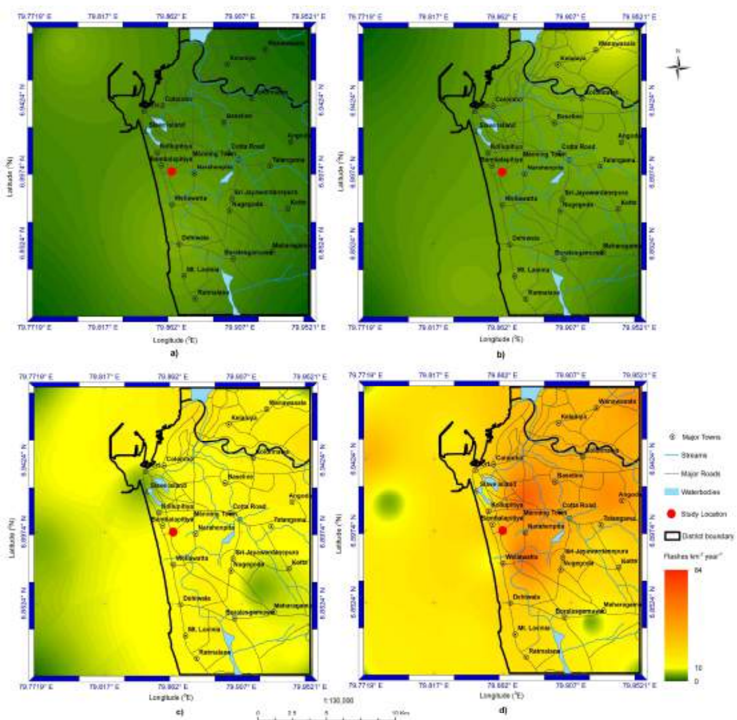

Figure 16. Spatial variation of diurnal lightning activities over the study area from 1998 to 2014: (a) 00.00 - 06.00 LT; (b) 06.00 -12.00 LT; (c) 12.00 -18.00 LT; (d) 18.00 -24.00 LT.

Fig. 17 presents the monthly variation of the recorded thunder days from 1998 to 2014 which were observed by the Colombo 07 weather station located at the Metrological Department of Sri Lanka, that is, 920 m away from the study location. According to the average monthly variation of the recorded thunder days as indicated by the solid line in Fig. 17, the maximum thunder days had been recorded in April and the second maxima was during November.

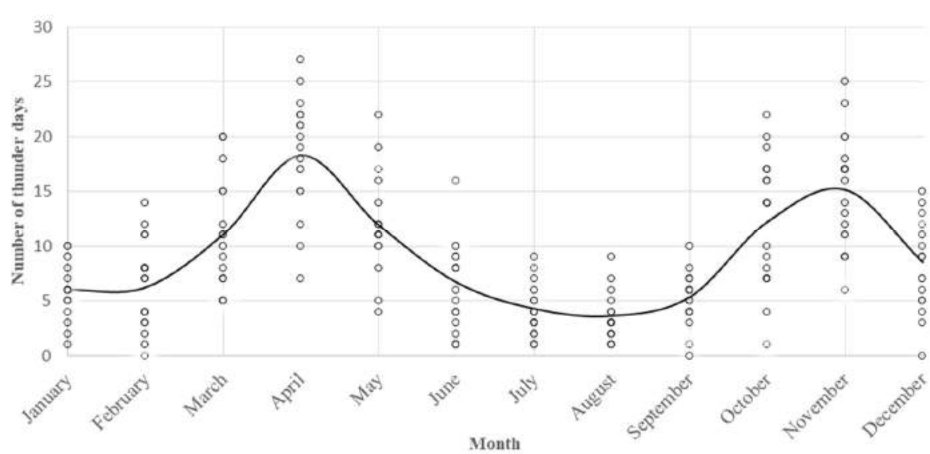

Figure 17. Monthly variation of thunder days which were obtained from the Metrological Department of Sri Lanka over the study area from 1998 to 2014 (the solid line indicates the average monthly variation of thunder days).

Fig. 18a shows the percentages of the lightning data from TRMM observations and recorded thunder data according to the number of days from 1998 to 2014. The annual variability of the thunder days together with lightning flash activities which were observed by LIS on the TRMM satellite is depicted in Fig. 18b. As can be seen in Fig. 18a, both the monthly variation patterns of lightning activity and the recorded number of thunder days show a similar variation pattern during the considered period.

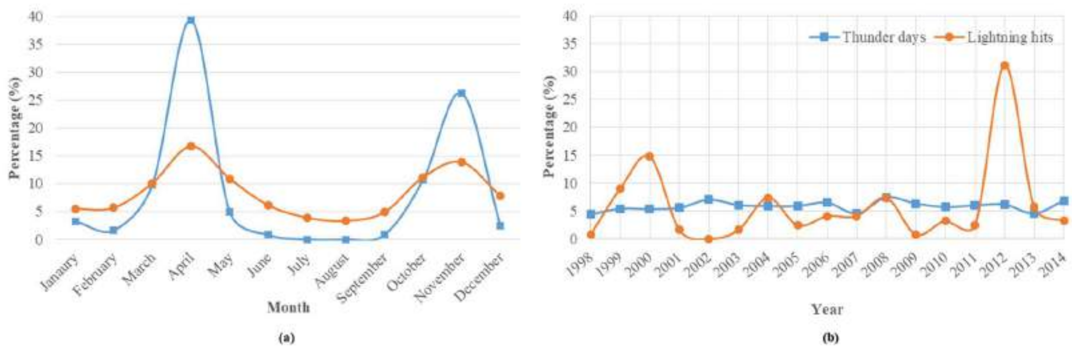

Figure 18. Comparison of lightning and thunder data from 1998 to 2014 which were obtained from LIS on TRMM and Metrological Department of Sri Lanka respectively (brown line indicates the lightning data and the blue line indicates thunder data): (a) Monthly variation; (b) Annual variation.

On the other hand, organizing or conducting outdoor school activities during thunderstorm seasons may create a high risk of ending up with lightning accidents. According to the results obtained from this study, for all schools located in the study area, after-school outdoor activities are highly vulnerable to students' safety as maximum lightning activities have been recorded in the afternoon hours.

When considering the above issues, all these schools need to develop and implement a set of appropriate lightning safety guidelines with the assistance of relevant authorities and other stakeholders to practice good lightning safety during school activities. Thus, the authors wish to propose five-level guidelines for lightning safety by including the original recommendations of Lightning Safety Guidelines (LSG) as reported in previous studies (Walsh et al., 1997; Holle et al., 1999; Walsh et al., 2013; Spengler et al., 2002; Lushine et al., 2015; Roeder, et al., 2010). These five levels of safety can be termed as scheduling outdoor activities, following the 30-30 rule (Jensenius et al., 2010; Lushine et al., 2015; Roeder, et al., 2010; Mary et al., 2015; Gomes et al., 2015), avoiding the most unsafe locations in terms of damage due to lightning, crouching action if required, and providing first-aid whenever necessary.

Describing further about the aforementioned five-level guidelines, it is a must that school outdoor activities should be scheduled to avoid the lightning hazard risk. According to this study, lower lightning activity had been recorded during the SWM and NEM seasons for the study area. Therefore, outdoor activities should be limited in the aforementioned time periods to minimize lightning accidents. Moreover, it should note that the activities which are away from a proper shelter are especially under threat to students other than the aforementioned months and mostly during afternoon sessions.

As mentioned in previously reported studies, the 30-30 rule can be followed to avoid lightning accidents in the schools in the study area. If the time to hear thunder after the lightning flash is 30 seconds or less, it is advisable to move towards a pre-identified safe location mostly inside a school building (Lushine et al., 2015; Roeder, et al., 2010). If the point of a strike is less than 10 km away from the respective school area probably it is in a danger zone. It could be substantial for thunderstorms that are rapidly moving towards the point of interest. It is important to stay in a safer place a minimum of 30 minutes after the last thunder before getting into planned activities or even called off since on many occasions most lightning casualties have been occurred during the latter part of the thunderstorm due to isolated lightning flashes (Lushine et al., 2015). From a general point of view, it is hard to find a safer place in the outside area during a thunderstorm. Elevated locations such as hills, open areas including sports fields, playgrounds, etc., and tall isolated objects like trees, flagpoles are outside locations with a high-risk level. Henceforth, it is vital to put attention to these locations inside the school area during a thunderstorm.

On the other hand, if the community is not properly aware of how lightning incidents occur, they will experience injuries due to lightning accidents. Especially when they are outside and away from proper shelter with inadequate time to reach the safest location, people should be aware of what they can take as an immediate action. As a temporary solution, the crouching action by keeping the feet together, squatting down, and tucking the head while covering the ears can be used to avoid lightning accidents in the field (Lushine et al., 2015).

Moreover, most of the fatal injuries due to lightning were from cardiac arrest and Cardio Pulmonary Resuscitation (CPR) should be performed followed by proper medical treatment. Therefore, having a first aid unit with proper training should be mandatory not only for lightning injuries but also for other various types of injuries inside the premises of any school.

Therefore, it is recommended that every school should implement these five-level guidelines for lightning safety by recognizing the importance of education along with the safety of persons who are at the premises of the school. Furthermore, improper lightning safety plans for a school could wither human safety and could affect the expected outcome of the scheduled activity in the absence of the consciousness of the prominence of lightning hazards. As mentioned earlier, all government and private schools in Sri Lanka have planned their outdoor activities for a specific period every year. On the other hand, the maximum and minimum lightning activities may change according to different regions. Henceforth, their scheduled plans should be changed according to regional spatiotemporal lightning activities in that period. It is recommended to follow the procedure adopted in this study to explore the lightning activities over the relevant region and to generate the respective risk level in terms of lightning hazards. Furthermore, authorized parties should pay attention to maintain the existing lightning earthing systems and should implement proper lightning earthing systems for unprotected buildings in schools to enhance the lightning safety of the school community in the country.

According to the Sri Lankan context, most of the schools have consisted of primary and secondary education levels or separate primary and secondary sections. As the primary students are not that matured and experienced to follow precautionary measures in vulnerable situations lightning warning systems can be addressed as one of the best solutions to overcome the issue. Moreover, teacher-student interaction on comprehensive awareness of the lightning risk, protection and safety methods may be lifesaving in the vulnerable situation. On the other hand, these findings and proposed guidelines are critically important not only in the Sri Lankan context but also for the global scenario, because it is believed that lightning activities have been confined to tropical regions. Therefore, this study is beneficial and can be presented as an apposite lending hand to authorized parties to implement specific precautionary measures in schools or similar institutions located in any country in the tropics to reduce the human vulnerability from lightning activities.

Conclusions

According to the results, the maximum number of lightning flashes (49%) had occurred in the FIM season with an average flash density of 29.19 flashes km^{-2} $year^{-1}$ over the study area in March and April in the period of 1998-2014. The second maximum number of lightning flashes of 37% had been recorded during the SIM season, whereas an average flash density during the SIM season was 23.00 flashes km^{-2} year^{-1}. On the other hand, a fewer number of lightning flashes of 7% had been recorded over the study area during the SWM and NEM seasons. According to the annual variation, an average lightning flash density was recorded as 9.43 flashes km^{-2} year^{-1}.

Moreover, the thunder data observed by the Meteorological Department of Sri Lanka covering the study area shows that the maximum number of thunder days had occurred in April and the second maxima was during November. Henceforth, it could confirm the accuracy of the variation patterns of the lightning activities in this study based on the satellite data considered. It is suggested that these schools should avoid outdoor activities, as much as they can, in the period of the first inter-monsoon season to avoid a high lightning hazard risk level. It would be better if the schools can schedule their work in the southwest or northeast monsoon seasons as it shows a fewer number of lightning activities.

It was observed that 4% of lightning flashes had been recorded in the morning hours (06.00- 12.00 LT) with an average flash density of 2.88 flashes km^{-2} year^{-1} and 27% of lightning flashes had been recorded between 12.00-18.00 LT with an average flash density of 4.08 flashes km^{-2} year^{-1} whereas during 18.00-24.00 LT it was 67% with an average flash density of 25.76 flashes km^{-2} year^{-1}. As per the results, it could be concluded that 94% of lightning flashes over the study area had been recorded after 14.00 LT, which coincides with the school ending time of its routing educational program. Consequently, after-school outdoor activities are highly vulnerable to students' safety, especially during April and November, which were the two highly active months for lightning. It is also recommended that the proposed five-level guidelines for lightning safety should be implemented effectively as a set of appropriate lightning safety guidelines with the assistance of relevant authorities and other stakeholders. Furthermore, enhancing the awareness about lightning safety among the school community and maintain the existing lightning protection system, and implementation of a proper lightning earthing system for unprotected buildings in schools in the country are proper solutions to minimize lightning-related accidents.

Acknowledgments

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