Impact of environmental factors on the spread of dengue fever in Sri Lanka

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Abstract

Dengue fever is a mosquito-borne viral disease caused by the dengue virus of the Flaviviridae family and is responsible for colossal health and economic burden worldwide. This study aimed to investigate the effect of environmental, seasonal, and spatial variations on the spread of dengue fever in Sri Lanka. The study used secondary data of monthly dengue infection and the monthly average of environmental parameters of 26 Sri Lankan regions from January 2015 to December 2019. Besides the descriptive measurements, Kendall's tau_b, Spearman's rho, and Kruskal–Wallis *H* test have been performed as bivariate analyses. The multivariate generalized linear negative binomial regression model was applied to determine the impacts of meteorological factors on dengue transmission. The aggregate negative binomial regression model disclosed that precipitation (odds ratio: 0.97, $p < 0.05$), humidity (odds ratio: 1.05, $p < 0.01$), and air pressure (odds ratio: 1.46, $p < 0.01$) were significantly influenced the spread of dengue fever in Sri Lanka. The bioclimatic zone is the vital factor that substantially affects the dengue infection, and the wet zone (odds ratio: 6.41, $p < 0.05$) was more at-risk than the dry zone. The climate season significantly influenced dengue fever transmission, and a higher infection rate was found (odds ratio: 1.46, $p < 0.01$) in the northeast monsoon season. The findings of this study facilitate policymakers to improve the existing dengue control strategies focusing on the meteorological condition in the local as well as global perspectives.

Keywords *Aedes* mosquito · Dengue fever · Meteorological factors · Negative binomial regression · Spatio-temporal analysis · Vector-borne disease

Introduction

Dengue fever is an arthropod vector-borne viral infection transmitted primarily by *Aedes aegypti* and secondarily by *Aedes albopictus* mosquitoes. It has a higher infection rate in tropical and subtropical areas and poses a global threat for around four billion inhabitants of more than 141 countries. It has been estimated that approximately 390 million dengue cases with 25,000 deaths have occurred worldwide annually (Brady et al. 2014; World mosquito program 2021). Three-quarters of the dengue cases come from the South-East Asia

and Western Pacific regions of WHO (Bhatt et al. 2013). In Sri Lanka, the first dengue case was confirmed in 1962, while the first outbreak had recorded in 1965 (Sirisena and Noordeen 2014). The dengue virus has four serotypes DENV 1, 2, 3, and 4. However, one new serotype, DENV 5, was identified in Malaysia in 2007 (Mustafa et al. 2015). All four dengue virus serotypes have been co-circulating in Sri Lanka for more than 35 years (Sirisena and Noordeen 2014). The country experienced its worst-ever dengue outbreak in 2017, with more than 175,000 cases and nearly 400 fatalities (Daily News 2017). A model predicted that the dengue infection will increase up to 2.25 billion worldwide by 2080 (Messina et al. 2019).

Climate plays a significant role in the spread of dengue through impacting the mosquito life cycle (Liyanage et al. 2016a). Mosquitoes are known as ectotherms, i.e., their breeding and activity depend mainly on the surrounding environment (Blanford et al. 2013). An entomological study showed that *Aedes* mosquitoes primarily breed in different containers with stagnant clean and organically

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rich water like plastic buckets, tier, coconut shells, etc. (Sirisena and Noordeen 2014; Rahman et al. 2021b). Precipitation plays a crucial role as water is required to hatch mosquito eggs and develop the larval stage (Wagner et al. 2020). Larvae live in water, and their development takes about 7–10 days. The dengue virus transmission creates a complex interrelation with local meteorological factors. Rainfall and temperature play a crucial role in dengue fever transmission (Naish et al. 2014). The transmission of the viruses occurs between 18 and 34 °C and peaks in the range of 26–29 °C (Mordecai et al. 2017). However, previous studies in different countries showed a range of combinations of various surrounding environmental parameters on dengue transmission (Choi et al. 2016; Johansson et al. 2016; Rahman et al. 2021a). The literature also stated that temperature, rainfall, relative humidity, and population density were associated with dengue infection in high-risk areas (Zhu et al. 2016; Sharmin et al. 2018). Investigations revealed that dengue fever incidence in Sri Lanka was caused by the factors: precipitation, wind, urbanization, land management, socio-demographic characteristics, etc. (Sirisena et al. 2017; Wagner et al. 2020). Rainfall positively impacts dengue incidence in Sri Lanka (Liyanage et al. 2016a; Sirisena et al. 2017). The country's two annual peaks of dengue incidence are correlated with the two monsoons season during May to September and December to February (Liyanage et al. 2016a, Prabodanie et al. 2020b). Consequently, western provinces possessed higher dengue cases (41% in 2017) than the eastern parts of the country (7% during the 2017 outbreak) (Lazarus 2021). Sri Lanka provides a compelling location for studying the effect of climate on dengue transmission due to highly varied rainfall patterns in the island (Prabodanie et al. 2020b). Moreover, dengue fever shared a few common clinical signs with COVID-19 infection which has created misdiagnosis and delay diagnosis during the pandemic (Rahman and Rahman 2020). The COVID-19 associated circumstances also hampered the usual surveillance and other programs of different diseases including dengue. Therefore, this study excluded the data of the year 2020.

Due to the climate-sensitive nature of dengue, a common control strategy may not work effectively throughout the country. Hence, dengue monitoring and prevention efforts should focus on the local scale (Ooi et al. 2006). This study attempted to understand the potential effect of various environmental, seasonal, and spatial factors on dengue infection in Sri Lanka. Monthly dengue data along with climate and weather indicators of 26 cities from January 2015 to December 2019 have been used in this research. The results will support concerned personnel to reduce the regional-based transmission risk and help prevent the spread of dengue infection.

Materials and methods

Study area

Sri Lanka is a tropical island of the Indian Ocean located within the tropics between 5° 55' N and 9° 51' North latitudes and between 79° 42' and 81° 53' East longitude. The island is divided into four climatic zones based on the yearly climate: wet, intermediate, dry, and arid. The wet zone receives rainfall in all seasons, and the average annual rainfall varies from 2000 to 5000 mm. Intermediate, dry, and arid zones receive 1100–2000 mm, 700–1000 mm, and less than 700 mm annual rainfall, respectively (Prabodanie et al. 2020b). In this study, the arid zone has been merged with the dry zone and considered the country into three distinct zones. The different climatic zones in Sri Lanka are presented in Fig. 1a. The monsoon winds of the Bay of Bengal and the Indian Ocean influence the pattern of precipitation which marks the climate seasons in the study area (Asian Disaster Reduction Center 2020). The spatial distribution of precipitation in different climate seasons in Sri Lanka is illustrated in Fig. 1b–e. The climate of Sri Lanka can be characterized into 4 seasons based on 12 months period that it inveterate: (1) The first inter-monsoon (FIM) season (March–April): this term is uncomfortable with thunderstorm-type rain, mainly throughout the afternoon or evening. The amount of rainfall varies between 100 and 250 mm in most parts of the island (Fig. 1b).

(2) Southwest monsoon (SWM) season (May–September): This term brings windy weather that eases off the hotness of the 1st inter-monsoon season, and the rainfall varies from about 100 mm to over 3000 mm in Sri Lanka. Relatively active southwest monsoon causes heavy rain and warm, humid air to the western part of the country (Fig. 1c). (3) Second inter-monsoon (SIM) season (October–November): In the second inter-monsoon season, thunderstorm-type rain and cyclones are common in the Bay of Bengal. Widespread rain with strong winds leads to floods and landslides on the island. The whole country receives 400 mm or more rain, and higher rainfall (750–1200 mm) occurs in Southwestern slopes during this season (Fig. 1d). (4) Northeast monsoon (NEM) season (December–February): This season comprises relatively cool but dry weather that makes immediate comfortable and pleasant conditions over most parts of Sri Lanka. The days remain full of sunshine, and nights are cool with a cloud-free sky. Unless this pleasant weather, some parts of the country experience rain during this season (Fig. 1e) (Climate of Sri Lanka 2021).

Data collection

This study used secondary data of monthly dengue infections and different environmental parameters of 26 regions of Sri Lanka from January 2015 to December 2019. The key

Fig. 1 Spatial distribution of climatic zones and average precipitation in different climate seasons in Sri Lanka

environmental factors considered in this study were temperature, relative humidity, precipitation, sky clearness, air pressure, and wind speed. In addition to these ecological factors, this study also included bioclimatic zone and climate season as exogenous variables suspected to influence the study variable significantly. Based on the annual rainfall, the country is divided into 3 bioclimatic zones in this study. From 26 regions, 13 regions belong to the dry zone, 6 to the intermediate zone, and 7 to the wet zone. The dengue infection data were collected from the Health Ministry of Sri Lanka (Epidemiology Unit of Ministry of Health 2019). The monthly dengue infection raw data for every year extracted from the website were organized in an excel sheet. Regions, months, and dengue cases were arranged in the first three columns in the excel sheet. The meteorological data were extracted from the NASA Power Data Access Viewer (NASA Power 2021). The environmental parameters were measured in different units: precipitation in millimeter (mm), relative humidity in percentage (%), air pressure in kilo Pascale (kPa), the

temperature in degree Celsius ($^{\circ}\text{C}$), wind speed in meter per second (m/s), whereas sky clearness was unitless. Generally, sky clearness is a dimensionless number between 0 and 1. It is defined as the ratio of radiation and extraterrestrial radiation (HOMER). The monthly averages of environmental factors were collected and systematically organized in each row corresponding to the individual region and months. The 4th and following columns were featured by the environmental factors, respectively. Eventually, the bioclimatic zone and climate season were included in the subsequent columns. This approach had been followed for each of the individual years. Finally, all 5-year data were merged into a single data file for the aggregate regression model.

Data analysis

The focal outcome variable considered in this analysis was the number of monthly dengue infections. Descriptive statistics for the chosen environmental variables were mean,

standard deviation (SD), maximum, minimum, skewness, and kurtosis. The 95% confidence interval indicates the impact size for the number of dengue cases in 26 cities of Sri Lanka. As the study variable considered here was a count variable, several statistical approaches were applied to find the appropriate statistical analysis. For testing the linearity of the variables, analysis of variance (ANOVA) tables was computed for each of the explanatory variables concerning the dependent variable. The p values corresponding to the deviation from linearity in the ANOVA table were observed, confirming the non-linear relationships ($p < 0.05$) between independent and dependent variables. Besides the linearity test, the one-sample Kolmogorov–Smirnov normality test was applied to the data and found no evidence of normality ($p < 0.05$). Since the variables considered in this study did not follow linearity and normality assumptions, it would be apposite to use the non-parametric statistical methods. To assess the bivariate relationship between the spread of dengue infections and various environmental variables, Kendall's tau_b and Spearman's rho correlation coefficients were computed. The meteorological variables which found significant in bivariate analysis were also considered in multivariate analysis. In addition to the climate variables, spatial and cyclical or seasonal variables were also included in the multivariate model. Kruskal–Wallis H test was applied as bivariate analysis to test the significant mean difference of *Aedes* infections among the spatial, temporal, and seasonal variable categories. The multivariate generalized linear model (GLM) was employed to determine the factors that significantly influence the spread of dengue disease in Sri Lanka. Since the study variable was a count variable, the Poisson regression (PR) model and the negative binomial regression (NBR) model with the log link function were used as non-parametric regression analysis.

Akaike information criteria (AIC) values were calculated for each model, and the best was chosen for the study. The AIC value for the NBR model was found least than that of the PR model. Hence, it can be said that the NBR model is better than the PR model. Firstly, the NBR model was applied for each individual year from 2015 to 2019. Secondly, it was also employed for the aggregate dataset

(2015–2019) as a whole. Augmented Dicky–Fuller (ADF) test was performed to test the possible existence of unit root in the aggregate dataset. The ADF test provides the evidence of no unit root, i.e., the dataset was stationary, indicating no restrictions to apply the usual statistical approach. Moreover, the Chi-square test statistic was calculated based on the NBR and PR model's loglikelihood deviation. The Chi-square test proved the evidence of overdispersion of the data. Hence, the NBR model had been consciously applied for the analysis as it is appropriate for the overdispersed count data. All the descriptive and bivariate analyses were performed on the IBM SPSS (Statistical Package for the Social Science) version 25, and multivariate GLM was conducted in R version 4.1.1.

Results and discussion

A descriptive analysis was performed for both study and explanatory variables before analyzing relationships between environmental factors and dengue fever. Table 1 represents the descriptive measures of various ecological parameters within the period of 2015–2019. The highest average precipitation was observed 7.28 mm in 2018. In contrast, the minimum value was recorded 3.67 mm in 2016. The 5-year average precipitation was 5.28 mm, and the average humidity level was 80.60%. In the study period, the maximum and minimum average humidity was recorded at 83.43% (2015) and 78.38% (2019), respectively, and it has a negatively skewed distribution. The mean air pressure was 99.42 (SD: 1.78) kPa, and it was found to have close to the mean value for all five individual years.

The 5-year mean temperature was 27.29 °C which ranges from 26.86 °C (2015) to 27.71 °C (2019). The highest average wind speed (4.27 m/s) was recorded in 2019 and the lowest (1.03 m/s) in 2015. The average sky clearness was 0.65 for the whole study period. The lowest value of sky clearness (0.50) was observed in 2019. The total number of dengue infections in different cities throughout 2019 is presented in Fig. 2 to observe the distribution of dengue infections in various Sri Lankan locations.

Table 1 Descriptive statistics of the selected environmental factors in Sri Lanka (2015–2019)

Environmental factors	Mean (2015)	Mean (2016)	Mean (2017)	Mean (2018)	Mean (2019)	2015–2019					
						Mean	SD	Min	Max	Skew	Kurt
Precipitation (mm)	5.11	3.67	4.23	7.28	5.12	4.72	3.99	0.03	19.06	1.18	0.79
Humidity (%)	83.43	79.52	79.35	82.34	78.38	80.60	6.07	60.63	100.00	−0.25	0.54
Air pressure (kPa)	99.49	99.43	99.40	99.41	99.35	99.42	1.78	93.39	101.33	−1.47	1.66
Temperature (°C)	26.86	27.57	27.39	26.94	27.71	27.29	2.02	20.90	33.14	−0.31	−0.11
Wind speed (m/s)	1.03	1.72	1.17	1.19	4.27	1.88	2.08	0.01	8.86	1.14	0.29
Sky clearness	0.69	0.68	0.68	0.68	0.50	0.65	0.08	0.37	0.71	−1.88	2.37

From Fig. 2, it is observed that the two most infected cities were Colombo ($n=20,718$) and Gampaha ($n=16,573$), which are located under the wet zone, and the lowest infection was found in Mannar ($n=271$) and Mullaitivu ($n=268$), located in dry areas of Sri Lanka.

A temporal and spatial comparison of the total number of *Aedes* infections is illustrated in Fig. 3a. The figure shows that the number of *Aedes* infections had an upward trend from 2015 to 2017 but dramatically fell in 2018. The maximum number of diseases was recorded in the wet zone in 2017, followed by the intermediate zone in the same year. The dry area had minimum conditions in 2015–2017 and observed the second most infected zone in 2018 and 2019. From Fig. 3a, it is observed that the wet zone had a maximum number of infections in all 5 years. To better understand the cyclical or seasonal impact on the *Aedes* infection transmission, this study also compares the seasonal variability of total contagions for the individual years, presented in Fig. 3b. The maximum number of *Aedes* infections was found in the southwest monsoon season in 2017, and the high illness was observed for the next 2 years in the same season.

The minimum number of *Aedes* infections was observed in the first inter-monsoon season for each of the years. A moderate number of diseases were found for both northeast-monsoon and second inter-monsoon seasons.

Besides the descriptive measures of environmental factors, we also calculated the descriptive statistics of the number of dengue infections in different regions of Sri Lanka in 2019 and presented in Table 2. It revealed that the maximum monthly mean of disease was found in Colombo (1726.59 ± 1122.81) followed by Gampaha (1381.08 ± 912.74), and the minimum mean infection was in Mannar (22.58 ± 35.90) followed by Moneragala (27.75 ± 24.26).

The distribution of disease was highly positively skewed ($\gamma_1=2.87$ and 2.83) and leptokurtic ($\gamma_2=8.53$ and 8.69) for Trincomalee and Mannar cities, respectively. In contrast, the distribution was negatively skewed ($\gamma_1=-0.09$ and -0.04) and platykurtic ($\gamma_2=-1.74$ and -1.81) for the cities Galle and Moneragala, respectively.

In addition to the descriptive statistics, the correlation coefficient of the dengue infections and different environmental factors was also measured and presented in Table 3.

Fig. 2 Total number of dengue cases recorded in different cities of Sri Lanka in 2019

Fig. 3 Temporal comparison of the total number of *Aedes* infections in different climatic zones and seasons in Sri Lanka

Table 2 Descriptive measures of the number of dengue infections in different regions of Sri Lanka in 2019

Cities	Mean (monthly)	Standard deviation	Minimum	Maximum	Skewness	Kurtosis	95% confidence interval for mean	
							Lower bound	Upper bound
Colombo	1726.50	1122.81	579	4217	1.22	0.81	1013.10	2439.90
Gampaha	1381.08	912.74	429	3154	0.60	−0.79	801.16	1961.01
Kalutara	699.58	399.80	202	1310	0.04	−1.64	445.56	953.60
Kandy	745.00	709.22	192	2444	1.54	1.78	294.39	1195.61
Matale	203.75	309.67	17	902	1.90	2.27	6.99	400.51
Nuwara Eliya	36.50	29.08	7	97	1.42	1.05	18.02	54.98
Galle	614.83	392.20	123	1155	−0.09	−1.74	365.64	864.03
Hambantota	170.75	75.46	80	272	0.17	−1.70	122.81	218.69
Matara	337.83	209.69	101	717	0.43	−1.06	204.60	471.07
Jaffna	688.42	971.78	59	2763	1.80	1.93	70.98	1305.85
Kilinochchi	33.00	42.32	5	141	2.11	3.68	6.11	59.89
Mannar	22.58	35.90	1	130	2.83	8.69	−0.23	45.39
Vavuniya	72.67	100.58	11	306	1.97	2.61	8.76	136.57
Mullaitivu	22.33	23.80	1	72	1.14	0.10	7.21	37.46
Batticaloa	237.33	274.23	66	1020	2.54	6.66	63.10	411.57
Ampara	32.33	20.19	11	81	1.51	2.25	19.50	45.16
Trincomalee	247.42	375.07	45	1366	2.87	8.53	9.11	485.72
Kurunegala	268.17	184.36	119	655	1.50	1.17	151.03	385.30
Puttalam	188.08	194.83	29	624	1.47	1.10	64.29	311.87
Anuradhapura	97.00	80.31	34	270	1.73	1.83	45.97	148.03
Polonnaruwa	46.75	30.32	19	108	1.51	1.35	27.49	66.01
Badulla	160.17	148.57	41	490	1.63	1.58	65.77	254.56
Moneragala	27.75	24.26	0	60	−0.04	−1.81	12.34	43.16
Ratnapura	340.50	156.31	165	687	0.79	0.61	241.18	439.82
Kegalle	226.33	128.83	90	494	0.80	−0.18	144.48	308.19
Kalmunai	127.42	149.01	29	497	2.01	3.19	32.74	222.09

It has been observed that humidity and temperature consistently significantly correlated with the number of *Aedes* contagions in all individual years. It can be said that the spread of infection increases with the increase in humidity in Sri Lanka.

Table 3 elucidates that air pressure had a significant negative correlation with dengue transmission. It has been

observed that both Kendall's tau_b and Spearman's rho correlation coefficient show consistent results from year to year. The non-parametric Kruskal–Wallis *H* test found that climate season, bioclimatic zone, and nominal years were significant with the spread of dengue infection, indicating a significant mean difference in dengue infection among the categories of the seasonal, spatial, and temporal

Table 3 Correlation between the spread of *Aedes* infections and environmental factors in individual years

Environmental factors	2015		2016		2017		2018		2019	
	Kendall	Spearman	Kendall	Spearman	Kendall	Spearman	Kendall	Spearman	Kendall	Spearman
Precipitation (mm)	0.03	0.03	0.02	0.02	0.01	0.03	0.05	0.05	.28**	.41**
Humidity (%)	.14**	.21**	.25**	.38**	.16**	.25**	.16**	.24**	.33**	.48**
Air pressure (kPa)	−.08*	−.13*	−.23**	−.34**	−.17**	−.25**	−.09**	−.15**	−0.053	−0.08
Temperature (°C)	−.18**	−.27**	−.28**	−.42**	−.09*	−.15**	−.13**	−.19**	−.23**	−.34**
Wind speed(m/s)	−0.04	−0.05	.11**	.17**	.12**	.18**	0.05	0.07	−0.04	−0.06
Sky clearness	.21**	.28**	.14**	.20**	.17**	.22**	0.001	0.003	−.25**	−.37**

** $p < 0.01$ (2-tailed); * $p < 0.05$ (2-tailed)

variables. Besides the bivariate analysis for individual years, it was also performed for the aggregate dataset of the year 2015–2019 and illustrated in Table 4.

The results in Table 4 illustrate that precipitation ($r=0.05$, $p<0.05$) and humidity ($r=0.11$, $p<0.05$) were positively significantly correlated with dengue transmission. The results also revealed temperature ($r=-0.14$, $p<0.05$) and air pressure ($r=-0.13$, $p<0.05$) had significant negative relationships with the spread of dengue. Wind speed ($r=0.06$, $p<0.05$) was found to have a substantial positive correlation with dengue infection, while sky clearness ($r=0.014$, $p>0.05$) was insignificant. This study found a significant negative correlation between temperature and the spread of *Aedes* infection ($r=-0.139$, $p<0.05$). Previous studies investigated the impact of different climatic features and found monthly rainfall, number of rainy days, relative

humidity, and minimum temperature have shown significant correlations with the disease in Sri Lanka (Withanage et al. 2018). Similarly, average temperature, humidity, and low to medium rainfall were found significantly associated with the dengue incidence in Bangladesh (Mutsuddy et al. 2019). A diagram of the monthly average of different environmental factors and dengue cases in 2019 is demonstrated in Fig. 4 to visually identify the relative impact of meteorological factors on the spread of dengue disease.

A positive relationship is observed between precipitation and relative humidity with the dengue infection. Figure 4a and 4b illustrates that cases increase with increased rainfall and humidity. Similar to this study, research revealed that the number of dengue infections increases with the increase in precipitation and humidity. (Liyanage et al. 2016b; Sirisena et al. 2017). Moreover, Fig. 4c, d is shown that sky clearness and temperature negatively affected the spread of infection. Furthermore, Fig. 4e, f depicted air pressure and wind speed did not affect the spread of dengue infection during 2019 in Sri Lanka. A study suggested that the dengue fever incidence was significantly related to temperature, rainfall, and sunshine (Lai 2018).

In this study, the influential factors that significantly impact the study variable were also determined by employing a generalized linear model. Table 5 compares the NBR model with log link results along with regression coefficients and odds ratios in different years, identifying the impact of meteorological, seasonal, and spatial factors on the spread of *Aedes* infection in Sri Lanka. The variable sky clearness was not included in the models as it was not significant in the

Table 4 Correlation between the spread of dengue infections and environmental factors (2015–2019)

Environmental factors	Kendall's tau _b		Spearman's rho	
	No. of dengue infection		No. of dengue infection	
	Corr.coeff. (r)	p value	Corr.coeff. (r)	p value
Precipitation (mm)	.050	0.003	.074	0.004
Humidity (%)	.108	0.000	.163	0.000
Pressure (kPa)	-.128	0.000	-.194	0.000
Temperature (°C)	-.139	0.000	-.212	0.000
Wind speed (m/s)	.060	0.000	.089	0.000
Sky clearness	0.014	0.446	0.019	0.457

Fig. 4 Monthly average of dengue cases with the average of environmental factors in 2019

Table 5 Temporal comparison of the impact of spatial, seasonal, and meteorological factors on the spread of dengue fever in Sri Lanka (negative binomial regression with log link)

Environmental factors	2015		2016		2017		2018		2019	
	<i>B</i>	<i>E(B)</i>	<i>B</i>	<i>E(B)</i>	<i>B</i>	<i>E(B)</i>	<i>B</i>	<i>E(B)</i>	<i>B</i>	<i>E(B)</i>
Intercept	− 50.9	0.00**	− 38.6	0.00**	− 37.3	0.00**	− 45.3	0.00**	− 17.5	0.00**
Precipitation(mm)	− 0.09	0.91**	− 0.08	0.92**	− 0.08	0.92**	− 0.04	0.96	0.07	1.07**
Humidity (%)	0.05	1.06	0.03	1.03	0.04	1.04	0.04	1.05**	0.03	1.03
Air pressure (kPa)	0.50	1.65**	0.39	1.48**	0.40	1.50**	0.48	1.61**	0.18	1.20*
Temperature (°C)	0.01	1.01	0.01	1.01	0.00	1.00	− 0.05	0.95	0.02	1.02
Wind speed (m/s)	− 0.02	0.98	− 0.02	0.98	0.13	1.14**	0.00	1.00	0.22	1.24**
Zone (Intermediate)	1.74	5.68**	2.21	9.07**	1.91	6.77**	1.49	4.45**	1.44	4.21**
Zone (Wet)	2.30	9.99**	2.35	10.4**	1.84	6.30**	1.45	4.26**	1.82	6.15**
Season (NEM)	0.77	2.16**	0.71	2.04**	− 0.49	0.61	0.17	1.19	− 0.10	0.91
Season (SIM)	0.74	2.09**	0.60	1.83**	− 0.32	0.72	− 0.32	0.73	0.35	1.43
Season (SWM)	− 0.35	0.71	0.06	1.06	− 0.05	0.95	0.06	1.06	− 0.78	0.46
AIC (NBR)	3186.801		3530.12		4394.15		3695.06		3989.47	
AIC (PR)	30,713.218		51,309.728		138,908.826		46,171.067		103,243.185	

** $p < 0.01$, * $p < 0.05$, *B* is the regression coefficient, *E(B)* is the odds ratio

aggregate bivariate analysis. The table shows that precipitation, air pressure, and climatic zone significantly impact dengue transmission almost every year. Wind speed was found to have a substantial influence in 2017 and 2019.

Negative binomial regression revealed a substantial effect of climate season on dengue infection in 2015 and 2016 but was not significant for the remaining years. The AIC values in Table 5 were least for NBR models than PR models, indicating the NBR model best fit the data than the PR model.

Like the regression analysis for single years, the overdispersed count data regression model was also applied for the aggregate dataset (2015–2019). The AIC value of the NBR aggregate model (AIC: 19587.67) was less than the PR model (AIC: 625303.13), indicating that the NBR model is appropriate for the current study. In the aggregate model, a new explanatory variable, "year," was introduced to investigate the yearly nominal risk of the spread of dengue infection and is presented in Table 6. The variable "year" was found significant with dengue infection in Sri Lanka, and the odds ratio was found 8.04 ($p < 0.01$) for the year 2017, indicating that the risk of dengue infection was 8.04 times higher in 2017 compared to 2015. The odds ratio for 2019 was 4.09 (95% CI 3.25–5.15, $p < 0.01$), approximately half of the year 2017. A study conducted in Sri Lanka supported the result of this study and disclosed that dengue infection increased significantly in 2017 compared to the preceding 5 years of surveillance (Tissera et al. 2020).

The aggregate negative binomial regression model disclosed that precipitation significantly influenced (Odds: 0.97, 95% CI 0.97–0.99, $p < 0.05$) the spread of dengue fever in Sri Lanka. The odds ratio of precipitation 0.97 indicates that the risk of spreading dengue incidence decreased by

3% for a one-unit increase in rainfall. A model analysis in Hong Kong found a negative relationship between rainfall and *Aedes* infection (Yuan et al. 2020). Moreover, heavy rainfalls create the chance of flushing or killing the immature mosquitoes and transiently reduce the infection risk, but the elevated humidity increases mosquito survival (Sarfraz et al. 2012). In contrast, some studies found that one extra rainy day in a month causes the increase in dengue cases by 6% in the following month (Rahman et al. 2020). Humidity (Odds: 1.05, 95% CI 1.04–1.07, $p < 0.01$) and air pressure (Odds: 1.46, 95% CI 1.36–1.56, $p < 0.01$) had substantial impacts on the dengue fever transmission. The odds ratio of humidity 1.05 indicates that for a one-unit increase in humidity, the risk of dengue infection also increases by 1.05 times. Similarly, the odds ratio of 1.46 for air pressure means for a 1 kPa increase in air pressure, the odds of dengue incidence would be 1.46 times more. A similar study supported our result, which found that relative humidity was significantly positively related to the increase in dengue incidence (Karim et al. 2012). Increased rainfall and relative humidity strongly affected Malaysia's dengue transmission (Ismail et al. 2010). Multivariate analysis did not show any significant impact of temperature on the spread of dengue infection. Similar to our findings, the literature found that temperature is not a significant factor and even had no immediate effect on dengue incidence (Sirisena et al. 2017; Santos et al. 2019). The relation between temperature and infection was insignificant in the capital city Colombo, located in the wet region (Prabodanie et al. 2020a). However, different studies revealed diverse conclusions regarding the effect of temperature on vector breeding and dengue infection rate. The recent literature stated that an increase

Table 6 Impact of spatial, seasonal, and environmental factors on the transmission of dengue infection in Sri Lanka (2015–2019)

Environmental factors	Coefficient	Standard error	Z-value	Odds ratio	95% Confidence interval (OR)		
					Lower limit	Upper limit	p value
Intercept	− 38.85	2.40	− 16.20	0.00	0.00	0.00	0.000
Precipitation (mm)	− 0.03	0.01	− 2.76	0.97	0.95	0.99	0.006
Humidity (%)	0.05	0.01	6.47	1.05	1.04	1.07	0.000
Air pressure (kPa)	0.38	0.03	12.41	1.46	1.36	1.56	0.000
Temperature (°C)	0.01	0.04	0.25	1.01	0.94	1.09	0.805
Wind speed (m/s)	0.06	0.02	2.78	1.06	1.02	1.11	0.005
Zone (Intermediate)	1.76	0.09	19.11	5.78	4.67	7.16	0.000
Zone (Wet)	1.86	0.08	24.53	6.41	5.49	7.50	0.000
Season (NEM)	0.38	0.12	3.21	1.46	1.15	1.84	0.001
Season (SIM)	0.14	0.11	1.31	1.16	0.92	1.45	0.191
Season (SWM)	0.01	0.09	0.10	1.01	0.85	1.20	0.920
Year (2016)	0.62	0.09	6.98	1.85	1.56	2.21	0.000
Year (2017)	2.13	0.09	24.83	8.40	7.07	9.98	0.000
Year (2018)	0.80	0.08	9.60	2.23	1.89	2.63	0.000
Year (2019)	1.41	0.12	11.88	4.09	3.25	5.15	0.000

in temperature could lead to the rapid development of the *Aedes* mosquitoes and increase subsequent dengue infections (Awang and Dom 2020). More precisely, a study in Thailand stated the rapid growth but lower survival rate of *Aedes albopictus* at higher temperatures (Phanitchat et al. 2017). Another study proved that a high-temperature condition with low fluctuation could raise the dengue cases in the next month (Sharmin et al. 2015). Moreover, the high instability of warmer temperatures has reduced the transmission (Carrington et al. 2013; Liu-Helmersson et al. 2014). This study revealed that wind speed (Odds: 1.06, 95% CI 1.02–1.11, $p < 0.01$) significantly impacted the spread of dengue infection, but negative impacts were found in the years 2015 and 2016. The literature supported the finding, which showed that the average wind speed has a significant negative correlation in Sri Lanka (Prabodanie et al. 2020a). A study revealed that *Aedes* infection decreased with the increased wind speed (Yin et al. 2019).

The results of this study revealed that the factor "bioclimatic zone" constantly substantially impacted the dengue fever transmission each year. Among the three bioclimatic zones, the intermediate zone (Odds: 5.78, 95% CI 4.67–7.16, $p < 0.01$) had a 5.78 times more significant risk of infection than the dry zone. Moreover, the wet zone (Odds: 6.41, 95% CI 5.49–7.50, $p < 0.01$) was 6.41 times more likely to be dengue infected than the dry zone. A previous study in Sri Lanka found that the wet zone and the surrounding areas contribute to the epidemic wave in the southwestern monsoon (June–August) (Prabodanie et al. 2020b). A study in Puerto Rico found that the associations between climate factors and dengue infection were varied spatially (Johansson et al. 2009). A study reviewed the full text of 128 articles

and observed that the arboviral epidemic depends on the climate zones (Liu et al. 2020).

Analyses showed that the climate season of Sri Lanka also had a significant impact on the spread of dengue infection. Among all the seasons, the NEM season (Odds: 1.46, 95% CI 1.15–1.84, $p < 0.01$) significantly influenced the increase in dengue infection in Sri Lanka. Our result was concordant with a similar study which also found that the two dengue epidemics in Sri Lanka have occurred in south-western monsoon from May to September and north-eastern monsoon from December to January (Sirisena and Noordeen 2014; Sun et al. 2017). A study of the seasonal variation on dengue transmission prediction in Thailand revealed that seasonal variation significantly impacted dengue incidence, and more *Aedes* larvae were observed in the rainy season than in the winter and summer season (Wongkoon et al. 2013).

From the discussions mentioned above, it can be concluded that precipitation negatively impacts the spread of *Aedes* contagions, and increasing rainfall causes the decrease of the disease. On the other hand, humidity and air pressure positively influence dengue fever. Growing humidity, air pressure, and wind speed increase the dengue illness. Bioclimatic zones substantially influence the spread of the infection, and the wet and intermediate zones were found more vulnerable to dengue disease than the dry zone. Moreover, the wet zone had the highest risk of spreading the disease among all other zones. Furthermore, the northeast monsoon season significantly impacted the *Aedes* infection in Sri Lanka, and in this season, the jeopardy of dengue disease was higher than in all other seasons. The risk of dengue infection was significantly higher

in 2017 than in other years. The precipitation, air pressure, wind speed, and bioclimatic zone greatly impacted the outbreak in 2017, and the people who stayed in the wet zone were more vulnerable to this disease in the same year. Despite the meteorological features, the dengue vector's spread may be influenced by other socio-economic, demographic, and geographical factors such as population density, drainage system, disposal waste management which were not considered in the current research. This study intensively investigated the meteorological factors by applying the more appropriate statistical methods. Therefore, the obtained results will help local authorities to take the necessary steps for dengue prevention based on the climatic condition of the study area.

Conclusion

Dengue is a mosquito-borne flu-like illness that causes severe health problems and is found as endemic in many countries. This study determines the essential environmental factors affecting dengue disease in Sri Lanka. This research also identifies the most at-risk bioclimatic zones and climate seasons using the most appropriate statistical methods based on the secondary data from January 2015 to December 2019 in Sri Lanka. Precipitation and air pressure had a significant effect on the spread of dengue fever each year. In addition to precipitation and air pressure, wind speed and bioclimatic zone are identified as the main influential factors for the dengue outbreak in 2017. The aggregate NBR model reveals that precipitation, air pressure, humidity, wind speed, bioclimatic zone, seasonal variation, and the nominal year significantly impacted the spread of dengue fever. The wet zone had a significant impact on the vast *Aedes* infection. The Northeast monsoon season greatly influenced the spread of dengue disease in Sri Lanka. Moreover, future research, including population density and mobility, health care system, drainage facility, disposal waste management, etc., should be done to identify the substantial reasons for dengue transmission. The study results indeed contribute to combating the enormous spread of dengue infection in the local as well as other tropical and subtropical areas in the world. These findings will help policymakers to take the necessary steps for dengue prevention based on the country's seasonal climate variability in different geographic regions.

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Code availability The code for this research will be provided on request.

Declarations

Conflict of interest The author declares that they do not have any conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

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