Impact of rainfall on the transmission of leptospirosis in Si Sa Ket, Thailand

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Abstract: Leptospirosis is a zoonotic disease found worldwide, but especially in tropical and sub-tropical countries. In Thailand during the rainy season, agricultural and livestock workers are the main occupational risk groups, who are likely to be in contact with contaminated environments. In this study, we aim to examine the impact of rainfall on the transmission of leptospirosis using a stochastic cellular automata model in Si Sa Ket, Thailand, which had the highest number of reported cases from 2014 to 2018. Two bi-dimensional square lattices are created to represent human and contaminated environmental lattices. The reported cases are used to fit in the simulation results by varying transmission probability. The transmission probability depends on sinusoidal function and the rainfall index, the results of which are compared. This study highlighted the way that seasonal rainfall contributed to the transmission dynamics of leptospirosis. The total epidemic size, which is the sum of the overtime cases, was investigated to find the critical transmission probability from the endemic to the epidemic state. Further study of other factors such as flooding and temperature, should be investigated for a better understanding of how the transmission of leptospirosis affects the environment.

1. Introduction

Leptospirosis is an important zoonotic disease that occurs worldwide but is found mostly in tropical and subtropical environments [1]. The disease is caused by pathogenic spirochete bacteria, genus *Leptospira* [2], which affects humans and animals. The transmission of this disease to humans or animals can occur by exposure to infected animals or via contaminated freshwater, soil, or mud [3]. Humans are mostly infected by exposure to a contaminated environment [4]. The time between exposure to the appearance of symptoms and signs (incubation period) of leptospirosis ranges from 7 to 12 days [3]. The symptoms at acute phase are fever, headache and myalgia [4]. Some symptoms such as conjunctivitis, abdominal pain, vomiting, cardiac arrhythmia, a skin rash, etc. may occur after the acute phase [4].

In Thailand, the occupation of farmers and agricultural workers is important, estimated around 30% of the population in 2018 [5]. Members of this occupation constitute a high risk group, i.e., agricultural workers usually walk barefoot in paddy fields leading to exposure to water for long periods, which may result in skin wounds and mucosae which provide routes of entry for leptospires into the body [6].
According to the epidemiology of leptospirosis, reported cases are mostly found in rural areas rather than urban ones because of the environmental factors mentioned [7]. The bacteria can survive for days or months in water or soil [8, 9], which results in outbreaks which typically occur in the rainy season. Thus, the weather is one of the major factors influencing the spread of the bacteria [10]. In Salvador, Brazil, the incidence of hospitalized leptospirosis patients was positively associated with increased rainfall [11]. The seasonal pattern of leptospirosis cases was observed along with the correlation of rainfall in India [12] and Sri Lanka [13].

Many studies have been carried out on leptospirosis mathematical models. Triampo et al. [14] presented a mathematical model for leptospirosis using the rate of transmission from infected rats to susceptible humans varies with the amount of rainfall in Phrae and Nakhon Ratchasima Thailand. They considered a number of leptospirosis cases in Thailand and showed their numerical simulations [15]. Zaman et al. [16] presented models are based on a system of Susceptible-Infectious-Recovered (SIR model) of human and vector (rat) population using the real data of Thailand for their numerical simulations. Holt et al. [17] used the SIR model to understand the behaviour of infection in an African rodent population of Tanzania. Pongsumpun et al. [18] developed the SIR-SI model to study the behaviour of leptospirosis, representing the rate of change for both the vector (rat) and the human population.

However, those studies did not consider the spatial aspect, which is important in leptospirosis transmission. Unlike, the mathematical model, which considers the homogeneity of the population, the spatial model can be used to consider the difference of the population at different geographical locations [19]. The spatial model allows the study of complex problems such as, population mobility and environment difference. The Stochastic Cellular Automata (SCA) is a model that is used to describe spatial dynamics, which are dynamic systems, discrete in space and time [20]. Each lattice cell can assume a state in a finite set, which can change every time step based on transition rules and the state of the cell or its neighbour. This model allows the study of the environmental transmission of leptospirosis.

Previously, Athithan et al. [21] presented a Cellular Automata based computational model for the spread of leptospirosis between humans and animals using voting rules. The simulation results are compared with the actual data of leptospirosis infection in Thailand during 2000 and 2001. They found that the results closely matched the data. However, the main leptospirosis human infection is mostly infected by exposure to a contaminated environment [4]. To be more realistic, the model should improve by adding the environmental lattice. The probability of changing the status of humans should depend weather conditions and seasonal effects [12].

In this work, we developed the Stochastic Cellular Automata model using heterogeneous rules that consist of two bi-dimensional lattices, i.e., human and environmental lattices for leptospirosis transmission. This model is a simple conceptual tool that provides a definite method of including the spatial location of individuals. The model is also used to include human movement, which can provide a definite direction within the space (this could not be studied using the mathematical model). We aimed to study the impact of transmission rates depending on the rainfall. The model was based on the rural shape of Si Sa Ket Thailand. In the model, we investigated the epidemic size to find the critical transmission probability from the endemic to the epidemic state.

2. Method

2.1. Data collection

In this study, we examined the leptospirosis outbreak in Si Sa Ket, Thailand. Data were collected from the national disease surveillance, Bureau of Epidemiology, Department of Disease Control, Ministry of Public Health, Thailand [22]. Data collection was performed as a part of routine clinical examination procedures. The amount of daily rainfall for the duration of the study 2014–2018 was obtained from the real-time TRMM Multi-Satellite Precipitation Analysis [23]. We derived daily precipitation from 3B42RT. The daily accumulated precipitation is obtained from TRMM 3B42RT Daily [14, 24].
2.2. Model
The proposed SCA model is based on existing knowledge about leptospirosis transmission. There are two bi-dimensional square lattices of 1000×1000, where a cell is in position (i,j). The total population is assumed as 350,000 individuals, who have agricultural and farm workers at Si Sa Ket. Each individual (Hij) is chosen randomly on a cell. Thus, the human lattice will consist of occupied or unoccupied sites. Human individuals can assume to be one of four states, which is in a susceptible state (S), an exposed state (E), an infectious state (I), and a recovered state (R) as illustrated in figure 1. The environmental lattice can contain both empty sites and a contaminated environment (representing the source of leptospirosis if infected), which is estimated to be 60% of the lattice size as illustrated in figure 1. To simplify the model, we assumed that contaminated environmental cells could transmit the infection to humans. In this model, we used the periodic boundary condition and took each time step to correspond to one day.

![Figure 1](image)

Figure 1. Schematic illustration of the transition state of the Stochastic Cellular Automata model.

In this study, we assumed human individuals, who are not infected with leptospires, who randomly chose to move into empty sites with the probability $\rho_{mob} = 0.5$ [25] each day. The length of human movement depends on the probability of the exponential step length, which is $P(r) = (r+\Delta r_0)^{-\beta}e^{-r/\kappa}$. Due to the limitation of data parameters in Thailand, in this work, we set the parameter that is extracted from mobile phone data in European countries, by fitting to a truncated power-law, which found the scaling exponent $\beta = 1.75$, the initial step size $\Delta r_0 = 1.5$ km and cut-off values $\kappa = 80$ km [26]. People can move within the maximum of half-length (1000/2). The angle of movement is randomly chosen from a uniform distribution $[0, 2\pi]$. The parameters for the human population and mobility was extracted from the literature and assumed to use in Si Sa Ket, as shown in table 1.

After human movement, if the position of the susceptible individual matches with the contaminated environment cell, the susceptible individual will be infected at a transmission rate ($\lambda$) to be in an exposed state. An exposed individual becomes an infected individual after a latent period of fixed length $\tau_E$. An infected individual will be infected for the $\tau_I$ period then enter a recovered state. This recovered individual will again enter a susceptible period of fixed length $\tau_R$. 

To study the seasonal dynamic, we assumed the transmission rate is time dependent determined by a simple sinusoidal function in (1). Due to the association of leptospirosis with rainfall, we assumed that the transmission rate depends on the rainfall index \(R(t)\) as a linear function in (2). The rainfall index is defined as a normalized amount of rainfall during 2014-2018 period. The transmission rate \(\lambda\) is given by:

\[
\lambda_1(t) = n_0 + n_1(1 + \sin(2\pi t/365) - \tau)
\]

\[
\lambda_2(t) = n_2 + n_3(R(t) - \tau)
\]

where \(n_0, n_1, n_2\) and \(n_3\) are constant values and \(\tau\) is the time lag as the delay effect varied 0-4 weeks.

The reported data during 2014 and 2018 is used to fit with the simulation results. The parameters \(n_0, n_1, n_2\) and \(n_3\) were chosen, where the Mean Square Error (MSE) is minimized.

| Description                              | Symbol | Values          |
|------------------------------------------|--------|-----------------|
| Human population size                    | \(N_H\) | 350,000         |
| Daily rate of human mobility             | \(\rho_{mob}\) | 0.5 [25]        |
| Water area density in environmental lattice | \(\rho_E\) | 0.6             |
| Incubation period in the human body      | \(\tau_E\) | 7 days [3]      |
| Duration of the infection in the human body | \(\tau_I\) | 7 days [3]      |
| Duration of loss immunity for the human body | \(\tau_R\) | 720 days (estimated) |

3. Result and discussion

In this work, we aimed to study the impact of the transmission rate as dependent on the rainfall index compared to the sinusoidal function using the SCA model in Si Sa Ket, Thailand. Figure 2 showed the relation between reported cases of leptospirosis, normalized rainfall index, and sinusoidal function. The number of reported cases all year round showed a seasonality pattern. The peak of the leptospirosis curve occurred between August and October corresponding to the rainy season. We found the peak of reported cases corresponded to the peak of the rainfall index and the sinusoidal curve.

Our results showed that the rainfall index more an impact than the sinusoidal function, which showed a better fit with the reported cases (figure 3). We used the mean square error (MSE) as a measure of the goodness of fit. We compared the reported data and simulation results. The minimum MSE was found to be 64.30 at lag 4 weeks for sinusoidal function and 47.35 at lag 2 weeks for rainfall (figure 3). The sinusoidal function captured the reported cases only for the small value. The simulation result of the transmission rate depends on the rainfall index with the associations observed at time lag of 2 weeks, which corresponded to previous studies [27]. The peak of the leptospirosis cases corresponds with the peak of simulation results in almost every year. However, it could not describe the data on 2017 due to the other factors such as the monsoon and heavy rainfall [28]. This finding indicates that the rainfall index contributed to the transmission dynamics of leptospirosis. Although, the sinusoidal function has been commonly used to represent seasonality in the epidemic models [29].
Figure 2. The relation between reported cases of leptospirosis, normalization rainfall index and the sinusoidal function for 2014-2018.

The leptospirosis epidemics are known to have a seasonal pattern. Rainfall is an important risk factor in leptospirosis outbreaks and is strongly associated with the tropical settings [30-32]. During the heavy rainfall, the pathogen leptospires may grow in freshwater from washed contaminated soil, which leads to humans can be exposed to them [33]. The outbreak of leptospirosis usually occurred after waterlogging from heavy rainfall due to this pathogen can survive for days to months in a contaminated environment.

Figure 3. The reported cases of leptospirosis and the simulation result prediction of the transmission depend on the sinusoidal function \( n_0 = 3.47 \times 10^{-7}, n_1 = 2.09 \times 10^{-6} \) and the rainfall index \( n_2 = 4.01 \times 10^{-6}, n_3 = 3.21 \times 10^{-5} \). The MSE for sinusoidal function equal to 64.30 and for rainfall equal to 47.35.
In epidemic models, it is important to how determined the final epidemic size from the parameters of the system or the components, which can used to determine the epidemic threshold [34]. In this study, we defined the final epidemic size as a fraction of those who recovered at steady state. To investigate the transmission rate contributes to the final epidemic size in our model. We set the transmission rate as a constant value ($\lambda = n_0$). The critical transmission rate (shown in figure 4), suggests that at some point there is a transition from the endemic phase to the epidemic the state.

![Figure 4](image)

**Figure 4.** The final epidemic size as predicted by the SEIR model is shown with respect to the transmission rate $\lambda=1 \times 10^{-6}$ to $1 \times 10^{1}$.

4. Conclusion
In the fitting process, our results suggested that using the rainfall index fit gives a better result than a sinusoidal function, which found the MSE equal to 47.35 compared to 64.30. Our results indicated that the transmission rate depends on the rainfall index with a time lag of 2 weeks to capture has an impact on the leptospirosis outbreak in Si Sa Ket. We also found the critical transmission rate, which can give an idea of controlling the outbreak. However, there are several factors which could influence leptospirosis such as flooding, temperature and humidity. Further study of other factors should be investigated for a better understanding of how the transmission of leptospirosis influences the environment.

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