

Model Simulation for the Spread of Rabies in Sarawak, Malaysia

Nur Asheila Abdul Taib[#], Jane Labadin[#], Phang Piau[#]

[#]Faculty of Computer Science and Information Technology, Universiti Malaysia Sarawak, Kota Samarahan, 94300, Malaysia

E-mail: ellataib@ymail.com, ljane@unimas.my, pphang@unimas.my

Abstract— There is a growing concern over the ongoing rabies epidemic in Sarawak that has remain unresolved ever since the outbreak began in July 2017. As of today, there has been 18 positive human rabies cases reported, which includes 17 fatalities, and one survivor who is now on life support after a severe neurological complications. Subsequently, the death rate now stands at approximately 94%. This paper is a preliminary report on the simulation of rabies transmission dynamics in Sarawak. At present, research is still lacking on the disease dynamics of rabies in Malaysia particularly in the state of Sarawak. We propose here a deterministic, compartmental model with SEIRS framework to fit actual data on the number of human infected rabies cases in Sarawak from June 2017 to January 2019. The simulation predicts that rabies in Sarawak will persist even with the current outbreak management and control efforts. Further, sensitivity analysis showed that dog vaccination rate is the most influential parameter and the basic reproduction number is estimated to be higher than 1. Henceforth, there is a need to increase the access to dog vaccines especially in remote rural areas with lack of health facilities. Our findings also suggest that controlling dog births could prevent the spread of rabies from perpetuating in the state. Neutering or using other fertility control methods would reduce the input of new susceptible domestic dogs into the population while Trap-Neuter-Vaccinate-Release (TNVR) method can be implemented to control new births of free-roaming strays. In summary, increasing the coverage of dog vaccination and reducing the number newborn dogs would be the more effective strategies to manage the current rabies outbreak in Sarawak.

Keywords— rabies; dynamics; transmission; mathematical modeling; simulation; Sarawak.

I. INTRODUCTION

Rabies is a zoonotic viral disease that is epidemic in more than 150 countries worldwide [1]. The causative rabies virus, of the genus *Lyssavirus* in the family *Rhabdoviridae*, enters the human body when the saliva from the rabid animal comes into contact with open wounds on the human skin following a deep bite or scratch. To date, dogs are the source of over 95% of the human rabies cases globally [2].

Malaysia notified its first case of human rabies-related death in nearly 20 years after two victims from Sarawak have succumbed to the disease in July 2017 [3]. The ongoing outbreak recorded a total of 17 positive human rabies cases, which includes 16 fatalities, and one survivor [4]. There are several rabies control measures implemented by the local government including dog mass vaccination and culling to manage the stray population. So far, a total of 121141 dogs have been vaccinated and another 2456 strays were removed whereas 8086 humans exposed to rabies have received post-exposure prophylaxis (PEP) treatment ([5],[6],[7]).

Mathematical modeling have become an important part for understanding the spread of rabies disease in several countries over the past decades. In 2009, Zinsstag et al. pioneered dynamics modelling of the dog-to-human rabies

transmission [8]. Their deterministic compartmental model considered four classes: the susceptible class (S), exposed class (E), infectious class (I) and recovered class (R), for each of the dog and human populations in the capital of Chad, Africa. The dynamics of these populations were described by a system of coupled ordinary differential equations (ODEs).

Chen et al. investigated the geographical inter-provincial spread of rabies in Mainland China [9]. They formulated a two-patch submodel; whereby each province is regarded as one single patch and utilized the model to simulate the regional human rabies data from 2004 to 2012 in three pairs of provinces in China. In 2015, an individual-based stochastic model is proposed by Durr and Ward to simulate rabies incursion into an area previously free of rabies [10]. The study showed that a 70% coverage of vaccination would help to reduce the number of infected dogs.

Asamoah et al. utilised an optimal control model to compare the effects of three control methods: pre and post-exposure prophylaxis, and culling on the number of infected dogs when applied at varying rates [11]. The study modified the model proposed by Zhang et al. [12] and highlighted the use of more pre-exposure treatment on dogs and human as the optimal way to eliminate rabies.

A review paper by Shigui Ruan compiles the past rabies modeling work in China [13]. His research team has built a seasonal rabies model in China where human rabies cases were observed to be notably higher in the summer and autumn. A deterministic, compartmental SEIR model with periodic transmission rates was used to simulate the monthly human rabies data from 2004 to 2010 and the basic reproductive number of 1.03 was obtained.

Later, Zhang et al. studied the spatial spread of rabies in China by adding a diffusion coefficient into the ODEs in order to create a reaction-diffusion partial differential equation (PDE) model [14]. The study was able to demonstrate the existence of traveling waves in the dog population and further numerical simulations showed dog dispersal as the main influencing factor.

Leung and Davis proposed an SEI model to describe the transmission of rabies in dogs whereby the dog population is separated into three sub-classes depending on its ownership status namely the strays, free-roaming and confined dogs [15]. The work showed that vaccination target can be quantified and is heavily affected by the rate of vaccination coverage, death rate of the strays as well as the density and types of the dog population. Bilinski et al. selected two districts in Tanzania, Africa and determine the optimal frequency and coverage of the vaccination campaign programmes. The findings suggested that the campaign frequency and coverage to effectively control rabies in a district would depend on the rates of rabies re-emergence from the neighbouring area [16].

In 2017, a study was conducted to investigate the effects of the immigration of infected dogs on the transmission of canine rabies with varying dog densities [17]. The results concluded that rabies would be eradicated eventually if the number of infective immigrants is managed. Huang et al. formulated a multi-host SEIR model which describes the rabies dynamics between human, dogs and Chinese ferret badgers [18]. Further, model simulations were in concordance with the yearly data on human rabies cases from 2004 to 2017.

A stochastic model has been developed to simulate the possible rabies transmission among wild dogs population in Australia [19]. Findings include an estimated 90 km/year speed of disease spread with a 21% probability of occurrence of the dog rabies epidemic. Another stochastic simulation model was proposed by Sparkes et al. to model the rabies spread among three distinct groups of dogs in Australia [20].

A linear deterministic time trend model was developed by Olarinmoye et al. which made use of the time series data of dog bite cases in Montserrat County [21]. The model were able to predict monthly future dog bite cases in the region .

Hudson et al. used a stochastic risk assessment model to calculate the risk of rabies emergence in the Northern Peninsula Area (NPA) of Australia following the eastward spread of rabies through Indonesian archipelago [22]. A 2018 study by Ndi et al. has employed crisp and fuzzy approaches to explore the impact of uncertainty and stochasticity on rabies dynamics and transmissions [23].

Yamada et al. used an individual-based model to investigate the probability of rabies incursion into a rabies-free Japan and utilised past outbreaks data to estimate a

value of 2.42 for the basic reproduction number [24]. The results also showed low risk of incursion with the current control and surveillance strategies. An individual-based model of canine rabies transmission was developed by Laager et al. to simulate the spread of rabies among dogs in N'Djame'na, Chad [25]. The study employed contact network data of 300 dogs and found that vaccinating below 70% coverage would re-establish major outbreak in N'Djame'na.

Even with the previous rabies modeling works mentioned above, nevertheless, there is still a dearth of research into the disease dynamics in Malaysia particularly in the state of Sarawak. In this preliminary paper, we propose an unprecedented SEIRS rabies model for the spread of rabies in Sarawak in hopes to expound the ongoing rabies situation in the state. We simulate the model with the observed number of infected human cases in Sarawak from June 2017 to January 2019. We then analyse the influence of initial conditions and parameter values on the number of infected humans.

II. MATERIALS AND METHOD

In order to investigate the dog-human transmission dynamics of rabies in Sarawak, this paper adopted the compartmental SEIRS model proposed by Zhang et al. [12] whereby each of the dog and human populations is divided into four classes according to their health status. The classes include: (i) the susceptible class who are healthy individuals that could potentially acquire rabies; (ii) the exposed class composed of infected individuals experiencing an incubation period therefore they are not yet infectious; (iii) the infectious class which refers to individuals who could transmit rabies virus; and lastly, (iv) the recovered class who are individuals that has gained immunity.

A. Model Formulation

The number of dogs in the classes susceptible, exposed, infectious and recovered at any given time t , is denoted as $S(t), E(t), I(t)$ and $R(t)$, respectively and the total dog population at any time t is $N(t)$. For humans, the total population size is given as $N_1(t)$ and the number of humans in the classes susceptible, exposed, infectious and recovered at any time t , is taken to be $S_1(t), E_1(t), I_1(t)$, and $R_1(t)$, respectively.

It is assumed that rabies virus can be transmitted among dogs and from the exposed and infected dogs to human, but humans do not spread the virus further. We slightly modified the rabies transmission flow diagram in [12] by adding the culling term as shown in the flowchart (Fig. 1). As one of the rabies control measures, Sarawak currently implements culling of dogs except for dogs that have been vaccinated. Hence, we slightly modified the second rabies model in [12] by removing the culling term in equation $\frac{dR}{dt}$. The modified model is described by a system of eight ordinary differential equations (1), with its compartmental flowchart given in Fig. 1.

$$\begin{cases}
\frac{dS}{dt} = A + \lambda R + \sigma(1 - \gamma)E - \beta SI - (m + k + e)S \\
\frac{dE}{dt} = \beta SI - (m + \sigma + k + e)E \\
\frac{dI}{dt} = \sigma\gamma E - (m + \mu + e)I \\
\frac{dR}{dt} = k(S + E) - (m + \lambda)R \\
\frac{dS_1}{dt} = B + \lambda_1 R_1 + \sigma_1(1 - \gamma_1)E_1 - m_1 S_1 - \beta_1 S_1 I \\
\frac{dE_1}{dt} = \beta_1 S_1 I - (m_1 + \sigma_1 + k_1)E_1 \\
\frac{dI_1}{dt} = \sigma_1 \gamma_1 E_1 - (m_1 + \mu_1)I_1 \\
\frac{dR_1}{dt} = k_1 E_1 - (m_1 + \lambda_1)R_1
\end{cases} \quad (1)$$

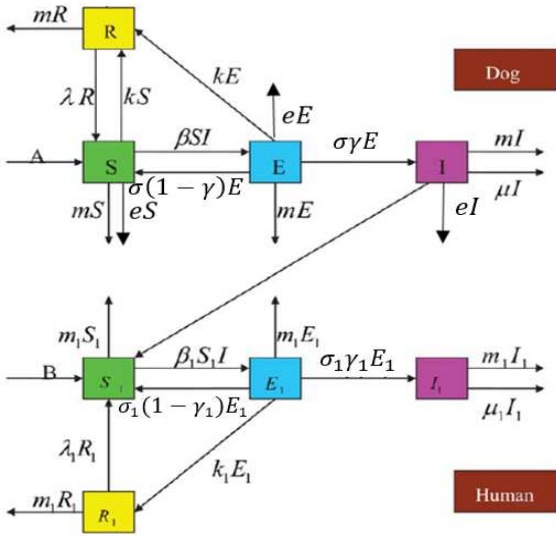


Fig. 1 Modified rabies transmission flowchart among dogs and humans as depicted in [12].

B. Disease Equilibria and Basic Reproduction Number

Assuming there is no rabies infection and by setting the right hand side of equation (1) to zero, we obtain the disease-free equilibrium:

$$\varepsilon_0 = (S^0, 0, 0, R^0, S_1^0, 0, 0, 0)$$

such that

$$S^0 = \frac{A(m + \lambda)}{\lambda(m + e) + m(m + e + k)}$$

$$R^0 = \frac{kA}{\lambda(m + e) + m(m + e + k)}$$

and

$$S_1^0 = \frac{B}{m_1}$$

Therefore, the basic reproduction number is defined to be

$$R_0 = \frac{\beta\sigma\gamma S^0}{(m + \sigma + k + e)(m + \mu + e)}.$$

Suppose rabies is present in both populations and by letting the right hand side of equation (1) to be zero, we obtain the endemic equilibrium point:

$$\varepsilon_1 = (S^*, E^*, I^*, R^*, S_1^*, E_1^*, I_1^*, R_1^*)$$

such that

$$S^* = \frac{S^0}{R_0}$$

$$E^* = \frac{I^*(m + \mu + e)}{\sigma\gamma}$$

I^*

$$= \frac{S^0 \sigma \gamma k \lambda + (A R_0 - S^0 (m + k + e)) \sigma \gamma (m + \lambda)}{\sigma \beta \gamma (m + \lambda) S^0 - R_0 (m + \mu + e) (\sigma (1 - \gamma) (m + \lambda) + k \lambda)}$$

$$R^* = \frac{k S^0}{(m + \lambda) R_0} + \frac{k (m + \mu + e)}{\sigma \gamma (m + \lambda)} I^*$$

S_1^*

$$= \frac{B (m_1 + \sigma_1 + k_1) (m_1 + \gamma_1)}{(m_1 + \beta_1 I^*) (m_1 + \sigma_1 + k_1) (m_1 + \lambda_1) - I^* [\lambda_1 k_1 \beta_1 + \sigma_1 \beta_1 (1 - \gamma_1) (m_1 + \lambda_1)]}$$

$$E_1^* = \frac{\beta_1 S_1^* I^*}{(m_1 + \sigma_1 + k_1)}$$

$$I_1^* = \frac{\sigma_1 \gamma_1 E_1^*}{(m_1 + \mu_1)}$$

and

$$R_1^* = \frac{k_1 E_1^*}{(m_1 + \lambda_1)}.$$

C. Parameter Estimation

Parameterization proved to be difficult due to limited data source as Sarawak had no history of rabies prior to the current outbreak. Therefore, the values of parameters in Table I and Table II are mainly from estimation made based on reported values and from assumption taken from literature search, respectively.

The total number of dogs in Sarawak is estimated to be 225000 according to online news. We assume the crude annual dog birth rate per 1000 population of dogs to be 300 which is in the range published in the paper by Conan et al. [26]. We then manipulate the value to estimate the monthly number of newborn puppies (A). A total of 103166 dogs have been vaccinated from July 2017 to February 2019 according to the World Animal Health Information System (WAHIS) database [6] and the value is used to estimate the dog vaccination rate (k). Sarawak Disaster Information website stated that a total of 15509 dogs have been removed from July 2017 until the end of February 2019. We then calculate the average number of dogs removed per month and found that an approximate 0.34% of dogs were removed monthly (e). Further, estimation of dog loss rate of vaccination immunity (λ) is based on the fact that dogs would lose immunity after one year. Due to scarce information on dog demography in Sarawak, some parameters are taken from published estimates in [12] and then converted to monthly unit as necessary. For example, the mean for dog incubation period ($1/\sigma$), the natural death rate of dogs (m), the risk of clinical outcome of exposed dogs (γ) and the dog disease-related death rate (μ) are assumed to be 2.5 months, 0.08 year^{-1} , 0.4 year^{-1} and 1 year^{-1} , respectively [12].

New cases of positive human rabies were announced from time to time by the Director-General of Health Malaysia via official online statements. Each case is reported with details which include the dates of onset clinical symptoms, diagnosis and death, as well as the time and geographic location for the associated dog-bite incident. The crude birth

rate and crude death rate per 1000 population in Sarawak available online from the Department of Statistics Malaysia are used to approximate the number of monthly human birth (B) and the natural human mortality rate (m_1), respectively.

Out of the total 18 cases of positive human rabies in Sarawak, 17 were fatalities with one survivor. Consequently, the death rate (μ_1) now stands at approximately 94% in the span of 20 months. All victims were local Sarawakian except for one foreigner who got bitten and died in Sarawak..We extract the news online on the dates of the biting incidents and the subsequent onset of clinical symptoms reported by each of the 18 cases. By calculating the duration of time between the period of being exposed and becoming symptomatic, we estimate the mean for human incubation period ($1/\sigma_1$) to be 2.5 months. According to an experimental study by Tepsumethanon et al. [27], around half of the total 1820 dogs with bite case history will turn rabid. Therefore, we estimate the human vaccination rate (k_1) by taking the proportion of the average number of human vaccinated per month and the total number of exposed human in which the frequency of bite cases is taken as proxy. All the data required for the estimation is obtained from the official portal of Sarawak Disaster Information [7].

Lastly, the transmission rates of rabies among dogs (β) and that of dog to human (β_1) are obtained from data fitting. Actual data on the number of infected humans dated June 2017 until January 2019 used for our model fitting are mostly obtained from KPK press release statement (*Kenyataan Akhbar KPK*) reported by the Director-General of Health Malaysia. The infected humans, by our definition, are those victims who are showing clinical signs of rabies. All parameters listed in Table I and Table II are non-negative with units of month⁻¹.

TABLE I
DESCRIPTION OF ESTIMATED PARAMETERS

Parameter	Value	Definition	Source
A	5600	monthly number of newborn puppies	estimation
k	0.024	dog vaccination rate	estimation
e	0.0034	culling rate	estimation
β	0.00014	dog-to-dog transmission rate	fitting
B	3000	human monthly birth	estimation
σ_1	0.4	reciprocal of human incubation period	estimation
m_1	$\frac{0.0047}{12}$	human natural mortality rate	estimation
k_1	0.02	human vaccination rate	estimation
β_1	1.8×10^{-10}	dog-to-human transmission rate	fitting
μ_1	0.94	human disease-related death rate	estimation

TABLE II
PARAMETERS OBTAINED FROM LITERATURE

Parameter	Value	Definition	Source
λ	$\frac{1}{12}$	rate of vaccination immunity loss in dogs	Zhang et al. (2011) [12]
σ	0.4	reciprocal of dog incubation period	Zhang et al. (2011) [12]
m	$\frac{0.08}{12}$	dog natural death rate	Zhang et al. (2011) [12]
γ	0.4	risk of clinical outcome of exposed dogs	Zhang et al. (2011) [12]
μ	1	dog disease-related death rate	Zhang et al. (2011) [12]
λ_1	$\frac{1}{12}$	rate of vaccination immunity loss in humans	Zhang et al. (2011) [12]
γ_1	0.4	risk of clinical outcome of exposed humans	Zhang et al. (2011) [12]

III. RESULTS AND DISCUSSIONS

A deterministic, compartmental SEIRS model is an essential tool to gain profound insights into the dynamical behaviour of infectious disease transmission. This predictive model, which is often used to simulate an epidemic, could help to identify the parameters responsible for disease prevalence as well as disease eradication. Therefore, the model can act as a guide in finding the best approach to contain an outbreak and eventually eliminate the disease.

By using the values of parameters in Table I and Table II, we simulate the SEIRS model by solving the system (1) and employing `deSolve` function `ode` in R. We aim at reproducing the number of infected human rabies cases in Sarawak from June 2017 to January 2019 available online from the official press release statements reported by the Director-General of Health Malaysia. Currently, the total number of dogs in Sarawak is approximately 225000 and the crude birth rate of dogs per 1000 population is taken as 300, thus we assume $S(0) = 150000$. According to the Department of Statistics Malaysia, the population size in Sarawak in 2017 is estimated to be 2.74 million, so we take $S_1(0) = 2740000$. We let $I_1(0) = 3$ as three cases of human infected with rabies were reported in July 2017, with their clinical symptoms reported in June 2017. Other initial conditions are chosen through fitting.

The solution $I(t)$ which is the number of infected human rabies at the requested time t is represented by the solid line in Fig. 2. The fitting between our simulated model and the monthly observed number of infected humans in Fig. 2 compares well considering the fact that we had to deal with sporadic cases of human rabies in Sarawak. We simulate the model further until we get a stable result as shown in Fig. 3.

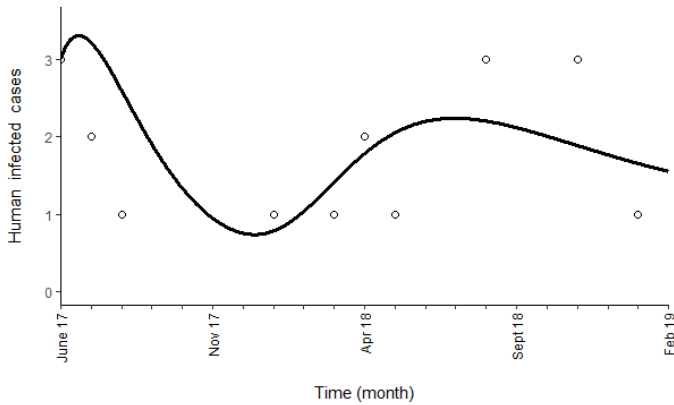


Fig. 2 The solid curve represents the simulation of infected human rabies cases over the course of 21 months starting June 2017 to February 2019. The points refer to the number of actual cases.

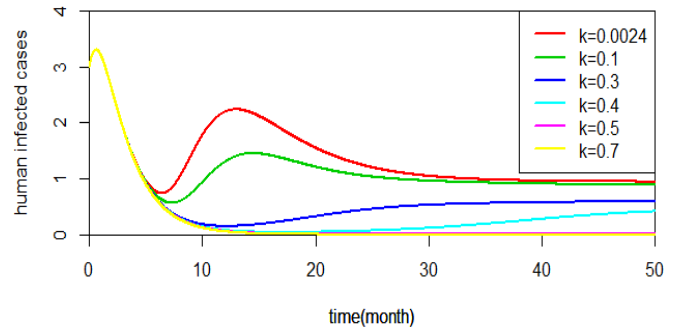


Fig. 4 The influence of the parameter dog vaccination rate k on the number of human infected cases.

We also observe the influence of the monthly number of newborn puppies on the number of infected human rabies cases. As denoted in Fig. 5, changing the monthly number of newborn dogs would not prevent the occurrence of the second outbreak as the graph can be seen to reach a noticeable high peak again after the 10th month and rabies would only be eliminated when the number of newborn puppies are as low as 500 dogs per month. This finding suggests that controlling dog birth would help to achieve rabies eradication as it would decrease the input of new susceptible dogs into the population. Furthermore, as indicated in Fig. 6, only when culling 10% of dogs per month will result in rabies eradication. Lower than that percentage, rabies will still be maintained in the population. However, it is not only unethical but also infeasible to cull that many dogs each month. Furthermore, Fig. 7 shows that 90% human vaccination rate will still lead to rabies persistence.

Therefore, reducing the number of monthly newborn puppies and increasing the rate of dog vaccination would be the more effective strategies to manage the current rabies outbreak in Sarawak. The number of monthly newborn puppies can be reduced if the public would neuter their pets or using other fertility control methods to prevent new births. There is also a need to increase the access to immediate rabies vaccination for dogs especially in the rural areas with lack of health facilities. Further, dog vaccination should instead replace large scale culling.

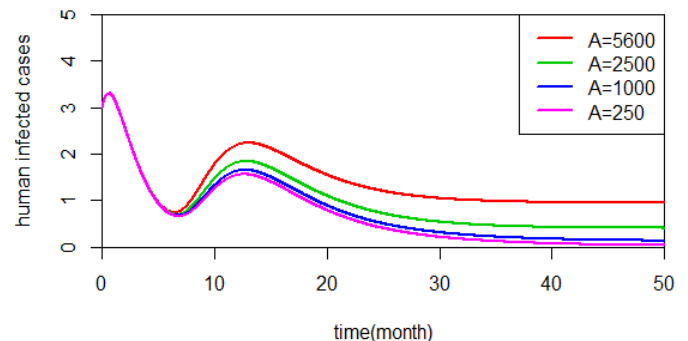


Fig. 5 The influence of the monthly number of newborn puppies on the number of human infected cases.

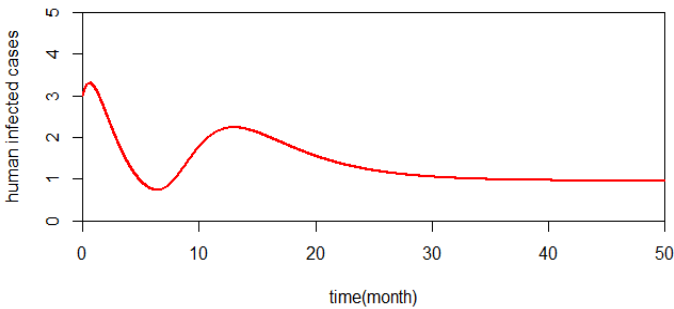


Fig. 3 Simulated number of infected human rabies cases for 51 months from month-0 (June 2017) to month-50 (August 2021).

Model simulation in Fig. 3 indicates that after the disease first emerged which can be seen as the first peak of the solid curve, the number of infected human will decrease for a few months before the second outbreak whereby the curve reaches another peak at around one year after the occurrence of the initial outbreak. The simulation predicts that rabies will continue to persist even with the current prevention and control strategies. We also estimate the basic reproduction number to be higher than 1 ($R_0 > 1$) in the context of Sarawak which further supports our prediction that the disease will survive in the population.

We then perform sensitivity analysis on some of the model parameters by simulating the model for 51 months while varying the parameter values. Our finding demonstrates that the dog vaccination rate k has an influence on the number of infected human rabies cases as shown in Fig. 4. The results showed that the occurrence of the second outbreak could not be avoided if the dog vaccination rate is at 10% or below. When the dog vaccination rate is at 30% - 40%, the number of infected human decreases after the initial outbreak but would continue to rise gradually. For example, even at 40% dog vaccination rate, the number of cases seems to decrease to zero but eventually starts to increase again after around 30 months from the initial outbreak. Only when the vaccination rate for dogs is at 50% or higher that the disease will ultimately be eradicated. This finding is aligned with the target of 70% vaccination coverage guideline from the World Health Organization (WHO).

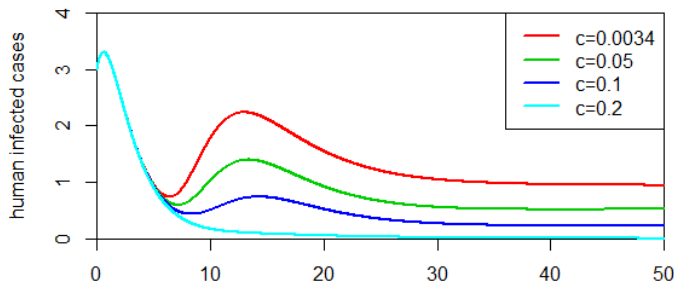


Fig. 6 The influence of dog culling rate on the number of human infected cases.

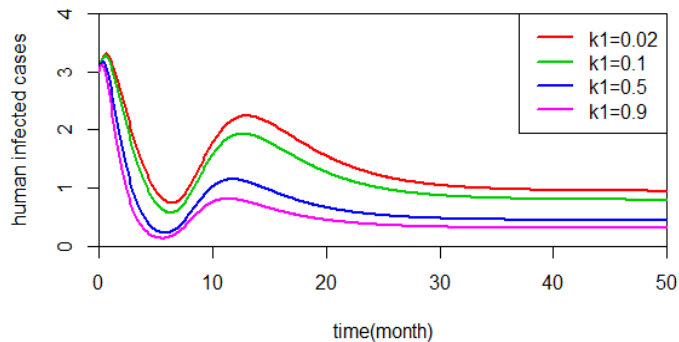


Fig. 7 The influence of the human vaccination rate on the number of human infected cases.

IV. CONCLUSION

Despite having to deal with sporadic cases of human rabies in Sarawak, we have fit the actual data on the number of human infected rabies cases in Sarawak from June 2017 to January 2019 by a simple vector-host SEIRS epidemic compartment model. In summary, our early investigation has revealed that reducing newborn dogs and increasing dog vaccination coverage would prevent the disease from perpetuating in the state. Rabies awareness campaign should be conducted more frequently in order to emphasize on the importance of reducing newborn dogs. Bringing pet dogs for neutering or using other fertility control methods could help to reduce the input of new susceptible dogs into the population. We also suggest the implementation of Trap-Neuter-Vaccinate-Release (TNVR) method to manage the strays instead of culling. TNVR is a method whereby stray dogs are caught, neutered and vaccinated before being released back to their natural environment. This would significantly control the spread of the disease as the stray dog population would decline through natural expiration. As compared to culling, vacuum effect wont occur with TNVR as no new dogs would migrate to fill the vacancy left by the dogs being culled. Furthermore, we would suggest that rabies vaccines for dogs should be made more available for those in the remote rural areas. Rabies eradication can be achieved if dog mass vaccination is intensified to achieve a target of more than 50% vaccination coverage. We would also like to point out that there are some limitations in this study especially on the lack of availability of data on dogs and human rabies. Future work should consider using a more rich data in order to estimate the parameter values of the model precisely. Moreover, the current model can be modified to include other hosts such as cats as the number of rabid cats are growing in Sarawak.

V. ACKNOWLEDGMENT

This work is part of the research project entitled “Digitising the Rabies Outbreak in Sarawak: An Approach to Generating Diagnostic Assays and Mathematical Modeling to Predict Disease Transmission”. The authors would like to thank the Sarawak Multimedia Authority (SMA) for their funding support of this research project under grant number RG/F08/SMA/05/2018.

REFERENCES

- [1] “Rabies,” *World Health Organization (WHO)*, 2018. [Online]. Available: <https://www.who.int/news-room/fact-sheets/detail/rabies>.
- [2] L. Knopf *et al.*, “The Road to Dog Rabies Control and Elimination—What Keeps Us from Moving Faster?,” *Front. Public Heal.*, vol. 5, no. May, pp. 1–8, 2017.
- [3] “First rabies deaths in Malaysia in 20 years,” *The Straits Times*, 2017.
- [4] “Latest victim succumbs to rabies in Sarawak,” *New Straits Times*, 2019.
- [5] “Sarawak set to Eliminate Rabies,” *The Sun Daily*, 2019.
- [6] WAHIS, “Rabies,” (*World Animal Information System*), 2019. [Online]. Available: http://www.oie.int/wahis_2/public/wahid.php/Countryinformation/Countryreports.
- [7] Sarawak Disaster Information, “Details of Rabies Outbreak,” 2019. [Online]. Available: <https://infodisaster.sarawak.gov.my/>.
- [8] J. Zinsstag *et al.*, “Transmission dynamics and economics of rabies control in dogs and humans in an African city,” *Proc. Natl. Acad. Sci.*, vol. 106, no. 35, pp. 14996–15001, 2009.
- [9] J. Chen, L. Zou, Z. Jin, and S. Ruan, “Modeling the Geographic Spread of Rabies in China,” *PLoS Negl. Trop. Dis.*, vol. 9, no. 5, pp. 1–18, 2015.
- [10] S. Dürr and M. P. Ward, “Development of a novel rabies simulation model for application in a non-endemic environment,” *PLoS Negl. Trop. Dis.*, vol. 9, no. 6, pp. 1–22, 2015.
- [11] J. K. K. Asamoah, F. T. Oduro, E. Bonyah, and B. Seidu, “Mathematical Modelling and Optimal Control of Rabies Transmission Dynamics,” *J. Appl. Math.*, 2016.
- [12] J. Zhang, Z. Jin, G. Q. Sun, T. Zhou, and S. Ruan, “Analysis of rabies in China: transmission dynamics and control,” *PLoS One*, vol. 6, no. 7, 2011.
- [13] S. Ruan, “Modeling the transmission dynamics and control of rabies in China,” *Math. Biosci.*, vol. 286, no. April, pp. 65–93, 2017.
- [14] J. Zhang, Z. Jin, G. Sun, X. Sun, and S. Ruan, “Spatial spread of rabies in China,” *J. Appl. Anal. Comput.*, vol. 2, no. 1, pp. 111–126, 2012.
- [15] T. Leung and S. A. Davis, “Rabies Vaccination Targets for Stray Dog Populations,” *Front. Vet. Sci.*, vol. 4, no. April, pp. 1–10, 2017.
- [16] A. M. Bilinski, M. C. Fitzpatrick, C. E. Rupprecht, A. D. Paltiel, and A. P. Galvani, “Optimal frequency of rabies vaccination campaigns in Sub-Saharan Africa,” *Proc. R. Soc. B Biol. Sci.*, vol. 283, no. 1842, 2016.
- [17] A. Mengistu Tulu, “The Impact of Infective Immigrants on the Spread of Dog Rabies,” *Am. J. Appl. Math.*, vol. 5, no. 3, p. 68, 2017.
- [18] J. Huang, S. Ruan, Y. Shu, and X. Wu, “Modeling the Transmission Dynamics of Rabies for Dog, Chinese Ferret Badger and Human Interactions in Zhejiang Province, China,” *Bull. Math. Biol.*, no. 11471133, pp. 1–23, 2018.
- [19] S. P. Johnstone-Robertson, P. J. S. Fleming, M. P. Ward, and S. A. Davis, “Predicted Spatial Spread of Canine Rabies in Australia,” *PLoS Negl. Trop. Dis.*, vol. 11, no. 1, pp. 1–21, 2017.
- [20] Wendy Y. Brown, J. Sparkes, P. J. S. Fleming, G. Körtner, G. Ballard, and S. McLeod, “Rabies disease dynamics in naïve dog populations in Australia,” *Prev. Vet. Med.*, 2016.
- [21] B. O. Olugasa *et al.*, “Time series analysis and mortality model of dog bite victims presented for treatment at a referral clinic for rabies exposure in Monrovia, Liberia, 2010–2013,” *Spat. Spatiotemporal. Epidemiol.*, vol. 22, pp. 1–13, 2017.
- [22] E. G. Hudson, V. J. Brookes, and M. P. Ward, “Assessing the Risk of a Canine Rabies Incursion in Northern Australia,” *Front. Vet. Sci.*, vol. 4, no. August, 2017.
- [23] M. Z. Ndi, Z. Amarti, E. D. Wiraningsih, and A. K. Supriatna, “Rabies epidemic model with uncertainty in parameters: Crisp and

- fuzzy approaches,” *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 332, no. 1, 2018.
- [24] K. Makita *et al.*, “A comparative review of prevention of rabies incursion between Japan and other rabies-free countries or regions,” *Jpn. J. Infect. Dis.*, 2018.
- [25] M. Laager *et al.*, “The importance of dog population contact network structures in rabies transmission,” *PLoS Negl. Trop. Dis.*, vol. 12, no. 8, pp. 1–18, 2018.
- [26] A. Conan, O. Akerele, G. Simpson, B. Reininghaus, J. van Rooyen, and D. Knobel, “Population Dynamics of Owned, Free-Roaming Dogs: Implications for Rabies Control,” *PLoS Negl. Trop. Dis.*, vol. 9, no. 11, 2015.
- [27] V. Sitprija, H. Wilde, B. Lumlertdacha, V. Tepsuethanon, F. X. Meslin, and C. Mitmoonpitak, “Survival of Naturally Infected Rabid Dogs and Cats,” *Clin. Infect. Dis.*, vol. 39, no. 2, pp. 278–280, 2004.