Dynamics Of Rabies Spread Using Mathematical Modeling And Simulation

Alonte, Jonel
Camarines Norte State College
Barangay Mampili
Basud, Camarines Norte
09394789057
jonelalonte@gmail.com

Benalla, Precy
Camarines Norte State College
Barangay Cabanbanan
San Vicente, Camarines Norte
09853075698
kikaybenalla5@gmail.com

Jamito, Evid Ros Andrae
Camarines Norte State College
Barangay Cahabaan
Talisay, Camarines Norte
09073436099
evidjamito95@gmail.com

Salvador, Marc Arvel
Camarines Norte State College
Barangay 7
Mercedes, Camarines Norte
09090634076
arvelsalvador@gmail.com

Tolentino, Jomar
Camarines Norte State College
Barangay Bactas
Basud, Camarines Norte
09350051994
jomartolentino2002@gmail.com

Villanueva, Reymar
Camarines Norte State College
Barangay Del Rosario
Mercede, Camarines Norte
09154648380
reymarfactor@gmail.com

***Abstract*—Rabies is so serious, affecting the health of each citizen of Camarines Norte due to the careless nature of most people and the lack of immediate treatment for dog bites in many. This study will focus on the spread of rabies in Camarines Norte using mathematical modeling and simulation to predict rabies transmission and to determine the target number of dogs to vaccinate. This simulation of data based on records of the number of persons bitten or vaccinated against rabies in the Animal Bite Center at Camarines Norte is to estimate the trends in the monthly number of cases of bites and to estimate the rise of the cases with time. Protocols for the treatment for rabies are prepared and enhanced in the hospitals to get a better response and a prevention strategy that reduces fatality rates caused by the rabies virus. Results of the simulation also provide monthly predictions of increases in the cases of bites, giving the health facilities an insight into periods of increased risk and thus preparing them well for such periods.**

Keywords— rabies; dynamics; transmission; vaccination; mathematical modeling; simulation; Camarines Norte

I. INTRODUCTION

Rabies is an acute viral infectious disease of human and other vertebrates belonging to the group of mammals, the etiology of which is the rabies virus of the Rhabdoviridae family and the Lyssavirus genus. It is acquired from the saliva of infected animals, mostly through a bite or an attack (Hanan Farihah et al., 2022). Globally, rabies is estimated to kill 59,000 human every year, with 99% of the victims having been bitten by dogs(Pongsumpun, 2022).

The first time that dog rabies was noted in the Philippines was in 1910, when a human case had been documented and Negri bodies seen in the cerebral tissue of the biting dog. A case analysis of human rabies reports in the Philippines from 1987 to 2006 reveals that a higher prevalence of rabies is associated with contact with animals with rabies, specifically dogs. According to the review, there is a strong call for continued awareness and control measures in preventing rabies transmission in the country(Dimaano et al., 2011).

To offer post-exposure prophylaxis (PEP) to bite patients, the Philippine government has set up fifteen Animal Bite Treatment Centers (ABTCs) in different regions throughout the island country. Yet the frequency of bite patient presentations has escalated, exponentially and rabidities in domestic dogs is still on the rise. Weak surveillance worsens the problem, resulting in low caseload identification and slower response to outbreaks(Rysava et al., 2022).

The contact patterns in this model were therefore influenced by the environment or density and interaction rates of the dogs(Nurdiansyah et al., 2024). Rabies prevalence and incidence studies across the geographical context shows that rabies may differ due to regional characteristics, thus may require customized vaccination and intervention programmes across specific groups of the population(Renald, 2020).

In the study titled "Sensitivity Analysis and Numerical Simulations for the Mathematical Model of Rabies in Human and Animal within and around Addis Ababa", the researchers found that factors such as the annual dog birth rate and the natural death rate of dogs are critical in influencing rabies transmission dynamics (Ega et al., 2015).

Rabies attacks rise by 100 percent in three provinces of Bicol region from January 1 to March 9 this year as per DOH-Bicol Region report on March 21, 2014 as sourced by Manila Bulletin. This rise underlines the major health risks associated with rabies in rural provinces including Camarines Norte (*Rabies Cases in 3 Bicol Provinces up 100%, Says DOH*, n.d.). Previous and post-intervention assessment of a study conducted in Bicol proved that raising awareness before and after project implementation improves rates of mass [illegible]s vaccinations and other preventive measures(Barroga et al., 2018).

Available information indicates that the best approach of controlling human rabies is through mass vaccination of the animals especially dogs(Britton, 2020). Analyses from another model indicated that a vaccination approach may cut down rabies occurrences, especially among stray dogs(Verma & Kunwar, 2024)

Several studies have pointed out that due to rabies altering the behaviour of affected dogs, the disease has a longer survival rate in dogs. Another study used a network-based model in an attempt to explain how behavior modification in infected dogs contributes to the transmission of rabies; the study posited that over 70% vaccination rate may be required to stem the disease (Brookes et al., 2019). Programs of vaccination and public health measures have been proved to reduce considerably incidence of rabies in domestic and wild animals, which translates directly to human health(Morters et al., 2013).

Simulation model on the other hand refers to the use of mathematical model to mimic the functioning of a process or a system at different time intervals. Various mass dog vaccination strategies are most conveniently analyzed with simulation model to estimate the public cost-effectiveness, and the information gained from the simulation outcomes can be useful for the animal health authorities to make the decisions on rabies control in the areas like Flores Island (Wera et al., 2017).

Various studies have adopted mathematical models to analyze rabies dynamics and the impact of control strategies. The study titled "Mathematical Models for Rabies focused on the rabies virus and its associated host–pathogen population dynamics, using this remarkable model system to develop mathematical models of infectious disease emergence and spread. Their work signifies a progression from simple susceptible-infectious-removed (SIR) compartment models of fox rabies emergence and spread across Western Europe to more complex models incorporating dynamics across heterogeneous landscapes, host demographic variation, and environmental stochasticity (Panjeti & Real, 2011).

In the present mathematical modeling of rabies, vaccination and culling have been incorporated in order to study the efficacy of the general preventive measures to control the disease(Hailemichael et al., 2022). Optimal control studies have established that effective vaccination with knowledge of rabies transmission dynamics can contribute to significant reduction of rabies incidence and towards the vision of no human rabies fatalities from dog bites by 2030(Hampson et al., 2020).

In this preliminary paper, we propose an unprecedented SEIRS rabies model for the spread of ra bies in Camarines Norte in hopes to expound the ongoing rabies situation. We simulate the model with the observed number of infected human cases in Camarines Norte from January 2009 to December 2023. We then analyze the influence of initial conditions and parameter values on the number of infec ted humans.

II. Materials And Method

In order to investigate the dog-human transmission dynamics of rabies in Daet, Camarines Norte, this paper adopted the compartmental SEIRS model proposed by

where each human and dog population is divided into four categories based on their case status. They include; (i) the Susceptible (S) category they are the person who is prone to rabies; (ii) the Exposed (E) category they include people who have come into contact with the rabies but have not developed the rabies, there is the incubation or latency period; (iii) the Infected (I) people in this category are those who are actively transmitting the rabies, they are infected and can infect others; and lastly, (iv) the Removed (R) category consists of individuals who are no longer part of the transmission cycle, either because they have developed immunity or have succumbed to the rabies.

A. Model Formulation

First, confirm that you have the correct template for your paper size. This template has been tailored for output on the A4 paper size. If you are using US letter-sized paper, please close this file and download the Microsoft Word, Letter file.

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 find the equilibrium point where the disease is absent:

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

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

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

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

Therefore, the basic reproduction number is defined to be

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

If rabies is present in both populations and we set the right-hand side of equation (1) to zero, we reach the endemic equilibrium point.

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

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

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

$$I^* = \frac{S^0\sigma\gamma k\lambda + (AR_0 - S^0(m+k+e))\sigma\gamma(m+\lambda)}{\sigma\beta\gamma(m+\lambda)S^0 - R_0(m+\mu+e)(\sigma(1-\gamma)(m+\lambda) + k\lambda)}$$

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

$$S_1^* = \frac{B(m_1+\sigma_1+k_1)(m_1+\gamma_1)}{(m_1+\beta_1 I^*)(m_1+\sigma_1+k_1)(m_1+\lambda_1) - I^*[\lambda_1 k_1 \beta_1 + \sigma_1\beta_1(1-\gamma_1)(m_1+\lambda_1)]}$$

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

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

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

C. Parameter Estimation

Parameterization proved to be difficult due to a limited data source, as Camarines Norte Provincial Hospital had no available census in the public in this current year. Therefore, the values of parameters in Table I and Table II are mainly from estimations made based on reported values and from assumptions taken from literature searches, respectively. Therefore, the values of parameters in Table I and Table II are mainly from estimations made based on reported values and from assumptions taken from literature searches, respectively.

The total number of dogs in Camarines Norte is estimated to be in 2023, according to the provincial veterinarian. 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 titled "Population Dynamics of Owned, Free-Roaming Dogs: Implications for Rabies Control"(Conan et al., 2015). We then manipulate the value to estimate the monthly number of newborn puppies (A). A total of 17824 dogs have been vaccinated from January 2023 to December 2023, according to the provincial veterinarian, and the value is used to estimate the dog vaccination rate (k). The provincial veterinarian stated that a total of 1470 dogs have been disposed of from January 2023 to December 2023. We then calculated the average number of dogs disposed of and found that an approximate 0.04% of dogs were removed from January to December in 2023. We then calculated the average number of dogs disposed of and found that an approximate 0.04 of dogs were removed from January to December in 2023. The estimation of the dog vaccination immunity loss rate is based on the assumption that dogs lose immunity after one year. Due to limited information on dog demographics in Camarines Norte, some parameters are derived from published estimates in (Zhang et al., 2011)and converted to monthly units as needed. For instance, the mean dog incubation period ($1/\sigma$), natural death rate of dogs (m), risk of clinical outcome for exposed dogs (y), and dog disease-related death rate (μ) are assumed to be 2.5 months, 0.08 years, 0.4 years, and 1 year, respectively(Zhang et al., 2011).

Cases of positive human rabies were provided by Camarines Norte Provincial Hospital. Each case is reported with details that include monthly data of the number of animal bites and exposure, category of exposure, immunization status, and the Total Cohort Report, which summarizes the total figures for the quarter of the associated dog-bite incident. The crude birth rate available from the Philippines Statistics Authority Region V-Bicol Region (*Vital Statistics | Philippine Statistics Authority V - Bicol*, n.d.) and the crude death rate per 1,000 population in Camarines Norte given by the Provincial Hospital are used to approximate the number of monthly human births (B) and the natural human mortality rate (m_1), respectively.

Out of the total 6988 cases of positive human rabies in 2023 in Camarines Norte, there was 1 fatality, resulting in 6987 survivors. Consequently, the death rate ($\mu 1$) now stands at approximately 0.014 over the span of 12 months, from January 2023 to December 2023. All victims were CamNortenios, including who were bitten and died in Camarines Norte. We extracted data on the biting incidents and subsequent onset of clinical symptoms reported by each of the 6988 cases in 2023. By calculating the duration of time between exposure and becoming symptomatic, we estimate the mean human incubation period ($1/\sigma 1$) to be 2.5 months.

According to an experimental study titled "Survival of naturally infected rabid dogs and cats(Tepsumethanon et al., 2004), 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 humans vaccinated per month and the total number of exposed humans in which the frequency of bite cases is taken as a proxy. All the data required for the estimation is obtained from the provincial hospital.

Lastly, the transmission rates of rabies among dogs (β) and that of dogs to humans (β_1) are obtained from data fitting. Actual data on the number of infected humans dated January 2023 until December 2023 used for our model fitting are mostly obtained from Provincial Hospital. 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.

TABLE I

DESCRIPTION OF ESTIMATED PARAMETERS

Parameter	**Value**	**Definition**	**Source**
A		monthly number of newborn puppies	
k		dog vaccination rate	
e		culling rate	
β		dog-to-dog transmission rate	
B		human monthly birth	
σ_1		reciprocal of human incubation period	
m		human natural mortality rate	
k		human vaccination rate	
β		dog-to-human transmission rate	
μ		human disease-related death rate	

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)
σ	0.4	reciprocal of dog incubation period	Zhang et al. (2011)
m	$\frac{0.08}{12}$	dog natural death rate	Zhang et al. (2011)
Υ	0.4	risk of clinical outcome of exposed dogs	Zhang et al. (2011)
μ	1	dog disease-related death rate	Zhang et al. (2011)

λ_1	$\frac{1}{12}$	rate of vaccination immunity loss in humans	Zhang et al. (2011)
γ_1	0.4	risk of clinical outcome of exposed humans	Zhang et al. (2011)

III. Results And Discussions

The compartmental SEIRS model is a mathematical model of description of the spread of infectious diseases. Finally, the analysis shows that SEIRS model is an effective approach to modeling and controlling dog rabies. It helps one understand ways in which the disease can spread, ways in which vaccination campaign can be conducted and how one can effectively control the disease. This model previously applied to estimate the patterns of rabies transmission in dog populations and the impact of infection, recovery, and vaccination.

By using the values of parameters in Table I and Table II, we simulate the SEIRS model by solving the system and employing deSolve function ode in R.) We aim at reproducing the number of infected human rabies cases in Camarines Norte from January 2009 to December 2023 data from the Provincial Hospital of Camarines Norte. In 2023, the total number of dogs in Camarines Norte is approximately 34627 and the crude birth rate of dogs per 1000 population is taken as 300, thus we assume (0) = 150000. According to the Cities and Municipalities Competitiveness Index, the population size in Camarines Norte in 2023 is estimated to be 609,226 (*Cities and Municipalities Competitiveness Index*, n.d.), so we take S_1 (0) = 609,226 . We let I1(0) = 6,988 as cases of human infected with rabies based on the data in January to December 2023 were reported in 2023. Other initial conditions are chosen through fitting.

The requested solution at time t is the number of infected human rabies, labeled as I(t) in the figure is displayed as a continuous line as shown in Fig. 2. This curve illustrates the trend of human infected cases whereby the numbers of infected humans rose to approximately 400 in month 1 to about 1000 cases in month 12. This is quite reasonable given the rather random nature of human rabies cases and the fitting between our simulated model and the observed monthly number of infected humans in Fig 2 is rather good. We further iterated the model to the extent where results were static and this is highlighted in Fig 3.

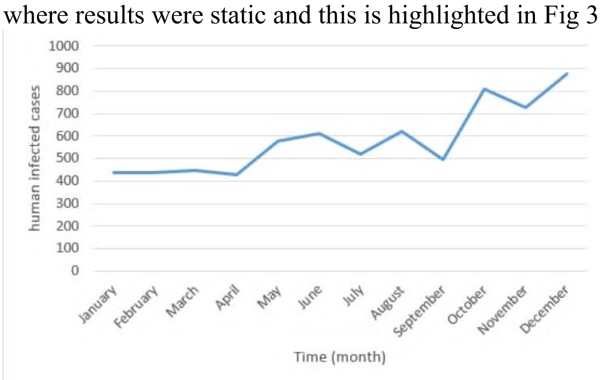

Fig 2. The solid curve in represents the number of human infected cases over a 12-month period starting January 2023 to December 2023

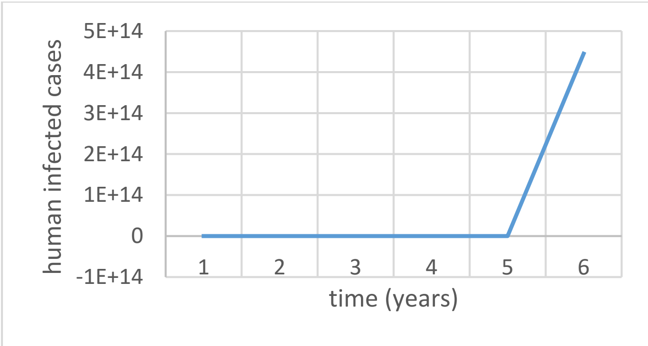

Fig 3 . Simulated number of infected human rabies cases over the course of 6 years starting June 2023 to February 2028

From the model simulation in Fig. 3, it emerges that the first four years, and the number of infected cases is static and almost negligible. From the fifth year, the cases increase sharply, and this trend continues up to the end of the sixth year. This high rise infers that there could have been a compromise of the control measures or there were enhanced predisposing factors explaining rabies spread. Therefore, using increases in the number of cases and deaths, we predict the basic reproduction number (R0) of the virus is more than 1 (R0 > 1). This means that each infected person can infect more than one other person this may lead to an outbreak if not contained.

We then perform sensitivity analysis on some of the model parameters by simulating the model for 60 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 fact that we proved that different rates of dog vaccination (k) fundamentally shift the number of human rabies cases over time. Figure 4 also shows that higher percentage of people vaccinated (e.g., (k=0.9)) reduces the number of human infection while lower percentage (e.g., (k=0.5)) increases the number of human infection. This therefore justifies the importance of dog vaccination against rabies so as to prevent spread to human populations.

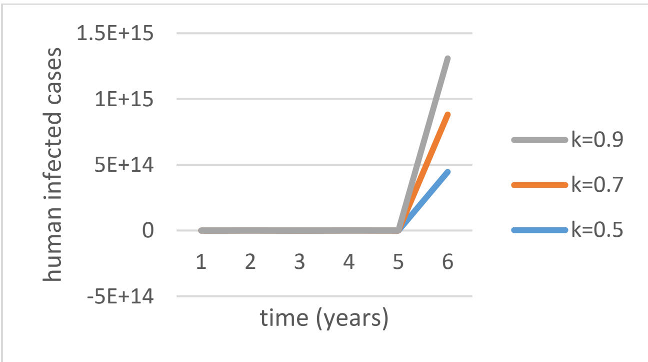

Fig 4. The influence of dog vaccination rates on the number of human rabies cases over time

We also observe the influence of the monthly number of newborn puppies on the number of infected human rabies cases. Fig. 5 shows how different numbers of newborn puppies (A=866, A=500, A=200, A=50) affect the number of human rabies infections over time. It proves that when there are only 50 newborn puppies monthly, cases of rabies in humans are few. But when the number of newborn puppies is increases to 200, 500 and 866, the number of human rabies cases are seen to rapidly escalate. This shows that the cases are even lower when the number of newborn puppies gets low. Additionally, as observed in Fig. 6 all culling rates result to reduction in human infected cases. Nevertheless, as time increases, the higher e culling rates especially e=2, lead to higher human infections after declining during the same period. Thus, it implies that peoples rate in turn hints that although eradication is effective in cutting out cases in the short run, a higher rate of the virus means more strains and cases in the long haul. Also, it can be clearly illustrated from Fig. 7 that, human vaccination rate has great impact on the number of human infected cases. This figure implies that as the k values increase meaning more of the population has been vaccinated the rate at which the cases of infection increase is also fast.

Hence, management of dog birth is another important in dealing with rabies because it reduces the flow of fresh susceptible dogs in circulation. Results presented here show that rabies control is not straightforward and should best be dealt with within an integrated manner and in conjunction with animal control and human vaccination approaches.

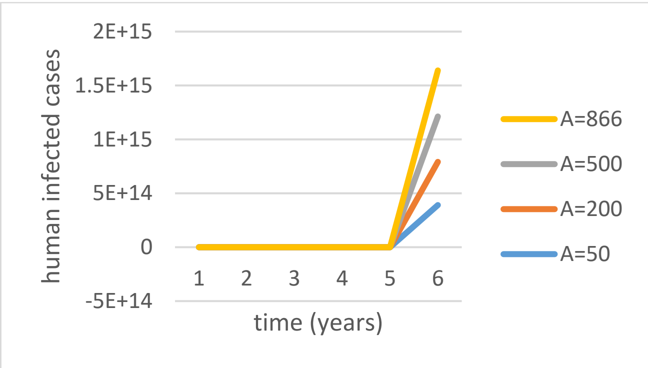

Fig 5. The influence of the monthly number of newborn puppies on the number of human infected cases.

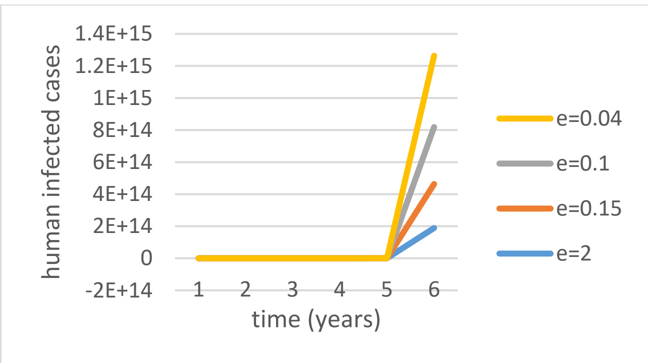

Fig6. The influence of dog culling rate on the number of human infected cases.

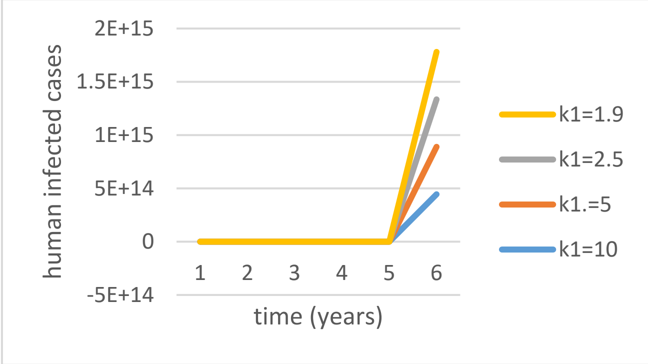

Fig 7. The influence of the human vaccination rate on the number of human infected cases

IV. Conclusion

Regardless of working through cases of human rabies in Camarines Norte, we need to align with the actual data on the number of human infected with rabies in Camarines Norte from January 2009 to December 2023 by a compartmental SEIRS model. In short our early investigations the dynamics of rabies transmission are intricately linked to the population of newborn puppies culling rates and human vaccination rates. The data clearly indicates that a lower number of newborn puppies significantly reduces the incidence of human rabies cases. While culling can initially decrease the number of infections excessively high culling rates may paradoxically lead to a resurgence of cases over time. Moreover the impact of human vaccination is profound, with higher vaccination rates correlating with a rapid increase in the number of infected cases

Our findings focus on several critical factors in controlling rabies spread. Firstly reducing the birth rate of puppies place a significant role in lowering the number of susceptible animals which in turn decreases human rabies cases over time The results suggest that controlling the input of new unvaccinated puppies is essential to managing overall infection rates.

Secondly, while culling can minimize infection rates initially high culling rates may lead to unintended increases in infections in the long term. This outcome focus on the need for cautious application of culling, possibly supplemented by other measures, to avoid potential resurgence. Thirdly dog vaccination rates are a key factor in minimizing rabies spread. Our model showed that higher vaccination coverage among dogs significantly reduces human rabies cases. Therefore sustained vaccination campaigns targeting at least 70%, of the dog population should be prioritized as an effective intervention. Last human vaccination particularly post exposure prophylaxis remains vital in preventing infection after potential rabies exposure Higher human vaccination rates especially in areas with high dog populations contributes to controlling rabies spread.

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