MODELLING THE IMPACT OF DICLOFENAC POISONING IN VULTURES OF THE INDIAN SUBCONTINENT

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by

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DECLARATION

I, Ritika Gupta, 2K22/MSCMAT/54, student of M.Sc. Mathematics, hereby declare that the project Dissertation titled “Modelling the impact of diclofenac poisoning in vultures of the Indian subcontinent” which is submitted by me to the Department of Applied Mathematics Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Science, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.

Place: New Delhi

Date: RITIKA GUPTA

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CERTIFICATE

We hereby certify that the Project Dissertation titled “Modelling the impact of diclofenac poisoning in vultures of the Indian subcontinent” which is submitted by Ritika Gupta, 2K22/MSCMAT/54 [Department of Applied Mathematics], Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Science, is a record of the project work carried out by the students under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

Place: New Delhi **Dr. Nilam**

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RITIKA GUPTA

ABSTRACT

Diclofenac, a Non-Steroidal Anti-Inflammatory Drug (NSAID), has significantly reduced vulture populations in the Indian subcontinent due to its presence in deceased livestock. Used in veterinary practice since the 1990s, diclofenac leads to visceral gout and death in vultures consuming treated cattle carcasses. This has resulted in a vulture population decrease of over 99% in 30 years, with severe ecological and socio-economic consequences. Despite bans in India, Nepal, and Pakistan since 2006, illegal use persists, with high diclofenac residues found in vulture carcasses.

This study uses the SEIR (Susceptible-Exposed-Infectious-Removed) model to simulate diclofenac’s impact on vultures.

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LIST OF ABBREVIATIONS

NSAID: Non-Steroidal Anti-Inflammatory Drug

CR: Critically Endangered

NT: Near Threatened

LC: Least Concern

IUCN: International Union for Conservation of Nature

SEIR: Susceptible-Exposed-Infectious-Removed

scipy.integrate.odeint: Python Library to Integrate a system of Ordinary Differential Equations.

np: Python Library NumPy

plt: Python Library Matplotlib.pyplot

sns: Python Library Seaborn

CHAPTER 1

INTRODUCTION

1.1. DECLINE IN VULTURE POPULATION

Non-Steroidal Anti-Inflammatory Drugs (NSAIDs) are commonly used to reduce pain, fever and inflammation in human and veterinary medicine. One of the NSAIDs, Diclofenac, which was introduced in the veterinary market in the early 1990s, has been the major cause of decline of vulture population in the Indian subcontinent as well as other parts of the world (Oaks et al. 2004).

When vultures feed on cattle that were treated with NSAIDs shortly before they died, the vultures often develop visceral gout, which causes death in up to three days, usually far from where they ate the carcass, thus making it difficult to trace the cause of their death ("The Threat of Veterinary Drugs to Raptors," n.d.). In April 2003, Watson et al. 2004 discovered that the correlation between renal failure in vultures and the presence of diclofenac in their body is 100%.

Once considered very abundant, Vulture population in the Indian subcontinent has faced a decline of more than 99% in the past 30 years. Vultures possess a complex scavenging behaviour. If gathered together in large number to feed, poisoned carcasses can wipe out entire populations of vulture at once (Rigas Tsiakiris et al. 2021).

The possible extinction of vultures has its social and economic impacts as well. Vultures play a natural role in carcass disposal. They are adept in disposing off a carcass before diseases like anthrax, tuberculosis, etc. even have a chance to spread. In the absence of these scavengers, the task of disposal of carcasses is naturally transferred to other animals like dog, rats, etc, which, increases the risk of new and above infections by many folds (Watson et al. 2004).

1.2. VULTURES OF INDIAN SUBCONITINENT

Three Gyps species resident to the Indian subcontinent have been labelled as Critically Endangered, viz., Gyps bengalensis (CR since 2000), Gyps indicus (CR since 2002) and Gyps tenuirostris (CR since 2002) by the IUCN (BirdLife International, 2021). Moreover, Gyps himalayensis, which was in the Least Concern (LC) category till 2012, has been listed as Near Threatened (NT since 2014) by the IUCN (BirdLife International, 2021).

According to BirdLife International, 2021, the number of mature: Gyps bengalensis was 4,000 – 6,000; Gyps indicus was 5,000 – 15,000; Gyps tenuirostris was 730 – 870; Gyps himalayensis was 66,000 – 3,34,000. With all four species undergoing a continuous decline with no extreme population fluctuations, mortality of vultures in the region is under serious threat.

1.3. BAN ON DICLOFENAC

In 2006, India, Nepal and Pakistan banned the veterinary use of the NSAID Diclofenac to tackle the declining vulture population. However, Nambirajan et al. 2018 concluded that even after its ban, diclofenac can continue to kill vultures. This unfortunate reality is a result of continued usage of nonveterinary diclofenac in veterinary purposes post ban.

Between 2011 and 2014, Nambirajan et al. 2018 collected 44 dead vultures from Assam, Gujarat and Tamil Nadu, and on an average, found the percentage of diclofenac residues in samples to be more than 60%. This was a surprising discovery for the post ban scenario. Presently, the actual data about the extent of diclofenac poisoning cannot be known for certain as many such cases go undocumented.

Also, the same study revealed that percentage of diclofenac residues was higher in Gyps himalayensis than in Gyps bengalensis, which suggests that the former is more exposed to the said NSAID than the latter. This further increases the threat for the Gyps himalayensis, presently classified as Near Threatened (NR).

Even though official measures were taken to ban diclofenac for veterinary purposes, the existence and sale of other toxic NSAIDs poses another deep threat to the vultures.

CHAPTER 2

SEIR MODEL FOR VULTURE - DICLOFENAC DYNAMICS

2.1. MODEL FORMULATION

The SEIR (Susceptible-Exposed-Infectious-Removed) model is a compartmental model commonly used in epidemiology to understand the spread of infectious diseases within a population. While the SEIR model is typically used for infectious disease modelling, its structure can be adapted to study the effect of diclofenac poisoning in vultures resulting from cattle carcasses contaminated with the drug.

Compartments:

Susceptibles, S(t): Vultures that have not consumed but are susceptible to ingesting diclofenac contaminated carcasses at time t.

Exposed, E(t): Vultures that have ingested diclofenac-contaminated carcasses but are not symptomatic at time t.

Infected, I(t): Vultures that have ingested diclofenac-contaminated carcasses and are symptomatic at time t.

Removed, R(t): Vultures that have died due to diclofenac toxicity at time t.

Dynamic Processes:

Susceptible to Exposed: Vultures consume contaminated carcasses.

Exposed to Intoxicated: Vultures begin to show toxic effects after the incubation period.

Intoxicated to Removed: Vultures die due to diclofenac toxicity.

Parameters:

$N(t)$: Total population at time t (units: vultures)

$S(t)$: Population of susceptibles at time t (units: vultures)

$E(t)$: Population of exposed at time t (units: vultures)

$I(t)$: Population of infectives at time t (units: vultures)

R(t): Population of removed at time t (units: vultures)

β (Transmission Rate): Represents the rate at which vultures come into contact with diclofenac-contaminated carcasses (units: year^{-1}).

σ (Incubation Rate): Represents the rate at which exposed vultures progress to the intoxicated state after ingesting diclofenac. Inverse of incubation period (units: year^{-1}).

γ (Removal Rate): Represents the rate at which intoxicated vultures die due to diclofenac toxicity. Can be measured using previous data of diclofenac residues in dead vultures (units: year^{-1}).

b (Birth Rate): The rate at which new vultures are added to the population through births (units: year^{-1}).

d (Natural Death Rate): The rate at which vultures die from causes other than diclofenac toxicity (units: year^{-1}).

C (Carcass Contamination Rate): The fraction or proportion of carcasses that are contaminated with diclofenac (units: dimensionless).

2.2. MODEL ASSUMPTIONS

1. Homogeneous Mixing: The model assumes that vultures mix homogeneously within the population, meaning that any susceptible vulture can come into contact with any diclofenac-contaminated carcass.

2. Constant Parameters: The model assumes that the parameters (transmission rate, incubation rate, removal rate, carcass contamination rate, birth and death rate) remain constant over the simulation period. This assumption simplifies the modelling process but may not always reflect real-world variability.

3. No Immunity: The model assumes that vultures do not develop immunity to diclofenac toxicity.

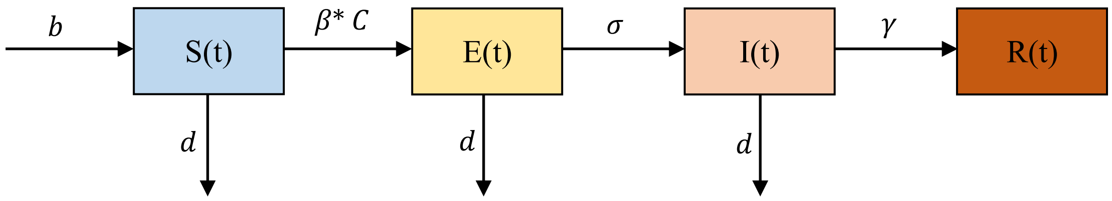
4. No Age Structure: The model typically does not consider age structure within the vulture population. All vultures are assumed to have the same susceptibility to diclofenac toxicity and the same rates of recovery or mortality.

5. No Seasonality: The model may assume constant parameters throughout the year and does not incorporate seasonal variations in carcass availability, vulture behaviour, or diclofenac contamination levels.

6. No External Factors: The model may neglect external factors such as human interventions, changes in diclofenac use, or other environmental stressors that could influence vulture populations.

These assumptions help simplify the model and focus on the core dynamics of diclofenac toxicity on vulture populations. However, it's essential to recognize these simplifications and assess their implications when interpreting model results and making real-world applications.

2.3. COMPARTMENTAL MODEL



2.4. MODEL USING DIFFERENTIAL EQUATIONS

$$\frac{dS}{dt} = bN - \beta SC - dS$$

$$\frac{dE}{dt} = \beta SC - \sigma E - dE$$

$$\frac{dI}{dt} = \sigma E - \gamma I - dI$$

$$\frac{dR}{dt} = \gamma I$$

CHAPTER 3

NUMERICAL SIMULATION IN PYTHON

3.1. BRIEF

Numerical simulation is a powerful tool used to analyse and predict the behaviour of complex systems that are difficult to solve analytically. In the context of the vulture-diclofenac model, numerical simulation plays a crucial role in understanding the dynamics of vulture populations affected by diclofenac contamination. By employing an SEIR model, we can simulate the interactions between different compartments of the model and assess the impact of various parameters on population dynamics.

In this study, with the help of numerical simulation we explore the annual decline in vulture population by varying key parameters such as transmission rate, removal rate and carcass contamination rate.

Through these simulations, we can identify thresholds and tipping points, significant for understanding the impact of diclofenac poisoning in vultures due to contaminated livestock.

3.2. NO VARYING PARAMETER

3.2.1. DATA AND OBSERVATIONS FOR INITIALISING PARAMETERS

1. According to the population details sourced from BirdLife International 2021 provided in Section 1.2, average population for the Critically Endangered Gyps bengalensis, Gyps indicus and Gyps tenuirostris is 15,800. We will use this data to set up the initial conditions for our model.
2. As mentioned in Section 1.1., Rigas Tsiakiris et al. 2021 notes that vultures demonstrate a highly complex foraging behaviour involving information exchange mechanisms and traveling long distances in search of food. This information can be used to observe that transmission between individual vultures is high, thus, the it makes sense to set a high transmission rate.
3. It should be noted that according to “The Threat of Veterinary Drugs to Raptors,” n.d., vultures take up to three days to die after consumption of NSAID; this has been noted in Section 1.1. Thus, incubation period for an exposed vulture can be taken as 3 days. Since we are dealing with ‘years’ as units, the converted incubation period would be 3/365 days, thus the incubation rate will be 365/3.
4. As stated in Section 1.3, Nambirajan et al. 2018 observed percentage of detection of diclofenac residues among organs of dead vultures to be more than 60%, so we will take the removal rate as 0.6. Appendix 1 can be referred for the data collected by them.
5. Between 2004 and 2005, Taggart et al. 2007 collected 1848 liver samples of domestic ungulate carcasses in India and observed the concentration of residual diclofenac in them. Prevalence of residual diclofenac was found to be 10.1% in these samples. This information will be used to set up the contamination rate as 0.101. Appendix 2 can be referred for the data collected by them.
6. Birth and natural death rates will be assumed to be at 10% per annum.

3.2.2. POPULATION V/S TIME

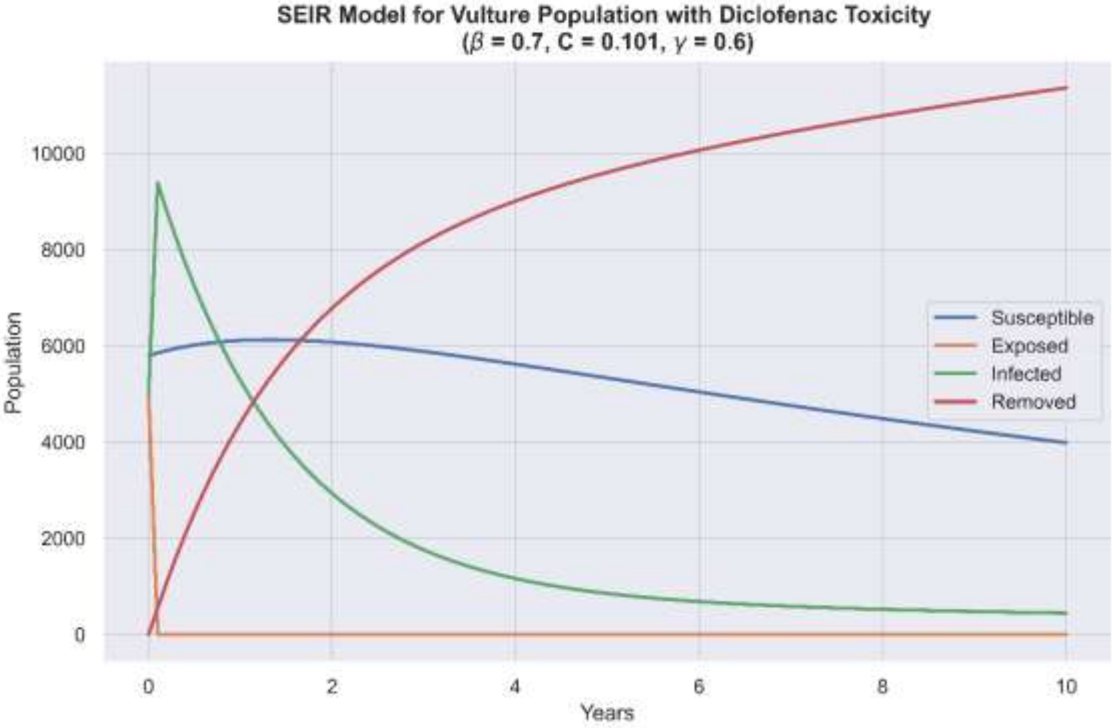
CODE:

```
import numpy as np
from scipy.integrate import odeint
import matplotlib.pyplot as plt
import seaborn as sns
# Define the SEIR model
def seir_model(y, t, beta, sigma, gamma, d, C):
    S, E, I, R = y
    N = S + E + I # Alive population
    dSdt = b*N - beta*S*C - d*S
    dEdt = beta*S*C - sigma*E - d*E
    dIdt = sigma*E - gamma*I - d*I
    dRdt = gamma*I
    return [dSdt, dEdt, dIdt, dRdt]
# Initial conditions
S0 = 5800
E0 = 5000
I0 = 5000
R0 = 0
y0 = [S0, E0, I0, R0]
# Parameters
beta = 0.7  # Adjusted transmission rate according to vulture behaviour
sigma = 365/3  # Incubation period
gamma = 0.6 # Death rate due to diclofenac poisoning
d = 0.1  # Natural death rate
C = 0.101  # 10.1% contamination rate
b = 0.1  # Birth rate
# Time grid (1 year)
t = np.linspace(0, 1, 365) # 1 year, daily intervals
```

```
# Calculating annual decline
sol = odeint(seir_model, y0, t, args=(beta, sigma, gamma, d, C))
S, E, I, R = sol.T
annual_decline = (S[-1] + E[-1] + I[-1]) / (S[0] + E[0] + I[0])
# Results for 10 years
t = np.linspace(0, 10, 101)
sol = odeint(seir_model, y0, t, args=(beta, sigma, gamma, d, C))
S, E, I, R = sol.T
# Plot results
sns.set_theme(style = 'dark')
fig,ax = plt.subplots(1,1,figsize=(10, 6),dpi=1000)
ax.grid(True,alpha=0.4,lw=0.5,color='gray')
ax.plot(t, S, label='Susceptible',lw=2)
ax.plot(t, E, label='Exposed',lw=2)
ax.plot(t, I, label='Infected',lw=2)
ax.plot(t, R, label='Removed',lw=2)
ax.set_xlabel('Years')
ax.set_ylabel('Population')
ax.legend()
ax.set_title('SEIR Model for Vulture Population with Diclofenac Toxicity \n($β$ = {}, C = {}, $\gamma$ = {})'.format(beta,C,gamma),fontsize=13,fontweight='bold')
plt.show()
print(f'Annual Decline: {100 * (1 - annual_decline):.2f}%')
```

Figure 1: Python code for SEIR model

OUTPUT:



```
Annual Decline: 27.85%
```

Figure 2: Population v/s Time for sample data

3.3. VARYING PARAMETERS

3.3.1. VARYING TRANSMISSION RATE

CODE:

```
# Solve ODE for a range of beta values to observe population decline
beta_values = [0.05,0.3,0.7,0.9]  # Range for beta
t = np.linspace(0, 2, 21)
fig,ax = plt.subplots(1,1,figsize=(10, 6),dpi=1000)
for beta in beta_values:
    sol = odeint(seir_model, y0, t, args=(beta, sigma, gamma, d, C))
    S, E, I, R = sol.T
    ax.plot(t, S+E+I, label=beta,lw=2)
ax.grid(True,alpha=0.4,lw=0.5,color='gray')
ax.set_xlabel('Years')
ax.set_ylabel('Alive population')
ax.legend()
ax.set_title('Alive population v/s years (varying transmission rate ; C = {}, $\gamma$ = {})'
             .format(C,gamma), fontweight='bold')
plt.show()
```

Figure 3: Python code for SEIR model with varying transmission rate

OUTPUT:

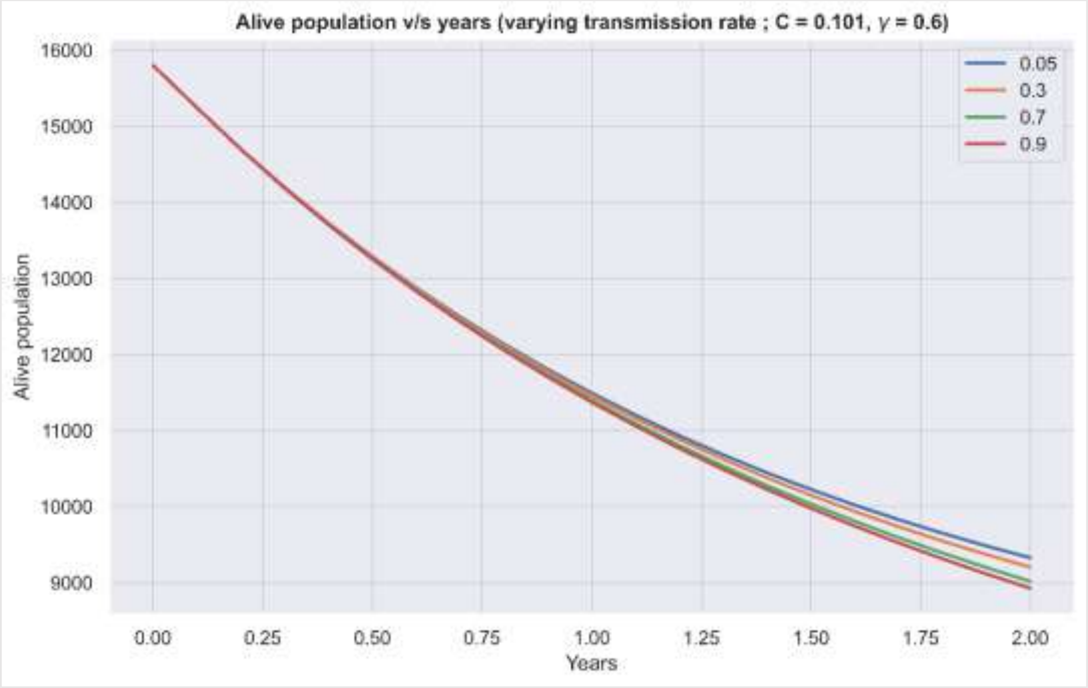


Figure 4: Alive population v/s Time (varying transmission rate)

Model with transmission rate 5% shows the slowest decline.

3.3.2. VARYING REMOVAL RATE

CODE:

```
# Solve ODE for a range of removal rates to observe population decline
gamma_values = [0.05,0.3,0.7,0.9]   # Range for gamma
t = np.linspace(0, 2, 21)
fig,ax = plt.subplots(1,1,figsize=(10, 6),dpi=1000)
for gamma in gamma_values:
    sol = odeint(seir_model, y0, t, args=(beta, sigma, gamma, d, C))
    S, E, I, R = sol.T
    ax.plot(t, S+E+I, label=gamma,lw=2)
ax.grid(True,alpha=0.4,lw=0.5,color='gray')
ax.set_xlabel('Years')
ax.set_ylabel('Alive population')
ax.legend()
ax.set_title('Alive population v/s years (varying removal rate ; β = {}, C = {})'
             .format(beta,C), fontweight='bold')
plt.show()
```

Figure 5: Python code for SEIR model with varying removal rate

OUTPUT:

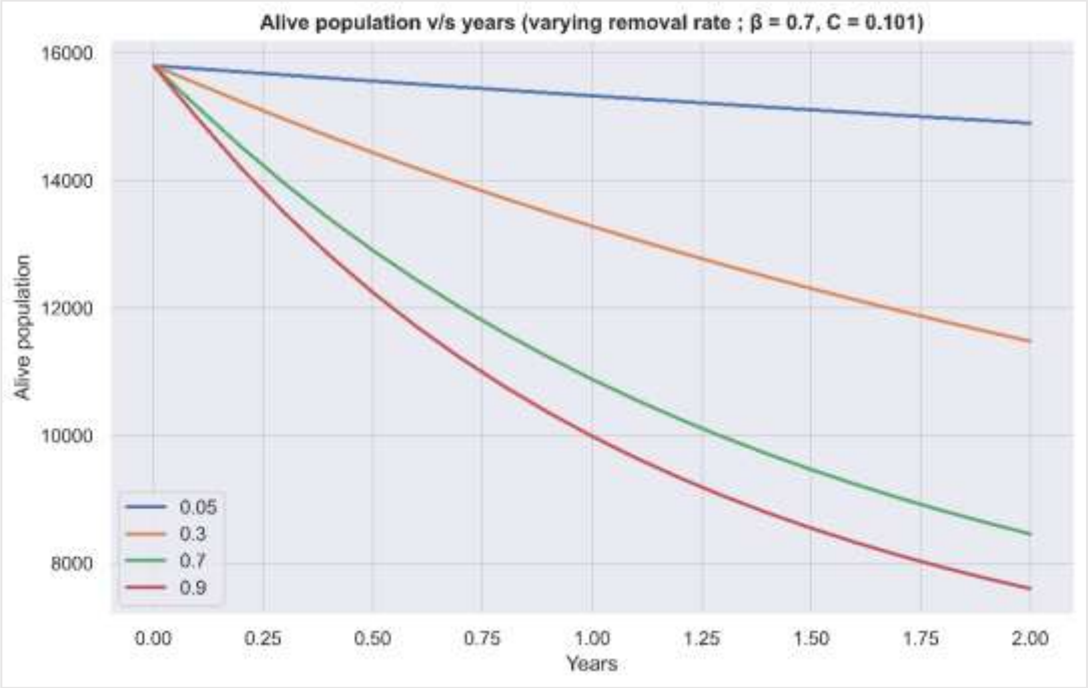


Figure 6: Alive population v/s Time (varying removal rate)

Model with removal rate 5% shows the slowest decline.

3.3.3. VARYING CARCASS CONTAMINATION RATE

CODE:

```
# Solve ODE for a range of contamination rates to observe population decline
C_values = [0.05,0.3,0.7,0.9]   # Range for C
t = np.linspace(0, 2, 21)
fig,ax = plt.subplots(1,1,figsize=(10, 6),dpi=1000)
for C in C_values:
    sol = odeint(seir_model, y0, t, args=(beta, sigma, gamma, d, C))
    S, E, I, R = sol.T
    ax.plot(t, S+E+I, label=C,lw=2)
ax.grid(True,alpha=0.4,lw=0.5,color='gray')
ax.set_xlabel('Years')
ax.set_ylabel('Alive population')
ax.legend()
ax.set_title('Alive population v/s years (varying carcass contamination rate ; β = {}, $\gamma$ = {})'
            .format(beta,gamma), fontweight='bold')
plt.show()
```

Figure 7: Python code for SEIR model with varying carcass contamination rate

OUTPUT:

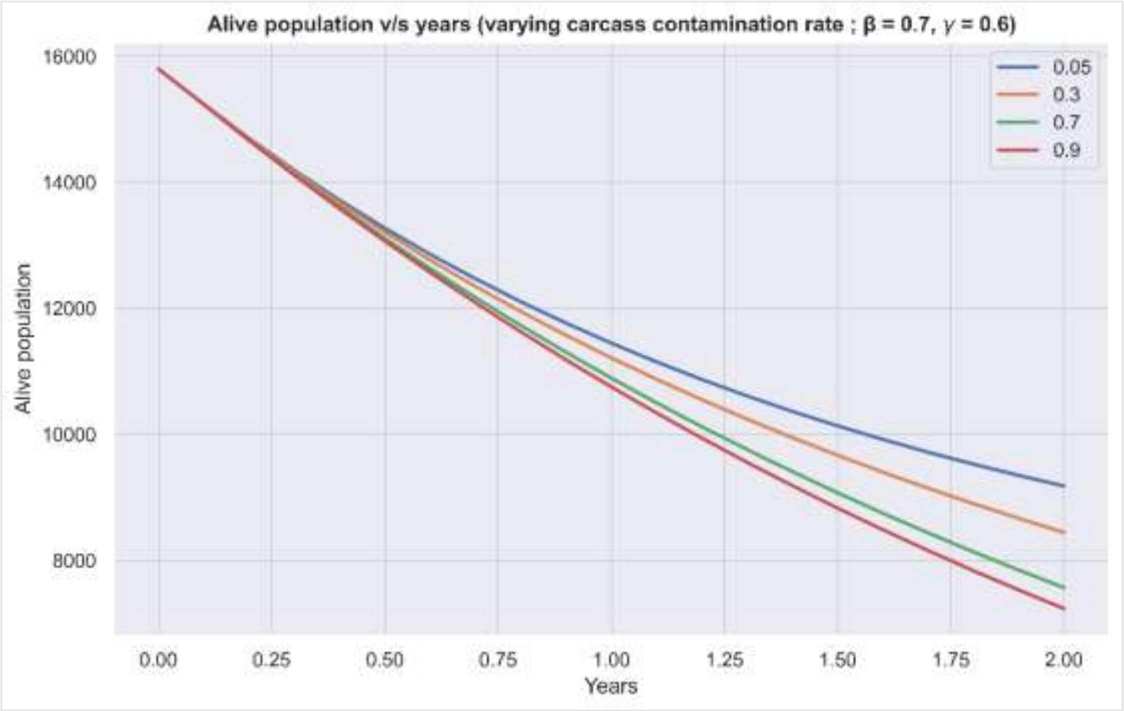


Figure 8: Alive population v/s Time (varying carcass contamination rate)

Model with carcass contamination rate 5% shows the slowest decline.

CHAPTER 4

RESULTS AND DISCUSSION

4.1. OBSERVATIONS

Observations from Figure 2: Population v/s Time for sample data

The graph shows variations in the populations of susceptible, exposed, infected, and removed vultures. The removed populations increased over time, while the alive population decreases. Decline in exposed and infected population is steep. This indicates that with sufficient exposure to contaminated carcasses, the susceptible population quickly transforms into the removed population due to a short incubation period of 3 days for exposed vultures. Additionally, the model predicted an annual decline of 27.85%.

Observations from Figure 4: Alive population v/s Time (varying transmission rate)

The graph shows variations in the alive populations when the model was evaluated for four different transmission rates “β” (0.05, 0.3, 0.7, 0.9). The model with β =0.05 saw the least decline in the alive population compared to the other three models, while the model with β=0.9 saw the steepest decline.

Observations from Figure 6: Alive population v/s Time (varying removal rate)

The graph shows strong variations in the alive populations when the model was evaluated for four different removal rates “γ” (0.05, 0.3, 0.7, 0.9). The model with γ=0.05 saw the least decline, while the model with γ =0.9 saw the steepest decline. Simulations indicate that the model is highly sensitive to the removal rate, with predicted alive populations at the end of two years being approximately 15,000 for $\gamma = 0.05$ and 11,500 for $\gamma = 0.3$, a significant difference of 3,500 vultures.

Observations from Figure 8: Alive population v/s Time (varying carcass contamination rate)

The graph shows variations in the alive populations when the model was evaluated for four different carcass contamination rates “C” (0.05, 0.3, 0.7, 0.9). The model with C=0.05 saw the least decline in the alive population compared to the other three models, while the model with C=0.9 saw the steepest decline. Variations were stronger than those observed with varying β but weaker than those observed with varying γ.

4.2. SENSITIVITY ANALYSIS

Simulations showed that the model is most sensitive to the removal rate (γ), least sensitive to the transmission rate (β), and moderately sensitive to the carcass contamination rate (C).

Sensitivity analysis involves systematically varying parameters to assess their impact on model predictions. In this context, it revealed that even minor changes in the removal rate could drastically alter population forecasts. This sensitivity highlights the need for precise parameter estimation to ensure accurate predictions. Understanding which parameters most influence the model's outcomes allows us to prioritize data collection efforts and refine our model for better reliability.

By focusing on sensitivity analysis, we can identify critical parameters that drive population dynamics. This process not only improves the accuracy of our predictions but also enables targeted interventions. For example, if the removal rate significantly affects outcomes, then strategies to manage this rate become crucial. Therefore, sensitivity analysis is essential for enhancing model accuracy and forming effective conservation strategies.

4.3. LIMITATIONS OF THE MODEL

Due to mathematical constraints and the assumptions placed, our use of SEIR model in modelling effects of diclofenac poisoning in vultures of the Indian subcontinent has its limitations and oversights. However modelling scenarios for varying parameters has provided some revelation into the effectiveness of this approach.

To improve the accuracy and reliability of the SEIR model, incorporating additional factors is essential. The additional factors such as:

1. Age Structure: Including age-specific parameters will lead to more precise predictions reflecting population heterogeneity.

2. Spatial Distribution: A spatially explicit model accounting for local differences, population density, and regional health infrastructure will provide more detailed predictions.

3. Seasonal Variations: Incorporating seasonal effects can enhance the model's temporal accuracy, reflecting periodic fluctuations in transmission rates.

CHAPTER 5

CONCLUSION

The SEIR model predicted an annual decline of approximately 27.85% with the sample data. Since our sample data was the closest to ground reality, this highlights the severe impact of the factors being modelled. Simulations indicate that predictions are highly sensitive to variations in the parameter ‘removal rate’. This is a significant discovery.

Furthermore, examining the weak implementation of diclofenac bans in India, Nepal, and Pakistan is vital. Despite regulations, diclofenac usage persists, contributing to vulture population declines. Investigating enforcement challenges and illegal use can offer new insights, improving our research's accuracy and impact. Addressing these factors will enhance our model and inform more effective conservation and disease management strategies.

APPENDICES

APPENDIX 1

Species	**Organs**	**No. of samples analysed**	**% of detection**
Gyps bengalensis	Overall	32	68.75
Gyps himalayensis	Overall	12	75

Table 1: Percentage detection of diclofenac residues among the organs of vultures collected dead between 2011 and 2014 in India.

Note. Data is sourced from Nambirajan K, Muralidharan S, Roy AA, Manonmani S. Residues of Diclofenac in Tissues of Vultures in India: A Post-ban Scenario. Arch Environ Contam Toxicol. 2018 Feb;74(2):292-297. doi: 10.1007/s00244-017-0480-z. Epub 2017 Nov 20. PMID: 29159701.

APPENDIX 2

State	No. of Samples	% of detection
All states	1848	10.1
Bihar	121	22.3
Rajasthan	310	17.1
Punjab	76	15.8
Madhya Pradesh	195	11.3
West Bengal	94	9.6
Gujarat	65	9.2
Uttar Pradesh	449	7.8
Maharashtra	194	5.7
Jammu and Kashmir	77	3.9
Jharkhand	54	3.7
Andhra Pradesh	161	3.7
Odisha	52	0.0

Table 2: Percentage of detectable residual concentrations of diclofenac in liver samples from domestic ungulate carcasses sampled in 12 states in India.

Note. Data is sourced from Taggart MA, Senacha KR, Green RE, Jhala YV, Raghavan B, Rahmani AR, Cuthbert R, Pain DJ, Meharg AA. Diclofenac residues in carcasses of domestic ungulates available to vultures in India. Environ Int. 2007 Aug;33(6):759-65. doi:10.1016/j.envint.2007.02.010. Epub 2007 Apr 16. PMID: 17433834.

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