Comparing West Nile Virus Intervention Strategies using Mathematical Modeling and comparing methods to curtail the spread

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***Abstract--* During 1962 – 1963, Camargue, South France, saw an outbreak of mosquito-borne disease. Later in 1996, an epidemic occurred in Europe, during which countries like Romania identified about 400 cases. This disease which causes fever and other related symptoms, was named West Nile Virus (WNV). The virus is now found throughout the world across the continental United States, Europe, Africa, The Middle East, and west Asia. In this paper, we will discuss the spread of WNV and its future trajectory based on the temperature and climate of regions. We will show how intervention strategies such as adulticides and mosquito repellents will change the graph of the model.**

Keywords--West Nile Virus, Mosquitos, Trajectory, Intervention.

1. BACKGROUND

West Nile Virus (WNV) is a virus that causes West Nile Fever. It is a single-stranded RNA virus. Cases of West Nile Virus normally occur from summer through winter when mosquito growth is high. Most people do not develop any symptoms. Only a fraction of people develops some symptoms like fever.

a) ***The pattern of transmission***: It is primarily spread to humans through mosquito bites. The primary host of the virus is birds. The virus is then typically transmitted to other animals from mosquitos that feed on the infected birds. The virus primarily remains in a bird-mosquito-bird cycle; however, it is occasionally spread to humans and other animals when an infected mosquito bites them. The virus is not spread through coughing, sneezing, or touching an infected individual. Handling live or dead infected specimens, or eating infected specimens, will not result in an infection for humans. However, birds can spread the virus to other birds through regular contact.

b) ***Vaccination*****:** There is no vaccination available for this virus. The reason is that most people who develop this disease are elderly and immunocompromised people. So, taking into consideration the health safety measures development of the WNV vaccine has been discarded.

c) ***Social and community interventions*****:** Some preventive measures may be taken against it, such as not letting standing water nearby and dumping it away if found. Babies and pregnant women must be protected with proper care and use mosquito repellents registered by the environmental protection agency. Further, all adulticides, larvicides, truck sprays, and aerial sprays should be used properly. Other methods include genetically modified mosquitos, irradiated mosquitos, and mosquitos with Wolbachia. [2]

d) ***Behavior*****:** Based on the data tests on the pools of mosquitos collected by the Chicago Department of Public Health and Environmental Health program, data were presented on the behavior of the virus outbreak in a small population in Chicago. Chicago Department of Public Health maintains an environmental surveillance program for West Nile Virus (WNV).

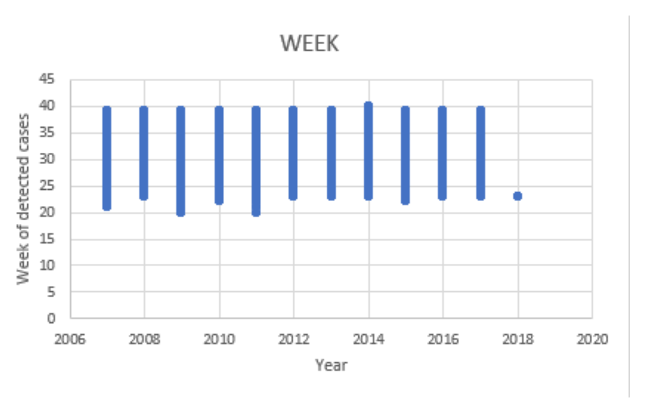


Figure 1: Visualization of weeks in the years when mosquito growth is expected to go high. Usually, during summer through fall.

The traps set throughout the city had collected different species of mosquitos that spread West Nile Virus. It can be seen that from *figure-1*, temperature and climate strongly affect the growth of the mosquito population, and hence during these periods, more infections can be found. It can also be seen from *figure-2* that the mosquitos with a probability of having the West Nile Virus can be mostly found during the peak times of the year when the climate and the temperature conditions are the most favorable.

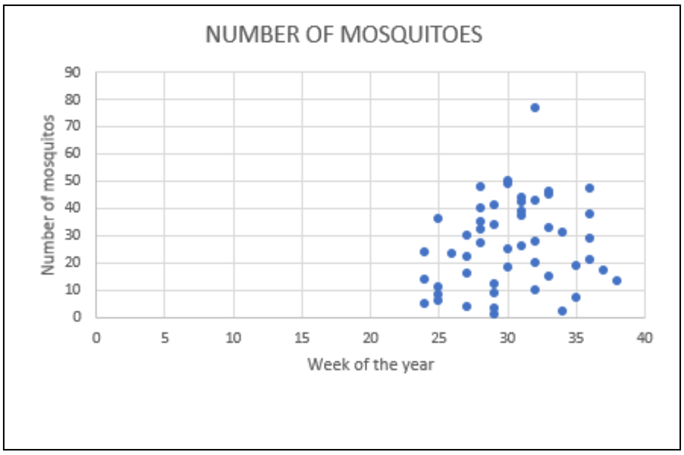


Figure 2: Distribution of detected or trapped mosquitos having the virus during the year's peak periods.

2. PROBLEM STATEMENT

Climate change is affecting the entire world. Many regions are projected to experience an increase in average temperatures and flooding, increasing mosquito populations. Seeing as mosquitos are the primary transmission vector of West Nile Virus, our team will be predicting the future trajectory of the virus in regions where it is currently endemic and in new areas. We will use different mathematical modelling techniques to establish the relations between different entities in spreading the West Nile Virus.

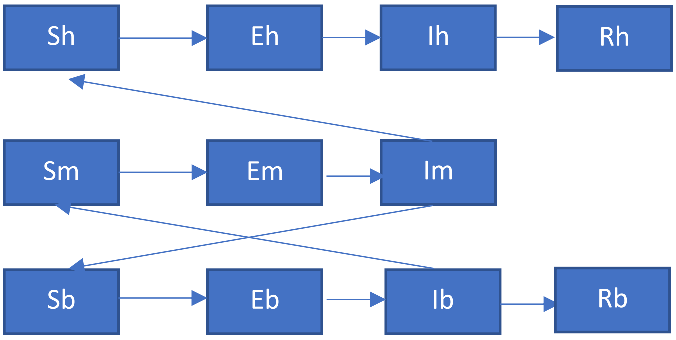
3. METHODOLOGY

We will use SEIR mathematical models to represent the future trajectory of West Nile Virus in endemic and new areas. We will construct this mathematical model with interventions and without intervention strategies and provide a study comparing the extent of this disease globally under different conditions. [1] We plan to give a regression analysis to guide the future trajectory of the disease using python. We will train the model using the obtained datasets by using 80% of the dataset for training and then the remaining 20% for testing the models. We plan to use Logistic Regression which uses an activation function to draw the curve of future trajectory. We plan to also design an agent-based model using Mesa that would capture the interactions between people, birds, and mosquitoes and show how the disease could spread across cities.

4. RESULTS

Mathematical Modelling

what we have done: In terms of the SEIR differential equations, we have modified the equations and added parameters to represent the proportion of the mosquito recruitment rate that survives adulticide. The equations have also been modified to reflect a decrease in the bite rate of mosquitos to humans when mosquito repellent is used.



$$\frac{dS_M}{dt} = \lambda_M \rho_M - \alpha_B \beta_{BM} \frac{S_M I_B}{N_B} - \delta_M S_M \quad (1)$$

$$\frac{dE_M}{dt} = \alpha_B \beta_{BM} \frac{S_M I_B}{N_B} - \delta_M E_M - \gamma_M E_M \quad (2)$$

$$\frac{dI_M}{dt} = \gamma_M E_M - \delta_M I_M \quad (3)$$

$$\frac{dS_B}{dt} = \lambda_B - \alpha_B \beta_{MB} \frac{S_B I_M}{N_B} - \delta_B S_B \quad (4)$$

$$\frac{dE_B}{dt} = \alpha_B \beta_{MB} \frac{S_B I_M}{N_B} - \delta_B E_B - \gamma_B E_B \quad (5)$$

$$\frac{dI_B}{dt} = \gamma_B E_B - \delta_B I_B - \mu_B I_B - \nu_B I_B \quad (6)$$

$$\frac{dR_B}{dt} = \nu_B I_B - \delta_B R_B \quad (7)$$

$$\frac{dS_H}{dt} = \lambda_H - \theta_H \alpha_H \beta_{MH} \frac{S_H I_M}{N_H} - \delta_H S_H \quad (8)$$

$$\frac{dE_H}{dt} = \theta_H \alpha_H \beta_{MH} \frac{S_H I_M}{N_H} - \delta_H E_H - \gamma_H E_H \quad (9)$$

$$\frac{dI_H}{dt} = \gamma_H E_H - \delta_H I_H - \mu_H I_H - \nu_H I_H \quad (10)$$

$$\frac{dR_H}{dt} = \nu_H I_H - \delta_H R_H \quad (11)$$

Figure 3 SEIR Modelling of WNV interactions between reservoir, vector, and host

Table 1: SEIR parameters

Parameter	Description	Type	Value
α_B	Per capita bite rate of mosquitos on birds	Fixed [12]	0.08
α_H	Per capita bite rate of mosquitos on humans	Fixed [12]	0.08
β_{BM}	Transmission probability of disease from birds to mosquitos	Fixed [15]	0.16
β_{MB}	Transmission probability of disease from mosquitos to birds	Fixed [12]	0.88
β_{MH}	Transmission probability of disease from mosquitos to humans	Estimated	0.23
δ_M	Death rate of mosquitos	Estimated	1 - 4
δ_B	Death rate of birds	Fixed [16]	$\frac{1}{8}$
δ_H	Death rate of humans	Fixed [13]	$\frac{1}{79}$
γ_M	Mosquito progression rate from exposed to infectious	Estimated	0.1741
γ_B	Bird progression rate from exposed to infectious	Estimated	0.0864
γ_H	Human progression rate from exposed to infectious	Fixed [17]	0.2
μ_B	Disease-induced death rate of birds	Estimated	0.1226
μ_H	Disease-induced death rate of humans	Fixed [3]	0.0362
λ_M	Recruitment rate of mosquitos	Estimated	6.2×10^9
λ_B	Recruitment rate of birds	Estimated	3.15×10^6
λ_H	Recruitment rate of humans	Fixed [14]	6.5×10^5
ν_B	Recovery rate of birds	Estimated	0.1
ν_H	Recovery rate of humans	Estimated	0.36
θ_H	Proportion of susceptible human population that is not protected by insect repellant	Estimated	0.75
ρ_M	Proportion of recruited susceptible mosquitos that will survive administration of adulticide	Estimated	0.4

West Nile Virus is an arbovirus with a complex transmission cycle between mosquitos, birds, and humans. Mosquitos are vectors for the disease, and birds are reservoirs. Mosquitos may contract the disease from an infected bird and may also spread the disease to an uninfected bird or human. Seeing as the disease has a latency period in which not all exposed show symptoms, a system of modified SEIR differential equations was best for modelling the transmission cycle of the disease. It is assumed that mosquitos never recover from the disease and are carriers for their lifetime. Therefore their portion of the model is SEI. Mosquito and bird population numbers were estimated due to the inherent difficulty of obtaining population numbers for insects and wild animals across a large region. Human population numbers were based on California's numbers from the Federal Census Bureau.

Looking at the equations for $\frac{dS_H}{dt}$ and $\frac{dE_H}{dt}$, we can determine that two factors that have a large impact on the number of humans that are ultimately exposed to and infected with WNV are the total number of infected mosquitos and the per capita bite rate of mosquitos on humans. Both factors are candidates for being subject to currently viable intervention strategies. Regarding the total number of infected mosquitos, adulticides have been shown to substantially reduce the number of mosquitos in mosquito pools [10], while insect repellants – specifically those containing D.E.E.T. – have been shown to prevent the biting of mosquitos for extended periods of time [11]. Using the SEIR model, we simulated the administration of these two intervention strategies to compare their results. As we can see from the graphs, both intervention strategies prove to be effective. While reducing the mosquito population proved to be more effective due to its effect on both the bird and human populations, the practice of administering insect repellant is logistically easier to implement and may be used in conjunction with adulticide to prevent the spread of WNV amongst human populations.

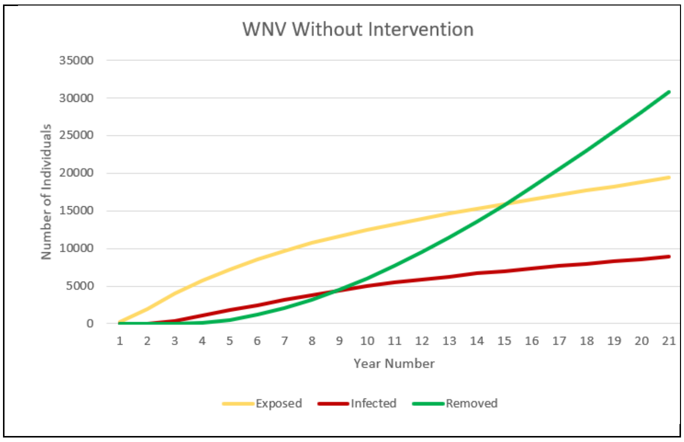


Figure 4 SEIR Modelling of a calculated population without any intervention strategies

The two intervention strategies that have been accounted for in our SEIR model are using adulticide to reduce the adult mosquito population and using insect repellent to reduce to bite rate from mosquitos to humans. These strategies were chosen due to their viability of implementation, as both have already been implemented successfully in areas with higher mosquito populations.

The above graph is interpolated using the above mathematical model and shows the virus actions in any given homogenous population when no intervention is done. Our discussion regarding the intervention lay solely with two techniques related to controlling mosquito growth in all endemic regions. This can be achieved using Repellents and Adulticides. Our graphs show satisfying results with both of these interventions, and it can be seen from the graphs below that both have different advantages. Using repellents causes fewer infections than with no interventions but slightly more than adulticide. But Repellents help in better recovery than adulticides.

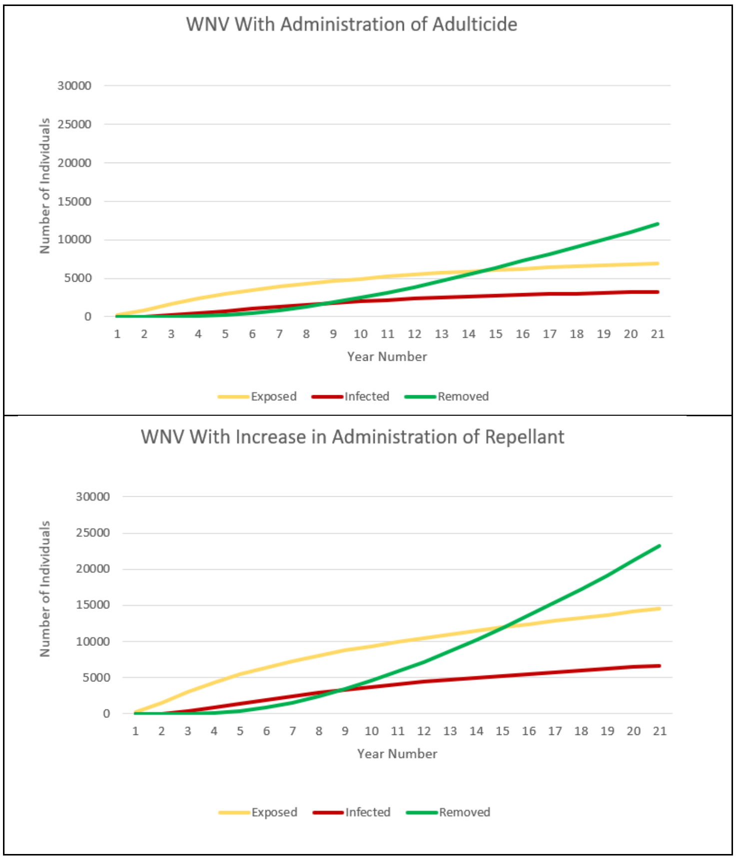
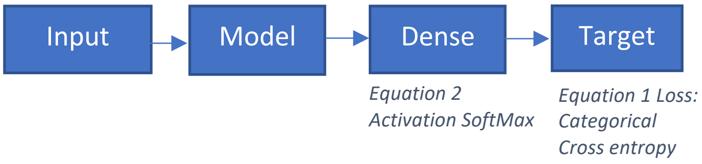


Figure 5 SEIR Modelling of a calculated population with intervention strategiesof Adulticide and Repellant

Regression Modelling

We are using regression analysis to predict whether a tested mosquito will result in positive or negative results in a given region and season. The model accuracy score was improved from 76.33 % to 87.6 % by including the temperature parameters in predicting the results and changing the loss function from categorical cross entropy to binary cross entropy as a loss function. Binary cross-entropy is a loss function that can be used in multi-class classification. An example can belong to one of many classes, and the model decides which classification to do.



The cross-entropy function calculates the loss of any given record by computing a formula. Binary cross-entropy is best used in most classification models where any record is believed to belong to a specific category with a probability of 1 and belongs to another category with a probability of 0.

We are also changing the activation function from SoftMax to Rectified Linear Unit (ReLu) function as an activation function after the logistic regression. As we speak of, the model's output always needs to be positive so that the *Log* of that value always exists. This is the main reason *SoftMax* activation was used earlier, which rescales the model output so that it stays on the positive property side, but ReLu works better in our case.

In addition to all the above methods in designing our model, we also use the Adam Optimizer with a learning rate of 0.01. We choose Adam Optimizer over the classical stochastic gradient descent algorithm. We use this to update the weights based on the training data. Adam stands for adaptive moment estimation. This optimizer is not only straightforward forwards implement and has low memory requirements but also is computationally efficient.

Adam is considered to have advantages over two other extensions of the stochastic gradient descent algorithm, AdaGrad, and RMSProp. This is why its authors recommend using it over all other optimization algorithms.

Next is the data; we are using the data from the Chicago data portal. A list of locations and test results for pools of mosquitoes are tested through the Chicago Department of Public Health Environmental Health program. The Chicago Department of Public Health maintains environmental surveillance for West Nile Virus (WNV). An important part of this program is the collection of mosquitoes from traps located around the city, identifying and sorting, and testing specific mosquito species for the West Nile virus. This can be seen in *Figure 6*.

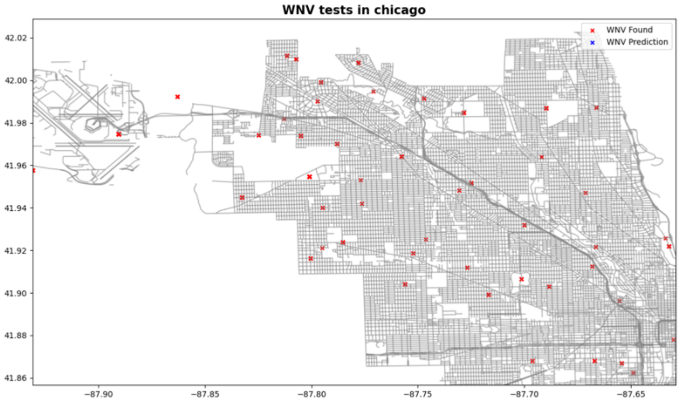


Figure 6: WNV Data Points in the Chicago area

We are collecting data available in CSV format, which contains strings and blank data. We are cleaning the data for this, including removing redundant data from the CSV file. This was easily achieved using Pandas Library, which is used here to import the data, clean it, and use it as data frames. Using Pandas, we are also Normalizing the data using the below formula.

$$\mathbf{x = (x - min(x)) / (max(x) - min(x))}$$

where x is each individual attribute of the CSV data. We have about eight features that we will need for the result prediction study, with extra data that can be added later from the Illinois dataset, which contains weather information with temperature parameters. These features include season-year, week, trap type, result, number of mosquitoes, species, latitude, and longitude. The latitude and longitude were combined using the *Haversine equation* and used as the prediction value. We have also included the Temperature data from the Illinois dataset obtained and interpolated the values to match the Chicago areas in our dataset. We will split the data into training and testing data, with 80 % of the dataset for training and the remaining 20 % for testing. Our input features for the result prediction will be a set of seven features season year, week, trap type, number of mosquitoes, species, latitude and longitude and Average Temperature. Before creating the logistic regression model, we converted the trap type, result, and species to Integer and Normalized the values. For the model creation, we are using the Keras (2.9.0) Library available in Google Collaboratory.

```
!python -c 'import keras; print(keras.__version__)'  > 2.9.0
```

We are using the Google Collaboratory for our model training since we did not require more computation time for our training. The model was created as a Sequential model and then a Dense layer of size 1 was added to it with its input size (7,:).

```
Model: "sequential"
_________________________________________________________________
 Layer (type)               Output Shape            Param #
=================================================================
 dense_6 (Dense)                 (None, 1)               8

 activation_6 (Activation)  (None, 1)               0
=================================================================
Total params: 8
Trainable params: 8
Non-trainable params: 0
_________________________________________________________________
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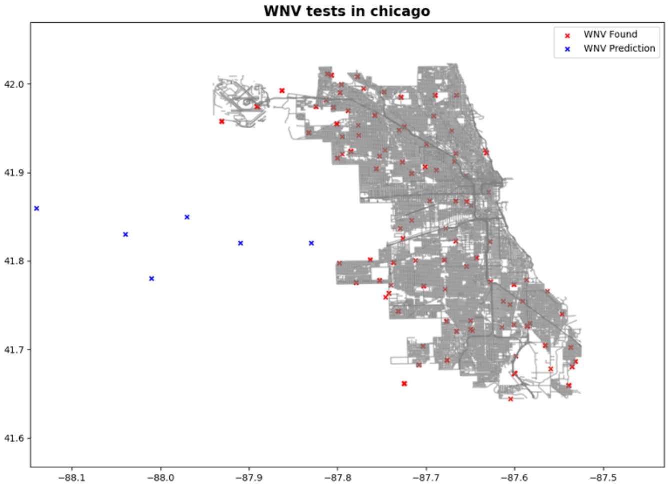

Figure 7: Chicago City with WNV found mosquitoes in Red and Predictions in Blue

We have met this paper's research objective by predicting the virus in new endemic regions. We convert the predicted latitude and longitude combination into separate latitude and longitude using the reverse method we used while combining them. A detailed view of it can be seen in Figure 5.

We add the *ReLu* Activation function and compile the model using Adam Optimizer. This model is then subject to fit with 5 epochs. The predicted values were passed to a scoring function, and around 87.6 % accuracy was obtained. In figure 4, we can see where mosquitoes were trapped or captured and tested and found to have West Nile Virus in the red cross mark. The ones in blue are the new endemic regions where the virus can be found based on the temperature and traps information obtained from the new endemic regions.

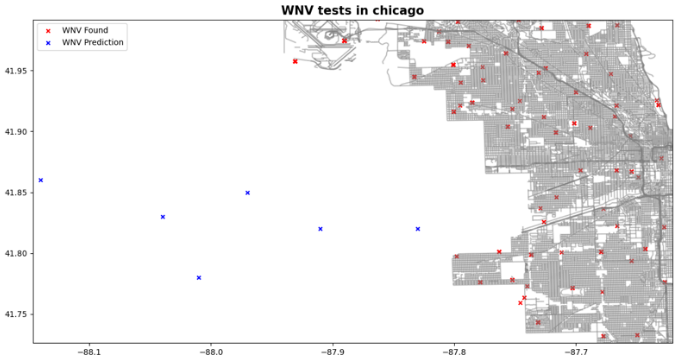

Figure 8: Detailed view of WNV Predictions

In an ever-changing world, where everything is in constant motion, and there are too many variables to mathematically know what is going on, we rely on numerical and computational simulations to give a concrete and visual representation of a process. As such, we will simulate the spread of the West Nile Virus using Agent-Based Modelling. However, even this task is difficult, as knowing the correct context of a specific phenomenon is very tedious. As our main task is to show temperature, humidity, and precipitation affect the spread of the West Nile Virus, we must make some simplifications:

1. The Birds have no migratory behavior and move at random.
    a. The main hosts of the West Nile Virus are Corvidae, and Corvidae is shown to have no specific migratory behavior. However, they are shown to wander around, especially when temperatures get extremely cold [4]. As such, Corvidae tends to locate in cities as the temperatures are slightly warmer due to a phenomenon is known as Urban Heat Islands [5]. We will not be considering this when it comes to modeling. (Especially since most Corvidae can already survive very harsh arctic weather.)
2. Mosquitoes slowly expand towards areas that become more habitable to them.
    a. The main effects we will consider when it comes to what is more "habitable" will only rely on three factors: temperature, humidity, and precipitation. Features such as elevation levels (i.e., "mosquito line") are either still debated or disregarded when it comes to how it affects Mosquito Population Rates [6], and as such, will not be considered. Some intervention strategies for eradicating mosquitoes (i.e., a cleaner environment) will be considered later. We will also assume that a city is uniformly susceptible and vulnerable, even if mosquito population rates vary within cities, depending on factors such as average neighborhood income levels [7].
3. All humans remain within their respective cities.
    a. One of the key features of West Nile Virus is that it does not depend specifically on humans due to its vector-borne nature. The main circulation method of West Nile seems to follow a mosquito-bird-mosquito pattern [8], completely independent of humans. As such, we will not be considering ideas such as gathering places (i.e., a local grocery store, school, etc.) or immigration rates (i.e., driving/flying between cities). Rather, humans will remain within their cities and randomly float within them.

The specific methodology we will use to measure newly susceptible areas is to initialize a space of 9 different cities. Each of them will contain a variable amount of people living within it. Since we have noted that human-to-human interaction is not a factor, we do not care about specific habits of the people's movements, and they will wander around the city borders aimlessly. As for the mosquitoes, we will assume they start within a variable region of the plane, whether within the lower-left most city or the right half of the map. As for the birds, they will initially be starting out in random locations and will move around randomly. In this case, a bird within the model could represent a singular bird or a flock of birds moving together.

We will then analyze how the infection spreads. We will start with the condition that a single mosquito has the virus. If a mosquito is within a certain radius of another agent, the mosquito will "feed" upon that agent. If a healthy mosquito "feeds" into a human (whether healthy or infected), nothing will occur; however, if a healthy mosquito "feeds" into an infectious bird, it will have a probability of becoming infectious itself. Likewise, if an infectious mosquito "feeds" into an agent, whether human or bird, the bird is likely to become infected (unless already infected). There will be no direct interactions between humans and birds.

The agent will continue to be in the infected state until after their period has passed, and then they enter the removed category. Once the agent has entered the recovery category, they will gain life-long immunity and continue on with their life.

5. DISCUSSION

Regression Modelling

Based on the results obtained from our previous reports, we include the temperature information in our dataset for the model to learn. This temperature is extrapolated from the Illinois weather dataset from previous years. We have also combined the latitude and longitude into one data. We then change the loss function to binary cross entropy. These changes and the Adam optimizer gave a model that predicts the new endemic regions with an accuracy of 87.6 %. We predict the new regions based on temperature and trap type to be put in new areas, and the part of the model output are some regions in Wheaton and Oak Brook in Illinois State.

Mathematical Modelling Perspective

From looking at the parameters in the equation derived for the reproduction number, it becomes apparent that the most important aspects of preventing the overall spread of West Nile Virus are increasing the mortality rate of mosquitos and decreasing the birth rate of mosquitos, meaning that mosquito population control should be the main focus of preventative measures in the case of an outbreak.

Some scientists also discuss methods to use drones to survey these regions and find the required parameters. Interventions, including repellents and adulticides and their impact, are already discussed above.

6. LIMITATIONS

For this study of predicting the West Nile Virus in new endemic regions, we are implementing a method combining latitude and longitude using the haversine formula. The prediction output looks good, with an accuracy score of 87.6 %. But plotting these requires us to separate the latitude and longitude data from the haversine output. In our study, we assume and discard some information from the output to interpolate our latitude and longitude. This information will give vague predicted areas away from our actual trained regions.

Some limitations we have encountered in our research are obtaining and implementing the mosquito death rate, obtaining an accurate number for the initial mosquito population, and obtaining an accurate number for the initial bird population due to the inherent difficulty and limitations of estimating wildlife populations.

REFERENCES

[1] Kushmaro A, Friedlander TA, Levins R (2015) Temperature Effects on the Basic Reproductive Number (R0) Of West Nile Virus, Based on Ecological Parameters: Endemic Vs. New Emergence Regions. J Trop Dis: S1-001. doi:10.4172/2329891X.S1-001

[2] Centers for Disease Control and Prevention. (2022, June 2). West Nile virus. Centers for Disease Control and Prevention. Retrieved September 24, 2022, from https://www.cdc.gov/westnile/index.html

[3] Modeling and control of local outbreaks of West Nile virus in the United States,Discrete and Continuous Dynamical Systems - B,21,8,2423,2449,2016-9-1,Jing Chen,Jicai Huang,John C. Beier,Robert Stephen Cantrell,Chris Cosner,Douglas O. Fuller,Guoyan Zhang,Shigui Ruan,1531-3492_2016_8_2423, sensitive analysis, transmission dynamics.,West Nile virus, mathematical modeling, basic reproduction number. doi: 10.3934/dcdsb.2016054

[4] David Holyoak (1971) Movements and Mortality of Corvidae, Bird Study, 18:2, 97-106, DOI: 10.1080/00063657109476300

[5] R. A. Memon, D. Y. C Leung, and LIU Chunho, "A review on the generation, determination and mitigation of Urban Heat Island", doi:10.1016/S1001-0742(08)60019-4

[6] Chen, H., Githeko, A.K., Zhou, G. et al. New records of Anopheles arabiensis breeding on the Mount Kenya highlands indicate indigenous malaria transmission. Malar J 5, 17 (2006). https://doi.org/10.1186/1475-2875-5-17

[7] Poor neighborhoods and mosquitoes , https://www.caryinstitute.org/news-insights/podcast/poor-neighborhoods-and-mosquitoes

[8] Centers for Disease Control and Prevention. (2022, June 2). West Nile virus. Centers for Disease Control and Prevention. Retrieved November 24, 2022, from https://www.cdc.gov/westnile/transmission/index.html

[9] Stiner, S., & Chellamuthu, V. (2020). An Agent-Based Model of West Nile Virus: Predicting the Impact of Public Health Agents and Vaccinations on Horses. Curiosity: Interdisciplinary Journal of Research and Innovation, 2, 44–66. https://doi.org/10.36898/001c.17130

[10] A. B. B. Wilke et al., "Effectiveness of adulticide and larvicide in controlling high densities of Aedes aegypti in urban environments," PLOS ONE, vol. 16, no. 1, p. e0246046, Jan. 2021, doi: 10.1371/journal.pone.0246046.

[11] M. S. Fradin and J. F. Day, "Comparative Efficacy of Insect Repellents against Mosquito Bites," New England Journal of Medicine, vol. 347, no. 1, pp. 13–18, Jul. 2002, doi: 10.1056/nejmoa011699.

[12] M. J. Wonham, T. de-Camino-Beck, and M. A. Lewis, "An epidemiological model for West Nile virus: invasion analysis and control applications," Proceedings of the Royal Society of London. Series B: Biological Sciences, vol. 271, no. 1538, pp. 501–507, Mar. 2004, doi: 10.1098/rspb.2003.2608.

[13] "California," www.cdc.gov, May 19, 2020. https://www.cdc.gov/nchs/pressroom/states/california/ca.htm

[14] "California Population 1900-2019," www.macrotrends.net. https://www.macrotrends.net/states/california/population

[15] F. Rubel et al., "Explaining Usutu virus dynamics in Austria: Model development and calibration," Preventive Veterinary Medicine, vol. 85, no. 3–4, pp. 166–186, Jul. 2008, doi: 10.1016/j.prevetmed.2008.01.006.

[16] jimena, "How Long Do Crows Live? Wild Vs. Captivity! Averages And Records," Bird Watching USA, Jul. 18, 2021. https://www.birdwatchingusa.org/crow-lifespan (accessed Nov. 28, 2022).

[17] World, "West Nile virus," Who.int, Oct. 03, 2017. https://www.who.int/en/news-room/fact-sheets/detail/west-nile-virus