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Research Article

Mathematical Assessment of Dengue Control Interventions in Cebu City, Philippines

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ABSTRACT

Dengue remains a significant public health challenge in the Philippines, with Cebu City experiencing recurrent outbreaks. In this study, we utilized a modified SIR-SI dengue model to understand the transmission dynamics in Cebu City and to assess the impact of dengue control interventions. Parameters in the model were estimated using weekly reported dengue data obtained from the Philippines' electronic Freedom of Information (eFOI) portal for the 20th to 52nd weeks of 2022. Our results indicate a substantial reduction in the reproduction number from 3.58, observed without any control measures, to 1.16 with the control interventions. Despite this reduction, the reproduction number remains above the critical threshold of 1, indicating a continued risk of outbreaks. Sensitivity analysis identified the mosquito biting rate and transmission rate as key parameters influencing dengue transmission. This suggests the need to enhance control interventions by focusing on reducing human-mosquito contact and lowering the mosquito population. We simulated dengue reduction scenarios with respect to two control measures: self-protective measures and vector control. The results reveal that implementing self-protective measures alone reduced hospitalized cases by 15.42%, while vector control measures led to a 49.38% reduction. Combining both strategies resulted in a substantial 98.6% reduction in hospitalized cases. These findings imply that the control interventions implemented in Cebu City during the 2022 dengue outbreak effectively reduced hospitalized cases (health-seeking individuals) by approximately 98.6%. To further reduce the number of infected individuals, the City government and regional health officials must enhance existing control measures by focusing on reducing human-mosquito contact and lowering the mosquito population through enhanced awareness programs.

Keywords: dengue; behavioral change; reproduction number; sensitivity analysis

1. INTRODUCTION

Dengue fever is a mosquito-borne viral disease transmitted primarily by Aedes aegypti, posing a persistent public health threat in tropical and subtropical regions. Globally, the incidence of dengue has escalated over recent decades, with an estimated 390 million infections reported annually, of which 96 million result in clinical manifestations (Andrand et al., 2012).

In the Philippines, dengue is endemic and continues to cause recurrent outbreaks, particularly in highly urbanized areas such as Cebu City. The sustained transmission in these regions is largely driven by the convergence of environmental, demographic, and behavioral factors (Bhatt et al., 2013). The transmission dynamics of dengue are multifaceted, governed by the complex interplay between human hosts, mosquito vectors, and environmental conditions (Carvalho et al., 2019). Mathematical modeling has emerged as a powerful tool to capture these interactions and to evaluate the efficacy of various intervention strategies (Dayap and Rabajante, 2025; Herdicho et al., 2025; Emmanuel et al., 2024; Oluwafemi et al., 2024; Brito da Cruz and Rodrigues, 2021). Compartmental models, particularly those that incorporate human and vector populations, allow researchers to simulate disease dynamics and assess the thresholds necessary for outbreak prevention. A central concept in these models is the basic reproduction number, R_0, which denotes the average number of secondary infections produced by one infectious individual in a completely susceptible population (de los Reyes and Escaner, 2018). Under the influence of control measures, this metric is adjusted to the control reproduction number, R_c , which accounts for the transmissibility of the disease in the presence of interventions (Harapan et al., 2020).

Dengue prevention strategies generally fall into two broad categories: those that aim to reduce human-vector contact and those that target the suppression of vector population density (Heesterbeek and Dietz, 1996). Self-protective measures such as the application of insect repellents, use of insecticide-treated curtains, and participation in awareness campaigns are designed to minimize exposure to mosquito bites (Heesterbeek and Roberts, 2007). In contrast, vector control strategies include environmental sanitation, elimination of breeding sites, larviciding, and adult mosquito control through misting or fogging operations (Ong et al., 2022). Integrated vector management approaches that combine these strategies have shown superior effectiveness compared to isolated interventions (Rather et al., 2017). In the context of Cebu City, dengue transmission experienced a significant resurgence in the post-pandemic period. Reported cases increased markedly from 399 in 2021 to 3,139 in 2022, with a pronounced seasonal trend observed between June and December, coinciding with the wet season (Bhatt et al., 2013). In response, the Cebu City Health Department implemented an intensified dengue prevention campaign across its 80 barangays. This comprehensive program included community-based information dissemination, behavioral campaigns such as the 4 o'clock habit and curtain impregnation, and systematic implementation of the 5S strategy (Search and destroy, Self-protection measures, Seek early consultation, Say yes to fogging only during outbreaks, and Sustain hydration). Additional efforts involved large-scale clean-up drives, misting operations to target adult mosquitoes, larval source management through larviciding, and active case and vector surveillance to guide control actions.

These interventions represent a dual approach involving both self-protective and vector suppression components. However, despite the extensive efforts and a notable reduction of 30.8% in dengue cases from 2022 to 2023 (with 967 cases reported in 2023), dengue transmission remains a public health concern in Cebu City (Rejuso et al., 2024). The persistence of new cases despite integrated control efforts suggests potential gaps in the optimal timing, intensity, or combination of interventions currently being implemented. Although previous modeling studies have provided valuable insights into dengue dynamics at national or regional levels (Undurraga et al., 2017), there remains a lack of localized, control-oriented mathematical models specifically calibrated to urban areas like Cebu City. Most existing models do not adequately reflect the operational complexity and simultaneous implementation of multiple control measures, as practiced in the city's public health programs. This limitation restricts the ability of decision-makers to formulate evidence-based policies grounded in the specific epidemiological and socio-behavioral context of their communities. To address this gap, the present study develops and analyzes a mathematical model of dengue transmission tailored to the epidemiological landscape of Cebu City. The model incorporates two control variables: one representing self-protective behaviors and the other reflecting vector control initiatives.

The study aims to (1) derive the control reproduction number R_c using the next-generation matrix approach in Cebu City, (2) conduct a sensitivity analysis to identify the parameters with the greatest influence on disease transmission, and (3) simulate various intervention scenarios to evaluate the effectiveness of different control strategies. By situating the model within a real-world, localized context, this research contributes to the evidence base needed to inform targeted and effective dengue control policies in urban settings.

2. METHODOLOGY

2.1. Dengue Transmission Model

The epidemiological model developed in this paper is a modification of SIR-SI compartmental model proposed by de los Reyes and Escaner IV (2018). The developed model aims to understand the transmission dynamics of dengue in Cebu City and assess the dengue control effforts implemented by the City government. The modifications introduced control parameters for self-protective measures (u_1) and vector control measures (u_2), as well as a mechanism to model the transition of the infectious population into a healthcare-seeking compartment. The equations for the model are provided below:

$$
\begin{aligned}
\frac{dS_h}{dt} &= b_h N_h - \frac{(1-u_1)\beta b_{vh} I_v S_h}{N_h} - \mu_h S_h, \\
\frac{dI_h}{dt} &= \frac{(1-u_1)\beta b_{vh} I_v S_h}{N_h} - (\alpha + \gamma_1 + \mu_h) I_h, \\
\frac{dP_h}{dt} &= \alpha I_h - (\gamma_2 + \mu_h) P_h, \\
\frac{dR_h}{dt} &= \gamma_1 I_h + \gamma_2 P_h - \mu_h R_h, \\
\frac{dS_v}{dt} &= b_v N_v \left(1 - \frac{N_v}{K}\right) - \frac{(1-u_1)\beta b_{hv} I_h S_v}{N_h} - (k u_2 + \mu_v) S_v, \\
\frac{dI_v}{dt} &= \frac{(1-u_1)\beta b_{hv} I_h S_v}{N_h} - (k u_2 + \mu_v) I_v
\end{aligned} \tag{1}
$$

where the variables and parameters are defined in Tables 1 and 2, respectively.

The flow diagram of the dengue model (1), presented in Figure 1, is developed under a set of simplifying assumptions. First, the model considers only a single dengue serotype to avoid the complexity associated with multiple strain interactions. Second, individuals who seek healthcare are assumed to be isolated and therefore do not contribute to further transmission. Third, re-infection is not taken into account, implying that individuals acquire complete immunity after recovery. Fourth, no dengue-related mortality due to low mortality rate in Cebu City (Undurraga et al., 2017). Finally, both human and mosquito populations are assumed to be homogeneous, disregarding heterogeneity in demographic or behavioral characteristics.

Table 1. Description of the variables in the model

Variables	Description
S_h	Susceptible human population
I_h	Infected human population who did not seek medication
P_h	Infected human population who seek medication
R_h	Recovered human population
S_v	Susceptible mosquito population
I_v	Infected mosquito population
N_h	Total human population
N_v	Total mosquito population

Table 2. Description of the parameters in the model

Parameter	Description
b_h	Birth rate of humans
μ_h	Natural death rate of humans
β	Biting rate of mosquitoes
b_{vh}	Transmission probability from mosquito to human
b_{hv}	Transmission probability from human to mosquito
γ_1	Recovery rate of non-healthcare-seeking individuals
γ_2	Recovery rate of healthcare-seeking individuals
b_v	Per capita oviposition rate
μ_v	Natural death rate of mosquitoes
K	Vector carrying capacity
k	Induced death rate of mosquitoes due to vector control effort
α	Rate of hospitalization
u_1	Control effort to reduce contact with mosquitoes
u_2	Control effort to reduce mosquito population

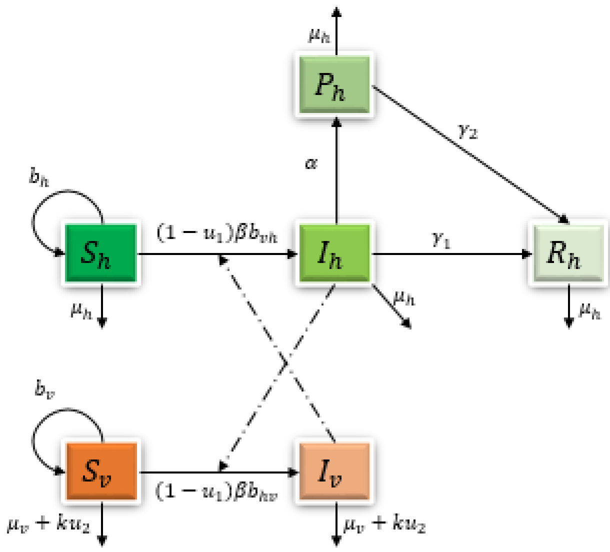

Figure 1. Schematic diagram of dengue transmission dynamics

2.2. *Epidemiological Data*

The dengue model (1) comprises fourteen parameters, some of which are known from the literature. Nine parameters, namely μ_h, b_h, β, b_{vh}, b_{hv}, α, K, u_1, and u_2, need to be estimated. The parameter μ_h is calculated as the inverse of the life expectancy reported in Van den Driesche (2017). The parameter b_h is estimated using population data for Cebu City from 2012 to 2022, acquired from the Philippine Statistics Authority. The other unknown parameters, β, b_{vh}, b_{hv}, α, K, u_1, and u_2, are estimated by fitting the dengue model (1) to weekly reported dengue data from Cebu City for the 20th to 52nd weeks of 2022, which correspond to the rainy season in the Philippines. The data were obtained through the Philippines' electronic Freedom of Information (eFOI).

2.3. *Parameter Estimation and Model Evaluation*

To estimate the unknown parameters in dengue model (1), we employ the curve-fitting function of Berkeley Madonna, which minimizes the mean of squared differences between the model and the observed data. Initially, we estimate the parameter b_h by fitting the population data to the exact solution of the differential equation $dN_h / dt = b_hN_h - \mu_hN_h$. On the other hand, the function $H = \alpha I_h$ is employed to fit the weekly reported dengue data, allowing for the estimation of the parameter values for μ_h, b_h, β, b_{vh}, b_{hv}, α, K, u_1, and u_2, as it captures the weekly reported healthcare-seeking individuals, H. Using the initial conditions presented in Table 3, the resulting model fit to the observed data is illustrated in Figure 2, with the corresponding estimated parameter values detailed in Table 4.

Table 3. Initial conditions used in the dengue transmission model

State Variables	Value
$S_h(0)$	1000000
$I_h(0)$	750
$J_h(0)$	75
$R_h(0)$	200
$S_v(0)$	5000000
$I_v(0)$	5500

Table 4. Values of the parameters in the model

Parameters	Value	Source
b_h	0.000503	Fitted
μ_h	0.000266	Fitted
β	0.70955	Fitted
b_{hv}	0.30367	Fitted
b_{vh}	0.58391	Fitted
γ_1	0.5	de los Reyes and Escaner (2018)
γ_2	1	de los Reyes and Escaner (2018)
b_v	75	de los Reyes and Escaner (2018)
μ_v	0.1	de los Reyes and Escaner (2018)
K	4579453	Fitted
k	1	Assumed
α	0.10139	Fitted
u_1	0.31868	Fitted
u_2	0.34	Fitted

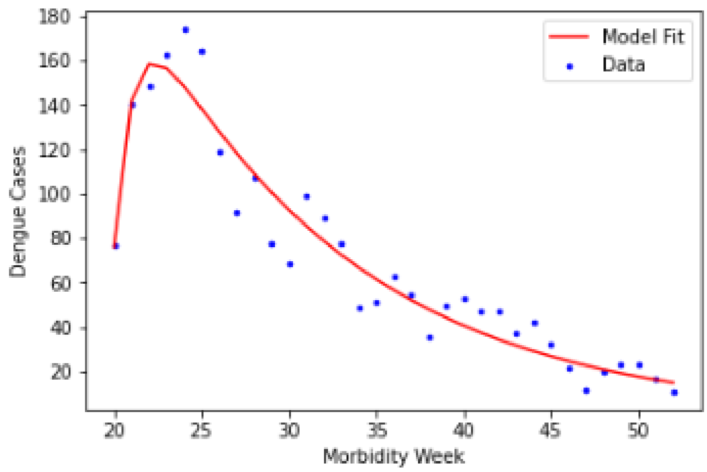

Figure 2. Model curve fitting of the weekly dengue cases in Cebu City, Philippines during 2022 dengue outbreak

The model evaluation was conducted by assessing the goodness-of-fit using the Root Mean Squared Error (RMSE). The RMSE, calculated to be 12.41, quantifies the average deviation of the model predictions from the observed data. This relatively low RMSE value indicates a high level of accuracy in the model's ability to replicate the observed dengue case dynamics in Cebu City for the year 2022.

3. RESULTS AND DISCUSSION

3.1. Parameter Estimates of the Intervention Efforts

Table 4 presents the estimated values of the control parameters $u_1 = 0.32$ and $u_2 = 0.34$, representing the intensities of self-protective measures to reduce human–mosquito contact and vector control strategies aimed at decreasing mosquito population density, respectively. These moderate control levels suggest that existing interventions, such as the use of personal protective methods (e.g., insecticide-treated bed nets and repellents) and vector management strategies (e.g., larviciding, environmental sanitation, and source reduction), are currently in place. However, their implementation may be insufficient to substantially curb dengue transmission. The results highlights the necessity of intensifying both behavioral and vector-targeted control efforts. Strengthening the coverage, compliance, and operational effectiveness of these interventions is likely to enhance their epidemiological impact, thereby facilitating a more pronounced suppression of dengue transmission and contributing to improved public health outcomes in endemic areas such as Cebu City.

3.2. Reproduction Number and Sensitivity Analysis

To evaluate the effectiveness of the control measures implemented by the Cebu City government, we calculate the control reproduction number (R_c) of the dengue model (1). This metric represents the average number of secondary cases produced by a single infectious individual in a susceptible population where control measures are in place (Van den Driesche and Watmough, 2002). In contrast, the basic reproduction number (R_0) measures the average number of secondary cases produced by a single infectious individual in a fully susceptible population with no control measures and no immune individuals. As a threshold, it determines whether the disease will become endemic (when $R_0 > 1$) or disappear (when $R_0 < 1$) with time. Utilizing the next generation matrix as described by Van den Driessche and Watmough (2002), the control reproduction number of dengue model (1) is given below

$$\mathcal{R}_c = \sqrt{\frac{K\beta^2 (1-u_1)^2 b_{hv} b_{vh} \mu_h (b_v - ku_2 - \mu_v)}{b_h b_v N_h (ku_2 + \mu_v)(\alpha + \gamma_1 + \mu_h)}}. \quad (2)$$

Using the parameter values in Table 4, the control reproduction number in Cebu City is calculated to be $R_c \approx 1.16$. This value indicates a relatively high potential for transmission, emphasizing the importance of enhancing the implemented control measures to curb the spread of dengue in this region. Without the control interventions, the calculated basic reproduction number R_0 (with $u_1 = u_2 = 0$) is approximately 3.58. This indicates that the control measures implemented by the city government have significantly reduced the reproduction number, although not sufficiently to bring it below the threshold value of 1. To further support this effort, it is necessary to conduct a sensitivity analysis to identify which parameters are most influential in increasing or decreasing the reproduction number. This analysis would help policymakers determine which control interventions should be prioritized for implementation.

Consequently, we compute the local sensitivity index of Rc concerning the parameter p. This index is defined as:

$$\mathcal{I}_p^{\mathcal{R}_c} = \frac{\partial \mathcal{R}_c}{\partial p} \times \frac{p}{\mathcal{R}_c}. \quad (3)$$

when the sensitivity index exceeds zero, it implies that the number of dengue cases rises with an increase in the parameter, and conversely, it declines when the parameter decreases. The results in (3) are visually depicted in Figure 3. The sensitivity analysis, based on the estimated values found in Table 4, reveals that the most sensitive parameter is β, while the least sensitive is b_v. There are five parameters with positive indices, indicating that an increase in their values would raise the value of R_c. These parameters include β, b_{hv}, b_{vh}, b_v, and K. The most positive sensitive parameter is β and its estimated value is 0.71 per day. From Figure 3, we can see that if β is decreased by 10%, then the reproduction number decreased by 10%. Conversely, the parameters b_h, μ_h, γ_1, μ_v, k, α, u_2, u_1, and N_h exhibit negative indices, suggesting that an increase in their values would lead to a reduction in R_c. The sensitivity analysis results are further corroborated by numerical simulations demonstrating the varying effects of these parameters on the infected population.

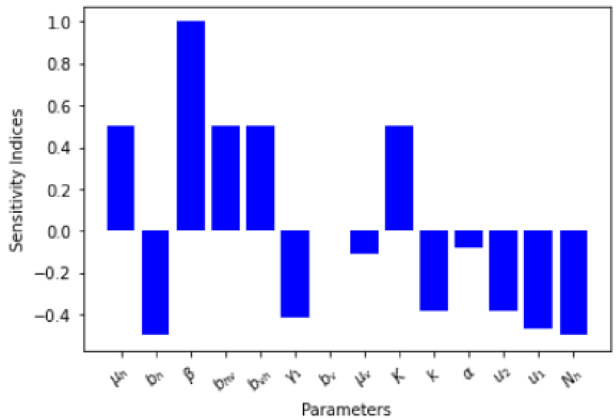

Figure 3. A histogram for the sensitivity indices of R_c

3.3. Effect of Varying Some Parameter Values

Figure 4 illustrates the effect of varying the mosquito biting rate (β) on dengue transmission, with higher β values leading to increased peak infections among both non-healthcare-seeking (NHS) (Figure 4a) and healthcare-seeking (HS) (Figure 4b) individuals. The NHS group exhibits a larger infection burden, suggesting a potential underreporting of cases. Across all scenarios, a higher β results in a prolonged epidemic, emphasizing the need for sustained vector control. Reducing β through interventions such as larval source reduction, and insecticide use can significantly mitigate transmission, while promoting early healthcare-seeking behavior may further limit disease spread. According to the simulated curves in Figure 5(a) and (b), a large vector carrying capacity will result in a large increase in the number of NHS and HS infected individuals so reducing the vector breeding sites through environmental cleaning is crucial to reducing dengue cases. This demonstrates the importance of reducing dengue infection by focusing on the vector carrying capacity.

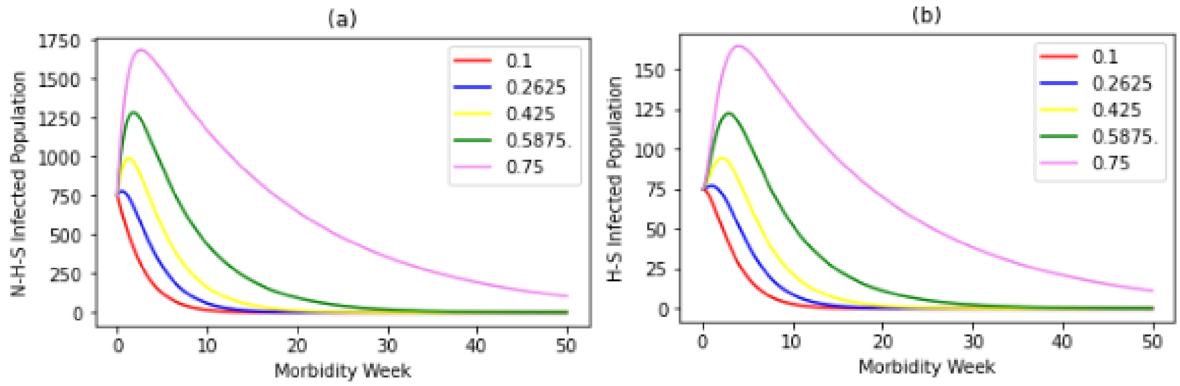

Figure 4. Effect of parameter β on (a) Non-healthcare seeking (NHS) infected and (b) Healthcare seeking (HS) infected individuals

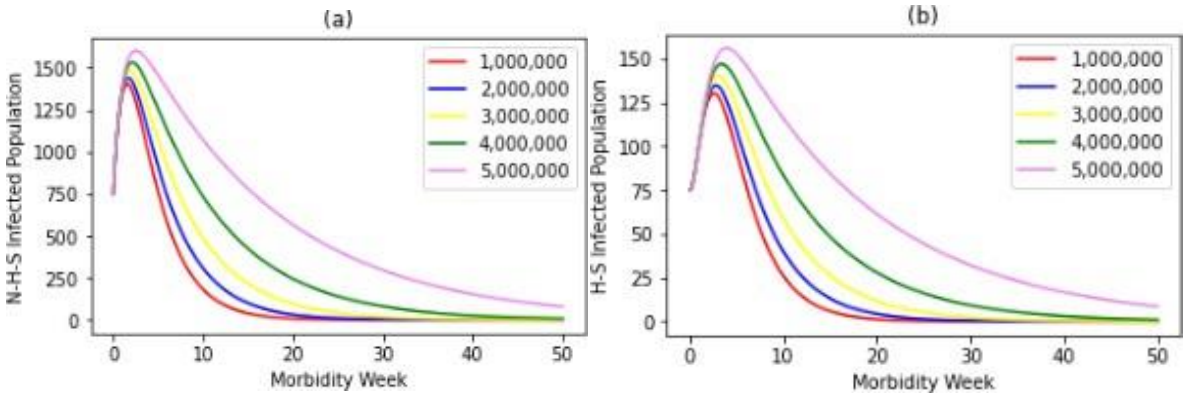

Figure 5. Effect of parameter K on (a) Non-healthcare seeking (NHS) infected and (b) Healthcare seeking (HS) infected individuals

Figure 6 illustrates the impact of varying the hospitalization rate (α) on dengue transmission, where higher hospitalization rates lead to a reduction in non-healthcare- seeking (NHS) infected individuals (Figure 6a) and an increase in the initial peak of healthcare-seeking (HS) infected individuals (Figure 6b), followed by a faster decline. When hospitalization is absent (α = 0), the NHS population experiences a prolonged infection burden, indicating potential underreporting and sustained transmission risk. As hospitalization increases, the NHS cases decrease significantly, while HS infections momentarily rise due to better case detection and healthcare access. This highlights the role of hospitalization in mitigating disease persistence by facilitating treatment and reducing secondary infections. Strengthening hospital capacity and encouraging early healthcare-seeking behavior can be effective in controlling dengue outbreaks.

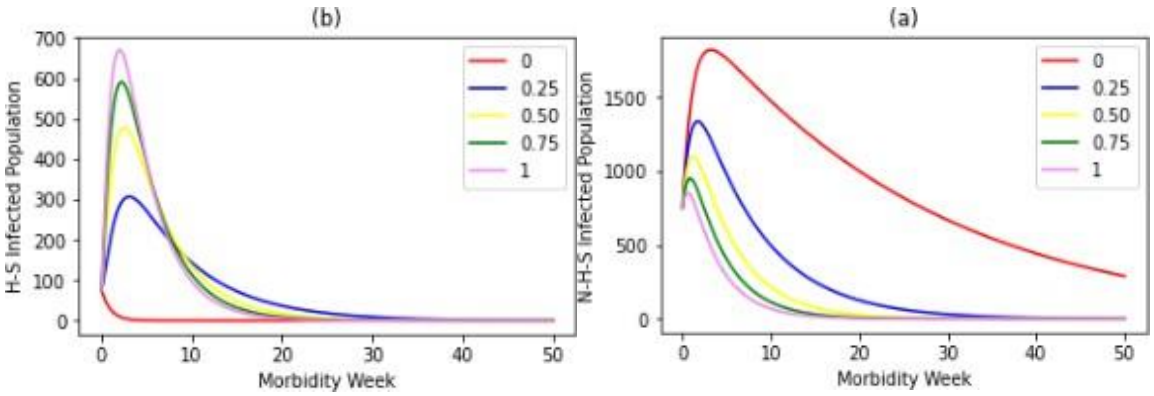

Figure 6. Effect of parameter α on (a) Non-healthcare seeking (NHS) infected and (b) Healthcare seeking (HS) infected individuals

Figure 7 demonstrates the impact of increasing the control effort (u_1) to reduce contact between humans and mosquitoes on dengue transmission. As u_1 increases, there is a significant decline in both non-healthcare-seeking (NHS) (Figure 7a) and healthcare- seeking (HS) (Figure 7b) infected populations over time. When control efforts are minimal ($u_1 = 0.2$), NHS and HS infections persist at higher levels, prolonging the epidemic. Conversely, higher control efforts ($u_1 = 0.8$) lead to a rapid reduction in infections, demonstrating the effectiveness of vector control measures such as insecticide-treated nets, repellents, and environmental management. These findings emphasize the importance of sustained and intensified mosquito control strategies to minimize dengue transmission and disease burden.

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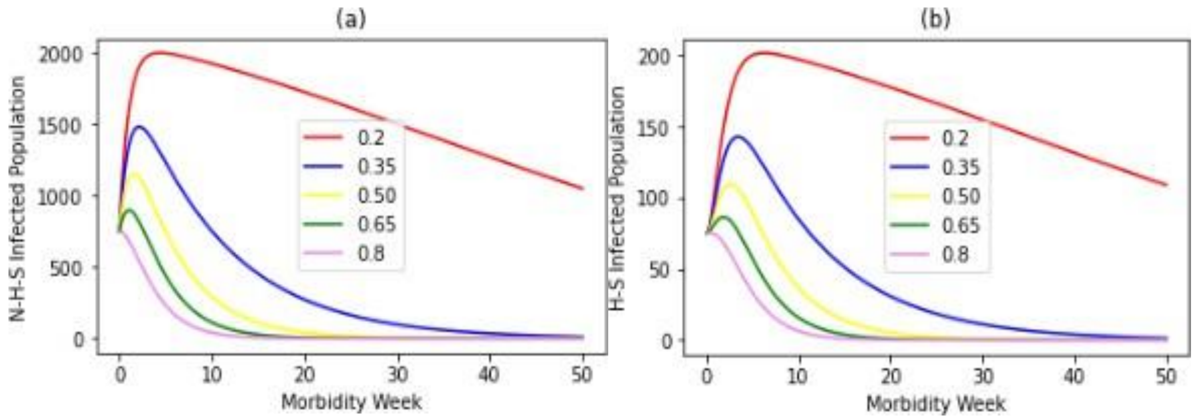

Figure 7. Effect of parameter u_1 on (a) Non-healthcare seeking (NHS) infected and (b) Healthcare seeking (HS) infected individuals

Figure 8 illustrates the effect of increasing the mosquito reduction control effort (u_2) on the dynamics of NHS (Figure 8a) and HS (Figure 8b) infected populations. A higher u_2 value, which represents intensified mosquito control measures such as larviciding, fogging, and source reduction, leads to a substantial decrease in infections over time. When u_2 is low ($u_2 = 0.2$), the number of infected individuals remains high for an extended period. In contrast, higher control efforts ($u_2 = 0.8$) significantly suppress the infected population, curbing the epidemic more effectively. These findings highlight the crucial role of sustained mosquito control interventions in mitigating disease spread and reducing the overall burden of dengue.

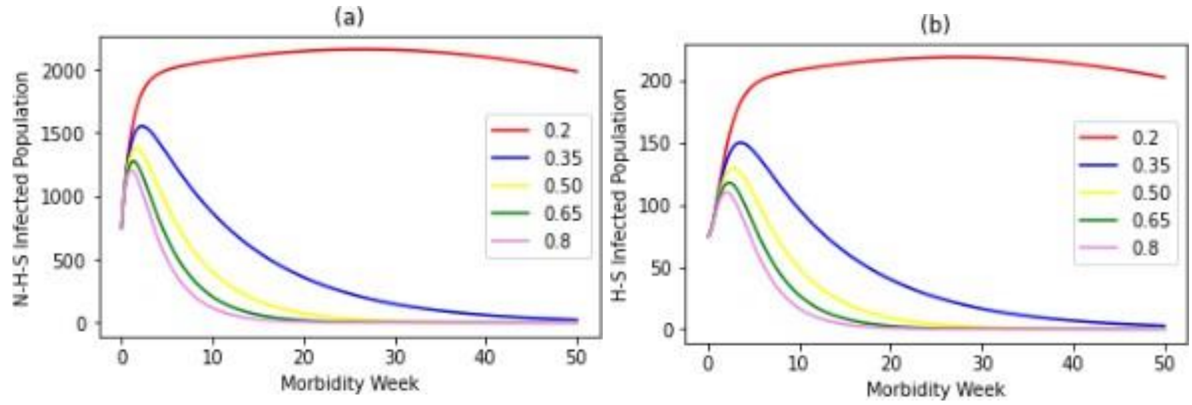

Figure 8. Effect of parameter u_2 on (a) Non-healthcare seeking (NHS) infected and (b) Healthcare seeking (HS) infected individuals

3.4. Dengue Reductions

Figure 9 illustrates three distinct intervention scenarios aimed at reducing dengue incidence: (1) implementation of self-protective measures only, (2) implementation of vector control measures only, and (3) a combined strategy integrating both interventions. The parameter values employed in these scenarios are consistent with those presented in Table 4, except for the control variables u_1 and u_2, which represent the intensities of self-protective and vector control measures, respectively. Specifically, in the self-protective measures only scenario, $u_1 = 0.3$ and $u_2 = 0$; in the vector control measures only scenario, $u_1 = 0$ and $u_2 = 0.3$; and in the combined intervention scenario, both are set to $u_1 = u_2 = 0.3$, while all other parameters remain unchanged. Self-protective measures, such as the use of repellents, protective clothing, and household-level preventive behaviors, result in a modest reduction of approximately 15.42% in dengue cases. Meanwhile, vector control interventions, including mosquito population reduction strategies such as larval source management and insecticide application, yield a more substantial 49.38% reduction in cases. Notably, the simultaneous implementation of both strategies achieves an almost complete suppression of dengue transmission, reducing cases by 98.6%. This synergistic effect underscores the importance of integrating both individual and community-wide interventions to achieve optimal disease control outcomes. The results emphasize that while personal protective measures contribute to risk reduction, vector control remains a more effective approach, and their combination is essential for achieving near-elimination of dengue cases.

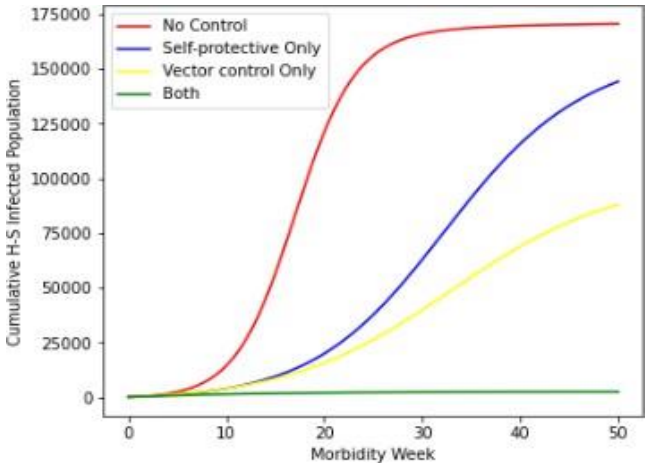

Figure 9. Numerical Simulations on Dengue Reductions based on four dengue reduction scenarios: (a) No controls, (b) Self-protective only, (c) Vector control only, and (d) Both Self-protective and Vector control measures

Although this study examined constant intervention strategies, such an assumption is often unrealistic due to budgetary and operational constraints. This limitation motivates a further research question: What is the optimal timing and intensity of control efforts that minimize intervention costs while effectively reducing dengue transmission? Future extensions of this work may incorporate the economic costs of control measures to formulate an optimal control problem. A suitable formulation can be expressed through the cost functional

$$J(u_1, u_2) = \int_0^T \left[AI_h(t) + \frac{1}{2}(B_1 u_1^2(t) + B_2 u_2^2(t)) \right] dt,$$

where A represents the weight associated with infection burden and B_1 and B_2 denote the relative costs of implementing self-protective and vector control measures, respectively. The objective is to minimize $J(u_1,u_2)$ subject to the system dynamics. The resulting optimal control problem can be analyzed using Pontryagin's Maximum Principle, which provides necessary conditions for determining time-dependent optimal control trajectories that balance epidemiological impact and cost efficiency. Integrating this framework would enhance the policy relevance of the model by identifying economically sustainable and epidemiologically effective dengue control strategies under realistic budget constraints.

4. CONCLUSION

This study employed a modified SIR-SI compartmental model to characterize the dengue transmission dynamics and evaluate the impact of control interventions during the 2022 outbreak in Cebu City, Philippines. Using weekly dengue case data retrieved from the electronic Freedom of Information (eFOI) portal for morbidity weeks 20 to 52, the estimated control reproduction number (Rc = 1.16) indicated sustained transmission despite ongoing mitigation efforts. Sensitivity analysis revealed that mosquito biting and transmission rates were the most influential parameters, reflecting the significant role of Cebu's climatic conditions and elevated vector density in driving transmission dynamics. Simulation results indicated that self-protective measures alone reduced hospitalizations by 15.42%, while vector control strategies achieved a 49.38% reduction. Importantly, the combined implementation of both strategies yielded a synergistic effect, resulting in a 98.6% decrease in hospitalized cases. These findings highlight the importance of integrated vector management approaches that simultaneously target human-vector contact and mosquito population control. The results provide quantitative evidence to guide the refinement of public health policies and support the development of context-specific, data-informed intervention strategies for dengue-endemic settings such as Cebu City.

Conflict of Interest
The authors declare no conflicts of interest.

Author Contribution Statement
Jonecis Dayap: Conceptualization, methodology, data analysis, writing original draft, supervision. Gemma Amazona: Data curation, writing original draft, review and editing. Audrey Verano: Conceptualization, writing original draft, review and editing. Carla Jean Ybañez: Data curation, review and editing.

Data Availability Statement
The authors confirm that the data supporting the findings of this study are available within the article.

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