Assessing the Role of Human Movement and Effect of Control Measures on Dengue Fever Spread in Connected Patches: From Modelling to Simulation

Afeez Abidemi

Department of Mathematical Sciences
Universiti Teknologi Malaysia

Introduction

- *Dengue* is a mosquito-borne viral disease endemic in many areas across the globe.
- The role of ***human movement*** and heterogeneity in populations have long been recognised as driving forces in dengue disease spread. Hence, there is the need to better understand the impact of human movement on dengue disease transmission, and the impact of combined efforts of various control measures in reducing the disease prevalence in the population.

Specific objectives

- To investigate the impact of human movement on dengue disease spread in two connected patches using a more realistic metapopulation model.
- To examine the effect of combined efforts of personal protection (c_P), larvicide (c_L) and adulticide (c_A) control measures on the disease spread in the connected patches.

Model Formulation

$$
\begin{aligned}
\frac{dS_{hi}}{dt} &= \mu_{hi}N_{hi} - (1-c_{P_i})b_{vi}\beta_{vi}\frac{I_{vi}}{N_{hi}}S_{hi} + \sum_{\substack{j=1\\j\neq i}}^{2} m_{ij}^{S}S_{hj} - \sum_{\substack{j=1\\j\neq i}}^{2} m_{ji}^{S}S_{hi} - \mu_{hi}S_{hi},\\
\frac{dE_{hi}}{dt} &= (1-c_{P_i})b_{vi}\beta_{vi}\frac{I_{vi}}{N_{hi}}S_{hi} + \sum_{\substack{j=1\\j\neq i}}^{2} m_{ij}^{E}E_{hj} - \sum_{\substack{j=1\\j\neq i}}^{2} m_{ji}^{E}E_{hi} - (\gamma_{hi}+\mu_{hi})E_{hi},\\
\frac{dI_{hi}}{dt} &= \gamma_{hi}E_{hi} + \sum_{\substack{j=1\\j\neq i}}^{2} m_{ij}^{I}I_{hj} - \sum_{\substack{j=1\\j\neq i}}^{2} m_{ji}^{I}I_{hi} - (\theta_{hi}+\mu_{hi})I_{hi},\\
\frac{dR_{hi}}{dt} &= \theta_{hi}I_{hi} + \sum_{\substack{j=1\\j\neq i}}^{2} m_{ij}^{R}R_{hj} - \sum_{\substack{j=1\\j\neq i}}^{2} m_{ji}^{R}R_{hi} - \mu_{hi}R_{hi},\\
\frac{dA_{vi}}{dt} &= \mu_{ei}\left(1-\frac{A_{vi}}{K_{Li}}\right)N_{vi} - (\gamma_{ai}+\mu_{ai}+c_{L_i})A_{vi},\\
\frac{dS_{vi}}{dt} &= \gamma_{ai}A_{vi} - (1-c_{P_i})b_{vi}\beta_{hi}\frac{I_{hi}}{N_{hi}}S_{vi} - (\mu_{vi}+c_{A_i})S_{vi},\\
\frac{dE_{vi}}{dt} &= (1-c_{P_i})b_{vi}\beta_{hi}\frac{I_{hi}}{N_{hi}}S_{vi} - (\gamma_{vi}+\mu_{vi}+c_{A_i})E_{vi},\\
\frac{dI_{vi}}{dt} &= \gamma_{vi}E_{vi} - (\mu_{vi}+c_{A_i})I_{vi},
\end{aligned}
\tag{1}
$$

with non-negative initial conditions.

Qualitative analysis of model (1)

- Positivity of solutions.
- Existence of two disease-free equilibria: Let $\mathcal{N}_i = \frac{\mu_{ei}\gamma_{ai}}{(\mu_{vi}+c_{A_i})(\gamma_{ai}+\mu_{ai}+c_{L_i})}$, $(i=1,2)$.
  - If $\mathcal{N}_i \leq 1$, there is a trivial equilibrium (TE, $\mathcal{E}_1$)

$$\mathcal{E}_1 = \left(S_{h1}^*, 0, 0, 0, 0, 0, 0, 0, S_{h2}^*, 0, 0, 0, 0, 0, 0, 0\right),$$

  - If $\mathcal{N}_i > 1$, there exists a biologically realistic disease-free equilibrium (BRDFE, $\mathcal{E}_2$)

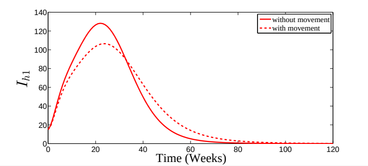
$$\mathcal{E}_2 = \left(S_{h1}^*, 0, 0, 0, A_{v1}^*, S_{v1}^*, 0, 0, S_{h2}^*, 0, 0, 0, A_{v2}^*, S_{v2}^*, 0, 0\right),$$

  where $S_{h1}^* = \frac{\mu_{h1}N_{h1}(m_{12}^S+\mu_{h2})+\mu_{h2}N_{h2}m_{12}^S}{\mu_{h1}\mu_{h2}+\mu_{h1}m_{12}^S+\mu_{h2}m_{21}^S}$, $S_{h2}^* = \frac{\mu_{h2}N_{h2}(m_{21}^S+\mu_{h1})+\mu_{h1}N_{h1}m_{21}^S}{\mu_{h1}\mu_{h2}+\mu_{h1}m_{12}^S+\mu_{h2}m_{21}^S}$, $A_{vi}^* = \left(1-\frac{1}{\mathcal{N}_i}\right)K_{L_i}$, and $S_{vi}^* = \frac{\gamma_{ai}}{(\mu_{vi}+c_{A_i})}\left(1-\frac{1}{\mathcal{N}_i}\right)K_{L_i}$.
- Travel-rate dependent basic reproductive number $\mathcal{R}_0$.
- Local and global asymptotic stability of BRDFE, $\mathcal{E}_2$.

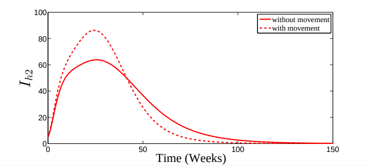
Effect of human travels

Bidirectional human movement between patches (cities).

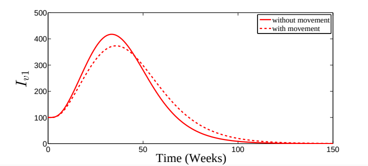
(a) Infectious individuals of City 1



(b) Infectious individuals of City 2



(c) Infectious mosquitoes of City 1



(d) Infectious mosquitoes of City 2

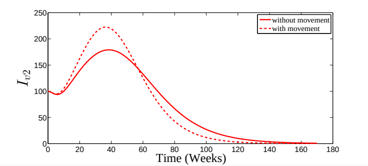
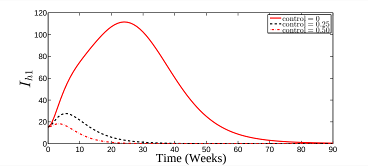


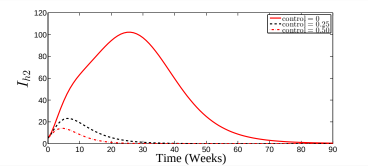
Figure 1: Dynamics of infectious individuals and mosquitoes of Cities 1 and 2 with bidirectional host mobility between the cities in the absence of any control measure.

Implementation of human self-protection, larvicide and adulticide controls with bidirectional human travels

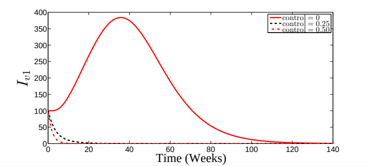
(a) Infectious individuals of City 1



(b) Infectious individuals of City 2



(c) Infectious mosquitoes of City 1



(d) Infectious mosquitoes of City 2

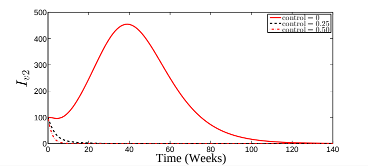


Figure 2: Dynamics of infectious individuals and mosquitoes of Cities 1 and 2 with bidirectional host mobility at different levels of combined controls implemented in Cities 1 and 2

Summary

- A two-patch model was developed and analysed for dengue disease transmission and control in two connected cities.
- BRDFE $\mathcal{E}_2$ of the model is LAS if $\mathcal{R}_0 < 1$, and unstable otherwise.
- The basic reproductive number for dengue outbreak in isolated City 1 and City 2 are approximately $\mathcal{R}_{01} = 2.396$ and $\mathcal{R}_{02} = 1.599$, respectively, and the basic reproductive number of the two-patch model in the absence of any control is approximately $\mathcal{R}_0 = 1.981$.
- The numbers of infectious humans and mosquitoes are reduced in City 1 and increased in City 2 with the presence of bidirectional human travel between the cities and absence of any control interventions.
- With bidirectional human movements between the connected Cities 1 and 2, applying the combined control in City 1 and City 2 simultaneously is found to be sufficient in eliminating dengue disease from human and mosquito populations of the two cities.

Ongoing work

- Derivation of optimal time-dependent control functions $c_P(t)$, $c_L(t)$ and $c_A(t)$ required for the disease control using optimal control theory.

Questions?