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Analysis of dengue fever disease transmission using suspected-infected-recovered (SIR) model

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Abstract. The Suspected-Infected-Recovered (SIR) model is proposed to study the dynamic transmission of dengue fever disease. The proposed SIR model contains two main populations, namely human population and mosquito population as the host and the vector of dengue virus, respectively. The overall aim of this research was to analyze the asymptotic stability of two equilibrium states (disease-free state and endemic state) of the dengue fever transmission model. Moreover, this work also showed the conditions of parameters that should be satisfied in order to guarantee the stability of the equilibrium points.

1. Introduction

The transmission process of a particular infectious disease can be represented by compartmental models. The fundamental principle of these mathematical models is to divide the population of the study into two or more subpopulations. The very first compartmental model was introduced by Kermack and Mckendrick [1] who categorized each individual in the population to exactly one of three subpopulations, namely suspected (S), infected (I) or recovered (R). Afterward, this model has been extensively developed and became the basis for more advanced epidemic models.

A compartmental model which consists of suspected, infected and recovered subpopulation is known as SIR model. Furthermore, the name of a compartmental model is based on the subpopulations of the model. The number of subpopulations depends on the transmission characteristics of infectious disease and the underlying assumptions of the models. For example, in the study of tuberculosis (TB) infection, one usually adds one more subpopulation into SIR model, that is exposed (E) subpopulation which represents an infected individual in the population but still does not show any symptom like infected individuals. In this situation, the SIR model becomes the SEIR model due to the presence of the exposed subpopulation [2,3].

In dengue fever transmission, human population should be studied as well as the mosquito population. This is the fundamental difference between dengue fever model and other compartmental models which usually consider the population of human only. This is because the spreading of dengue fever is literally not only affected by the dynamics of dengue virus in the human body but also in mosquitoes as the carrier or vector of dengue virus [4]. Due to the presence of two populations in the model of dengue fever transmission, the dynamical system of the dengue fever model becomes more complicated than one population model such as the epidemic model for TB disease.

The main objective of this study is to formulate the transmission of dengue fever based on the SIR model with two populations (host and vector). The asymptotic stability of the equilibrium disease-free state and endemic state of the transmission model is then shown by using Routh's criteria [5]. In



addition, the conditions of the model's parameters given to achieve the stability state are also investigated in detail. This study is essential to be conducted since its mathematical concepts will guarantee the proposed model's convergence and stability when it applies to real-life problems.

2. Dengue fever SIR model

Dengue fever disease is caused by the dengue virus through the biting of two kinds of mosquito, namely *Aedes aegypti* and *Aedes albopictus*. Dengue virus has four serotypes (dengue virus 1 (DEN-1), dengue virus 2 (DEN-2), dengue virus 3 (DEN-3) and dengue virus 4 (DEN-4) [6]. However, this study only focusses on constructing a mathematical model of dengue fever based on one serotype which is the simplest model among them.

In this work, the transmission process of dengue fever is assumed to follow SIR model. This means that the population will be separated into three subpopulations (suspected, infected and recovered). However, according to the dynamical transmission process of dengue fever disease, this study considers two populations, namely human population as the host and mosquito population as the vector or carrier of the virus [7,8]. Human population (N_h) consists of three subpopulations, such as individuals who are still healthy but they are susceptible to be infected (S_h), individuals who are infected by the virus (I_h) and individuals who recovered from the disease (R_h). Meanwhile, the vector population (N_v) contains two subpopulations, namely susceptible mosquitoes (S_v) and infected mosquitoes (I_v). In other words, this model assumes that the infected mosquitoes unable to recover once they are infected by the dengue virus.

In this study, the number of vectors is assumed to be fixed although the spread of the virus continues in the population. In other words, the recruitment rate of the mosquitoes is assumed as a constant (C). Meanwhile, the initial number of suspected individuals is affected by the birth rate of human (σ) which should be equal to the human mortality rate (μ_h) to keep the initial number of suspected human still constant. At each time period, both human and mosquitoes must belong to exactly one respected subpopulation. The probability of the virus transmission from the vector to the host and the probability of the opposite transmission (from the host to the vector) are symbolized by β_h and β_v respectively. The biting rate of the mosquitoes to the human is b whereas human recovery rate and vector mortality rate are γ_h and μ_v , respectively. The probability of suspected individuals become infected people is represented by the formula $\frac{\beta_h b I_v}{N_h}$, where $\beta_h b$ can be interpreted as the sufficient rate of the transmission from the human to the mosquitoes. It is also assumed that human will immediately receive any treatment when they just get infected. When infected people are treated, they will have lifetime immunity which means that the re-infection condition is not allowed. In the population of the vector, the probability of the mosquitoes to be infected is represented by $\frac{\beta_v b I_h}{N_h}$, where $\beta_v b$ is the sufficient rate of the transmission from the infected mosquitoes to the human. The whole dynamical system of dengue fever epidemic model in both the host population and vector population can be described by a differential equations system as follow

$$\frac{d}{dt} S_h = \mu_h N_h - \left(\frac{\beta_h b I_v}{N_h} + \mu_h \right) S_h \quad (1a)$$

$$\frac{d}{dt} I_h = \left(\frac{\beta_h b I_v}{N_h} \right) S_h - (\gamma_h + \mu_h) I_h \quad (1b)$$

$$\frac{d}{dt} R_h = \gamma_h I_h - \mu_h R_h \quad (1c)$$

$$\frac{d}{dt} S_v = C - \frac{\beta_v b}{N_h} I_h S_v - \mu_v S_v \quad (1d)$$

$$\frac{d}{dt} I_v = \frac{\beta_v b}{N_h} I_h S_v - \mu_v I_v \quad (1e)$$

Since the total number of the human population is the sum of each human subpopulation, the first condition of the model is

$$N_h = S_h + I_h + R_h \Rightarrow R_h = N_h - S_h - I_h \quad (2)$$

Meanwhile, the total number of the mosquito population is $N_v = S_v + I_v$. So, we get

$$\frac{d}{dt} N_v = \frac{d}{dt} (S_v + I_v) = C - \mu_v N_v. \quad (3)$$

It is assumed that the total number of mosquitoes is constant so that $\frac{dN_v}{dt}$ is equal to zero and Equation (3) becomes

$$\frac{d}{dt} N_v = C - \mu_v N_v \Leftrightarrow 0 = C - \mu_v N_v \Leftrightarrow N_v = \frac{C}{\mu_v},$$

which gives the second condition:

$$\frac{C}{\mu_v} = S_v + I_v. \quad (4)$$

Therefore, the system (1a)-(1e) can be simplified as follows

$$\frac{d}{dt} S_h = \mu_h N_h - \left(\frac{\beta_h b I_v}{N_h} + \mu_h \right) S_h \quad (5a)$$

$$\frac{d}{dt} I_h = \left(\frac{\beta_h b I_v}{N_h} \right) S_h - (\gamma_h + \mu_h) I_h \quad (5b)$$

$$\frac{d}{dt} I_v = \frac{\beta_v b}{N_h} I_h S_v - \mu_v I_v. \quad (5c)$$

The system (5a)-(5c) can also be normalized by expressing $S'_h = \frac{S_h}{N_h}$, $I'_h = \frac{I_h}{N_h}$ and $I'_v = \frac{I_v}{N_v} = \frac{I_v}{C/\mu_v}$. Therefore, the equation (5a) can be simplified as

$$\begin{aligned} \frac{d}{dt} S'_h &= \mu_h - \left(\frac{\beta_h b I_v}{N_h} + \mu_h \right) \frac{S_h}{N_h} \\ \Leftrightarrow \frac{d}{dt} S'_h &= \mu_h (1 - S'_h) - \left(\frac{\beta_h b I_v}{N_h} S'_h \right) \\ \Leftrightarrow \frac{d}{dt} S'_h &= \mu_h (1 - S'_h) - \left(\frac{\beta_h b N_v I'_v}{N_h} S'_h \right) \\ \Leftrightarrow \frac{d}{dt} S'_h &= \mu_h (1 - S'_h) - \left(\frac{\beta_h b C}{N_h \mu_v} I'_v S'_h \right) \\ \Leftrightarrow \frac{d}{dt} S'_h &= \mu_h (1 - S'_h) - \alpha I'_v S'_h. \end{aligned} \quad (6a)$$

Then, Equation (5b) becomes

$$\begin{aligned} \frac{d}{dt} I'_h &= \left(\frac{\beta_h b I_v}{N_h} \right) \frac{S_h}{N_h} - (\gamma_h + \mu_h) \frac{I_h}{N_h} \\ \Leftrightarrow \frac{d}{dt} I'_h &= \alpha I'_v S'_h - \beta I'_h. \end{aligned} \quad (6b)$$

Meanwhile, Equation (5c) can be simplified as

$$\begin{aligned} \frac{d}{dt} I_v &= \frac{\beta_v b}{N_h} I_h S_v - \mu_v I_v \\ \Leftrightarrow \frac{d}{dt} I'_v &= \beta_v b I'_h \frac{S_v}{N_v} - \mu_v I'_v \\ \Leftrightarrow \frac{d}{dt} I'_v &= \beta_v b I'_h \left(\frac{N_v - I_v}{N_v} \right) - \mu_v I'_v \\ \Leftrightarrow \frac{d}{dt} I'_v &= \gamma (1 - I'_v) I'_h - \delta I'_v, \end{aligned} \quad (6c)$$

where $\alpha = \frac{\beta_h b C}{N_h \mu_v}$, $\beta = \gamma_h + \mu_h$, $\gamma = \beta_v b$ and $\delta = \mu_v$.

3. Results and analysis

In this section, the equilibrium points of the system of differential equations (6a)-(6c) will be determined. Then, the asymptotic stability of the equilibrium points obtained is examined by using Routh's criteria.

3.1. Equilibrium points

The equilibrium states (S_h^*, I_h^*, I_v^*) of the dynamical system can be obtained by adjusting the right-hand side of equations (6a)-(6c) to zero. Consequently, the first equilibrium states are obtained, that is the disease-free state $E_0(1,0,0)$.

Endemic equilibrium points occurs when $I_h' \neq 0$ and $I_v' \neq 0$. Therefore, by setting $\frac{d}{dt}S_h' = \frac{d}{dt}I_h' = \frac{d}{dt}I_v' = 0$, the systems (6a)-(6c) becomes

$$\mu_h(1 - S_h') - \alpha I_v' S_h' = 0, \quad (7a)$$

$$\alpha I_v' S_h' - \beta I_h' = 0, \quad (7b)$$

$$\gamma(1 - I_v')I_h' - \delta I_v' = 0. \quad (7c)$$

By substituting Equations (7a) and (7b) into Equation (7c) yielding the second equilibrium points, that is the endemic state $E_1(S_h^*, I_h^*, I_v^*)$ where

$$S_h^* = \frac{\mu_h \gamma + \beta \delta}{\gamma(\mu_h + \alpha)}, \quad (8a)$$

$$I_h^* = \frac{\mu_h(\gamma\alpha + \beta\delta)}{\beta\gamma(\mu_h + \alpha)}, \quad (8b)$$

$$I_v^* = \frac{\mu_h(\gamma\alpha + \beta\delta)}{\alpha(\gamma\mu_h + \beta\delta)}. \quad (8c)$$

3.2. Routh's criterion

The asymptotic stability of equilibrium points of a differential equations system can be shown by using Routh's criterion [4]. Let \mathbf{M} is a matrix that represents a differential equations system. The eigenvalues of \mathbf{M} are the roots of the characteristic polynomial $\det(\lambda\mathbf{I} - \mathbf{M}) = a_n\lambda^n + a_{n-1}\lambda^{(n-1)} + a_{n-2}\lambda^{(n-2)} + \dots + a_1\lambda + a_0$ with $a_n = 1$. According to Routh's criterion, the asymptotic stability of \mathbf{M} evaluated at equilibrium points can be investigated directly by analyzing the coefficients $\{a_i\}$ where $i = 0, 1, \dots, n$. The procedure of Routh's criterion can be written in the following way:

1. Arrange $\{a_i\}$ in the form of Routh's matrix:

$$\mathbf{R} = \begin{bmatrix} a_n & a_{n-2} & a_{n-4} & \dots \\ a_{n-1} & a_{n-3} & a_{n-5} & \dots \\ b_1 & b_2 & b_3 & \dots \\ c_1 & c_2 & c_2 & \dots \\ \vdots & \vdots & \vdots & \dots \end{bmatrix}, \quad (9)$$

where the coefficients $\{b_i\}, \{c_i\}, \dots$ can be obtained by using these following formulas:

$$b_1 = \frac{a_{n-1}a_{n-2} - a_n a_{n-3}}{a_{n-1}}, b_2 = \frac{a_{n-1}a_{n-4} - a_n a_{n-5}}{a_{n-1}}, \dots$$

$$c_1 = \frac{b_1 a_{n-3} - a_{n-1} b_2}{b_1}, c_2 = \frac{b_1 a_{n-5} - a_{n-1} b_3}{b_1}, \dots$$

2. The scheme in the first step will be continued until only zeroes appear.
3. It is also assumed that the first $n+1$ elements of the first column of Matrix (9) are well defined and nonzero.
4. Based on the assumption in the previous step, the matrix \mathbf{R} has eigenvalues with negative real part if and only if the elements in the first column all have the similar sign. In other words, if each element of the first column of Matrix (9) is positive, the system which is represented by matrix \mathbf{M} is stable around the equilibrium points considered.

3.3. Stability analysis

In this works, the asymptotic stability of two equilibrium points of differential equations system (6a)-(6c) will be investigated by using Routh's criterion. In order to conduct the analysis, the differential equation system (6a)-(6c) should be firstly linearized so it can be written as follows:

$$f(S'_h, I'_h, I'_v) = \mu_h(1 - S'_h) - \alpha I'_v S'_h, \quad (9a)$$

$$g(S'_h, I'_h, I'_v) = \alpha I'_v S'_h - \beta I'_h, \quad (9b)$$

$$h(S'_h, I'_h, I'_v) = \gamma(1 - I'_v)I'_h - \delta I'_v. \quad (9c)$$

By linearization of the Equations (9a)-(9c), it yields

$$\frac{\partial f}{\partial S'_h} = \frac{\partial f(\mu_h(1-S'_h) - \alpha I'_v S'_h)}{\partial S'_h} = -\mu_h - \alpha I'_v,$$

$$\frac{\partial f}{\partial I'_h} = \frac{\partial f(\mu_h(1-S'_h) - \alpha I'_v S'_h)}{\partial I'_h} = 0,$$

$$\frac{\partial f}{\partial I'_v} = \frac{\partial f(\mu_h(1-S'_h) - \alpha I'_v S'_h)}{\partial I'_v} = -\alpha S'_h,$$

$$\frac{\partial g}{\partial S'_h} = \frac{\partial(\alpha I'_v S'_h - \beta I'_h)}{\partial S'_h} = \alpha I'_v,$$

$$\frac{\partial g}{\partial I'_h} = \frac{\partial(\alpha I'_v S'_h - \beta I'_h)}{\partial I'_h} = -\beta,$$

$$\frac{\partial g}{\partial I'_v} = \frac{\partial(\alpha I'_v S'_h - \beta I'_h)}{\partial I'_v} = \alpha S'_h,$$

$$\frac{\partial h}{\partial S'_h} = \frac{\partial(\gamma(1-I'_v)I'_h - \delta I'_v)}{\partial S'_h} = 0,$$

$$\frac{\partial h}{\partial I'_h} = \frac{\partial(\gamma(1-I'_v)I'_h - \delta I'_v)}{\partial I'_h} = \gamma(1 - I'_v),$$

$$\frac{\partial h}{\partial I'_v} = \frac{\partial(\gamma(1-I'_v)I'_h - \delta I'_v)}{\partial I'_v} = -\gamma I'_h - \delta.$$

All of these linearizations become the elements of the Jacobian matrix (**J**) which has the form

$$\mathbf{J} = \begin{bmatrix} \frac{\partial f}{\partial S'_h} & \frac{\partial f}{\partial I'_h} & \frac{\partial f}{\partial I'_v} \\ \frac{\partial g}{\partial S'_h} & \frac{\partial g}{\partial I'_h} & \frac{\partial g}{\partial I'_v} \\ \frac{\partial h}{\partial S'_h} & \frac{\partial h}{\partial I'_h} & \frac{\partial h}{\partial I'_v} \end{bmatrix},$$

so that it can be obtained a Jacobian matrix of differential equation system (6a)-(6c) as follows

$$\mathbf{J} = \begin{bmatrix} -\mu_h - \alpha I'_v & 0 & -\alpha S'_h \\ \alpha I'_v & -\beta & \alpha S'_h \\ 0 & \gamma(1 - I'_v) & -\gamma I'_h - \delta \end{bmatrix}. \quad (10)$$

3.4. Stability analysis of disease free equilibrium point.

Substituting the disease-free equilibrium point $E_0(1,0,0)$ into Jacobian matrix (10) yields the following matrix

$$\mathbf{J}' = \begin{bmatrix} -\mu_h & 0 & -\alpha \\ 0 & -\beta & \alpha \\ 0 & \gamma & -\delta \end{bmatrix}. \quad (11)$$

To determine the eigenvalues of the Matrix (11), nontrivial solutions are needed for the following equation

$$(\lambda \mathbf{I} - \mathbf{J}')\mathbf{x} = 0, \quad (12)$$

where λ is the eigenvalue, \mathbf{I} is identity matrix with respect to matrix \mathbf{J}' and \mathbf{x} is a column vector of the variables. The Equation (12) has nontrivial solutions if and only if $|\lambda\mathbf{I} - \mathbf{J}'| = 0$. Consequently, by using MAPLE 11, the characteristic equation of Jacobian matrix (11) which is evaluated on the disease-free equilibrium point can be written as

$$\lambda^3 + \lambda^2(\delta + \beta + \mu_h) + \lambda(\beta\delta + \mu_h\delta + \mu_h\beta - \alpha\gamma) + (\mu_h\alpha\gamma - \mu_h\beta\delta) = 0. \quad (13)$$

Let $x = \delta + \beta + \mu_h$, $y = \mu_h(\delta + \beta) - (\alpha\gamma - \beta\delta)$, and $z = \mu_h(\alpha\gamma - \beta\delta)$. By using the values x, y and z , the Routh matrix of the characteristic equation (13) can be obtained as follows

$$\mathbf{R}' = \begin{bmatrix} a_n & a_{n-2} & a_{n-4} \\ a_{n-1} & a_{n-3} & a_{n-5} \\ b_1 & b_2 & b_3 \\ c_1 & c_2 & c_2 \end{bmatrix} = \begin{bmatrix} 1 & y & 0 \\ x & z & 0 \\ \frac{xy-z}{x} & 0 & 0 \\ z & 0 & 0 \end{bmatrix}.$$

By using Routh's criterion, we should check the first column in the Matrix \mathbf{R}' . If each element in the first column has the same sign, it can be concluded that the differential equations system (6a)-(6c) is stable around the equilibrium point $E_0(1,0,0)$.

It is clear that $1, x > 0$ since δ, β and μ_h are positive. The value of $c_1 = z > 0$ if and only if $\alpha\gamma > \beta\delta$. Meanwhile, the value of $b_1 = \frac{xy-z}{x} > 0 \Leftrightarrow xy > z \Leftrightarrow x > \frac{z}{y} \Leftrightarrow (\delta + \beta + \mu_h) > \frac{\mu_h(\alpha\gamma - \beta\delta)}{\mu_h(\delta + \beta) - (\alpha\gamma - \beta\delta)}$. Therefore, the system is stable around $E_0(1,0,0)$ if and only if $\alpha\gamma > \beta\delta$ and $(\delta + \beta + \mu_h) > \frac{\mu_h(\alpha\gamma - \beta\delta)}{\mu_h(\delta + \beta) - (\alpha\gamma - \beta\delta)}$.

3.5. Stability analysis of endemic equilibrium point

Inserting the endemic equilibrium point $E_1(S^*_h, I^*_h, I^*_v)$ into Jacobian matrix (10) yielding

$$\mathbf{J}'' = \begin{bmatrix} -\mu_h \left(\frac{\gamma(\mu_h + \alpha) + 2\beta\delta}{\gamma\mu_h + \beta\delta} \right) & 0 & -\alpha \frac{\mu_h\gamma + \beta\delta}{\gamma(\mu_h + \alpha)} \\ \frac{\mu_h(\gamma\alpha + \beta\delta)}{(\gamma\mu_h + \beta\delta)} & -\beta & \alpha \frac{\mu_h\gamma + \beta\delta}{\gamma(\mu_h + \alpha)} \\ 0 & \gamma \left(1 - \frac{\mu_h(\gamma\alpha + \beta\delta)}{\alpha(\gamma\mu_h + \beta\delta)} \right) & - \left(\frac{\mu_h(\gamma\alpha + \beta\delta)}{\beta(\mu_h + \alpha)} + \delta \right) \end{bmatrix}. \quad (14)$$

By using similar steps with the stability analysis for $E_1(S^*_h, I^*_h, I^*_v)$ in the previous subsection and the help of MAPLE, the characteristic equation of the Jacobian matrix (14) can be obtained as follows

$$\lambda^3 + \lambda^2(t + \beta + \mu_h p) + \lambda(t\beta + pt\mu_h + p\beta\mu_h - qs\alpha\gamma) + (qrs\alpha\gamma - pqs\mu_h\alpha\gamma + pt\beta\mu_h) = 0, \quad (15)$$

where

$$p = \left(\frac{\gamma(\mu_h + \alpha) + 2\beta\delta}{\gamma\mu_h + \beta\delta} \right),$$

$$q = \left(\frac{\mu_h\gamma + \beta\delta}{\gamma(\mu_h + \alpha)} \right),$$

$$r = \left(\frac{\mu_h(\gamma\alpha + \beta\delta)}{(\gamma\mu_h + \beta\delta)} \right),$$

$$s = \left(1 - \frac{\mu_h(\gamma\alpha + \beta\delta)}{\alpha(\gamma\mu_h + \beta\delta)} \right),$$

$$t = \left(\frac{\mu_h(\gamma\alpha + \beta\delta)}{\beta(\mu_h + \alpha)} + \delta \right).$$

Let $x' = t + \beta + \mu_h p$, $y' = t\beta + pt\mu_h + p\beta\mu_h - qs\alpha\gamma$ and $z' = qrs\alpha\gamma - pqs\mu_h\alpha\gamma + pt\beta\mu_h$. By using the values of x', y' and z' , the Routh matrix of the characteristic equation (15) can be obtained as follows

$$\mathbf{R}'' = \begin{bmatrix} 1 & y' & 0 \\ x' & z' & 0 \\ \frac{x'y'-z'}{x'} & 0 & 0 \\ z' & 0 & 0 \end{bmatrix}.$$

Therefore, the differential equation system (6a)-(6c) is stable around the endemic equilibrium point $E_1(S_h^*, I_h^*, I_v^*)$ if and only if $qrs\alpha\gamma + pt\beta\mu_h > pqs\mu_h\alpha\gamma$ and $(t + \beta + \mu_h p)(t\beta + pt\mu_h + p\beta\mu_h - qs\alpha\gamma) > qrs\alpha\gamma - pqs\mu_h\alpha\gamma + pt\beta\mu_h$.

4. Conclusions

In this paper, we have developed a compartmental SIR model of the dengue fever spreading based on several assumptions given which contains two equilibrium points, namely disease-free equilibrium point and endemic equilibrium point. The asymptotic stability of both equilibrium points was analyzed by using Routh's criterion. The analysis showed that there are several conditions of parameters that should be satisfied in order to guarantee the asymptotic stability of the equilibrium points.

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