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A MATHEMATICAL MODEL OF A ZIKA VIRUS TRANSMISSION WITH IMPACT OF AWARENESS BY MEDIA

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Abstract. This paper has studied the transmission of Zika Virus with the impact of media. We analyzed the impact of the awareness programs on social media for the Zika Virus transmission model with saturated incidence rate. The Beddington-De Angelis functional responses used to explain the interaction between a suspected human and an infected human. The dynamical analysis identified by computing the disease-free equilibrium(DFE) and endemic equilibrium(END). The Basic Reproduction Number was identified by Next Generation Matrix(NGM) method. Then the stability of DFE and END were analyzed locally by computing the determinant of Jacobian. The DFE was identified as locally stable when the basic reproduction number was less than unity and was identified as unstable otherwise. Otherwise, the END was identified as existents when the basic reproduction number was greater than unity. The Routh-Hurwitz Criterion showed that the END was locally stable under a specific condition. In the last, the stability of the equilibrium point was also identified numerically depending on certain parameter values.

1. INTRODUCTION

Zika virus is mostly transmitted through a bite from an Aides Aegypti mosquito during the day or night. Zika is also spread through sexual contact between an infected human and an uninfected human. In some cases, Zika is also passed on by pregnant women to her fetus which, causes a birth defect. No vaccine has been found to prevent Zika virus [1]. Based on [2], preventing Zika can be done by using insecticide-treated bed nets and mosquito repellent using a condom and prohibiting pregnant women to travel to the area with Zika outbreak [1].

Recently, most people change their mode of communication from face-to-face into online communication. Social media is one of the best forms of technology that responds to people's needs to communicate and share information online. Some common social media are Facebook, Twitter, Youtube, Whatsapp, and Instagram can be accessed easily by using smartphones and cellular applications [3].

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In a disease's epidemiology, social media has an important role to inform the disease's outbreak. Social media and TV advertising is one method to prevent transmission. Misra [4] has made a mathematical model to see the impact of TV advertising and social media on the dynamics of infectious diseases. There are vulnerable populations that are vulnerable to infection as well as populations that often access information through social media. The Zika virus transmission can be informed through social media, then people can take preventive measures. Zika virus outbreak is expected to be controlled or does not spread into outer territory. The mathematical model of social media impact for the epidemiological disease has been researched by some authors. In 2014, the effects of media for influenza epidemic was discussed [5]. The SEIR model was constructed by including the media function. The function $f(I,p)$ was determined to reduce the transmission. In 2018, a mathematical model of Zika virus transmission has been constructed and developed [6] [7]. In this paper, we study the impact of awareness programs on social media. The new parameter m, which becomes the basis of the exponential will be analyzed. We consider some of the trigger factors and preventive actions which are explained in a saturated model using Beddington DeAngelis incident rate.

2. MATHEMATICAL MODEL

A modification model for the Zika virus transmission with the saturated incidence rate and the impact of social media are as follows:

$$\begin{aligned}
\frac{dS_h}{dt} &= \Lambda_h - \frac{\beta_1 e^{mI_h} S_h I_h}{1+\alpha_1 S_h + \alpha_2 I_h} - \frac{\beta_2 S_h I_v}{1+\alpha_3 S_h} - \mu_h S_h, \\
\frac{dI_h}{dt} &= \frac{\beta_1 e^{mI_h} S_h I_h}{1+\alpha_1 S_h + \alpha_2 I_h} + \frac{\beta_2 S_h I_v}{1+\alpha_3 S_h} - (\gamma+\mu_h) I_h, \\
\frac{dR_h}{dt} &= \gamma I_h - \mu_h R_h, \\
\frac{dS_v}{dt} &= \Lambda_v - \beta_3 S_v I_h - \mu_v S_v, \\
\frac{dI_v}{dt} &= \beta_3 S_v I_h - \mu_v I_v,
\end{aligned} \tag{2.1}$$

where $S_h(t), I_h(t), R_h(t), S_v(t), I_v(t)$ stand for suspected human, infected human, recovered human, suspected mosquitoes, and infected mosquitoes respectively. In this study, all of parameters are positive, where Λ_h denote the growth rate of human, Λ_v denote the growth rate of mosquitoes, β_1 is the rate of direct transmission of human, β_2 is the rate of transmission from mosquitoes to human, and β_3 is the rate of transmission from human to mosquitoes. The per capita recovery rate of the infective population defined by *gamma*, α_1, α_2 the parameter that measure the inhibitory effect of human transmission, α_3 the parameter that measure the inhibitory effect of mosquitoes bite, μ_h means the death rate of human, μ_v means the death rate of mosquitoes, respectively.

Let $(S_h, I_h, R_h, S_v, I_v)$ is the solution of the system, with positive initial value. N_h and N_v are the total population of human and mosquitoes respectively, whereas $N_h = S_h + I_h + R_h$ and $N_v = S_v + I_v$. We assume all parameter and variables are

positives. Then the solution of system are in the following :

$$\left\{\Omega = (S_h, I_h, R_h, S_v, I_v) \in {R_+}^5; N_h \leq \frac{\Lambda_h}{\mu_h}, N_v \leq \frac{\Lambda_v}{\mu_v}\right\}. \tag{2.2}$$

The derivation respect to time of the total population of the model 2.1 are :

$$\frac{dN_h}{dt} = \Lambda_h - \mu_h N_h. \tag{2.3}$$

The solution of $\frac{dN_h}{dt} + \mu_h N_h = \Lambda_h$ is $\frac{\Lambda_h}{\mu_h} - Ce^{\mu_h t}$. If $N_h \leq \frac{\Lambda_h}{\mu_h}$, then $\frac{\Lambda_h}{\mu_h} \geq 0$. If $N_h > \frac{\Lambda_h}{\mu_h}$, then $\frac{\Lambda_h}{\mu_h} < 0$. Then choose the initial value as follows :

(1) $N_h(0) = 0$, then the solution is $N_h(t) = \frac{\Lambda_h}{\mu_h}(1 - e^{\mu_h t})$,
(2) $N_h(0) = \frac{\Lambda_h}{\mu_h}$, the solution is $N_h(t) = \frac{\Lambda_h}{\mu_h}$,
(3) $N_h(0) > 0$, the solution is $N_h(t) = \frac{\Lambda_h}{\mu_h}(1 - e^{\mu_h t}) + N_h(0)e^{\mu_h t}$.

The total population of humans and mosquitoes are in the following :

$$0 \leq N_h(t) \leq N_h(t) = \frac{\Lambda_h}{\mu_h}(1 - e^{\mu_h t}) + N_h(0)e^{\mu_h t}, \tag{2.4}$$

and

$$0 \leq N_v(t) \leq N_v(t) = \frac{\Lambda_v}{\mu_v}(1 - e^{\mu_v t}) + N_v(0)e^{\mu_v t}. \tag{2.5}$$

In particular :

$$N_h(t) \leq \frac{\Lambda_h}{\mu_h}, N_v(t) \leq \frac{\Lambda_v}{\mu_v}, \quad \text{when} \quad N_h(0) \leq \frac{\Lambda_h}{\mu_h}, N_v(0) \leq \frac{\Lambda_v}{\mu_v}. \tag{2.6}$$

Then the area $\left\{\Omega = (S_h, I_h, R_h, S_v, I_v) \in {R_+}^5; N_h \leq \frac{\Lambda_h}{\mu_h}, N_v \leq \frac{\Lambda_v}{\mu_v}\right\}$ is bounded.

For $N_h = S_h + I_h + R_h$ and $N_v = S_v + I_v$ then we rewrite the model 2.1 into the following model:

$$\begin{aligned}
\frac{dN_h}{dt} &= \Lambda_h - \mu_h N_h, \\
\frac{dI_h}{dt} &= \left(\frac{\beta_1 e^{mI_h} I_h}{1 + \alpha_1(N_h - I_h - R_h) + \alpha_2 I_h} + \frac{\beta_2 I_v}{1 + \alpha_3(N_h - I_h - R_h)}\right)(N_h - I_h - R_h) - (\gamma + \mu_h)I_h \\
\frac{dR_h}{dt} &= \gamma I_h - \mu_h R_h, \\
\frac{dN_v}{dt} &= \Lambda_v - \mu_v N_v, \\
\frac{dI_v}{dt} &= \beta_3(N_v - I_v)I_h - \mu_v I_v.
\end{aligned} \tag{2.7}$$

3. MATHEMATICAL ANALYSIS

Let the right hand equation of the system 2.7 by zero. Then we found two kinds of equilibrium points, namely disease free equilibrium (DFE) and endemic equilibrium (END) [10]. The disease free equilibrium of the system 2.7 is

$$DFE = ({N_h}^0, {I_h}^0, {R_h}^0, {N_v}^0, {I_v}^0) = \left(\frac{\Lambda_h}{\mu_h}, 0, 0, \frac{\Lambda_v}{\mu_v}, 0\right). \tag{3.1}$$

The DFE is always exists.

Basic reproduction ratio is represent the natural compartmented for disease transmission model, established by the system of ordinary differential equation. In this work, the basic reproduction ration compute by NGM as follows [10].

$$F = \begin{pmatrix} \frac{\beta_1 {N_h}^0}{1+\alpha_1 {N_h}^0} & \frac{\beta_2 {N_h}^0}{1+\alpha_3 {N_h}^0} \\ \beta_3 {N_v}^0 & 0 \end{pmatrix}, \quad V = \begin{pmatrix} \gamma+\mu_h & 0 \\ 0 & \mu_v \end{pmatrix}. \tag{3.2}$$

F is the jacobian of infection matrix with respect to DFE, and V the jacobian matrix which decrease the infection.

$$V^{-1} = \begin{pmatrix} \frac{1}{\gamma+\mu_h} & 0 \\ 0 & \frac{1}{\mu_v} \end{pmatrix}, \quad F.V^{-1} = \begin{pmatrix} \frac{\beta_1 {N_h}^0}{(1+\alpha_1 {N_h}^0)(\gamma+\mu_h)} & \frac{\beta_2 {N_h}^0}{(1+\alpha_3 {N_h}^0)\mu_v} \\ \frac{\beta_3 {N_v}^0}{(\gamma+\mu_h)} & 0 \end{pmatrix}. \tag{3.3}$$

Furthermore, the basic reproduction number is the largest number of eigenvalues of $F.V^{-1}$.

$$R_0 = \frac{R_{01} + \sqrt{R_{01}^2 + 4R_{02}}}{2}; \tag{3.4}$$

where,
$R_{01} = \beta_1 P_1$,
$R_{02} = \beta_2 \beta_3 P_1 P_2 \frac{N_v}{N_h}$.

Lemma 1. *The disease-free equilibrium (DFE) of the system is locally asymptotically stable when $R_0 < 1$ and $N_h < \frac{\mu_v \sigma_2 \delta}{\mu_v \beta_1 \sigma_2 + \beta_2 \beta_3 \sigma_1 N_v}$, otherwise it is unstable.*

Proof. The Jacobian of model 2.7 is

$$J(DFE) = \begin{pmatrix} -\mu_h & -J_0 & 0 & 0 & -J_1 \\ 0 & J_0 - \mu_h - \gamma & 0 & 0 & J_1 \\ 0 & \gamma & -\mu_h & 0 & 0 \\ 0 & -\beta_3 N_v & 0 & -\mu_v & 0 \\ 0 & \beta_3 N_v & 0 & 0 & -\mu_v \end{pmatrix}. \tag{3.5}$$

where,

$J_0 = \frac{\beta_1 N_h}{\sigma_1}$ and $J_1 = \frac{\beta_2 N_h}{\sigma_2}$.
The jacobian of DFE have five eigen values, which are $-\mu_h$, $-\mu_h$ and $-\mu_v$. The two others are analyzed by identify the characteristic polynomials (3.6) as follows,

$$P(\lambda) = \lambda^2 + a_1 \lambda + a_0. \tag{3.6}$$

where,
$a_1 = \frac{1}{\sigma_1}(-\beta_1 N_h + \sigma_1 \delta)$,
$a_0 = \frac{1}{\sigma_1 \sigma_2}(\mu_v \sigma_1 \sigma_2 \delta - N_h(\mu_v \beta_1 \sigma_2 + \beta_2 \beta_3 \sigma_1 N_v))$.

The polynomial 3.6 have two negative real part eigen values, if $a_0 > 0$ which is $N_h < \dfrac{\mu_v\sigma_2\delta}{\mu_v\beta_1\sigma_2 + \beta_2\beta_3\sigma_1 N_v}$. ■

Lemma 2. *The endemic equilibrium (END) of the system is exist if* $R_0 > 1$ *and* $\alpha_1\delta - (\beta_1 e^{-mI_h} + \alpha_2\mu_h) > 0$.

Proof. The endemic equilibrium of the system 2.7 is

$$END = (N_h^*, I_h^*, R_h^*, N_v^*, I_v^*). \tag{3.7}$$

Where,
$N_h^* = \dfrac{\Lambda_h}{\mu_h}, \quad R_h^* = \dfrac{\gamma}{\mu_h} I_h^*, \quad N_v^* = \dfrac{\Lambda_v}{\mu_v}, \text{ and } \quad I_v^* = \dfrac{\beta_3\Lambda_h}{\mu_v(\beta_3 I_h^* + \mu_v)} I_h^*.$

The poin I_h^* is the positive root of the polynomial $P(I_h^*)$ as follow.

$$P(I_h^*) = b_3 {I_h^*}^3 + b_2 {I_h^*}^2 + b_1 I_h^* + b_0, \tag{3.8}$$

with $\delta = \gamma + \mu_h, \quad \Delta = \alpha_1\delta - \alpha_2\mu_h,$
and,
$b_3 = \alpha_3\mu_v\beta_3\delta^2(\alpha_1\delta - (\beta_1 e^{-mI_h^* + \alpha_2}\mu_h)),$
$b_2 = \delta\mu_v[\delta\alpha_3(\mu_v\Delta - (\mu_h\beta_3\varphi_1 + \alpha_2\mu_h)) + \beta_3(\mu_h\varphi_2(\beta_1 e^{-mI_h^*} - \Delta) - \beta_2 N_v\Delta) + \beta_1 e^{-mI_h^*}\alpha_3(\mu_h\beta_3 N_h - \alpha_1\delta)],$
$b_1 = \mu_h\mu_v[\beta_2\beta_3 N_h N_v\Delta + \mu_v\delta\varphi_2(\beta_1 e^{-mI_h^*} - \Delta) + \mu_h\beta_3\delta\varphi_1\varphi_2 + \delta\varphi_1(\beta_2\beta_3 N_v - \alpha_3\mu_v\delta) + \beta_1 e^{-mI_h^*} N_h\varphi_2(\alpha_3\mu_v\delta - \mu_h\beta_3)],$
$b_0 = \mu_h^2\mu_v^2(\varphi_1\varphi_2(\delta - N_h\beta_1 e^{-mI_h^*}) - \varphi_1\beta_2\beta_3 N_h\dfrac{N_v}{\mu_v}).$
By calculus, the positiveness of constant b_3, b_2, b_1 and b_0 are identified. Then the polynomial 3.8 have one positive roots if $\alpha_1\delta - (\beta_1 e^{-mI_h + \alpha_2}\mu_h) > 0$. ■

The stability of endemic equilibrium(END) are identified in the following Lemma.

Lemma 3. *The END is locally stable if* $(N_v^* - I_v^*) < \dfrac{(\mu_v + \beta_1 I_h^*)(\mu_h K_2 + \gamma K_3)}{\beta_3\mu_h K_4}$.

Proof. The local stability of END is identified by analyzing the following Jacobian.

$$J(END) = \begin{pmatrix} -\mu_h & 0 & 0 & 0 & 0 \\ K_1 & K_2 & K_3 & 0 & K_4 \\ 0 & \gamma & -\mu_h & 0 & 0 \\ 0 & 0 & 0 & -\mu_v & 0 \\ 0 & -\beta_3(N_v^* - I_v^*) & 0 & \beta_3 I_h^* & -(\beta_3 I_h^* - \mu_v). \end{pmatrix}. \tag{3.9}$$

where,
$K_1 = \Delta_1(\dfrac{1 + \alpha_2 I_h^*}{1 + \alpha_1(N_h^* - I_h^* - R_h^*) + \alpha_2 I_h^*} + \Delta_2\dfrac{1}{1 + \alpha_3(N_h^* - I_h^* - R_h^*)}) > 0,$
$K_2 = -\Delta_1(1 - \dfrac{1 - mI_h^*}{I_h^*}(N_h^* - I_h^* - R_h^*) - \dfrac{(\alpha_2 - \alpha_1)}{1 + \alpha_1(N_h^* - I_h^* - R_h^*) + \alpha_2 I_h^*} - \dfrac{\Delta_2}{1 + \alpha_3(N_h^* - I_h^* - R_h^*)}) -$
$\delta < 0,$
$K_3 = \dfrac{-(1 + \alpha_2 I_h^*)\Delta_1}{1 + \alpha_1(N_h^* - I_h^* - R_h^*) + \alpha_2 I_h^*} - \dfrac{\Delta_2}{1 + \alpha_3(N_h^* - I_h^* - R_h^*)} < 0,$
$K_4 = \dfrac{\beta_2(N_h^* - I_h^* - R_h^*)}{1 + \alpha_3(N_h^* - I_h^* - R_h^*)} > 0.$

Clearly, the eigen value of matrix $J(END)$ are $-\mu_v, -\mu_h$, and the three others are the roots of the following polynomial $P_{END}(\lambda)$.

$$P_{END}(\lambda) = \lambda_3 + c_2\lambda_2 + c_1\lambda_1 + c_0, \tag{3.10}$$

where,
$c_2 = \beta_3 I_h^* + \mu_v + \mu_h - K_2 > 0$,
$c_1 = \mu_v\mu_h - K_2(\mu_v + \mu_h) + \beta_3 I_h^*(\mu_h - K_2) + \beta_3 K_4(I_v^* - N_v^*) - \gamma K_3 > 0$,
$c_0 = -\beta_3\mu_h K_4(N_v^* - I_v^*) - (\mu_v + \beta_3 I_h^*)(\mu_h K_2 + \gamma K_3)$.
By using Routh-Hurwitz Criterion [8] the polynomial $P_{END}(\lambda)$ have three negative real parts eigenvalue since $c_2 > 0$, and $c_1c_2 - c_0 > 0$. Then, the parameter $c_0 > 0$ when $(N_v^* - I_v^*) < \dfrac{(\mu_v\beta_1 I_h^*)(\mu_h K_2 + \gamma K_3)}{\beta_3\mu_h K_4}$. Hence, the the END is locally stable under condition $(N_v^* - I_v^*) < \dfrac{(\mu_v + \beta_1 I_h^*)(\mu_h K_2 + \gamma K_3)}{\beta_3\mu_h K_4}$. ■

4. NUMERICAL RESULT AND DISCUSSION

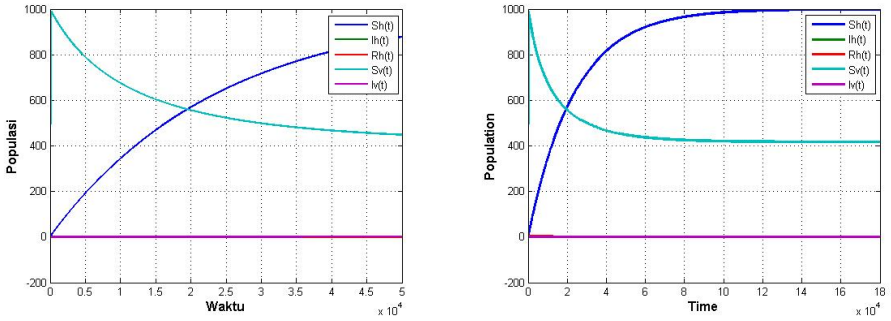
In this section, we describe the numerical simulation of the model 2.7 to verify the analytical result. Under some certain condition which satisfies the qualification of basic reproduction number, the trajectory of the system 2.7 are identified. The sensitivity analysis also needs to analyze the most sensitive parameter in the model. For simulation, we choose some parameter value which satisfies the qualification condition. The following table provides the parameter description and the parameter value which is used in the numerical simulation.

TABLE 1. The parameter probability by [6] [11]

Parameter	Probability(value)
Λ_h	$\mu_h N_h$ (person per-day)
μ_h	$\frac{1}{\text{lifetime}} = \frac{1}{65x365} = 0.00004215$ (per-day)
α_1	$0 \leq \alpha_1 \leq 1$ (person x day)
β_1	$0 \leq \beta_1 \leq 1$ (person x day)
β_2	$0 \leq \beta_2 \leq 1$ (person x day)
β_3	$0 \leq \beta_3 \leq 1$ (mosquitoes x day)
γ	$0 \leq \gamma \leq 1, \gamma = \frac{1}{recoverytime} = \frac{1}{7} = 0.1428$ (per-day)
Λ_v	$\mu_v N_v$ (mosquitoes per-day)
μ_v	$\frac{1}{\text{lifetime}} = \frac{1}{14} = 0.0714$ (per-day)

Then take the parameter values as follow : $\Lambda_h = 0.004215, \mu_h = 0.00004215, \mu_v = 0.0714, \beta_1 = 0.0001, \beta_2 = 0.002, \beta_3 = 0.0001, \gamma = 0.1428, \Lambda_v = 71.4, m = 2, \alpha_1 = 0.95, \alpha_2 = 0.1$, and $\alpha_3 = 0.96$. Under that parameter value than we have the following result.

The figure 1a and figure 1b tell us the trajectories of the system 2.7 when the basic reproduction number is less than unity. The solution of the system will tends to the suspect human and mosquitoes which means the infected population is extinct. Then the system is free from disease along certain times.



(A) Simulation 1 (B) Simulation 2

FIGURE 1. Numerical Result of model (2.7) when $R_0 < 1$, (a) Simulation when $t = 4000$ (b) Simulation when $t = 18000$

The sensitivity analysis was performed to determine the relative importance of model parameters of disease transmission. Choose the parameter value, $\mu_v = 0.0714, \mu_h = 0.00004215, \Lambda_h = 10, \Lambda_v = 20, \beta_1 = 0.02, \beta_2 = 0.0007, \beta 3 = 0.01, \alpha_1 = 0.35, \alpha_3 = 0.95, \gamma = 0.1428$. Based on mathematical computation and normalization the sensitivity index of R_0, we have the following result (Table 1).

TABLE 2. Table of sensitivity index for each parameter of the system 2.7

Parameter	Sensitivity Index	Interpretation (Increasing or decreasing)	Rank
Λ_h	0.00000621	Λ_h by 10%, R_0 increasing by 0.000621%	7
μ_h	-0.000213693	μ_h by 10%, R_0 decreasing by 0.021%	6
α_1	-0.40627261	α_1 by 10%, R_0 decreasing by 40.6%	4
α_2	0	α_2 by 10%, R_0 by increasing 0%	8
α_3	-0.296859936	α_3 by 10%, R_0 decreasing by 29.6%	3
β_1	0.4062775	β_1 by 10%, R_0 increasing by 40.6%	4
β_2	0.296861253	β_2 by 10%, R_0 increasing by 29.6%	5
β_3	0.296861253	β_3 by 10%, R_0 increasing by 29.6%	5
γ	-0.7029312644	γ by 10%, R_0 decreasing by 70.2%	1
Λ_v	0.4975303648	Λ_v by 10%, R_0 increasing by 49%	3
μ_v	-0.5937225055	μ_v by 10%, R_0 decreasing by 59.3%	2

According to table 2, we can see that the most sensitive parameter of the model x is the recovery rate of the infection population (γ). The second one is the death rate of mosquitoes (μ_v) and the third one is the parameter that measures the inhibitory effect of mosquitoes bite (α_3). The solution we can do to prohibit the problem of Zika virus, beginning with the pursuit of healing of infected humans, such as conducting treatment and providing vaccines. Then reduce the mosquito population by maintaining environmental cleanliness and prevent mosquito-spread according to government recommendations. Additionally, by taking precautions to be free from Aedes Aegyepti mosquito bites. Conversely, the least sensitive parameter is the parameter that measures the inhibitory effect of human transmission (α_2). So

for further model development, these parameters α_2 do not need to be used.

5. CONCLUSION

In this paper, we have discussed the interaction among human which suspected, infected, recovered from Zika virus and mosquitoes which infected and suspected Zika. The parameter of social media is also used to see the impact on that model. To see the effects of social media on the transmission of Zika virus, mathematical models using systems with five nonlinear differential equations were constructed. The boundedness problem of the system is analyzed and proved by ordinary mathematical calculations. By letting the right-hand side of the system by zero, the two types of equilibrium points were obtained with a certain existing condition, namely disease-free and endemic. The basic reproduction numbers are the basis for the conditions of stability and the existence of equilibrium points, were found by using the Next Generation Matrix (NGM). The dynamical analysis has been solved out by using supporting theorems such as Descartes and Routh-Hurwitz criteria. Based on the analytical result, the disease-free equilibrium points are locally asymptotically stable when the basic reproduction number was less than unity. Moreover, the endemic equilibrium point exists and locally stable when the basic reproduction number is more than unity and satisfied the certain parameter requirement. The sensitivity analysis is also analyzed to identify the sensitivity of each parameter of the model. Then, the most sensitive parameter of the model 2.7 is the recovery rate of the infective population (γ). Conversely, the least sensitive parameter is the inhibitory effect of human transmission (α_2). It becomes a recommendation for the next model development, the parameters α_2 is no need to be used. Numerical simulations of the dynamic behavior of equilibrium points were also presented to complete the analytical results. Then generally it can be concluded that social media affect reducing the spread of the Zika virus.

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