Computational Model for the Prognosis, Control and Simulation of Ebola Virus Disease

O. Sarjiyus[1], J. Sunday[2*] and I. Manga[1]

[1]*Department of Computer Science, Adamawa State University, Mubi, Nigeria.*
[2]*Department of Mathematics, Adamawa State University, Mubi, Nigeria.*

Authors' contributions

This work was carried out in collaboration between all authors. Author OS presented the prognosis of the EVD and also the model adopted. Author JS simulated the model and presented the results. Author IM presented the procedure for the control of the EVD. All authors read and approved the final manuscript.

Original Research Article

ABSTRACT

Ebola Virus Disease (EVD) has garnered public interest mostly because of its low survival rate compared with most other modern epidemic diseases. This research is hinged on the Prognosis, Control and Simulation of the EVD. A model called the Susceptible-Latent-Infected-Recovered (SLIR) model was adopted in this research to study the trend of the disease. From the stability analysis, it was found that the necessary and sufficient condition for the control and possibly, total eradication of the disease in West Africa is that the product of total breakdown of the susceptible and latent classes most be less than the product of the total removal rates from both the latent and the infectious classes. The computational method adopted in this research also gives the values of parameters needed to hold the epidemic under control, reduce mortality rate arising from the EVD, reduce the rate of infected class and increase the rate of recovered class.

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Corresponding author: E-mail: joshuasunday2000@yahoo.com;

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1. INTRODUCTION

EVD is a severe infection affecting several African countries, mainly Guinea, Sierra Leone, and Liberia. It was first discovered in 1976 in the Democratic Republic of Congo (in the present day South Sudan), near the Ebola River, where the virus takes its name, but recently was also identified in West Africa [1].

The outbreak of the disease was first reported in Guinea in 1976 (before it later spread to the neighboring countries of Liberia, Sierra Leone and Nigeria). An initial report by the World Health Organization (WHO) showed that as at July 2nd 2014, the total number of deaths attributed to this epidemic in Guinea, Liberia and Sierra Leone was 481, out of the 779 known cases (approximately 62% case fatality rate), making it the 'largest and deadliest' Ebola outbreak in history. The odds of the disease moving further to other African countries, especially along the West African coasts with cross boarder commercial and social activities were distressing. The fear was that Ebola in densely populated cities like Lagos in Nigeria could spell huge catastrophe, given our history of a weak health system, poor planning and delayed emergency responses. Eventually, Ebola was reported in Lagos, Nigeria in July 2014.

As at 8th May, 2016 the WHO and respective government agencies reported that a total of 28,616 suspected cases and 11,310 deaths were recorded globally with most of cases recorded in West Africa.

Mathematical models are a powerful tool for investigating human infectious diseases, such as Ebola virus. Epidemic models date back to the early twentieth century, to a set of three articles from 1927, 1932, and 1933 by Kermack and McKendrick, whose models were used for modeling the plagues and cholera epidemics, see [6].

The most commonly implemented models in epidemiology are the SIR and SEIR models. The SIR model consists of three compartments: Susceptible individuals S, Infectious individuals I, and Recovered individuals R. In many infectious diseases, there is an exposed period after the transmission of the infection from susceptible to potentially infective members but before these potentially infective members can transmit the infection. Thus, an extra compartment was introduced, it is called the Exposed class E, and we use compartments S, E, I and R to give a generalization of the basic SIR model, [7].

In this paper, we shall employ the SLIR model which is almost same with the SEIR model. Here, we replace the 'Exposed' compartment with 'Latently' infected compartment. It is important to note that persons who are 'Exposed' to the disease become 'Latently infected' in the sense that they have the virus but have not started exhibiting the symptoms of the disease. Thus, the SLIR and the SEIR models are synonymous; and the choice of SLIR instead of SEIR was for convenience.

Authors like those in [8] worked on SLIR for Tuberculosis, among others. We are motivated to work on EVD because of the devastation it has caused most especially on the West African coastal countries.

2. THE PROGNOSIS OF EVD

According to the author in [9], the virus is transmitted to people as a result of direct contact with body fluids containing virus (vomits, sweat, stool, urine, tears, breast milk, saliva and respiratory secretions) of an infected patient during the acute stage of disease. Epidemiological studies have revealed that family members are at high risk of infection because they may come in contact with infected body fluids or may help to prepare the corpse of an infected person for burial. Direct contact with virus containing material from contaminated hands of caregivers to their own mouth or eyes is the most common cause. Caregivers who work both at home and in hospitals are at greatest risk of exposure. While studies have proved the spread of EVD via aerosol particles under controlled laboratory conditions, such transmission rarely appeared in humans in a hospital or household setting during epidemics. Further, infection can occur through sexual contact and the virus has been traced in semen for up to seven weeks after recovery. It is recommended to control and use condoms during intercourse, and to avoid breast feeding for at least three months after recovery as to prevent secondary cases.

The Center for Disease Control and Prevention (CDC) has clearly outlined isolation procedures. The spread of infections are also the product of nosocomial or occupational transmission.

Table 1. Showing some West African countries with the cases, deaths and last updates of EVD

Country	Cases	Deaths	Last Update
Nigeria	20	8	Outbreak ended 19th October, 2014 Source: [2]
Guinea	3,804	2,535	Outbreak ended 1st June, 2016 Source: [3]
Sierra Leone	14,122	3,955	Outbreak ended 17th March, 2016 Source: [4]
Liberia	10,666	4,806	Outbreak ended 9th June, 2016 Source: [5]

For instance, in the first epidemics of Ebola, in Zaire, in 1976, the usage of contaminated needles resulted in simultaneous outbreak among over one hundred patients. Another example covers spread of the virus to an entire surgical team who performed an exploratory laparotomy on an EVD infected patient in Kikwit in 1995. In fact, healthcare workers coming in contact with affected people were mostly affected as the first generation cases in previous outbreaks. The propagation of infectious diseases can be avoided among health care workers through early detections of subjects and enforcement of appropriate preventive practices.

According to the authors in [10], outbreaks have gradually burned themselves out or have been controlled by effective public health measures including isolation of sick individuals and appropriate barrier protection methods for care providers and funeral services. It is believed that transmission of viruses needs direct contact or contact with infectious fluid rather than a possible aerosol route of transmission.

According to [11], outbreaks have been associated with human sporadic cases, involve high rates of case-fatality and cause social and economic disruption. The substantial clinical appearance of both EVD with severe hemorrhaging in most cases has also contributed to the high transmission rate and the fear of epidemic and imported cases. According to the US CDC and EVD have been classified as Category 'A' bioterrorism agent due to their highly infectious nature and potential use in biological weapons.

3. THE CONTROL OF EVD

According to the available data, barriers to preventing and controlling the EVD in affected countries include irresolute and disorganized health systems, substandard sanitary conditions, poor personal hygiene practices, and false beliefs and stigma related to EVD, [12]. There

are further hindrances due to the unavailability of electricity, water, adequate communication services between health officials, and poor facilities for transportation of patients and specimens, [13]. The public health sector along with the respective chief authorities in developing countries must devise strategies, keeping the available resources in mind, to deal with the outbreak before it occurs.

As a first step, communities should be educated on EVD's symptoms, history, mode of transmission, and methods of protection, including the importance of personal hygiene practices, via seminars, newspapers, and other social media. A Popular Opinion Leader (POL) giving this information would further help to remove the misconception about the nature of the disease and indirectly improve the quality of life of affected patients and their families, [14,15]. In addition, health systems should formulate proper plans for emergency care, ensuring adequate quarantine facilities, proper surveillance, case management, and contact tracing. Training should be given to healthcare providers in areas such as prompt diagnosis and isolation of a suspected patient, the importance of wearing personal protective equipment, and safe burial techniques [12]. There should be adequate distribution of gloves, gowns, masks, soaps, and disinfectants to healthcare facilities, and safety precautions should be devised especially for laboratory personnel including pre-transfusion testing, [16]. The CDC guidelines for monitoring patients (including symptomatic and asymptomatic), and precautions for healthcare professionals (including wearing personal protective equipment, practicing personal hygiene, use of disposable medical instruments, minimizing pricking and aerosol producing procedures, monitoring exposed staff, and adequate environment control) should be practiced, [17]. Special ambulances should also be reserved to enable the safe transport of EVD patients.

Incident Management Systems (IMSs), such as the one adopted by the CDC for the control of the current epidemics, has proven efficacious in preventing the spread and adequately controlling the disease [18,19]. A report about the employment of an IMS divulged that Nigeria has successfully limited the outbreak and no further cases have been reported since 19th October, 2014, see [2]. The employment of such a system has resulted in a decrease of EVD patients in Liberia, see [19].

Many drugs are being probed as preventive medications for EVD, such as amiodarone, chloroquine, and clomiphene [14]. An effective vaccine is also being devised; recombinant vesicular stomatitis virus vaccine has been the most promising, yet its efficacy has so far not been tested in humans, [20]. Another study found that Virus-Like Particles (VLPs) can provide post-exposure protection by amplifying Type 1 interferon signaling in macrophages and dendritic cells, which are thought to be the initial Ebola virus infection sites, [21].

Thus, taking these preventive measures will drastically reduce the outbreak of the EVD.

4. SIMULATION OF THE EVD

In simulating the EVD, the Susceptible-Latent-Infected-Recovered (SLIR) model shall be employed. In the model, the population is partitioned into four (4) compartments or classes based on the epidemiological state of individuals in the population, this is to enable us describe the Ebola disease dynamics within the population. The compartments are: the Susceptible, the Latent, the Infectious and the Recovered compartments.

The susceptible compartment increases due to the coming in of newborn babies and those treated and recovered from the disease. The class reduces due to infection of some people in the susceptible class who become latently infected in the sense that they have the virus but have not started exhibiting the symptoms of the disease. The class also reduces as a result of death from natural causes. The population of the Latent class increases as a result of the infection of some people in the susceptible class with the virus. The compartment decreases due to the progression of some people from this class to the infectious class, the recovery of latently infected individuals though treatment and care, as well as death from natural causes. The infectious

compartment increases due to the progression of latently infected individual into this class. The compartment decreases due to the recovery of people who have received treatment and are cured of the disease, as well as due to death from Ebola-related causes and natural death.

The recovered compartment increases due to the coming in of latently and actively infected people who have successfully been treated and so are recovered and decreases due to the fact that recovered individual do not have any form of immunity against the virus and so once again become susceptible to the infection. The compartment also decreases due to death from natural causes.

4.1 Assumptions from the EVD SLIR Model

We make the following assumptions in the model;

- That the individuals that make up the population can be grouped into different compartments or classes based on their epidemiological state. In other words, the population is assumed to be heterogeneous,
- That the population size in each compartment is differentiable with respect to time and that the epidemic process is deterministic. In other words, that the changes in population of a compartment can be calculated using only history to develop the model,
- That the population mixes homogeneously. That is, all the susceptible individuals are equally likely to be infected by infectious individuals in case of contact,
- That people in each compartment have equal natural death rate,
- That the only way of entry into the population is through newborn babies and the only way of exit is through death from natural causes or death from EVD related causes. In other words, that there are no immigration or emigration,
- That the infection does not confer any immunity to the cured and recovered individuals and so they go back to the susceptible compartment,
- That all newborns are previously uninfected by Ebola virus and therefore join only the susceptible class,
- That there is presently no vaccination that provides immunity against the EVD, and

- That infected individuals could be treated and cured of the virus.

4.2 Definition of Variables and Parameters

The variables and parameters used in this model are defined as follows:

S(t): The population of Susceptible individuals at time t
L(t): The population of Latently infected individuals at time t
I(t): The population of Infected individuals at time t
R(t): The population of individuals who have been treated and have Recovered from the infection at time t.
α : The rate at which susceptible individuals become latently infected with the virus.
β : The rate at which latently infected individual become actively infected with the disease.
π : The rate at which actively infected individuals recover from the disease.
γ : The rate at which latently infected individuals recover from the disease.
k: The rate at which recovered individuals return to the susceptible compartment.
μ : The natural mortality or death rate.
d: The Ebola virus disease-induced mortality or death rate
$\wedge$: The population of newborn babies entering the population.
N: The total population size.

Based on the assumptions and the inter-relationships between the variables and the parameters presented above, the EVD dynamics can be described by the following system of differential equations:

$$\left.\begin{array}{l} \dfrac{dS}{dt} = \wedge - \alpha SI - \mu S + kR \\[2mm] \dfrac{dL}{dt} = \alpha SI - (\mu + \beta)L - \gamma L \\[2mm] \dfrac{dI}{dt} = \beta L - (\pi + \mu + d)I \\[2mm] \dfrac{dR}{dt} = \pi I - (k + \mu)R + \gamma L \end{array}\right\} \quad (1)$$

Note that the total population N, is given by

$$N = S + L + I + R \quad (2)$$

The schematic representation of the EVD SLIR model is presented in the Figure below;
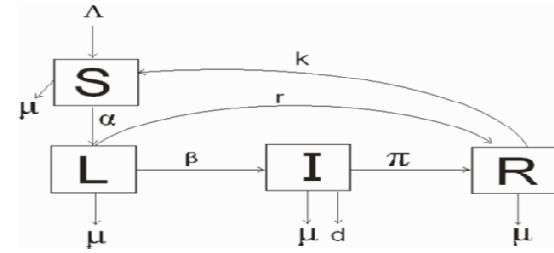

Fig. 1. Schematic presentation of the SLIR EVD model

4.3 Deductions from the EVD SLIR Model

The following deductions will be made from the EVD SLIR model.

4.3.1 Equilibrium point

At the point of equilibrium, we have,

$$\frac{dS}{dt} = \frac{dL}{dt} = \frac{dI}{dt} = \frac{dR}{dt} = 0 \quad (3)$$

This implies that:

$$\wedge - \alpha SI - \mu S + kR = 0 \quad (4)$$

$$\alpha SI - (\mu + \beta)L - \gamma L = 0 \quad (5)$$

$$\beta L - (\pi + \mu + d)I = 0 \quad (6)$$

$$\pi I - (k + \mu)R + \gamma L = 0 \quad (7)$$

4.3.2 Disease-free equilibrium state

The disease-free equilibrium state is the state of total eradication of the disease. Suppose the disease-free equilibrium point is $E^* = (S^*, L^*, I^*.R^*)$. At the disease-free equilibrium state,

$$L^* = I^* = 0 \quad (8)$$

Substituting equation (8) into equations (4) and (7) gives

From (4),

$$\wedge - \mu S + kR = 0 \quad (9)$$

and from (7),

$$-(k + \mu)R = 0 \quad (10)$$
$$\Rightarrow R^* = 0$$

We substitute R = 0 into (9) to obtain,

$$\Lambda - \mu S = 0$$
$$\Rightarrow S^* = \frac{\Lambda}{\mu} \qquad (11)$$

Therefore, $E^* = \left(\dfrac{\wedge}{\mu},\ 0,\ 0,\ 0 \right)$

4.3.3 Stability analysis of the disease-free equilibrium point

We determine the Jacobian matrix of the system in order to analyze the stability of the disease-free equilibrium. The Jacobian matrix, J, of the system of equations is given by:

$$J = \begin{bmatrix} -\mu & 0 & -\alpha S & k \\ \alpha I & -(\mu + \beta + r) & \alpha S & 0 \\ 0 & \beta & -(\pi + \mu + d) & 0 \\ 0 & r & \pi & -(k + \mu) \end{bmatrix}$$

At the disease-free equilibrium point, the Jacobian matrix gives:

$$J^* = \begin{bmatrix} -(\alpha I + \mu) & 0 & -\alpha \frac{\Lambda}{\mu} & k \\ 0 & -(\mu + \beta + r) & \alpha \frac{\Lambda}{\mu} & 0 \\ 0 & \beta & -(\pi + \mu + d) & 0 \\ 0 & r & \pi & -(k + \mu) \end{bmatrix}$$

Let λ_i be the Eigen values of the system, then the characteristic equation is $|J^* - \lambda I| = 0$

$$\begin{vmatrix} -(\alpha I + \mu) & 0 & -\alpha \frac{\Lambda}{\mu} & k \\ 0 & -(\mu + \beta + r) & \alpha \frac{\Lambda}{\mu} & 0 \\ 0 & \beta & -(\pi + \mu + d) & 0 \\ 0 & r & \pi & -(k + \mu) \end{vmatrix} = 0$$

$$-(\mu + r) \begin{vmatrix} -(\mu + \beta + r) - \lambda & \alpha \frac{\Lambda}{\mu} & 0 \\ \beta & -(\pi + \mu + d) - \lambda & 0 \\ r & \pi & -(k + \mu) - \lambda \end{vmatrix} = 0$$

$$-(\mu + \lambda) - (k + \mu + \lambda) \begin{vmatrix} -(\mu + \beta + r + \lambda) & \alpha \frac{\Lambda}{\mu} \\ \beta & -(\pi + \mu + d + \lambda) \end{vmatrix} = 0$$

Thus, either

$$[\![(\mu + \lambda) - (k + \mu + \lambda)]\!] = 0 \qquad (12)$$

Or

$$\begin{vmatrix} -(\mu + \beta + r + \lambda) & \alpha \frac{\Lambda}{\mu} \\ \beta & -(\pi + \mu + d + \lambda) \end{vmatrix} = 0 \ (13)$$

Solving equation (12) gives:

$$\lambda_1 = -\mu,\ \lambda_2 = -(\mu + k)$$

Let,

$$A = \begin{pmatrix} -(\mu + \beta + r) & \alpha \frac{\Lambda}{\mu} \\ \beta & -(\pi + \mu + d) \end{pmatrix}$$

It is also important to note that the Routh-Hurwitz necessary and sufficient conditions for the remaining two Eigen values of the characteristic equation to have negative real parts, implying asymptotic stability, is that trace A< 0 and det A > 0.

$$\text{Trace } A = -(\mu + \beta + r) - (\pi + \mu + d)$$

It is clearl that, trace A< 0, since all the parameters are positive. For det A to be positive, (i.e. det A > 0), we must have

$$\begin{vmatrix} -(\mu + \beta + r) & \alpha \frac{\Lambda}{\mu} \\ \beta & -(\pi + \mu + d) \end{vmatrix} > 0$$

Or

$$(\mu + \beta + r)(\pi + \mu + d) - \alpha \beta \frac{\Lambda}{\mu} > 0$$
$$\Rightarrow \alpha \beta \frac{\Lambda}{\mu} < (\mu + \beta + r)(\pi + \mu + d) \qquad (14)$$

4.4 Simulation of the EVD SLIR Model

In simulating the EVD SLIR model, we shall apply the computational method derived by the authors in [22]. They derived a computational one-step hybrid block method of the form,

$$A^{(0)} \mathbf{Y}_m = E \mathbf{y}_n + h d \mathbf{f}(\mathbf{y}_n) + h b \mathbf{F}(\mathbf{Y}_m) \qquad (15)$$

using the first six terms of Legendre polynomial as our basis function of the form;

$$y_6(x) = 9 + 22x + 69x^2 - 100x^3 - 245x^4 + 126x^5 + 231x^6 \qquad (16)$$

The parameters in equation (15) are defined by;

$$\mathbf{Y}_m = \begin{bmatrix} y_{n+\frac{1}{5}} & y_{n+\frac{2}{5}} & y_{n+\frac{3}{5}} & y_{n+\frac{4}{5}} & y_{n+1} \end{bmatrix}^T,\quad \mathbf{y}_n = \begin{bmatrix} y_{n-\frac{4}{5}} & y_{n-\frac{3}{5}} & y_{n-\frac{2}{5}} & y_{n-\frac{1}{5}} & y_n \end{bmatrix}^T$$

6

$$\mathbf{F}(\mathbf{Y}_m) = \begin{bmatrix} f_{n+\frac{1}{5}} & f_{n+\frac{2}{5}} & f_{n+\frac{3}{5}} & f_{n+\frac{4}{5}} & f_{n+1} \end{bmatrix}^T , \quad \mathbf{f}(\mathbf{y}_n) = \begin{bmatrix} f_{n-\frac{4}{5}} & f_{n-\frac{3}{5}} & f_{n-\frac{2}{5}} & f_{n-\frac{1}{5}} & f_n \end{bmatrix}^T$$

$$A^{(0)} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad E = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad d = \begin{bmatrix} 0 & 0 & 0 & 0 & \frac{19}{288} \\ 0 & 0 & 0 & 0 & \frac{14}{225} \\ 0 & 0 & 0 & 0 & \frac{51}{800} \\ 0 & 0 & 0 & 0 & \frac{14}{225} \\ 0 & 0 & 0 & 0 & \frac{19}{288} \end{bmatrix}$$

$$b = \begin{bmatrix} \frac{1427}{7200} & \frac{-133}{1200} & \frac{241}{3600} & \frac{-173}{7200} & \frac{3}{800} \\ \frac{43}{150} & \frac{7}{225} & \frac{7}{225} & \frac{-1}{75} & \frac{1}{4500} \\ \frac{219}{800} & \frac{57}{400} & \frac{57}{400} & \frac{-21}{800} & \frac{3}{800} \\ \frac{64}{225} & \frac{8}{75} & \frac{64}{225} & \frac{14}{225} & 0 \\ \frac{25}{96} & \frac{25}{144} & \frac{25}{144} & \frac{25}{96} & \frac{19}{288} \end{bmatrix}$$

The computational method in equation (15) is capable of simulating the EVD SLIR model.

Experiment: we shall consider a sampled population with a total number of 105,000 persons. Suppose the population is affected by the EVD and at the initial point (time), the population satisfies the following conditions;

$$t_0 = 0, S(t_0) = 70000, L(t_0) = 20000,$$
$$I(t_0) = 15000, R(t_0) = 0, h = 0.1$$

We then apply the computational method in equation (15) to simulate the EVD SLIR model defined in equation (1) using the parameters in Table 2 and the initial conditions presented above. This gives the graphical results presented in Figs. 2 and 3. The graphical results were generated using MATLAB programming language.
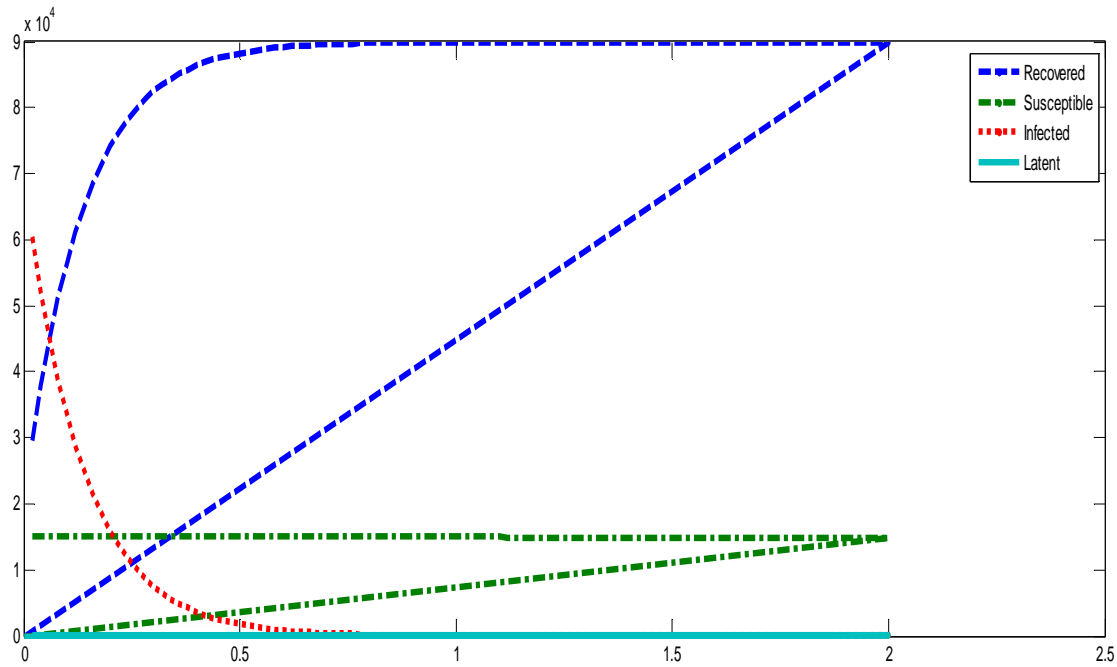
4.4.1 Discussion and interpretation of results

In Fig. 2, we observed that (on applying the parameters in Table 2) the number of recovered class increases with time while the number of infected class reduces. The susceptible class also reduces slowly (which is not visible on the graph because of the slow change) with time while the latently infected class maintains a steady state.

Table 2. Values of the parameters for the EVD model

Figure	$\wedge$	α	μ	κ	β	π	γ	d
Fig. 2	0.0001	0.0001	0.0001	0.004	0.0002	0.005	0.002	0.002
Fig. 3	0.0001	0.0005	0.0001	0.0004	0.0002	0.0005	0.0002	0.0003
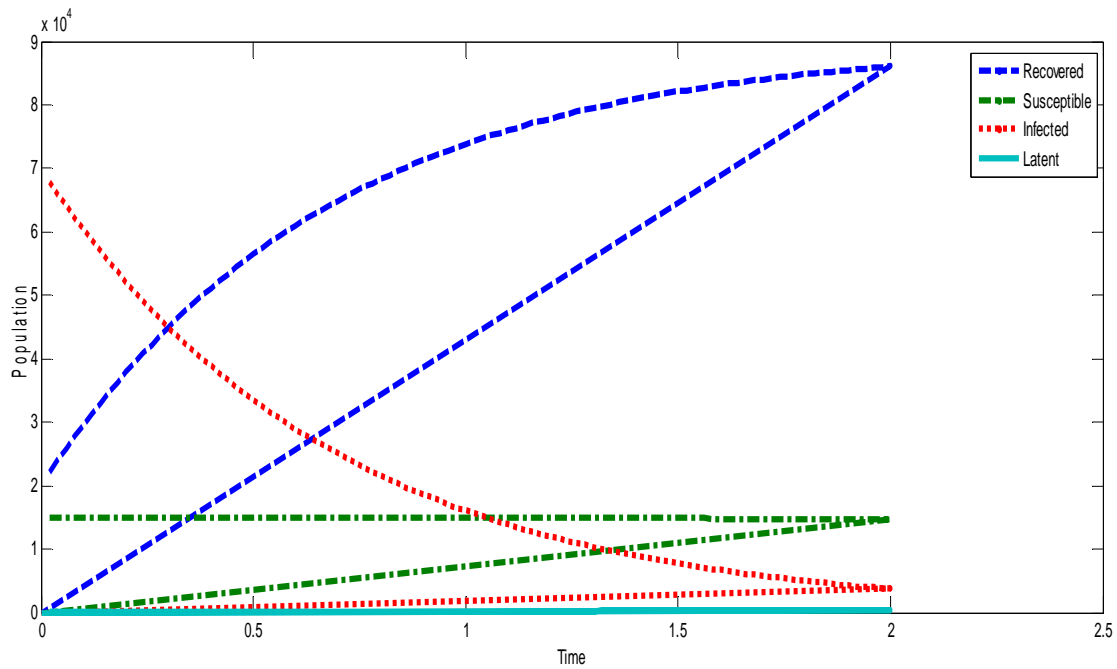
Fig. 2. Graphical results for the EVD SLIR model based on the parameters in Table 1

Fig. 3. Graphical results for the EVD SLIR model based on the parameters in Table 1

In Fig. 3, we observed that (on applying the parameters in Table 2) the number of recovered class increases sharply while the number of infected class reduces sharply with time. As in Fig. 2, the susceptible class maintains a slow reduction with time while the latently infected class maintains a steady state.

5. CONCLUSION

It is clear from this research that Governments need to put in more effort in combating the menace of EVD. More conscious efforts also need to be put in place by enlightening people on this disease.

Also, from the simulations carried out on the EVD SLIR model using the computational method derived by [22]; it is obvious that in order to hold the epidemic under control, reduce mortality rate arising from EVD, reduce the rate of infected class and increase the rate of recovered class, the parameters in Table 1 has to be strictly adhered to. We also observed that the parameters used in generating Fig. 3 performs better than those used in generating Fig. 2.

Finally, it is important to state that one of the major advantages of the results obtained in this research is that through simulation of the model, approximate values of parameters have been provided that will help guarantee efficient outputs/results; thus, an improvement over existing ones.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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