World Health Organization
Regional Office for Africa
Cit du Djou, P.O.Box 06 Brazzaville
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Dear Dr. W.T.Gwenigale,

After doing some research into the matter, here's our research into the effects of a potential 2020 outbreak of Ebola to the cities of Harper and Monrovia, Liberia. It's divided into the following sections:

- Background Information
- Models for Harper, Liberia
- Models for Monrovia, Liberia
- Final Conclusions

Ultimately, through our research, we find that the speedy implementation of the quarantine reduces the number of people who die within an outbreak - an intuitive observation. Furthermore, we find that the larger the initial infected population is, the speedier the course of the endemic seems to go. We'll investigate the details of this in the enclosed report.

1 Background Information

Liberia is a country in the western portion of the African continent. Its capital, Monrovia, is also its largest city, but the other city under consideration of our model, Harper ranks at the 4th largest city in Liberia. Using 2020 UN estimates, Harper and Monrovia have a population of 32,661 and 1,021,762, respectively.

Liberia would not face Ebola for the first time were it to be reintroduced in 2020. In 2014-2016, Liberia experienced an outbreak which infected 6,326 people. Ebola is an immunizing disease, and thus, the people who have survived that outbreak (3,163 people) will not be susceptible to a 2020 outbreak. Furthermore, Ebola is a disease which is transmitted through contact with the fluids of others. People who have recovered from Ebola can infect others through blood/spit/sweat (if immediately after) or through sexual intercourse (if it is up to 1 year after). Finally, an important characteristic of Ebola is that people are not infectious until they start showing symptoms, which is usually 9 days after contracting the illness.

Our Model Assumptions are the following:

- Assume Ebola is not infectious before it's symptomatic
- Assume no dormancy period
- Assume no births, deaths, migrations
- Assume the dead are cleaned up within a day (so they don't infect others)
- Assume Infection rates don't change seasonally
- Assume Recovered people don't infect others (as this is hard to measure)
- Assume incubation period is 9 days
- Assume infectious period is 25 days
- Assume r0 is 1.75
- Assume mortality rate of 50 percent
- Assume populations are 32661 (Harper), 1021762 (Monrovia)

Variables Encountered in This Report:

- T = time (in days)
- Beta = infection rate of the symptomatic = .0000214
- Delta = rate people become symptomatic = 1/9
- Mu = proportion of infected who die = .02
- Lambda = proportion of infected who recover and become immune = .021
- Xi = rate of quarantining = 1/14

2 Models for Harper, Liberia

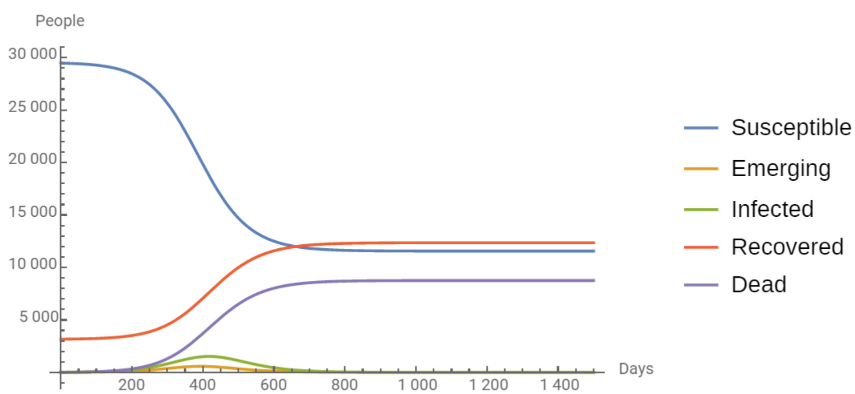
Response to Question One: Without any intervention, how long would it take for $S0 = 0$ in Harper, Liberia in an Ebola outbreak starting with 20 infected individuals?

Initial Conditions

- $S0 = 29478$
- $E0 = 0$
- $I0 = 20$
- $R0 = 3163$
- $D0 = 0$

Equations used in this model

- $S(t) = -beta * S(t) * I(t)$
- $E(t) = beta * S(t) * I(t) - delta * E(t)$
- $I(t) = delta * E(t) - lambda * I(t) - mu * I(t)$
- $R(t) = lambda * I(t)$
- $d(t) = mu * I(t)$



As we can see, Harper never reaches a point where $S0 = 0$, due to reaching the herd immunity threshold around 700 days into the endemic. The dead level off at around 8,000, while the recovered rest around 12,000 each.

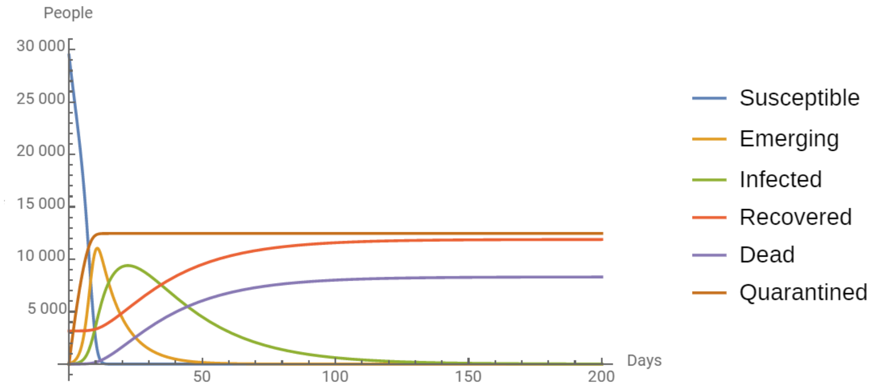
Response to Question Two: How would this situation change if the WHO quarantines 50 percent of the population each week immediately?

Initial Conditions

- $S0 = 29459$
- $E0 = 0$
- $I0 = 20$
- $R0 = 3163$
- $D0 = 0$
- $Q0 = 0$

Equations used in this model

- $S(t) = -beta * S(t) * I(t) - xi * S(t)$
- $E(t) = beta * S(t) * I(t) - delta * E(t)$
- $I(t) = delta * E(t) - lambda * I(t) - mu * I(t)$
- $R(t) = lambda * I(t)$
- $D(t) = mu * I(t)$
- $Q(t) = xi * s(t)$ Notice the inclusion of the Quarantine Equation



With an immediate quarantine, we see that the susceptible population drops sharply, hitting zero around day 15. But we also see the death rate rising at a lot slower rate, settling to a lower final number than the non-quarantined situation.

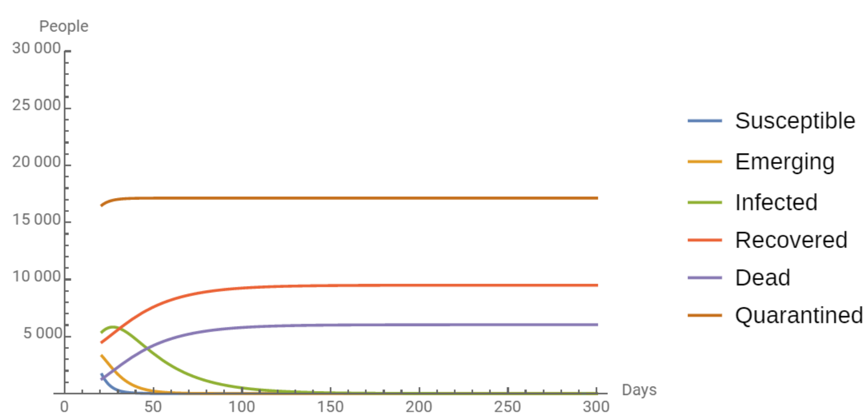
Response to Question Three: How would this situation change if the WHO quarantines 50 percent of the population each week with a 3 week (21 day) delay?

Initial Conditions

- $S0 = S[21] frommodel1$
- $E0 = E[21] frommodel1$
- $I0 = I[21] frommodel1$
- $R0 = R[21] frommodel1$
- $D0 = D[21] frommodel1$
- $Q0 = 0$

Equations used in this model

- $S(t) = -beta * S(t) * I(t) - xi * S(t)$
- $E(t) = beta * S(t) * I(t) - delta * E(t)$
- $I(t) = delta * E(t) - lambda * I(t) - mu * I(t)$
- $R(t) = lambda * I(t)$
- $D(t) = mu * I(t)$
- $Q(t) = xi * s(t)$



With a delayed response, the disease is already on its way towards transitioning, and the addition of a quarantine, though helping, doesn't show the same marked improvement as an immediate response does.

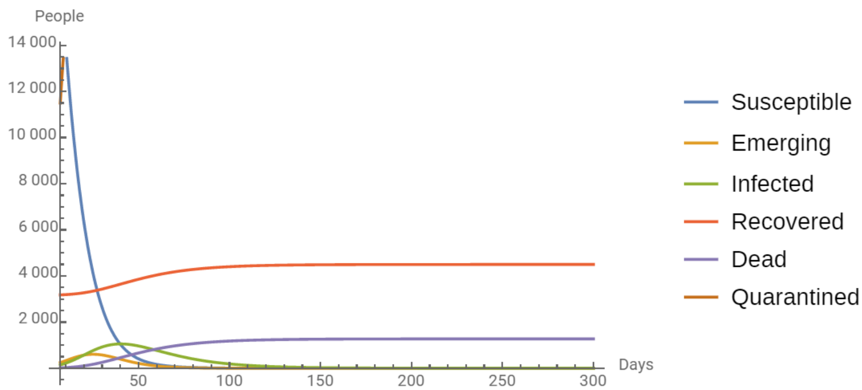
Response to Question Four: How would this situation change if the WHO quarantines 50 percent of the population each week with a 1 week (7 day) delay?

Initial Conditions

- $S0 = S[7] frommodel1$
- $E0 = E[7] frommodel1$
- $I0 = I[7] frommodel1$
- $R0 = R[7] frommodel1$
- $D0 = D[7] frommodel1$
- $Q0 = 0$

Equations used in this model

- $S(t) = -beta * S(t) * I(t) - xi * S(t)$
- $E(t) = beta * S(t) * I(t) - delta * E(t)$
- $I(t) = delta * E(t) - lambda * I(t) - mu * I(t)$
- $R(t) = lambda * I(t)$
- $D(t) = mu * I(t)$
- $Q(t) = xi * s(t)$



There's a marked difference between the death rates of a 21 day delay and that of a 7 day delay - it's significantly helpful to reduce the delay times. We also see that this reduces the time of the Endemic.

3 Models for Monrovia, Liberia

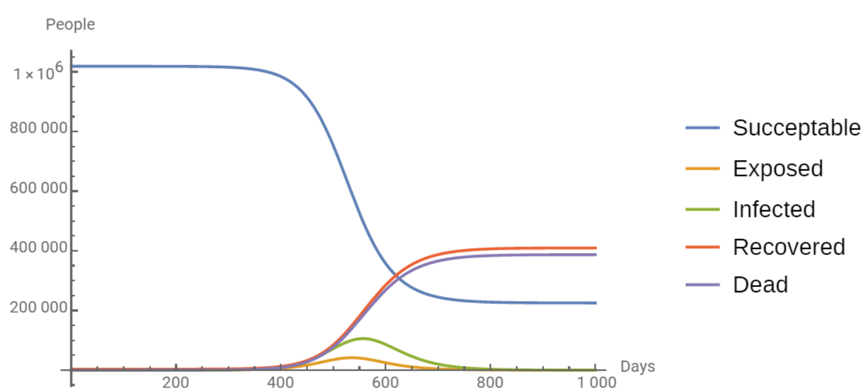
Response to Question Five: If an infected individual visits the capital city of Monrovia, how long before S = 0 without intervention?

Initial Conditions

- $S0 = 1018589$
- $E0 = 0$
- $I0 = 1$
- $R0 = 3163$
- $D0 = 0$

Equations used in this model

- $S(t) = -beta * S(t) * I(t)$
- $E(t) = beta * S(t) * I(t) - delta * E(t)$
- $I(t) = delta * E(t) - lambda * I(t) - mu * I(t)$
- $R(t) = lambda * I(t)$
- $d(t) = mu * I(t)$



In Monrovia, we see that, similar to Harper, the Susceptible population never hits 0, with the general length of the endemic just under 800 days, or a little over 2 years.

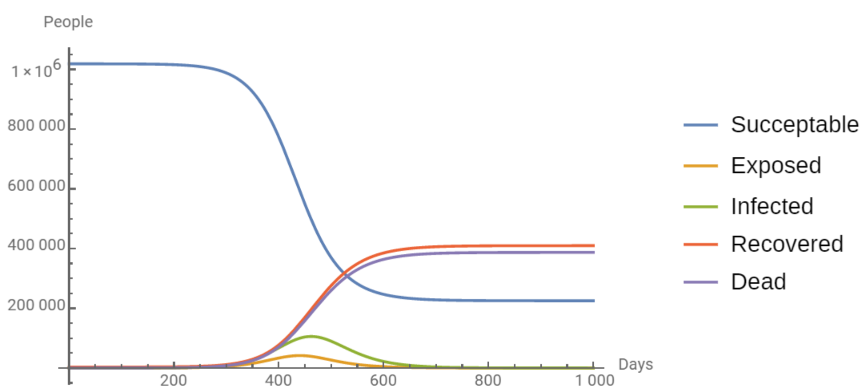
Response to Question Six: If an an infected family (I0 = 5) visits the capital city of Monrovia, how long before S = 0 without intervention?

Initial Conditions

- $S0 = 1018585$
- $E0 = 0$
- $I0 = 5$
- $R0 = 3163$
- $D0 = 0$

Equations used in this model

- $S(t) = -beta * S(t) * I(t)$
- $E(t) = beta * S(t) * I(t) - delta * E(t)$
- $I(t) = delta * E(t) - lambda * I(t) - mu * I(t)$
- $R(t) = lambda * I(t)$
- $d(t) = mu * I(t)$



With a larger initial infected population, we see two things: first, the number of dead are slightly higher than the graph from question 5, but the pandemic length is also a lot shorter - intuitively, we could reasonably consider that the larger the initial infected population is, the faster rate of intervention we may need, as it seems like the endemic length shortens with a higher infected population.

4 Final Conclusions

As we can see, much to our intuition, a quarantine can help reduce the death rates of an Ebola endemic. Furthermore, a larger initial infected population creates a quicker endemic, as the infection rate starts higher and infects faster. This could imply that WHO resources should be allocated in such a way that the areas with the highest initial infected get priority, as quarantines will only be effective if they're within a smaller window of time. This somewhat fits into our understanding of Harper as well, as its starting I of 20 was higher than the initial Is of Monrovia, and their endemic was shorter by nearly 150 days.

However, we do want to note a few things for further research. First, we didn't include births, deaths, migrations, and so on. As the line of inquiry sent to us searched for when the Susceptible population hits 0, we thought it was not an important component of the model, but should one want to make a more detailed model, it's an important thing to include. Furthermore, we would likely need to account for the infectious rate of the newly dead and the recovered, or first, find some way to estimate their ability to infect others. Finally, an interesting line of research can be dedicated to how behavior change as more and more people get infected. Especially since Ebola is a particularly distasteful disease to witness, it would stand to reason that the population behavior would change as more and more people get infected. Furthermore, as this is a disease that requires fluid contact, this change would make a significant difference into our variables because, unlike airborne illnesses, we would need to be close to the infected person in order to become infected by them.

To health, washing our hands, and prosperity.

Best,
Hannah Hunt, Vee Kalkunte, and Elisha Lisson