Extra Exercises for Chapter 8. Epidemic Dynamics: Yellow Fever

Yellow Fever is an acute infectious viral disease of short duration and varying severity. It is transmitted in urban areas by the bite of infective Aedes aegypti mosquitoes.

These exercises are based on the Stella model in Fig 1, which was adapted from a Dynamo model by Kjell Kalgraf in Michael Goodman's 1983 book, Study Notes in System Dynamics. Kalgraf described the urban form of yellow fever in which humans contract yellow fever from the bites of infectious mosquitoes. The mosquitoes, in turn, become infectious by biting contagious humans. Kalgraf based the model on a 1989 epidemic in Veracruz, Mexico in 1989 in which deaths reached 460 per month (around 15/day) at the peak of the epidemic.

Veracruz had around 20,000 people living within contact of around 500,000 mosquitoes. The model below simulates the interactions between the two populations, with people on the right, and mosquitoes on the left. Peak day values are superimposed on the stocks and flows.

Figure 1. Peak day conditions in a Stella simulation of a Yellow Fever Epidemic.
The Mosquitoes: Adult mosquitoes emerge from the pupae at the rate of 27,778 per day. Total population remains at around 500,000 for the duration of the epidemic. The mosquitoes live for 18 days. They need four blood feeds during their lifetime, so the average mosquito bites 0.2 persons per day, causing around 100,000 bites/day. Mosquitoes become “safe” if they do not bite a contagious human during their first 3 days. If they do bite a contagious human during this period, they become dangerous to humans. Their remaining 15 days are 12 days of incubation and 3 days infectious.

The Humans: A human contracts yellow fever if bitten by an infectious mosquito. This person enters an incubation period for 4.5 days, followed by a contagious period of 4.5 days and a sick period of 2.5 days. After experiencing the sickness for 2.5 days, 90% of the humans recover and become immune to yellow fever. The model keeps track of the immune population and the cumulative number of deaths.

Figure 2. Vensim version of the Yellow Fever model used in these exercises. The Vensim diagram follows the Stella example: mosquitoes on the left, people on the right. The total human population is in the top right with shadow variables to make the summation clear. (This corresponds to the human population in Stella which used a Sum function with a + sign inside the variable, but only a portion of the + sign is visible.) Fig 2 highlights deaths per day. We expect to see a peak of 18 deaths/day when running the Vensim model.
Exercises

#1, Build the Vensim model in Fig. 2, and Verify the Results in Fig 3.
Initialise four of the stocks with:
19,900 vulnerable people,
100 incubating people,
417,000 safe mosquitoes and
83,000 new mosquitoes
Then initialise the other stocks at zero.

Set mosquito parameters as in Fig 1
emerging mosquitoes = 27,778/day
new interval = 3 days
remaining interval = 15 days
incubation period = 12 days
infectious period = 3 days
bites/day per mosquito = 0.2

Set the humans parameters as in Fig 1:
incubation period = 4.5 days
contagious period = 4.5 days
sickness period = 2.5 days
recovery fraction = 0.9

Write equations for the other variables, remembering to use “Friendly Algebra”
(in other words, either add, subtract, multiply or divide). Be sure to resist the temptation to write in the numerical values in Fig. 1 since these numbers are the peak results, not input values.

Figure 3. Base case simulation of the Vensim model in Figure 2. Deaths/day peak at 18 half way through the simulation. This pattern corresponds to Kalgraf’s model and the Stella model.
Create a Customized Vensim Graph to Verify the Results in Fig 4.

This graph adds the different categories of people. The stack confirms that the total remains constant at 20,000. (The stack includes cumulative deaths and there is no migration in or out of the city.) Vensim allows you to name the data set created when you run the model. This data set was named “no reduction” as there is no reduction in the number of emerging mosquitos during the simulation. Click on the “fill” option and Vensim colors the spaces in the stack: blue for the vulnerable people, green for incubating people, etc. (I selected these colors in my version of Vensim, so your colors may differ from mine.) The stack starts with 19,900 vulnerable people and 100 incubating people, so the blue plus green areas add to 200,000 in the 1st day.

Contagious people are next, shaded in purple, followed by sick people shaded in black. These slices look small compared to others, but they lead to the deaths which are accumulated and displayed in brown at the top of Fig. 4.
#3. Create Customized Graphs to Verify the Results in Figures 5, 6, 7, 8, 9

**Figure 5: Mosquito Population**

The Stacked graph of Mosquitoes shows their total number at around 500 thousand. This is to be expected with 27.8 thousand/day emerging and a 18 day life expectancy, as deaths should be 500 K/18 days = 27.8K/day. The vast majority of the mosquitos are safe, so their bites cannot infect humans.

The slivers of incubating and infections mosquitos is ever so small in this comparison, but they are responsible for the deaths in Fig 3.

**Fig 6. Mosquitos’ daily emergence and deaths**

Mosquitoes emerge at the rate of 27,770 per day. The initial values are 83K NEW, 417K SAFE, for a total of 500K. The green curve shows eaths/day that keep the population constant at around 500K for the entire simulation.
Figure 7: Deaths/day with different assumptions on bites/day.

The blue curve shows deaths/day at zero if the mosquitos only have 0.1 bite/day,

The green curve shows the base case result: deaths/day peak at 18 with 0.2 bites/day.

The brown & black curves assume 0.3 and 0.4 bites/day. These assumptions cause the epidemic to appear sooner and reach higher peaks in daily deaths.

Figure 8: Sick People with different assumptions on bites/day

The blue curve shows zero sick people with mosquito bites at 0.1/day. The green curve is the base case, with number of sick people peaking just below 500.

The brown & black curves show peaks in the sick population exceeding 1,000 with 0.3 bites/day and exceeding 1,500 with 0.4 bites/day.

Figure 9: Cumulative Deaths with different assumptions on bites/day.

The blue curves show zero deaths if there are only 0.1 bites/day. The green curve is the base case with 0.2 bites/day. Cumulative deaths reach an inflection point in the 140th day and levels off around 1,800 by the end of the simulation.

The simulations with 0.3 or 0.4 bites/day level off at 2,000 cumulative deaths, which is 10% of the 20,000 people in the urban area.