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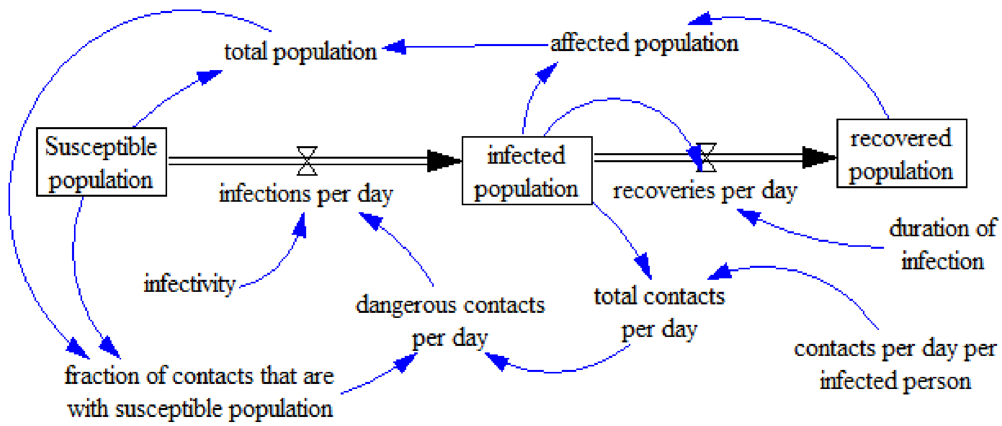
EAS 550/STRATEGY 566: Systems Thinking for Sustainable Development and Enterprise

Lab 9 Modeling epidemic dynamics
Questions in purple

1. S-I-R Model

Build the complete S-I-R model as described below:

a. Stock and flow diagram:



b. Model parameters

i. Population = 10,000

1. 2 infected and 9,998 susceptible

ii. Duration of infection = 2 days

iii. Contacts per day per infected person = 6

iv. Infectivity = 0.25 (25% of these contacts will cause infection.)

v. Recoveries per day = infected population / duration of infection

vi. We assume the fraction of contacts with a susceptible person is identical to the fraction of the population that is susceptible.

vii. Fraction of contacts that are with susceptible population = susceptible population / total population

viii. Dangerous contacts per day = fraction of contacts that are with susceptible population × total contacts per day

ix. Total contacts per day = infected population × contacts per day per infected person

x. Infections per day = infectivity × dangerous contacts per day

xi. Affected population = infected population + recovered population

xii. Total population = susceptible population + affected population

Questions:

Simulate the model for 40 days with a time-step of 0.125 days. Provide your model results of susceptible population, infected population, recovered population, and affected population as a graph below.

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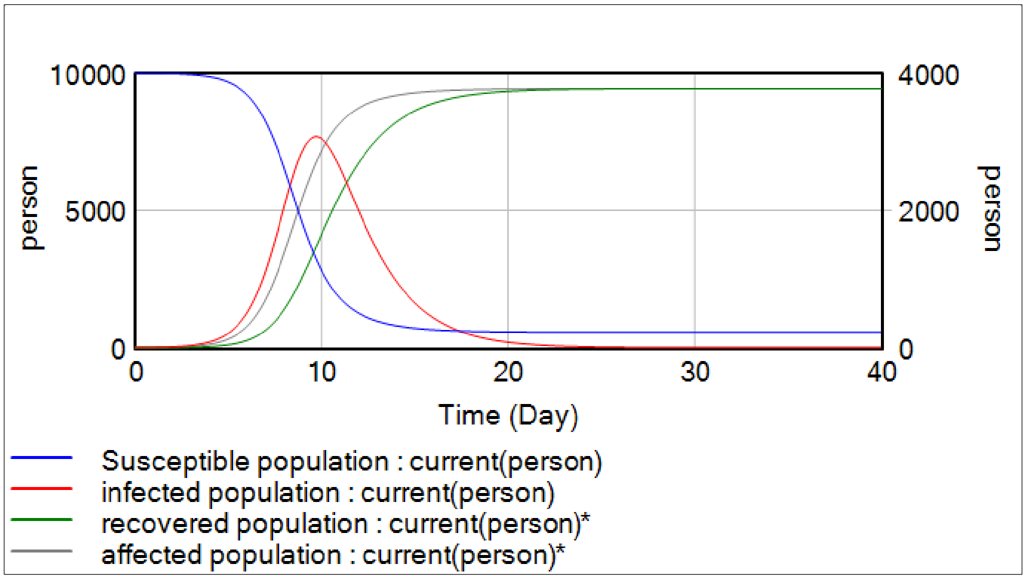
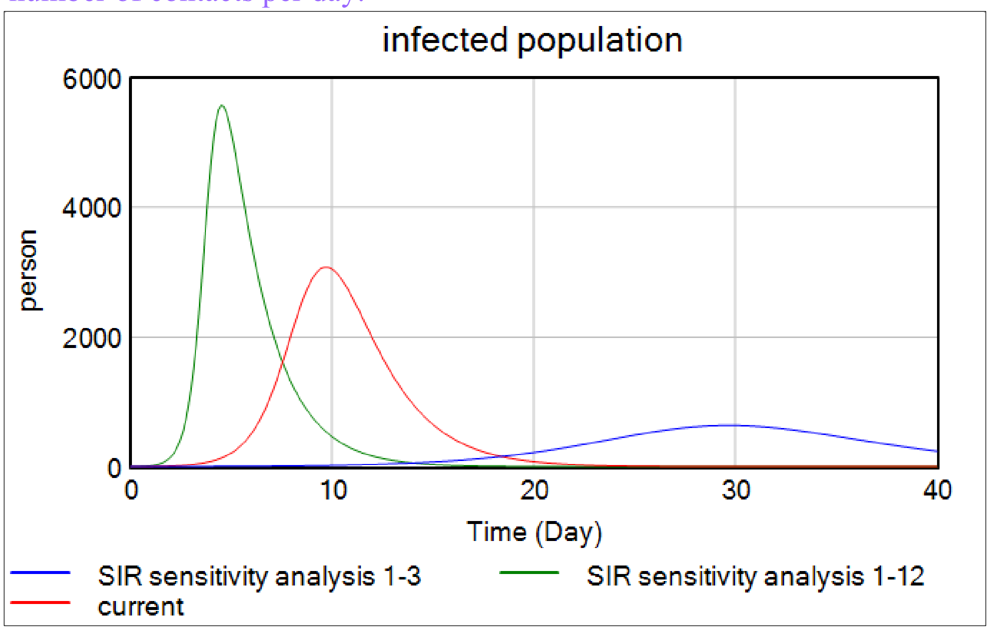


Sensitivity analysis 1: Conduct three simulations with the contacts per day per infected person set to 12, 6, and 3. Provide your results of the infected population below. Briefly describe the effect of the number of contacts per day.



Higher number of contacts per day per infected person leads to greater value of the peak infected population, and the results are seen earlier throughout the simulation. As presented in the image above, the green line indicating 12 contacts per day per infected person has its peak on approximately the 5th day, and has the most substantial value on that day. The red line showing 6 contacts per day per infected person has its peak on the 10th day and the greatest number is lower than the green line. The blue line representing 3 contacts per day per infected person has its peak on the 30th day, and has the lowest peak among the three. At the end of this simulation, only the green and the red lines reach their equilibrium, where all population has been infected so is at about 0. The blue line may reach its equilibrium at 0 if the simulation takes place longer.

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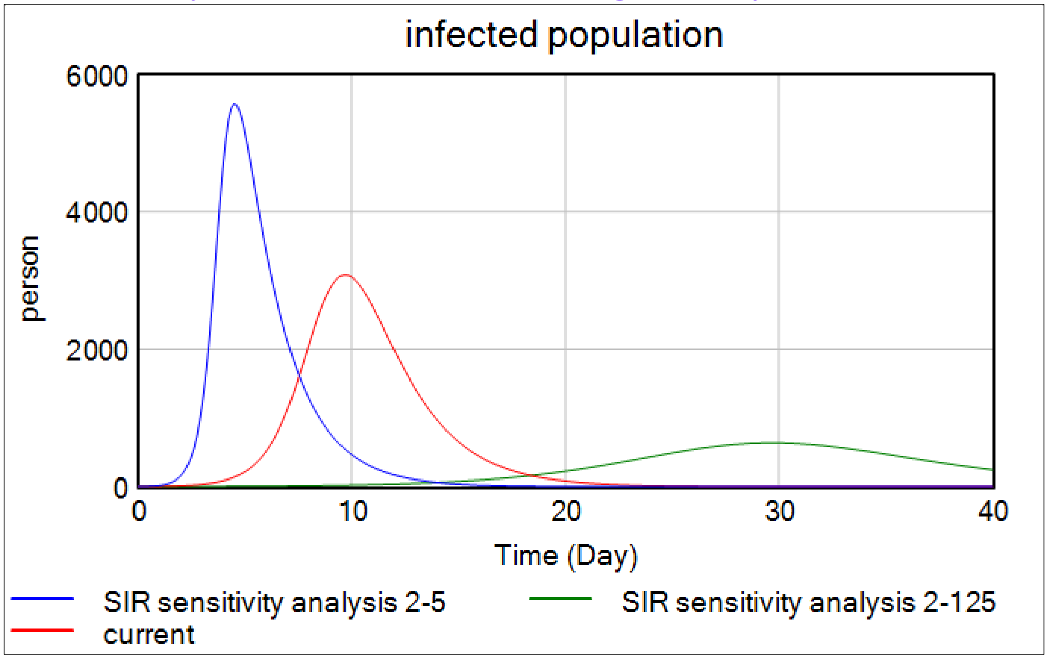
Sensitivity analysis 2: Reset contacts per day per infected person back to 6. Conduct three simulations with infectivity set to 50%, 25%, and 12.5%. Provide your results of the infected population below. Briefly describe the effect of decreasing infectivity.



The effects of the change in the infectivity looks similar to the number of contacts per day per infected person. Higher proportion of infectivity leads to greater value of the peak infected population, and the results are seen earlier throughout the simulation. The blue line indicating 0.5 infectivity has its peak on approximately the 5th day, and has the most substantial value of infected population on that day. The red line showing 0.25 infectivity has its peak on the 10th day and the greatest number is lower than the blue line. The green line representing 0.125 infectivity has its peak on the 30th day, and has the lowest peak among the three. At the end of this simulation, only the blue and the red lines reach their equilibrium, where all population has been infected so is at about 0. The green line may reach its equilibrium at 0 if the simulation period is set to be longer.

To conclude, the effect of decreasing infectivity are the lower peaks and the later the peaks are seen.

Sensitivity analysis 3: Reset infectivity to 25%. Conduct three simulations with the duration of disease set to 4 days, 2 days, and 1 day. Provide your results of the infected population below. Briefly describe the effect of decreasing duration of infection.

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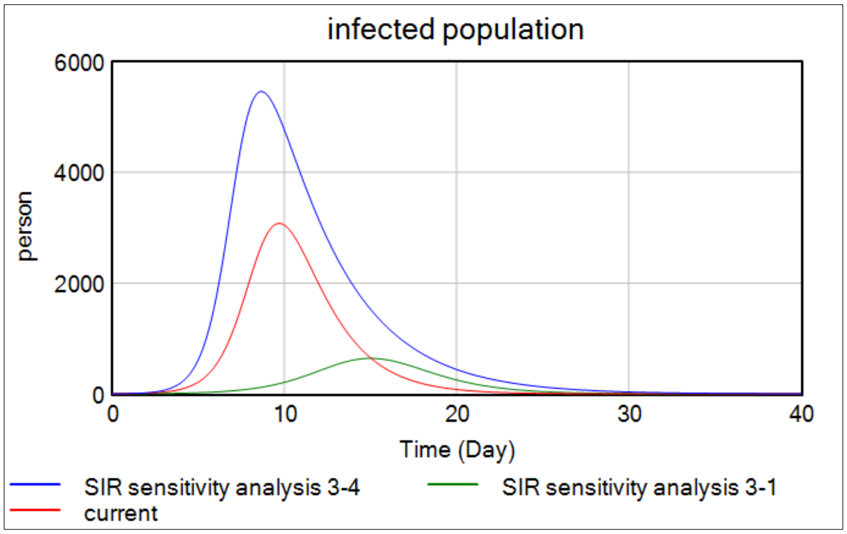
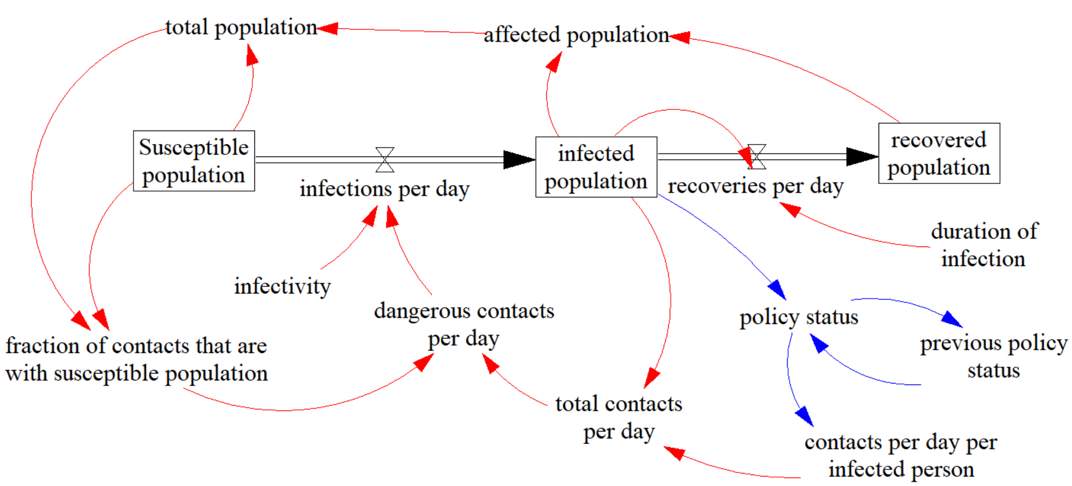


When the duration of disease is set to 4 days, the infected population shows a highest peak and the earliest time of reaching its peak among the three different values of duration of disease. Decreasing the period to 2 days, the infected population at the peak has been decrease greatly, and the peak is reached a few days later than the 4-day duration. Further decreasing the period to 1 day, the infected population at the peak keeps decreasing from the 2-day period, and the peak is reached even later in this simulation. To sum up, the effects of decreasing duration of infection are lengthening the time to reach the most infected population and lowering the peak values.

Policy analysis: We'll make a few changes to the model to help simulate the impact of a policy to reduce the contacts between the infected population and the susceptible population. Follow the model structure shown below, where the blue arrows are new connections and red are your previous model. Make sure to use the parameters originally introduced, not the values you used for sensitivity analysis.



We need to write three equations for the new variables (policy status and previous policy status) and contacts per day per infected person. Conceptually, we want the daily contacts to be cut in

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half if the situation becomes sufficiently serious to warrant a change in behavior. Assume this level is when the infected population reaches 2,000.

For simplicity, we'll code the policy taking effect as either a 1 or a 0, depending on if the policy is in place or not. If the policy to reduce daily contacts was in place, then it remains in place. until the end of the simulation. We'll ensure this happens through the use of "previous policy status"

- Set previous policy status as: DELAY FIXED(policy status, 0, 0)

Otherwise, if the infected population has reached 2,000, the policy should take effect. If it wasn't in place to begin with, and the infected population is less than 2,000, then daily contacts will not be reduced.

Question: Write an equation for "policy status" that achieves this goal, copy below.
Hint: You can nest "if then else" statements.

$$\boldsymbol{policy\ status = IF\ THEN\ ELSE(previous\ policy\ status = 1, 1, IF\ THEN\ ELSE(infected\ population\ >=\ 2000, 1, 0)\,)}$$

(unit: 1)

Finally, we need to update the equation for contacts per day per infected person. As a reminder, what we want to happen is once the policy takes effect the contacts per day will drop from 6 to 3.

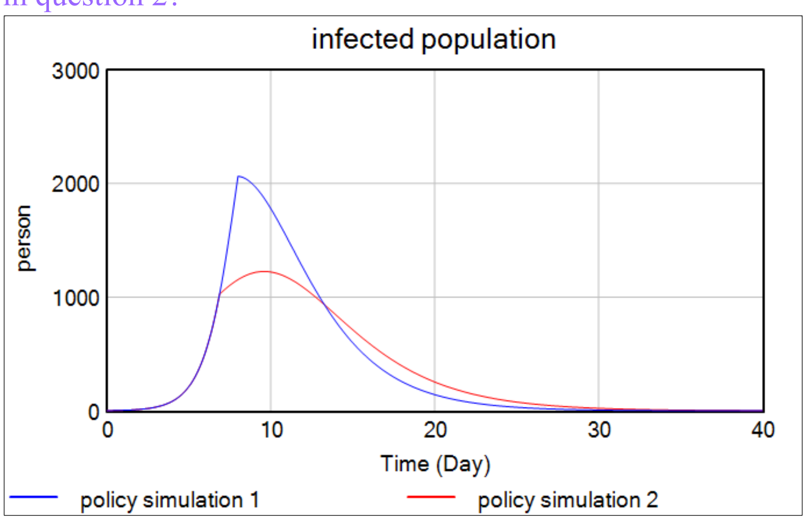
Question: Write an equation for "contacts per day per infected person," copy below.

$$\boldsymbol{contacts\ per\ day\ per\ infected\ person = IF\ THEN\ ELSE(policy\ status = 1, 3, 6)}$$

(unit: $\boldsymbol{\frac{person}{Day*person}}$**)**

Simulate the model and store the dataset under the name "policy simulation 1". Then alter the parameters so that the daily contacts cut in half when the infected population remains 1,000. Simulate the model and store the dataset under the name "policy simulation 2".

Question: Provide a graph showing infected population over time for both policy simulations. ~~How does the behavior compare to the behavior of infected population from the graph in question 2?~~



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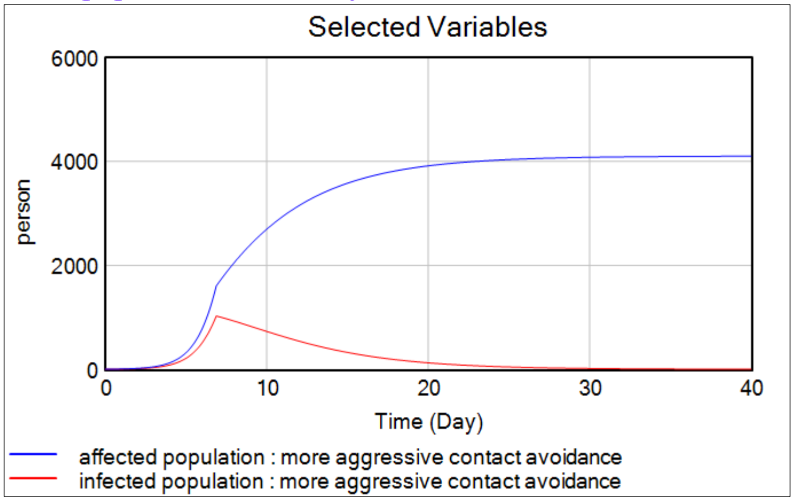
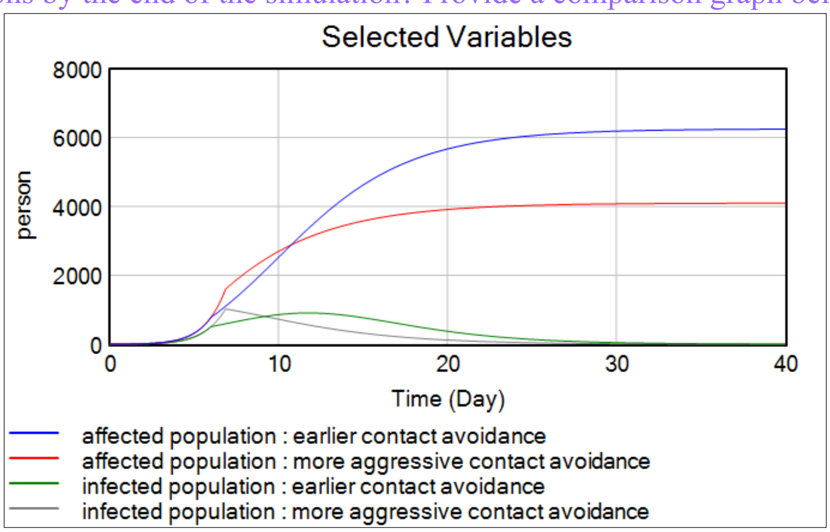
More aggressive contact avoidance: Let's cut the contacts from 6 to 2 after the infected population exceeds (is greater than or equal to) 1,000. What will happen to the infected population and affected population? Provide your results below.



Earlier contact avoidance: Reduce contacts from 6 to 3 after the infected population exceeds (is greater than or equal to) 500. Compare these results with the previous policy of cutting contacts from 6 to 2 when the infected population exceeds 1,000. Which policy leads to a lower number of affected persons by the end of the simulation? Provide a comparison graph below.



The more aggressive contact avoidance policy leads to a lower number of affected population by the end of the simulation.

Educational Campaign: The health department is considering an educational campaign in advance of an epidemic that could increase awareness and lead to a reduction in the contacts per day once the epidemic is underway.

> **Question:** Design a scenario to test this idea, copy your model structure and equations below. In 3-4 sentences, describe how you made your modeling choices. Hint: You can use assumptions/your intuition for this question.

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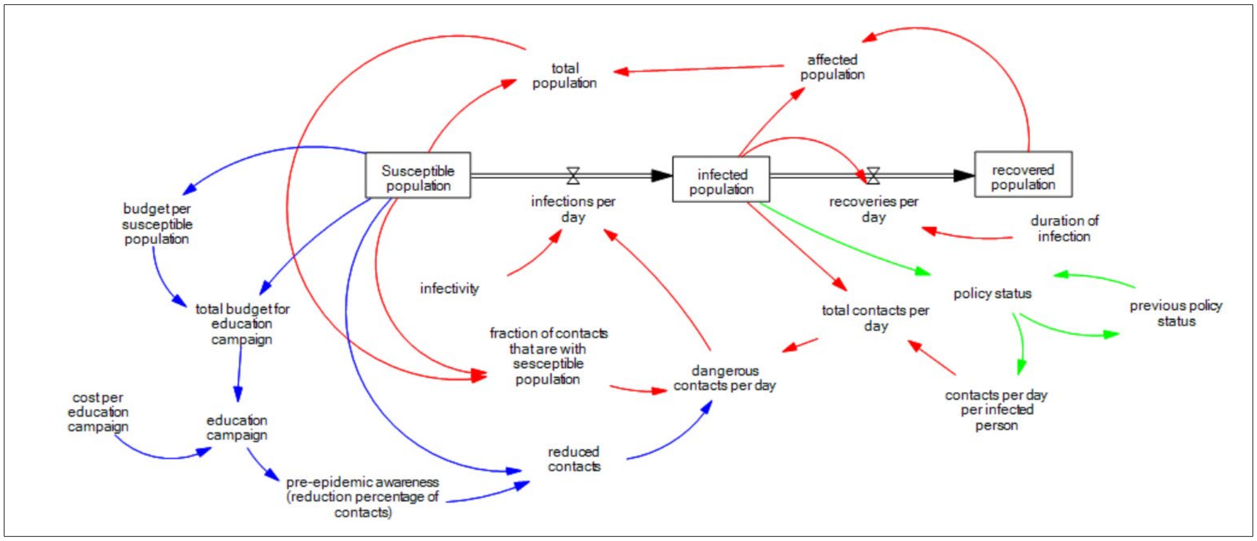

Before cutting into education campaign, I first scope the budget, which floats with susceptible population. At the first half of 10000 population, the more susceptible population there is, the more the budget per susceptible population is. However, the government is clever enough to do detailed and accurate cost-benefit analysis on planning for the budget, and decides that when more than 6500 people are susceptible, they will reduce the budget amount because situations cannot be better-off. The total budget for education campaign decides how many times education campaign will be held a day, while each education campaign's cost is set fixed to 4000 dollars. Different frequencies of education campaigns a day then results in different level of pre-epidemic awareness, which is critical to the reduced contacts per day, and affects the infected population and the affected population. Similar to the budget planned per susceptible population, there is an increase in pre-epidemic awareness associated with the increase of times of education campaigns. And then a decrease is seen in the trend because people become unaware of the degree of danger of the disease once they are exposed to too many times of promotions.

Equations:

- $\boldsymbol{budget\ per\ susceptible\ population =}$ $\boldsymbol{Susceptible\ population\ with\ LOOKUP([(0,0) - (10,10)],(0,3),(1000,7),(2000,15),(3000,25),(4000,40),(5000,53),(6000,60),(7000,15),(8000,10),(9000,3),(10000,0.5))}$
  (unit: dollar/person)
- $\boldsymbol{total\ budget\ for\ education\ campaign =}$ $\boldsymbol{IF\ THEN\ ELSE(\ Susceptible\ population * budget\ per\ susceptible\ population\ >\ 0\ , Susceptible\ population * budget\ per\ susceptible\ population, 0)}$
  (unit: dollar)
- $\boldsymbol{education\ campaign = \frac{total\ budget\ for\ education\ campaign}{cost\ per\ education\ campaign}}$
  (unit: time)
- $\boldsymbol{cost\ per\ education\ campaign = 4000}$
  (unit: dollar/time)

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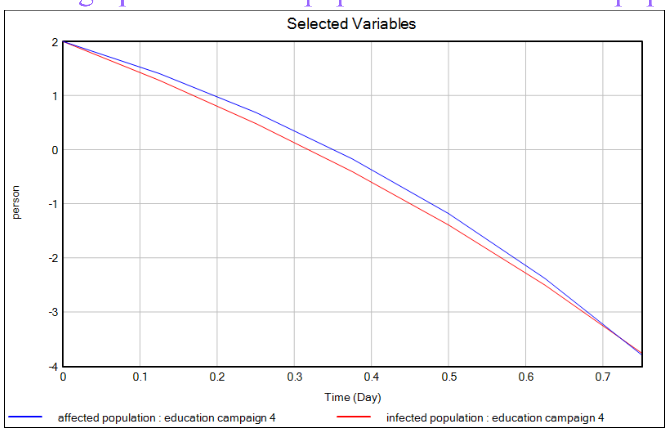
- $\boldsymbol{pre - epidemic\ awareness\ (reduction\ percentage\ of\ contacts) = education\ campaign\ with\ LOOKUP([(0,0) - (10,10)], (0,0), (1, 0.001), (2, 0.009), (3, 0.06), (4, 0.1), (5, 0.15), (6, 0.11), (7, 0.1))}$
  (unit: 1/Day)
- $\boldsymbol{reduced\ contacts = pre - epidemic\ awareness\ (reduction\ percentage\ of\ contacts) * Susceptible\ population}$
  (unit: person/Day)
- $\boldsymbol{dangerous\ contacts\ per\ day = (fraction\ of\ contacts\ that\ are\ with\ sesceptible\ population) * total\ contacts\ per\ day - reduced\ contacts}$
  (unit: person/Day)

Question: Provide a graph of infected population and affected population below.



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2. Yellow Fever Model

Yellow Fever has been described as a "major and terrifying scourge in the Americas, causing endemic disease in jungle and swamp areas from Canada to Chile and claiming tens of thousands of lives in periodic urban epidemics" (Garrett 1994, p. 66). Garrett reports that "a 1793 epidemic in Philadelphia killed 15% of the city's population and sent one of three residents fleeing into the countryside." Yellow fever is transmitted in urban areas by the bite of infective Aedes aegypti mosquitoes. It is "an acute infectious viral disease of short duration and varying severity" where the "case fatality rate may exceed 50% among no indigenous groups and in epidemics" (Benneson 1990, 486).

These exercises introduce you to a model to simulate the spread of Yellow Fever. The model was adapted from a Dynamo model by Kjell Kalgraf's published in Goodman's (1983) Study Notes in System Dynamics. Kalgraf describes the classical (urban) form of yellow fever in which a human contracts yellow fever from the bite of infectious mosquitos. The mosquitos, in turn, can only become infectious by biting contagious humans. The model is more complex than the S-I-R model, so it is good practice to expand on what you have learned in class.

The figure below shows a model based on a human population of 20,000. Kalgraf mentions an epidemic in Veracruz, Mexico, a city of 20,000 people back in 1899. Yellow Fever spread through the Veracruz in 1899, and deaths reached 460 per month at the peak of the epidemic. The model assumes that the humans live within contact of a mosquito population of around 500,000. Mosquitoes are shown on the left; humans on the right. Values are shown for the peak day of a simulated epidemic. <u>You are expected to use these numbers to derive necessary equations for the model.</u> (For example: you should use the value for "fraction of humans vulnerable" to derive that its equation is vulnerable people / population). The values for the stocks should not be used, see questions 1.

Note: <immune people> and <sick people> are shadow variables (top right corner) which represent the existing variables in the system. Shadow variables are used to help reduce the amount of arrows that might be crossing around the entire model. They can be created by using the “Shadow Variable” button.

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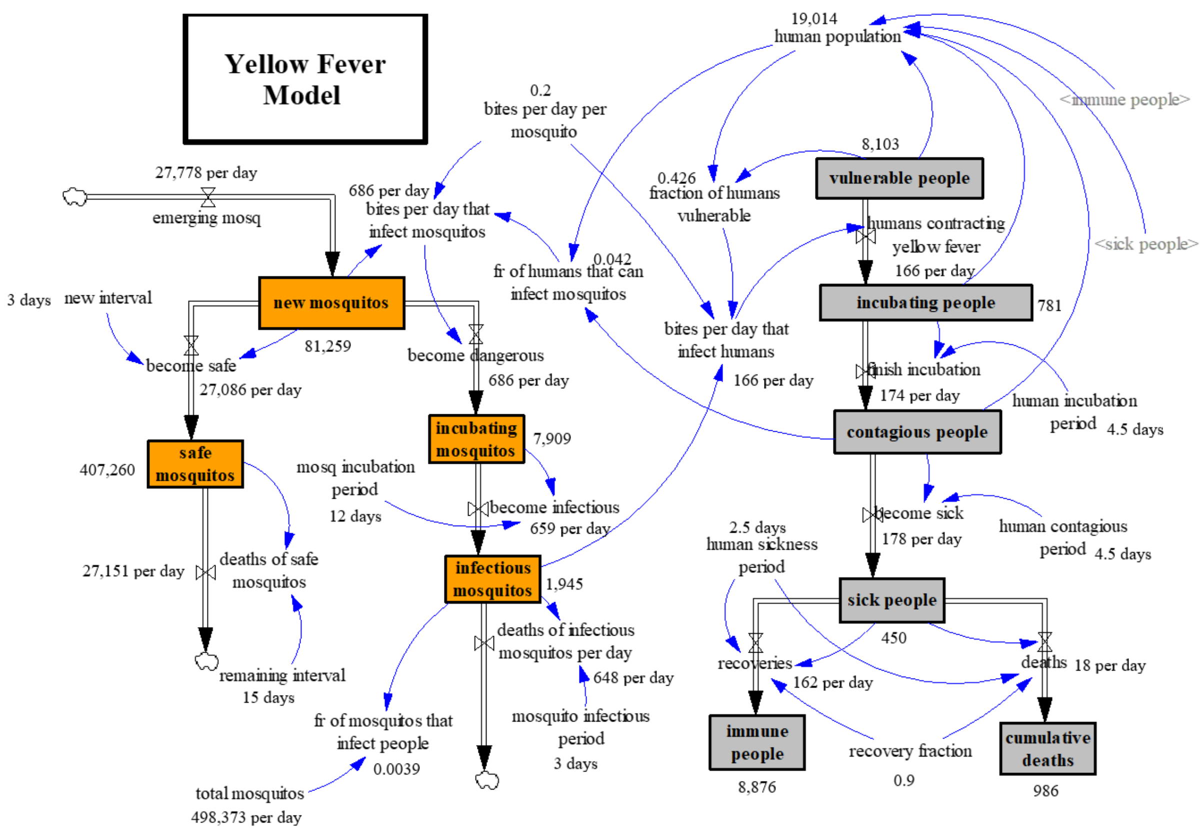

The Mosquitoes: Adult mosquitoes are assumed to emerge from the pupae at the rate of 27,778 per day; the total population remains at around 500,000 for the duration of the epidemic. The mosquitoes live for 18 days and need four blood feeds during their lifetime. This means the average mosquito bites 0.2 persons per day, so there would be around 100,000 bites each day. If a mosquito avoids biting a contagious human during their first three days, they "become safe" for the remainder of their adult life. If they bite a contagious human during this initial period, they become dangerous to humans. The remaining 15 days is characterized by a 12 day incubation period and a 3 day infectious period.

The Humans: A human contracts yellower 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

1) **Build and verify:** Build the model above. Initialize the model with 19,900 vulnerable people and 100 incubating people. The mosquitoes may be initialized with 417,000 safe mosquitos and 83,000 new mosquitos. All other stocks may be set to zero. Simulate the model for 280 days.
   *** adding "people per bite (people/bite)" and "mosquito per bite (mosq/bite)" to the model, so that the units are ok**
   Question: Provide a graph of vulnerable people, deaths, and cumulative deaths below.

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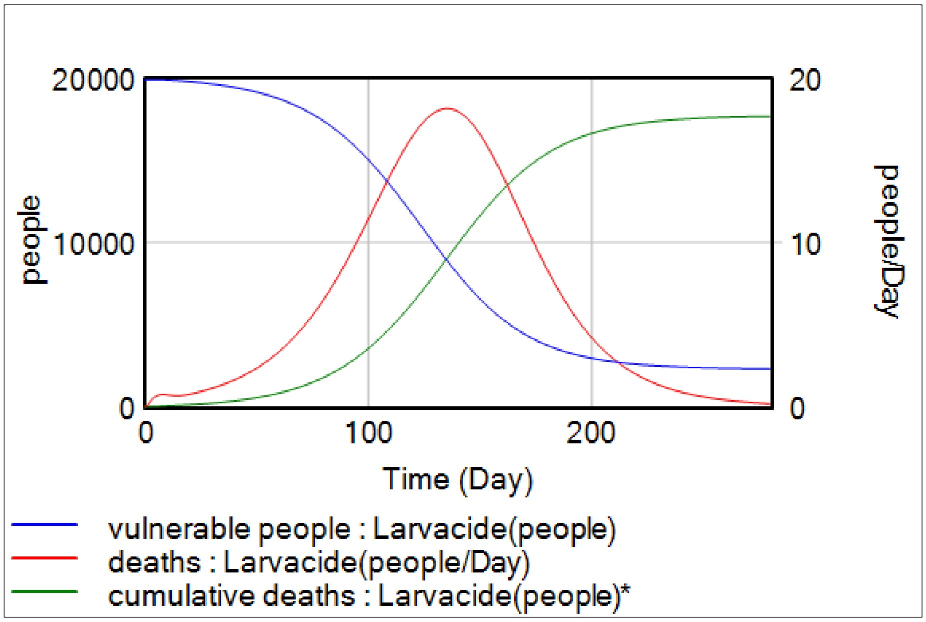
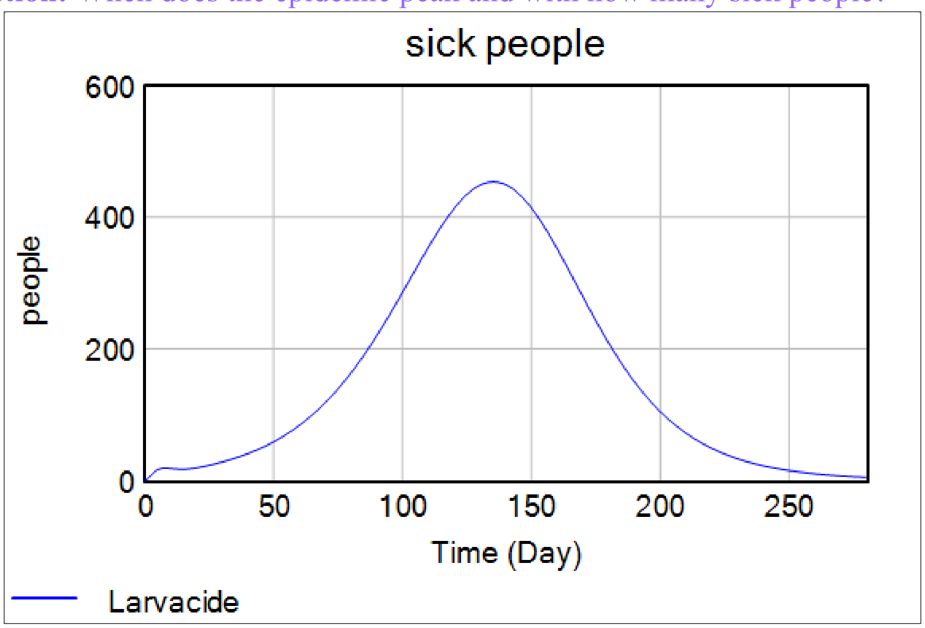


Question: When does the epidemic peak and with how many sick people?



The epidemic peaks at the 135.25th year, and the peak has 453.658 sick people, which is approximately 454 people being sick.

Question: What is the peak death rate?

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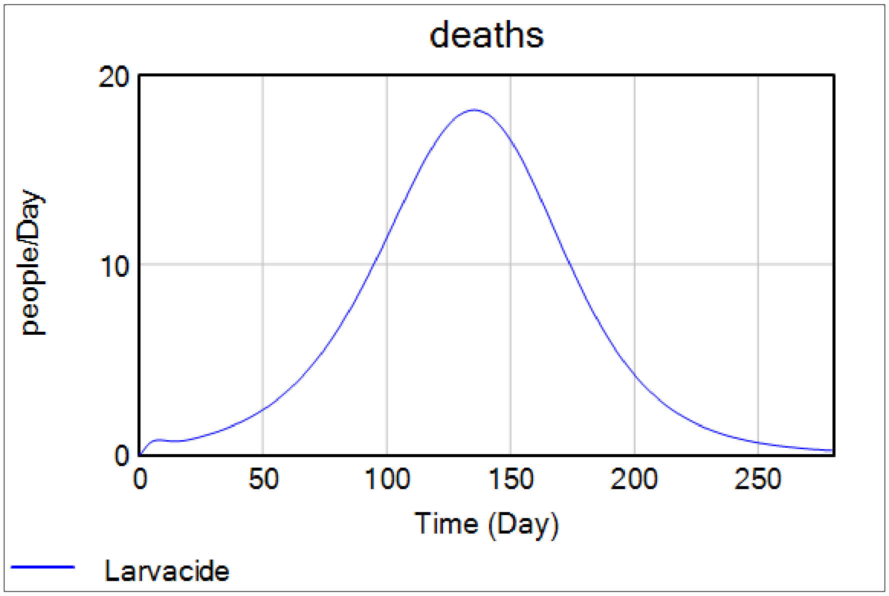
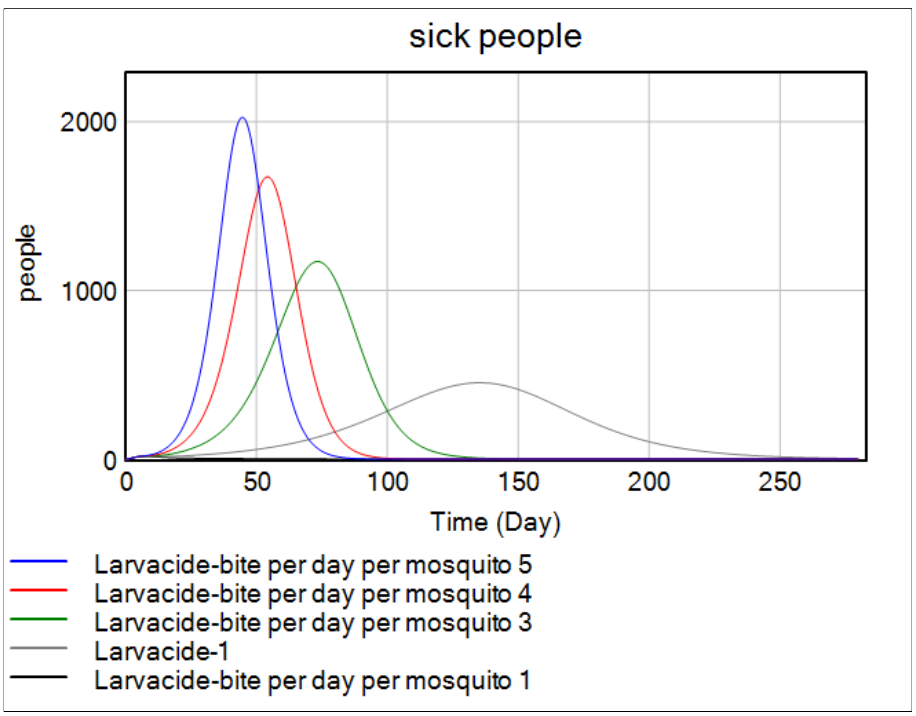


The peak death rate has 163.317 people per day and is on the 135.25th day.

2) **Sensitivity to bites per day per mosquito:** Vary the bites per day per mosquito from 0.1-0.5.

Question: Provide a figure showing sick people under different bites per day per mosquito below.



Question: Under which range will the epidemic be eliminated?

If the number of sick people less than one indicates that the epidemic is eliminated: With 0.1 bite per day per mosquito, the epidemic will be eliminated on the 109.125th day. With 0.2 bite per day per mosquito, the epidemic will be eliminated on the

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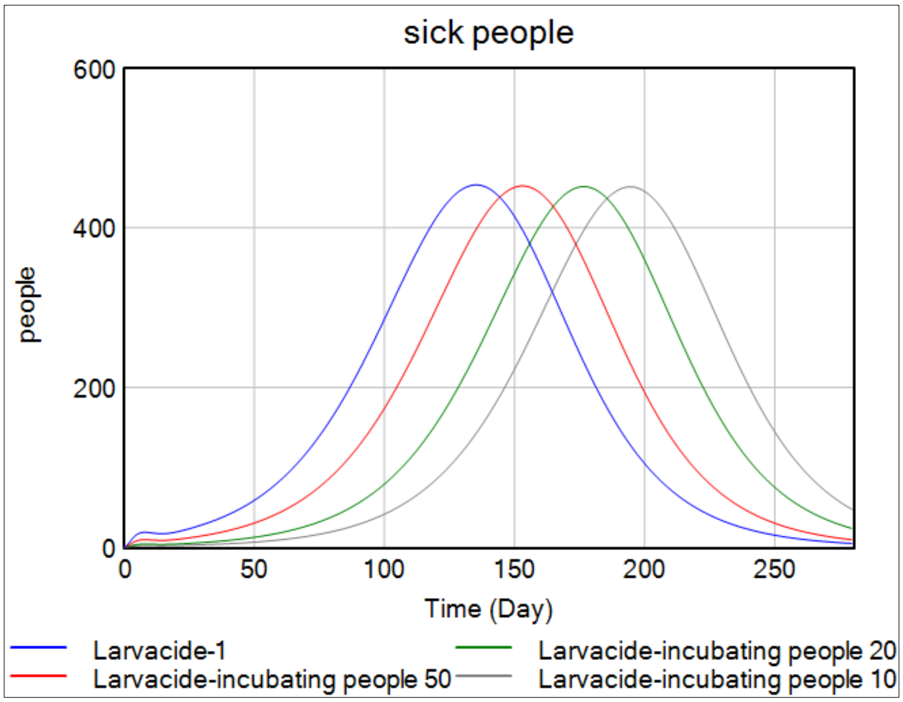
110.625th day. With 0.3 bite per day per mosquito, the epidemic will be eliminated on the 159th day. With 0.4 bite per day per mosquito, the epidemic will not be eliminated throughout our 280-day simulation. With 0.5 bite per day per mosquito, the epidemic will be eliminated in the 95th day.

3) **Sensitivity to the Initial Number of Incubating Humans:** Reset bites per day per mosquito to 0.2. Test the sensitivity of sick people to a change in the initial value of the number of incubating people.

   Question: Create a comparative time graph with the initial number of incubating people set at 10, 20, 50 and 100.



4) **Policy analysis:** Expand the model to simulate the impact of a program to reduce the size of the mosquito population by the application of larvacide. You may assume that the larvacide will reduce the number of emerging mosquitoes, but it will not directly affect the adult population. Include the start date and the percent reduction in emerging mosquitoes as program parameters that may be specified by the model user. Experiment with varying start dates and varying percent reductions.

   Question: Are you able to limit the impacted people to 500 or less? Define the total impacted population by subtracting the vulnerable people from the 20,000 people in the city at the start of the simulation. Provide your results (screenshot of new model structure and graphs) and discussion.

   New variables and equations:

$$\boldsymbol{larvacide\ effect\ date = (5, 30, 95, 160)}$$
$$\boldsymbol{(change\ for\ experiment\ purpose)}$$

(unit: Day)

$$\boldsymbol{larvacide\ effect\ on\ mosquito\ reduction\ percentage\ per\ day = (0.2, 0.4, 0.6, 0.8)}$$

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$$(change\ for\ experiment\ purpose)$$

(unit: mosquito/Day)

$$total\ impacted\ population = human\ population - vulnerable\ population$$

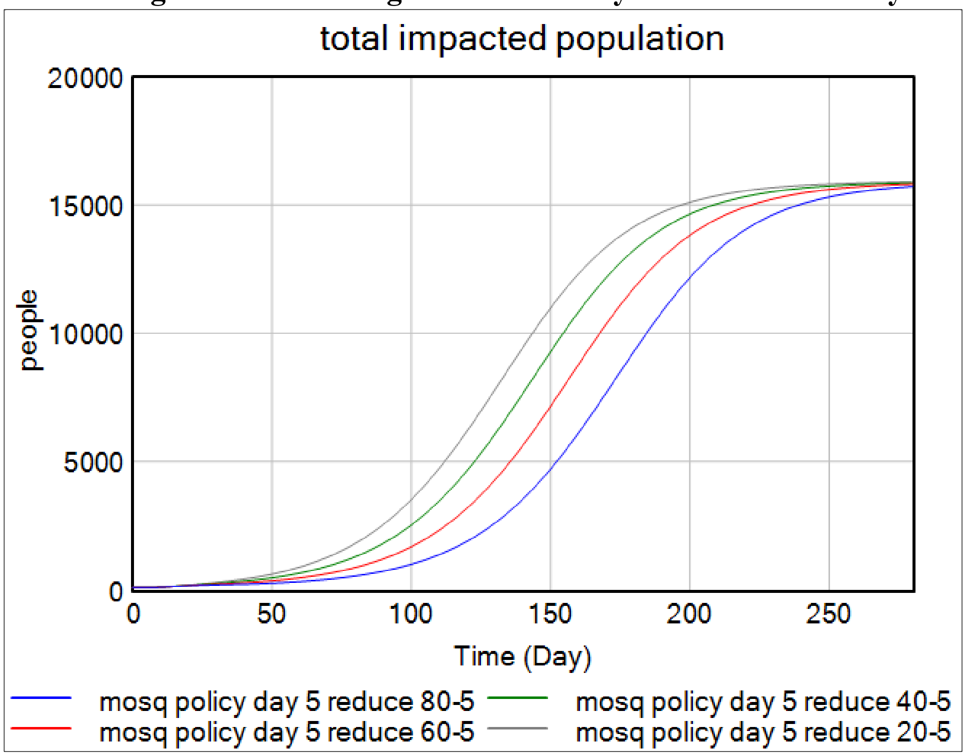
(unit: people)

Adjusted variable and equation:

$$emerging\ mosquito = 27778 * PULSE(\ 0, larvacide\ effetive\ date) + 27778 * PULSE(larvacide\ effetive\ date, 30) * (1 - larvacide\ effect\ on\ mosquito\ reduction\ percentage\ per\ day) + 27778 * PULSE(30 + larvacide\ effetive\ date, 290 - 30 - larvacide\ effetive\ date)$$

(unit: mosq/Day)

For larvicide being effective starting from the 5th day and lasts for 30 days:



For larvicide being effective starting from the 30th day and lasts for 30 days:

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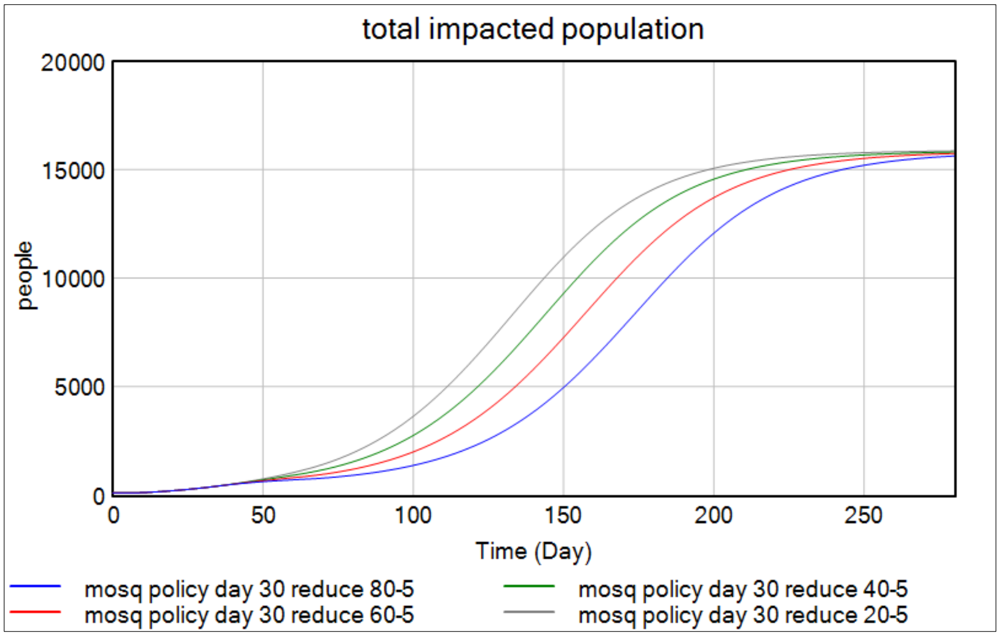
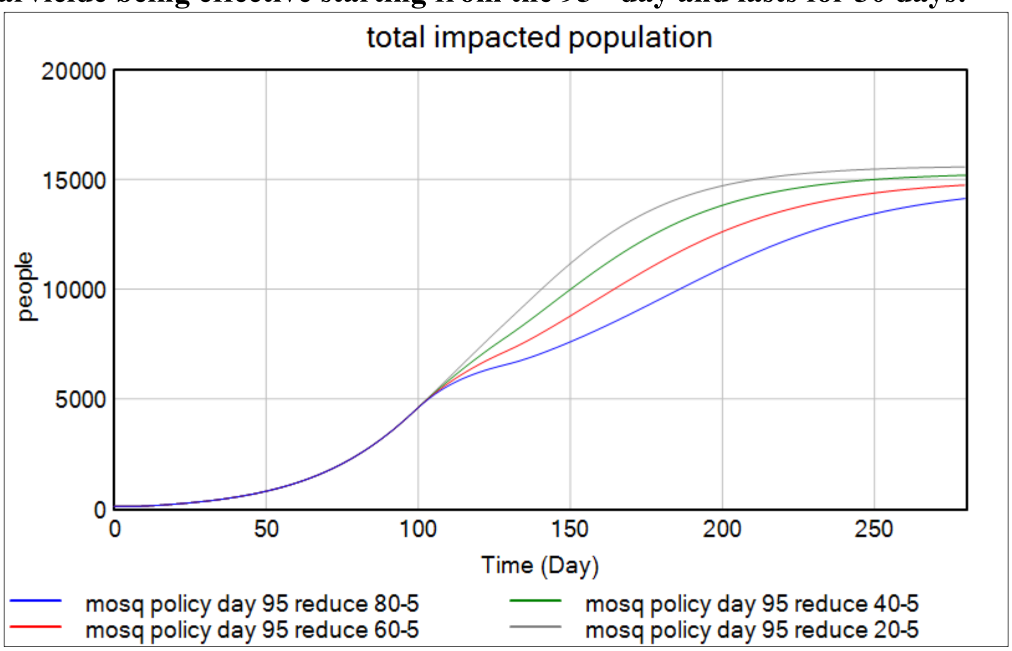


For larvicide being effective starting from the 95th day and lasts for 30 days:



For larvicide being effective starting from the 160th day and lasts for 30 days:

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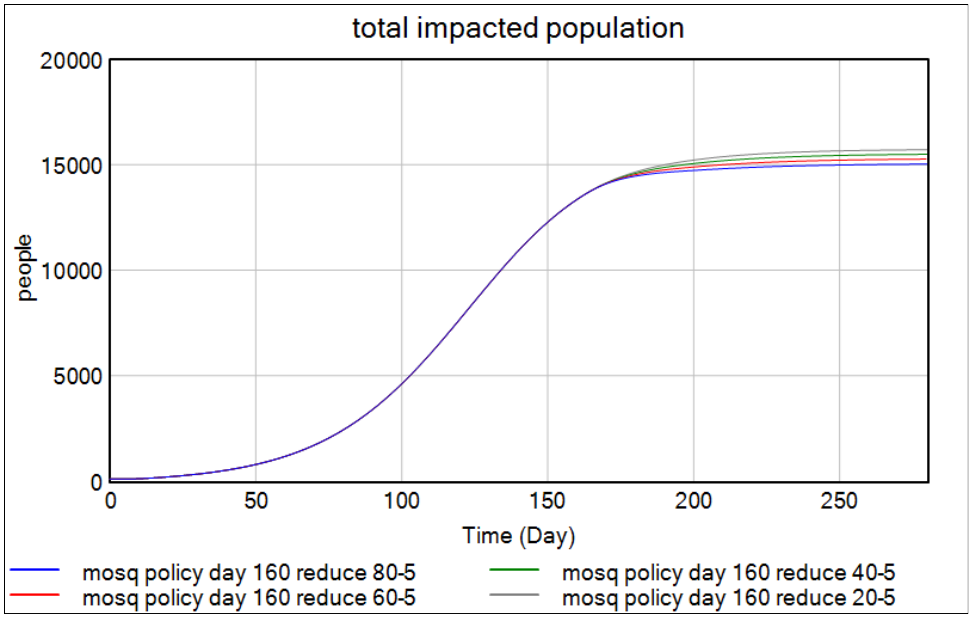
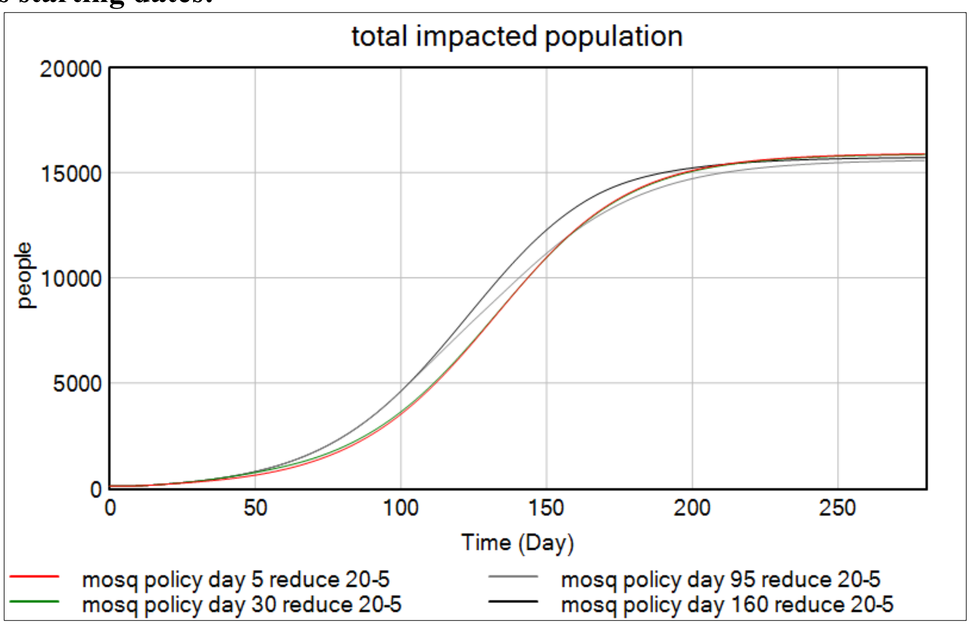


For the effect of larvicide on mosquito reduction percentage per day at 0.2 with various starting dates:



For the effect of larvicide on mosquito reduction percentage per day at 0.4 with various starting dates:

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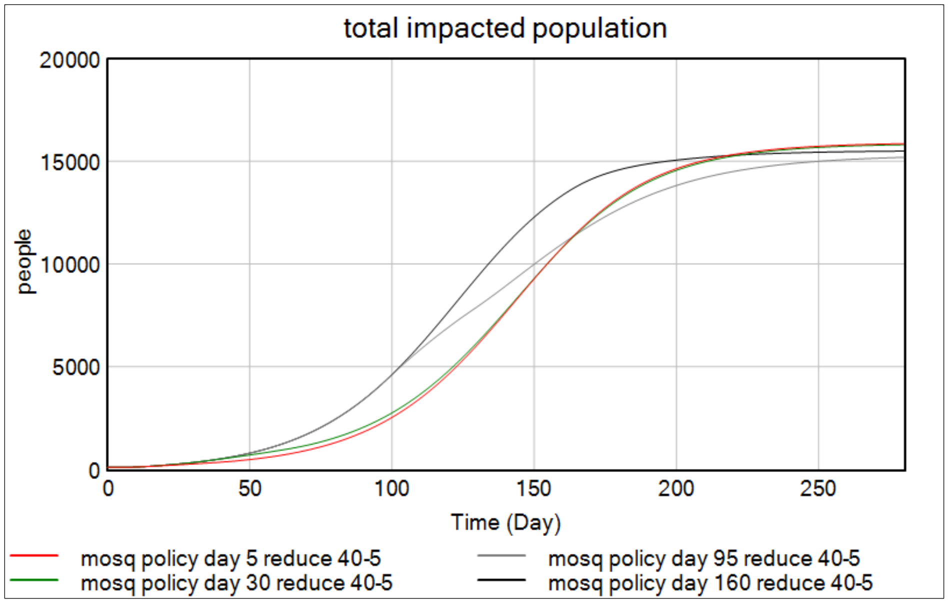
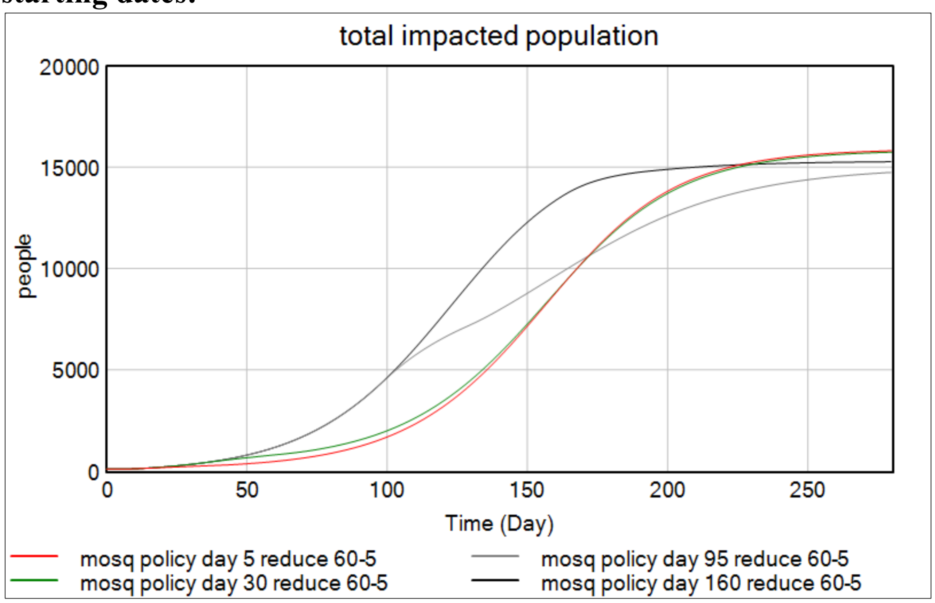


For the effect of larvicide on mosquito reduction percentage per day at 0.6 with various starting dates:



For the effect of larvicide on mosquito reduction percentage per day at 0.8 with various starting dates:

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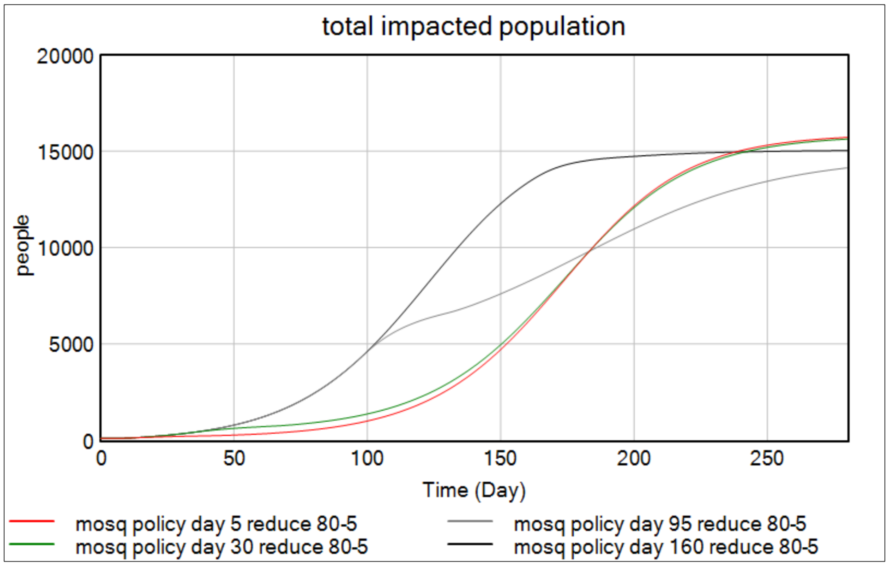
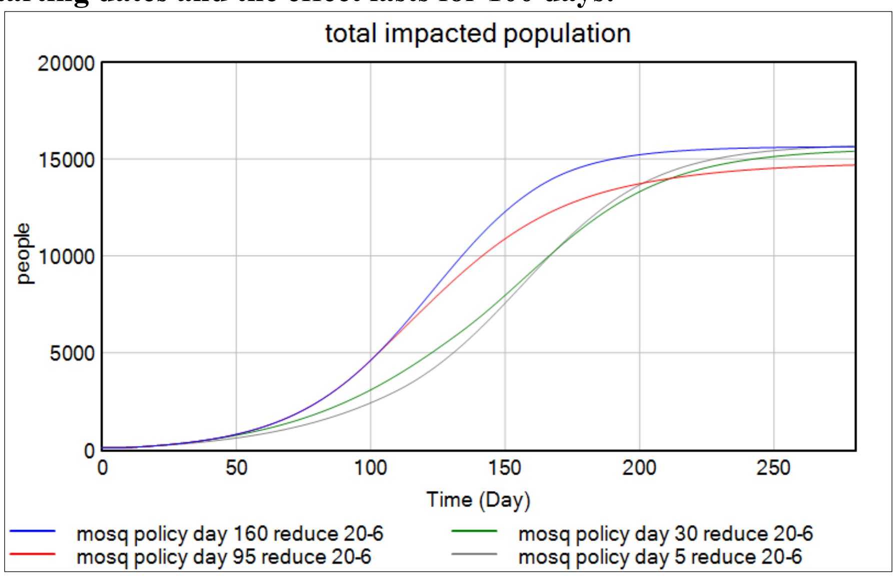


For the effect of larvicide on mosquito reduction percentage per day at 0.2 with various starting dates and the effect lasts for 100 days:



I cannot find a way to limit the impacted people to 500 or less. Even setting the duration of effect of larvicide to 100 days, almost half-way through the simulation, the total infected population remains high.

Model Structure:

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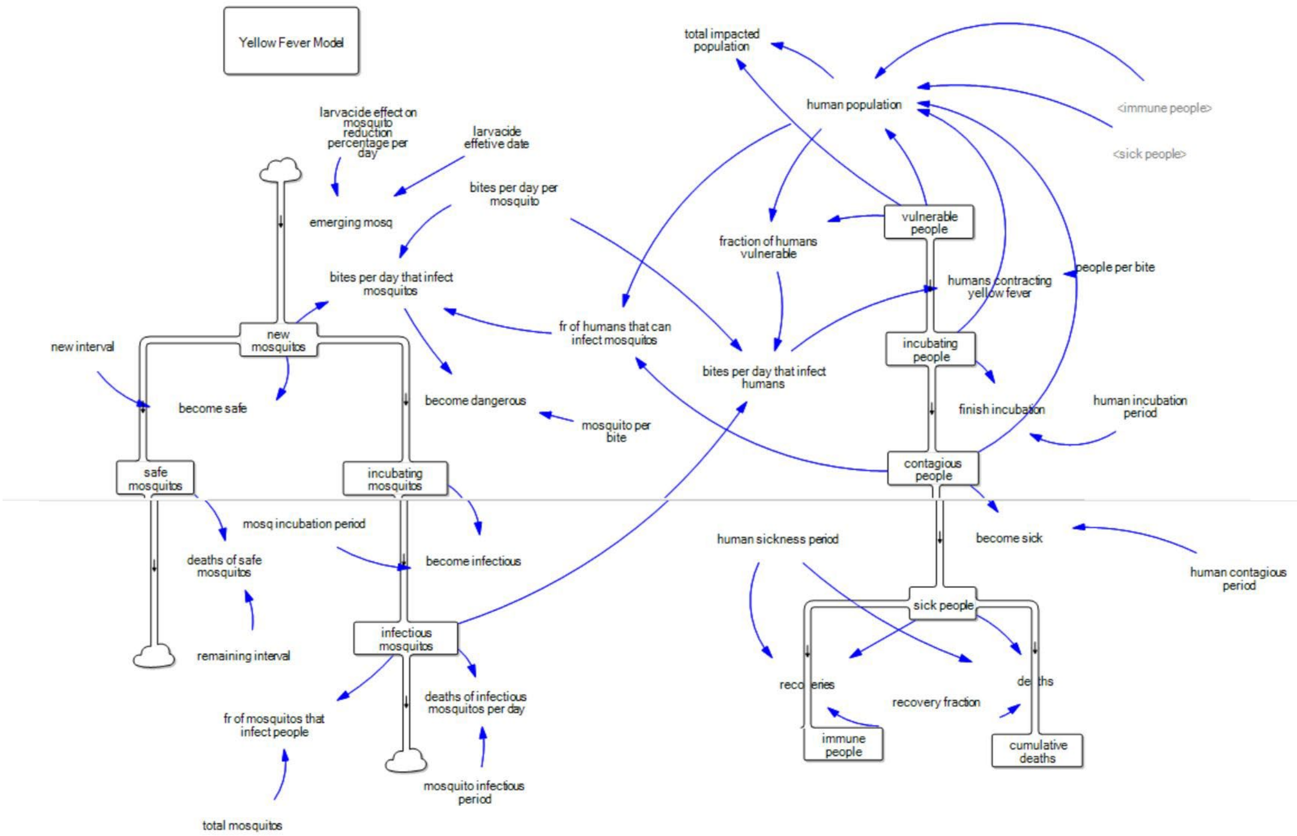

This may be hard to read. I'm also uploading the model to the assignment submission.