INTRODUCTION

In 2019, the island country of Samoa experienced a devastating measles epidemic. In this case study, you will model several scenarios for this epidemic using the Epidemic Simulator. You will consider how the SIR graphs generated by the simulator relate to what is happening in the population. You will also evaluate the impact of vaccination by modeling different vaccination rates and comparing the resulting graphs. These concepts and models apply to infectious diseases all over the world.

This case study is divided into the following parts:

- **In Part 1**, you will learn about the 2019 measles epidemic in Samoa and consider how the virus spread in the population.
- **In Part 2**, you will prepare to model the epidemic by exploring key parameters.
- **In Part 3**, you will model the epidemic with no vaccination.
- **In Part 4**, you will model the epidemic using the vaccination rate at the start of the epidemic in 2019.
- **In Part 5**, you will model the epidemic using the vaccination rate in 2013, which was much higher than the 2019 vaccination rate.
- **In Part 6**, you will learn about herd immunity and how it affects disease spread.

MATERIALS

- access to the Modeling Disease Spread Click & Learn
- computer or mobile device that can take screenshots, download files, or print images

PROCEDURE

In this case study, you will learn about the 2019 measles epidemic in Samoa (timeline shown in Figure 1) and answer related questions. Complete the questions in the order they are shown, as each question builds on information from previous questions.

**PART 1: The 2019 Measles Epidemic in Samoa**

**Measles** is an infectious disease caused by the measles virus. Symptoms include fever, coughing, and rashes. More severe cases may lead to hospitalization and even death, especially for young children.

Many countries use a measles vaccine to protect people from the disease. They typically give two doses of the vaccine to increase its effectiveness. The first dose is usually given to **infants** (in this case, children less than 1 year old). All the vaccination rates reported below are for the first dose.

In 2021, the global vaccination rate for measles was about 81%. Samoa, a small island country in the South Pacific Ocean, originally had an even higher vaccination rate for measles. Many rural communities in Samoa were very supportive of vaccination, so Samoa’s vaccination rate was about 92% in 2013. However, between 2013 and 2017, more people moved to urban areas with less vaccine support. As a result, Samoa’s vaccination rate decreased to about 67% by 2017.

1. To protect a population against an infectious disease like measles, does everyone in the population need to be vaccinated? Explain your answer, including how vaccines reduce disease spread in a population.
On July 6, 2018, two nurses made a rare mistake preparing a measles vaccine. They accidentally mixed the vaccine with the wrong liquid, which resulted in the deaths of two infants. While investigating the deaths, the Samoan government paused measles vaccinations for children until November 2018. Because the cause of the deaths was unclear at the time, people became hesitant to use the vaccine. Samoa’s vaccination rate for measles dropped to 40%, and measles cases began to appear by September 2019.

2. Where did the measles virus that caused these cases come from? Propose some possible sources for the virus.

In October 2019, while the public was still unaware that measles was spreading, many families gathered for a national holiday, White Sunday, that celebrates children. Unfortunately, these gatherings likely promoted the spread of the measles virus.

3. How would large gatherings help a virus spread?

On November 15, 2019, Samoa declared a state of emergency. The government implemented multiple lockdown measures (when individuals stay where they are to reduce contact with others) — including closing schools, restricting children from public gatherings, and setting curfews.

Residents of Samoa were also required to be vaccinated for measles. Over 150 medical teams traveled throughout the country to help vaccinate people. Within six weeks, the vaccination rate of the prioritized groups (children and women of childbearing age) rose to 96%. The state of emergency was lifted on December 29, 2019.

4. Propose one way to determine whether the vaccination and lockdown efforts succeeded.

The number of measles cases in Samoa peaked around November 26, 2019, and the last reported case was on January 12, 2020. By the end of the epidemic, 1,868 people had been hospitalized due to complications from measles, and 83 had died. Most of them were children.
Figure 1. Timeline of the events and measles vaccination rates (first dose) associated with the 2019 measles epidemic in Samoa. The same information is shown in Tables 1 and 2.

Table 1. Timeline of the events associated with the 2019 measles epidemic in Samoa.

<table>
<thead>
<tr>
<th>Date(s)</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013–2017</td>
<td>People in rural areas move to urban centers, away from vaccine advocacy groups</td>
</tr>
<tr>
<td>July 6, 2018</td>
<td>Two infants die from error in preparing measles vaccine</td>
</tr>
<tr>
<td>July–Nov 2018</td>
<td>Measles vaccination suspended</td>
</tr>
<tr>
<td>Sept 2019</td>
<td>Measles cases reported</td>
</tr>
<tr>
<td>Oct 13, 2019</td>
<td>White Sunday celebrations</td>
</tr>
<tr>
<td>Nov 15, 2019</td>
<td>State of emergency declared</td>
</tr>
<tr>
<td>Nov 18, 2019</td>
<td>Control measures put in place (vaccinations, lockdowns)</td>
</tr>
<tr>
<td>Nov 26, 2019</td>
<td>Peak of infections</td>
</tr>
<tr>
<td>Dec 29, 2019</td>
<td>State of emergency lifted</td>
</tr>
<tr>
<td>Jan 12, 2020</td>
<td>Last case reported; 5,707 total cases</td>
</tr>
</tbody>
</table>
Table 2. Measles vaccination rates (first dose) associated with the 2019 measles epidemic in Samoa.

<table>
<thead>
<tr>
<th>Year</th>
<th>Vaccination Rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013</td>
<td>92</td>
</tr>
<tr>
<td>2014</td>
<td>85</td>
</tr>
<tr>
<td>2015</td>
<td>75</td>
</tr>
<tr>
<td>2016</td>
<td>75</td>
</tr>
<tr>
<td>2017</td>
<td>67</td>
</tr>
<tr>
<td>2018</td>
<td>40</td>
</tr>
<tr>
<td>2019</td>
<td>96</td>
</tr>
</tbody>
</table>

5. The Samoan government used various control methods, including lockdowns and vaccinations, to reduce the spread of measles. Describe one strength and weakness of each method in the table.

<table>
<thead>
<tr>
<th>Method</th>
<th>Strength</th>
<th>Weakness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lockdowns</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vaccinations</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

6. There have been measles cases all around the world. Research and briefly describe the most recent measles outbreak or epidemic in your region (i.e., city, state, or country).

PART 2: Exploring Measles Transmission Rate and Recovery Rate

Epidemics like the 2019 measles epidemic in Samoa can, and have, happened in many other countries, including the US. To learn more about how vaccination impacts disease spread, you will model various scenarios for the 2019 epidemic using the SIR model.

To prepare, read the “Disease Spread Background” tab in the “SIR Model Advanced” section of the Modeling Disease Spread Click & Learn. Then answer the questions below.

7. Scientists estimated that the $R_0$ for measles during the 2019 epidemic was 6.5.
   a. In your own words, describe what an $R_0$ of 6.5 means.

   b. Given this $R_0$, what might happen without any control measures (i.e., no lockdowns or vaccinations)?
8. Based on this $R_0$, scientists determined that measles had an average transmission rate ($t$) of 130% per day during the 2019 epidemic. In your own words, explain what an average transmission rate of 130% per day means, including how this transmission rate would affect the population during the epidemic. (It may be helpful to explain what would happen to an infectious or susceptible individual in this case.)

9. The average recovery rate ($r$) for measles is 20% per day. In your own words, explain what an average recovery rate of 20% per day means, including how this recovery rate would affect the population during the epidemic. (It may be helpful to explain what would happen to an infectious or removed individual in this case.)

**PART 3: Modeling the Impact of 0% Vaccination**

You’ll now model what might have happened during the 2019 epidemic without any vaccination or other control measures. To do so, go to the Epidemic Simulator (bottom half of the “Simulate an Epidemic” tab in the “SIR Model Advanced” section) and enter the following settings. (As described in the simulator, the values for transmission rate and recovery rate are percentages per day.)

- Total Days: 60
- Transmission Rate ($t$): 130
- Recovery Rate ($r$): 20
- Initial Susceptible Individuals: 199,999
- Initial Infectious Individuals: 1
- Initial Removed Individuals: 0

Select “Simulate” to start the simulation. The SIR graph will automatically appear in the “Results” section.

10. Following the guidance of your instructor, download, print, or sketch an image of your graph. Label it as “0% Vaccination.” Make sure to include your graph when submitting this handout, in whichever format your instructor asks for.

11. Examine the relationship among the three curves (susceptible, infectious, and removed) in the graph.
   a. The susceptible curve should decrease over time. What happens to individuals who leave the susceptible group? (In other words, which group do they move into?)
   
   b. The removed curve should increase over time. Where do new individuals in the removed group come from?
   
   c. The infectious curve should increase, then decrease. Where do new individuals in the infectious group come from, and what happens to them once they leave the infectious group?
Review the “Summary” section under “SIR Model Basics,” which has more information about the SIR graph. The illustration in the “Analyzing and Interpreting an SIR Graph” section shows how different parts of the graph relate to the main stages of an outbreak or epidemic.

12. For each stage of the epidemic (early, peak, and late), select a random day and record it in the table below. Also record the number of individuals in each group on that day. (You can hover over points on the SIR graph in the simulator to display the number of individuals.)

<table>
<thead>
<tr>
<th>Groups</th>
<th>Early Day</th>
<th>Peak Day</th>
<th>Late Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Susceptible (S)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Infectious (I)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Removed (R)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

13. Use your graph to answer the following questions.
   a. Which curve(s) shows the number of infectious cases (i.e., infectious individuals) on a given day?
   b. How many days did it take to reach peak infection (the day with the greatest number of infectious individuals)?
   c. How many individuals were infectious at peak infection?
   d. What was the total length (in days) of the epidemic? Assume the epidemic is over when there are exactly 0 infectious individuals (without rounding) in the population. You may need to increase “Total Days” in the settings and select the “Simulate” button again until you find the end of the epidemic.
   e. How many individuals were infected over the course of the entire epidemic?
   f. Were there any susceptible individuals in the population at the end of the epidemic?

14. Compare the results of your model (as shown in your graph) to data from the real 2019 epidemic (as shown in Figure 1).
   a. Did your model and the real epidemic take a similar number of days to reach peak infection? Why or why not?
   b. During the real epidemic, there were 5,707 reported cases of measles (3% of the population in Samoa). Is this similar to your model? Why or why not?
   c. Describe one difference between the model and the real epidemic. What do you think caused this difference?

15. This first model did not include any vaccination. At the start of the real epidemic, however, about 40% of the population was vaccinated. Consider how including this initial vaccinated population could impact the model — in particular, the three curves (susceptible, infectious, and removed) in the SIR graph.
a. Briefly describe, or draw directly on your graph from Question 10, how each curve might shift if you included the initial vaccinated population. For example, would some curves shift to the right/left, up/down, or not at all?

b. Explain your reasoning for the shifts you predicted.

**PART 4: Modeling the Impact of a 40% Vaccination Rate**

Let’s now incorporate the initial vaccinated population into the model.

16. Which settings(s) in the Epidemic Simulator could you modify to indicate that 40% of the population was vaccinated at the start of the epidemic?

17. You’ll now model how measles would spread when 40% of the initial population is vaccinated. You can use the same total number of days, transmission rate, and recovery rate as before, but you will need to adjust the number of individuals initially in each group.

   a. Assuming that the population has 200,000 individuals and that there is initially one infectious individual, list your new settings below:
      - Total Days: 60
      - Transmission Rate (t): 130
      - Recovery Rate (r): 20
      - Initial Susceptible Individuals: __________
      - Initial Infected Individuals: __________
      - Initial Removed Individuals: __________

   b. Enter the settings above, then start the simulation to generate a new graph. Following the guidance of your instructor, download, print, or sketch an image of your graph. Label it as “40% Vaccination.” Make sure to include your graph when submitting this worksheet, in whichever format your instructor asks for.

18. How does this graph compare to what you predicted in Question 15?

19. For each stage of the epidemic (early, peak, and late), select a random day and record it in the table below. Also record the number of individuals in each group on that day.

<table>
<thead>
<tr>
<th>Groups</th>
<th>Early Day</th>
<th>Peak Day</th>
<th>Late Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Susceptible (S)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Infectious (I)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Removed (R)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

20. Use your graph to answer the following questions.
   a. How many days did it take to reach peak infection?
b. How many individuals were infectious at peak infection?

c. What was the total length (in days) of the epidemic? Assume the epidemic is over when there are exactly 0 infectious individuals (without rounding) in the population. You may need to increase “Total Days” in the settings and select the “Simulate” button again until you find the end of the epidemic.

d. How many individuals were infected over the course of the entire epidemic?

e. Were there any susceptible individuals in the population at the end of the epidemic?

21. Compare your new SIR graph (40% vaccination) with your previous SIR graph (no vaccination).
   a. How do the curves in these two graphs differ? (Compare the timelines and number of individuals in each group.)

   b. You may have heard that vaccines can help “flatten the curve.” Which curve is being “flattened,” and why might this be desirable?

22. This model assumes that all vaccinated individuals are always in the removed group. When might this assumption not be true in real life?

23. Was the initial 40% vaccination rate sufficient to protect the population from an epidemic? Explain your answer.

PART 5: Modeling the Impact of a 92% Vaccination Rate

In 2013, Samoa had a 92% vaccination rate against measles. Let’s explore what might have happened if the 2013 vaccination rate had been maintained.

24. Consider how a 92% initial vaccination rate would compare to the 40% initial vaccination rate in Part 4.
   a. Briefly describe, or draw directly on your graph from Question 17b, how each curve might shift if 92%, rather than just 40%, of the population had been initially vaccinated.

   b. Explain your reasoning for the shifts you predicted.

25. You’ll now model how measles would spread when 92% of the initial population is vaccinated. You can use the same total number of days, transmission rate, and recovery rate as before, but you will need to adjust the number of individuals initially in each group.
a. Assuming that the population has 200,000 individuals and that there is initially one infectious individual, list your new settings below:
- Total Days: 60
- Transmission Rate ($t$): 130
- Recovery Rate ($r$): 20
- Initial Susceptible Individuals: __________
- Initial Infected Individuals: __________
- Initial Removed Individuals: __________

b. Enter the settings above, then start the simulation to generate a new graph. Following the guidance of your instructor, download, print, or sketch an image of your graph. Label it as “92% Vaccination.” Make sure to include your graph when submitting this worksheet, in whichever format your instructor asks for.

26. How does this graph compare to what you predicted in Question 24?

27. Use your graph to answer the following questions.
   a. Did an epidemic occur?
   b. Describe one piece of evidence that supports your response to Part a.
   c. How does the graph you created in Question 25 compare to the graphs you generated in Question 10 and Question 17?
   d. How many individuals were infected in this scenario?

28. Based on this model, if the vaccination rate of 92% had been maintained, would there have been an epidemic? Explain your reasoning.

PART 6: Herd Immunity
Individuals and populations can gain immunity, which reduces the spread of a pathogen. Learn more about individual immunity, herd immunity, and the herd immunity threshold (HIT) by reading the “Immunity Background” tab in the “SIR Model Advanced” section.

29. Return to the Epidemic Simulator with the same settings as in Question 25. The HIT is displayed below the SIR graph. Compare the 2013 vaccination rate (92%) to the HIT. Explain your findings from Question 28 in light of this comparison.

30. What would have happened if the vaccination rate was 80% (slightly below the HIT for measles in this population) before the measles virus entered the population? Describe your reasoning.
31. You’ll now model how measles would spread when 80% of the initial population is vaccinated. You can use the same transmission rate and recovery rate as before, but you will need to adjust the number of individuals initially in each group.
   
a. Assuming that the population has 200,000 individuals and that there is initially one infectious individual, list your new settings below:
   - Transmission Rate (τ): 130
   - Recovery Rate (γ): 20
   - Initial Susceptible Individuals: __________
   - Initial Infected Individuals: __________
   - Initial Removed Individuals: __________

b. For the “Total Days,” choose a number that allows you to observe an increase, peak, and decrease in the number of infectious individuals. You can keep redoing the simulation with different numbers of days until you have a suitable graph.

c. Following the guidance of your instructor, download, print, or sketch an image of your final graph. Label it as “80% Vaccination.” Make sure to include your graph when submitting this worksheet, in whichever format your instructor asks for.

32. How does this graph compare to what you predicted in Question 30?

33. Use your graph to answer the following questions.
   a. How many days did it take to reach peak infection?
   b. How many individuals were infectious at peak infection?
   c. What was the total length (in days) of the epidemic? Assume the epidemic is over when there are exactly 0 infectious individuals (without rounding) in the population. You may need to increase “Total Days” in the settings and select the “Simulate” button again until you find the end of the epidemic.
   d. How many individuals were infected over the course of the entire epidemic?

34. Compare disease spread under different vaccination rates by completing the table below. Refer to your graphs from the previous parts of this handout as needed.

<table>
<thead>
<tr>
<th>Vaccination Rate</th>
<th>0% (Part 3, Question 13)</th>
<th>40% (Part 4, Question 20)</th>
<th>80% (Part 6, Question 33)</th>
<th>92% (Part 5, Question 27)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day of peak infection</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of infectious individuals at peak infection</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Total length (in days) of epidemic

<table>
<thead>
<tr>
<th>Vaccination Rate</th>
<th>80%</th>
<th>40%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (in days)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Total number of individuals infected

<table>
<thead>
<tr>
<th>Vaccination Rate</th>
<th>80%</th>
<th>40%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of infected</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

35. How does the spread of measles with an 80% vaccination rate (Part 6) compare to that with a 40% vaccination rate (Part 4)?

36. Is it beneficial to increase the vaccination rate even if the population doesn’t reach herd immunity? Why or why not?