UNDERWATER OUTBREAK: DIVING INTO AQUATIC INFECTIOUS DISEASE DYNAMICS

Isabelle Danforth
Virginia Institute of Marine Science

Grade Level
High School

Subject Area
Biology

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Title: Underwater Outbreak: Diving Into Aquatic Infectious Disease Dynamics

Focus: Modelling the spread of a fish virus in a rainbow trout population with a simulation game. Introduces students to epidemiological models and applications in aquatic disease management.

Grade Level: High School Biology

Virginia Standards of Learning:

BIO.1 The student will demonstrate an understanding of scientific and engineering practices by

a) asking question and defining problems
   - ask questions that arise from careful observation of phenomena and/or organisms, from examining models and theories, and/or seek additional information
   - determine which questions can be investigated within the scope of the school laboratory or field to determine relationships between independent and dependent variables
   - generate hypotheses based on research and scientific principles
   - make hypotheses that specify what happens to a dependent variable when an independent variable is manipulated

b) interpreting, analyzing and evaluating data
   - construct, analyze, and interpret graphical displays of data

c) constructing and critiquing conclusions and explanations
   - make quantitative or qualitative claims regarding the relationship between dependent and independent variables
   - apply scientific ideas, principles, and/or evidence to provide an explanation of phenomena and design solutions

BIO.4 The student will investigate and understand that bacteria and viruses have an effect on living systems. Key ideas include

a) viruses depend on a host for metabolic processes
b) bacteria and viruses have a role in other organisms and the environment

BIO.7 The student will investigate and understand that populations change through time. Key ideas include

c) Genetic variation, reproductive strategies, and environmental pressures affect the survival of populations

Learning Objectives:

Students will explore how compartmental models are used to study infectious disease dynamics by modeling an IHNV outbreak in rainbow trout using a board game.

Students will demonstrate their understanding of infectious disease dynamics by:

- Simulating an outbreak of a disease in rainbow trout through a board game
- Graphing the numbers of susceptible, infected, recovered and dead fish in the population as the outbreak progresses
- Calculating key epidemiological parameters using the data collected in the board game
- Predicting how changes in these parameters will change the progression of the outbreak

Suggesting an intervention strategy to end the epidemic

Total length of time required for the lesson: 1 to 1.5 hours

Vocabulary:

Stock: a population of one species of fish.

Raceway: a shallow channel often made of concrete with continuous flow of water in which fish (e.g. rainbow trout) are farmed. Occurs on land, not in the ocean.

Disease: a state of being that deviates from a normal state of being.

Pathogen: a microorganism (like a bacteria, virus, fungus or protozoan) that causes disease.

Infectious Hematopoietic Necrosis Virus (IHNV): an RNA virus in the family *Rhabdoviridae* which commonly causes disease in salmonids (salmon, trout and charr)

Virus: a biological entity (some consider it to be a living organism, others do not), typically smaller than bacteria. Relies on the host for reproduction.

Viral strain: a genetic variant of a virus. Note that this is similar to the term isolate. The primary difference is that isolates refer to a specific isolation event. For example, the viral isolate SV76 was isolated from a specific fish at a specific timepoint.

Culling: a process in which infected fish are removed and humanely euthanized to prevent the spread of a pathogen in farms.

Virucidal: compounds that "kill" viruses. Examples include bleach or chlorine.

Quarantine: a period of isolation from other fish. Allows time for the fish to develop symptoms, indicating to the farm managers that it is infected with some pathogen. This reduces the probability that new fish infect raceways of other fish.

Vaccine: an intervention that teaches a host's immune system how to recognize and fight off an infection.

Epidemiological Model: any model that is used to study the spread of a disease in a population. Compartmental models are a type of epidemiological model that breaks host populations into compartments.

SIR Model: a type of epidemiological model called a compartmental model in which a population experiencing an epidemic is divided into three compartments: S (susceptible), I (infected), and R (removed). Removed individuals may have died or they may have recovered. This is the fundamental structure of most compartmental models. Here, we are assuming that infected fish can either die or recover, and that they can no longer be infected after they recover. Therefore, the removed compartment is divided into recovered or dead compartments.

Host: an organism infected by a pathogen.

Transmission: Process by which susceptible individuals become infected.

Recovery: Process by which infected individuals recover.

Mortality: Process by which infected individuals die.

Probability: the likelihood of an event happening. In this case, the likelihood of a susceptible fish getting infected, or the likelihood of an infected fish recovering, or the likelihood of an infected fish dying.

Background Information:

As wild fish **stocks** decline, fish farming is a rapidly growing industry that has the potential to supply the world with a more sustainable source of protein. Rainbow trout (*Oncorhynchus mykiss*) are one of the most profitable species of farmed fish in the United States. In fact, the industry was valued at $103 million in 2022 (USDA NASS, 2022). The US rainbow trout farming industry is concentrated in the Hagerman Valley in Idaho where farmers typically pull water from neighboring rivers into the **raceways** in which the fish are kept.

Although fish farming can be a lucrative industry, **diseases** remain one of the biggest limitations to expansion. Like humans, rainbow trout are susceptible to a wide variety of infectious diseases that can be caused by many kinds of **pathogens**. One of these pathogens is **infectious hematopoietic necrosis virus (IHNV)**, which is a **virus** that causes the disease Infectious Hematopoietic Necrosis or IHN. Fish infected with IHNV commonly display symptoms such as bulging eyes, behavioral abnormalities, distended bellies and darkened skin (Fig. 1).

Fig 1: Characteristic symptoms of IHNV include darkened skin, distended bellies, bulging eyes, bloody eyes and behavioral changes.

IHNV causes an acute disease in members of the Salmonidae family (salmonids), which include fish that are commonly found in grocery stores like Atlantic salmon (*Salmo salar)*, sockeye salmon (*Oncorhynchus nerka)* or rainbow trout *(O. mykiss)*. The severity of the disease vary depending on fish-related factors, virus-related factors and environmental factors. For example, smaller and younger fish often develop more severe infections while adults are usually able to fight off the infection, though they may remain chronically infected and show no clinical signs of disease. There are also several **viral strains** of IHNV, with some strains causing high mortality in rainbow trout and others causing more mortality in sockeye salmon (Dixon et al. 2016). Environmental factors like water temperature are also important as they can impact the ability of the virus to infect a fish and the ability of the fish to combat the infection.

The global rainbow trout farming industry has been heavily impacted by IHNV. The virus can kill up to 90% of fish in a raceway and survivors may develop scoliosis, making them undesirable to consumers. IHNV is also highly infectious, causing many farmers to humanely euthanize an entire raceway of fish as soon as they detect the virus. This process is known as **culling**. Although culling can be an effective way to prevent the disease from spreading, it also causes even more financial loss for the farmers. Consequently, many farms rely on other disease management protocols to prevent epidemics. These include treating incoming water with ozone or UV irradiation to kill any virus or washing equipment with virus-killing (**virucidal**) substances like bleach. Newly arriving fish are usually put into **quarantine** before being added to the farm, and fresh eggs are sanitized with iodine to kill virus on the eggs. Farmers can also vaccinate fish with anti-IHNV **vaccines** or choose to raise fish that are selectively bred to be resistant to IHNV (Dixon et al. 2016). In fact, the subject of my research aims to understand how these intervention strategies might be impacting the evolution of the virus.

Scientists called epidemiologists work to understand how diseases spread through populations. These approaches can indicate how effective management strategies like vaccination will be. To do this, scientists may build a type of **epidemiological model** called a compartmental model, which allows them to understand the dynamics of a disease at a population level. In these models, the population is sub-divided into compartments. Then, scientists develop mathematical equations that describe the flow of individuals from one compartment to the next. One of the most widely used compartmental models is known as the **SIR model**. Here, the letters S, I and R represent the compartments in which **hosts** are. In this lesson plan, the host population that is being modeled is rainbow trout in a raceway. All members of the population start off as S (*susceptible*). Some individuals may become infected, at which point they move into the I (*infected*) compartment (Keeling and Rohani, 2008). From the infected compartment, hosts then move into the R (*removed*) compartment. This removed compartment accounts for individuals who die and those who recover. However, because IHNV causes high levels of mortality, this lesson plan will use a fourth compartment called D (*dead*) to account for fish that die, and the R compartment will only contain fish that recovered (Fig. 2). The movement of individuals from the *S (susceptible)* compartment to the *I (infected)* compartment is determined by a process called **transmission**. Similarly, the movement of individuals from the *I (infected)* compartment to the *R (recovered)* compartment is determined by **recovery** and the movement of individuals in the *I (infected)* compartment to the *D (dead)* compartment is determined by **mortality.** In practice, transmission, recovery, and mortality are rates that can be calculated with calculus, but this process can become extremely complicated. For the purposes of this lesson plan, we will simplify this by using **probability**. In other words, the transmission rate is the *probability that a fish gets infected*, the recovery rate is the *probability that it recovers*, and the mortality rate is the *probability that it dies*. We will also choose not to consider natural mortality (i.e. the rate at which fish die due to non-virus factors like predation or old age). The probability of transmission, recovery and mortality will be used to complete the IHNV outbreak simulation game.

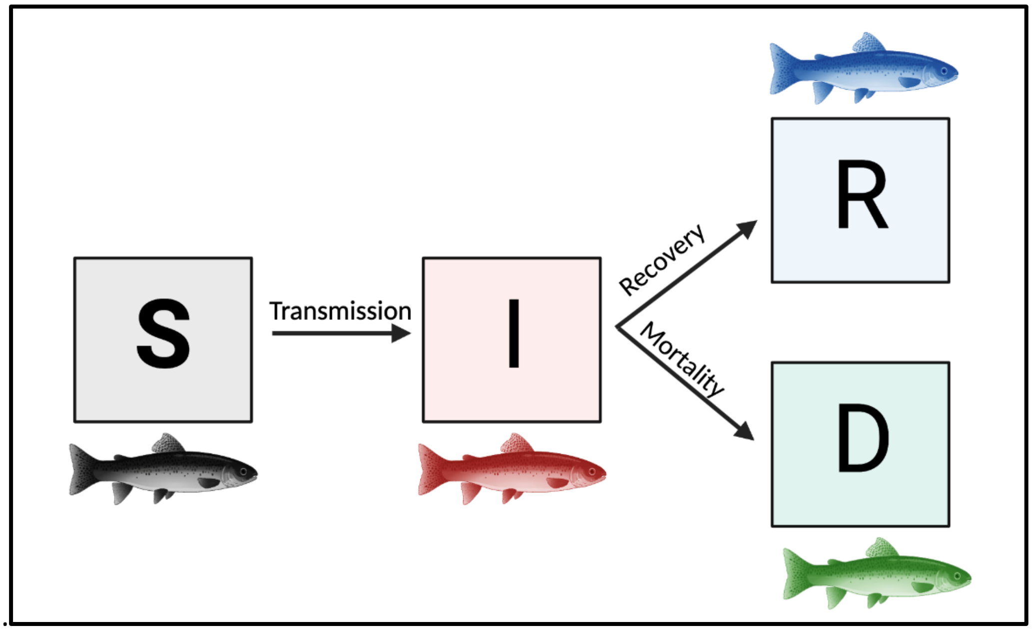


Fig 2: Depiction of the fundamental components in the SIR model. S = susceptible, I = infected, R = recovered, D = dead.

In this lesson, students will play a board game that simulates the spread of IHNV in a rainbow trout population with a mock SIR model. At each turn, they will record the number of susceptible, infected, recovered and dead individuals in a table. They will then graph the table and use these numbers to calculate the proportion of fish in each compartment at several timepoints. Information like this is used by scientists to understand how a disease is spreading or how it can be controlled. There are two versions of the game, each with different model parameters (transmission probability, recovery probability and mortality probability) for their game. This will result in two different graphs depending on the version of the game that is played. The idea is that groups will play different versions of the game and so students will be able to compare their results at the end of the class to understand how changes in the probability of transmission, recovery and mortality impact the way in which a disease spreads.

Materials & Supplies:

- Worksheet
- Underwater Outbreak Game Instructions and Materials (gameboard, recording table, game versions)
- Instructor Keys for Worksheet
- Accompanying PowerPoint introduction
- Computer and projector (in person) OR computer, Internet, and screen-sharing capabilities (remote learning) for PowerPoint presentation
- Pens/pencils
- Colored dry-erase markers (blue, red, black, green)
- Tissue paper/paper towel (for erasing dry-erase markers)
- Colored pencils (blue, red, black, green)
- 10-sided dice (one per group, can be obtained online)
- Optional: graphing software (e.g,: Microsoft Excel or Google Sheets)
    - ***Link to Excel template:*** please create a copy of the sheet for use. https://masweb.vims.edu/bridge/VASEA/LessonPlanDocuments/VASEA_Danforth_ExcelTemplate_2025.xlsx
    - ***Link to Google Sheets template****:* please create copy of the sheet for use. https://docs.google.com/spreadsheets/d/19tSe7_jmVES0fu0l1wkGWxaNO--mf-hKrnWYXNQjpFM/edit?usp=drive_link

Teacher Preparation:

- 1 copy of worksheet per group
- 1 version of game: each group of students will receive a card with parameters for use in the game along with game instructions.

Teachers may choose to laminate the board and cards for repeated use. 10-sided dice can either be purchase or obtained online at the following websites:

- https://flipsimu.com/dice-roller/roll-d10/. (a little slower, but closer simulation of dice roll)
- https://rolladie.net/roll-a-d10-die (much faster, but not as similar to actual dice roll).

Teachers may also choose to assign the following videos for review:

- https://www.youtube.com/watch?v=2hcRFhPgcV4 – introduction to IHNV in rainbow trout
- https://media.hhmi.org/biointeractive/click/modeling-disease-spread/basics-background.html - video is at the bottom of this page. Note that this model does not include a death compartment, but the premise is identical.

Classroom Set-Up: arrange desks so that students in groups of 4 may work together.

Procedure:

Introduction: PowerPoint slides (I recommend opening presentation mode as I left notes to accompany each slide).

Game: Give each group of 4: (1) a copy of the game instructions (appendix A), (2) a copy of the recording table (appendix B), (3) a copy of gameboard (appendix C), (4) card with version of the game (appendix D), (5) Colored pencils, (6) Colored dry erase markers. Colored pencils are not required if the students will be using Excel or Google Sheets for graphing. It is ideal for both versions of the game to be used so that students can compare their results as a class. If you choose to play the game as a class instead of in groups, I recommend using version 1 of the game.

- The students will play the game and record the number of S, I, R and D fish at each turn
- The students will graph the curves for S, I, R, and D (excel, google sheets or in worksheet)

Complete worksheet: Complete after playing the game.

Class Jigsaw: Have the students from each group report their results to the rest of the class.

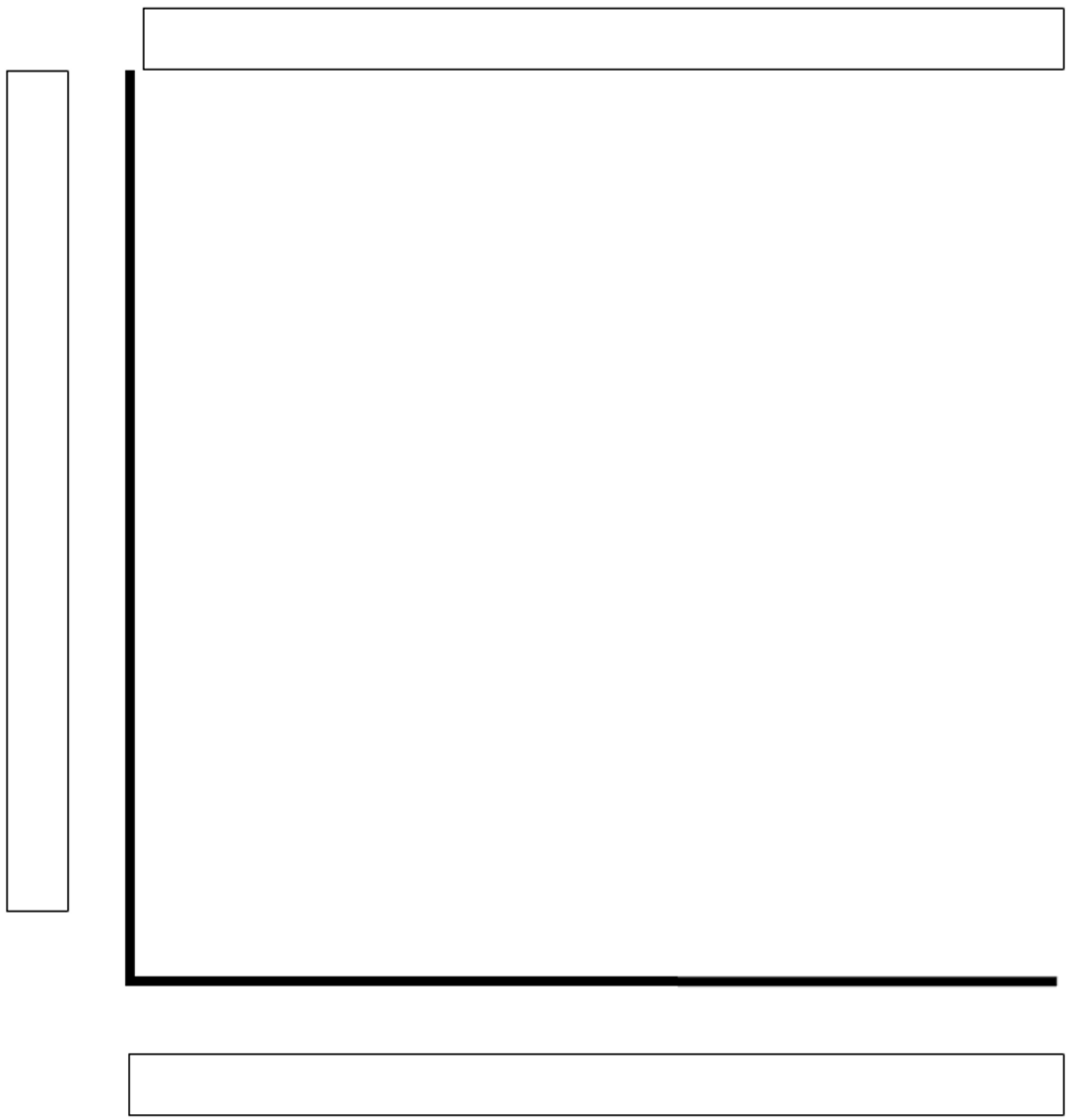
Assessment:

Students will be assessed on their completion of the worksheet and their participation in the game.

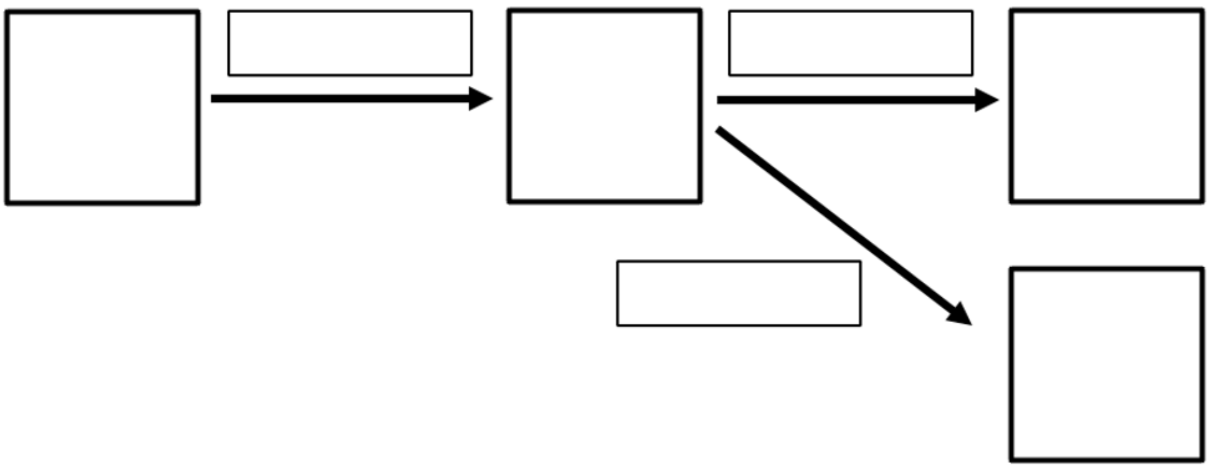
Worksheets:

Create a line graph with the number of S (susceptible), I (infected) R (recovered) and D (dead) fish over time. Make sure to add a title and x and y axis labels.

Version of Game: ____________________



1. Fill in the blanks below with the following terms:
    - I (infected)
    - D (dead)
    - Transmission
    - S (susceptible)
    - Mortality
    - R (recovered)
    - Recovery



2. Which day had the highest number of infected fish?

3. On day 5, what proportion of the fish are susceptible? What proportion of the fish are infected? What proportion of the fish are recovered? What proportion of the fish are dead? Write your answer as a fraction.

4. On day 10, what proportion of the fish are susceptible? What proportion of the fish are infected? What proportion of the fish are recovered? What proportion of the fish are dead? Write your answer as a fraction.

5. Why does the number of infected individuals increase and then decrease? Hint: consider the box and arrow diagram from question 1.

6. What are three kinds of approaches could be used to reduce the spread of the disease? Consider how public health professionals do this in human populations. Are there approaches that can be used in aquaculture but not in humans?

7. What are some assumptions that we made with this simulation? Hint: I have listed a few in the game instructions. Can you think of any others?

8. Imagine that game version 1 is modeling an outbreak of a specific IHNV strain called **220-90**. Game version 2 is modeling an outbreak of another IHNV strain called **SV76** (these are both real IHNV strains that we frequently use in the lab). If you detected one of these strains on your fish farm, which strain would you be most concerned about?

9. CLASS JIGSAW: Now compare your graph with the graphs of your classmates and your answers to questions 3 and 4. Consider: why are their results different from yours?

Answer Key:

Worksheet: Actual answers may vary by version of the game, but also due to the random chance nature of rolling the dice.

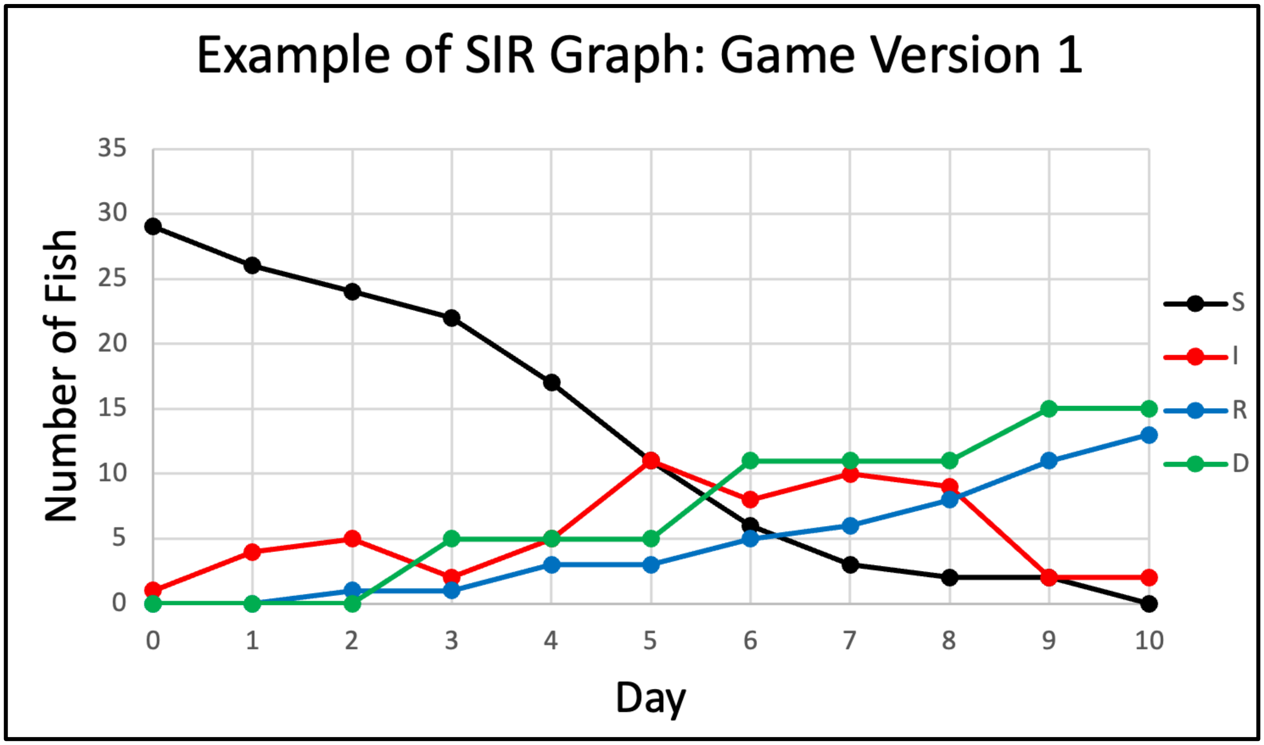
Example for game version 1:

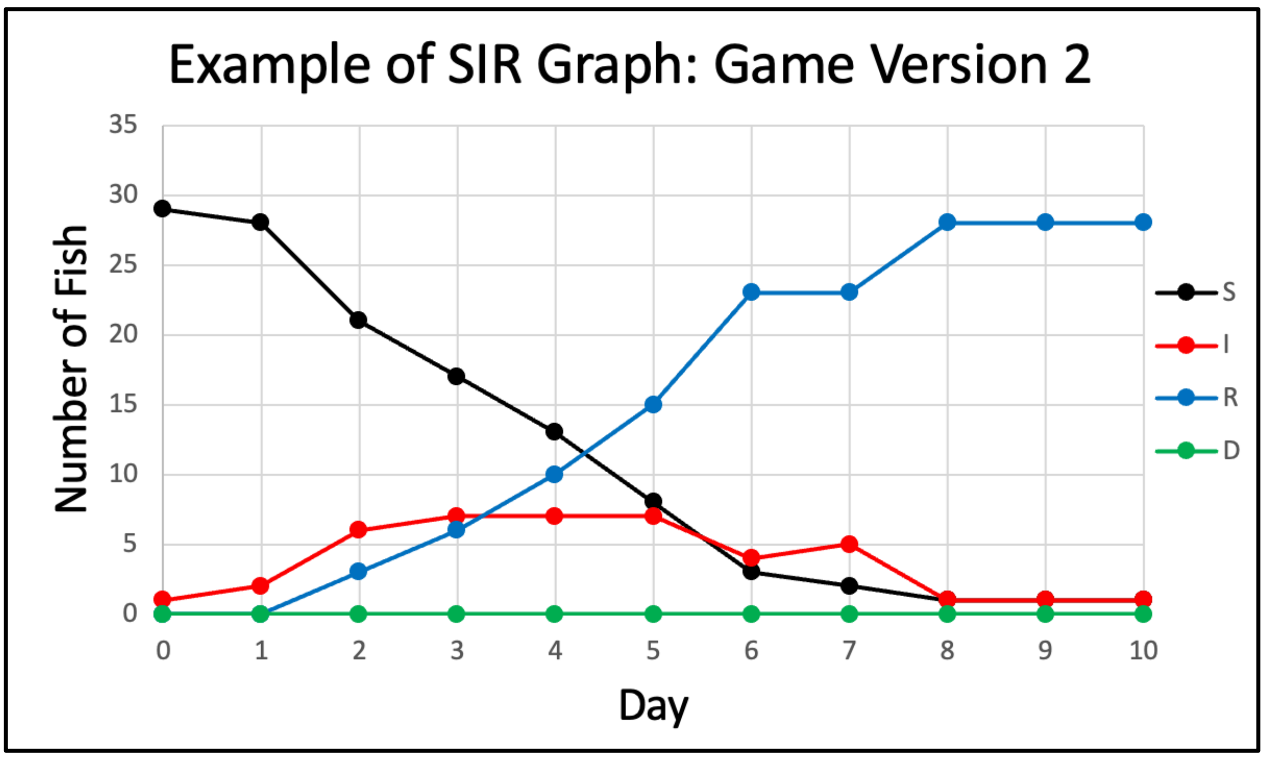
Turn Number	Day of Outbreak	S (susceptible)	I (infected)	R (recovered)	D (dead)	N (total) = S+I+R+D
0	0	29	1	0	0	30
1	1	26	4	0	0	30
2	2	24	5	1	0	30
3	3	22	2	1	5	30
4	4	17	5	3	5	30
5	5	11	11	3	5	30
6	6	6	8	5	11	30
7	7	3	10	6	11	30
8	8	2	9	8	11	30
9	9	2	2	11	15	30
10	10	0	2	13	15	30

Example for game version 2

Turn Number	Day of Outbreak	S (susceptible)	I (infected)	R (recovered)	D (dead)	N (total) = S+I+R+D
0	0	29	1	0	0	30
1	1	28	2	0	0	30
2	2	21	6	3	0	30
3	3	17	7	6	0	30
4	4	13	7	10	0	30
5	5	8	7	15	0	30
6	6	3	4	23	0	30
7	7	2	5	23	0	30
8	8	1	1	28	0	30
9	9	1	1	28	0	30
10	10	1	1	28	0	30

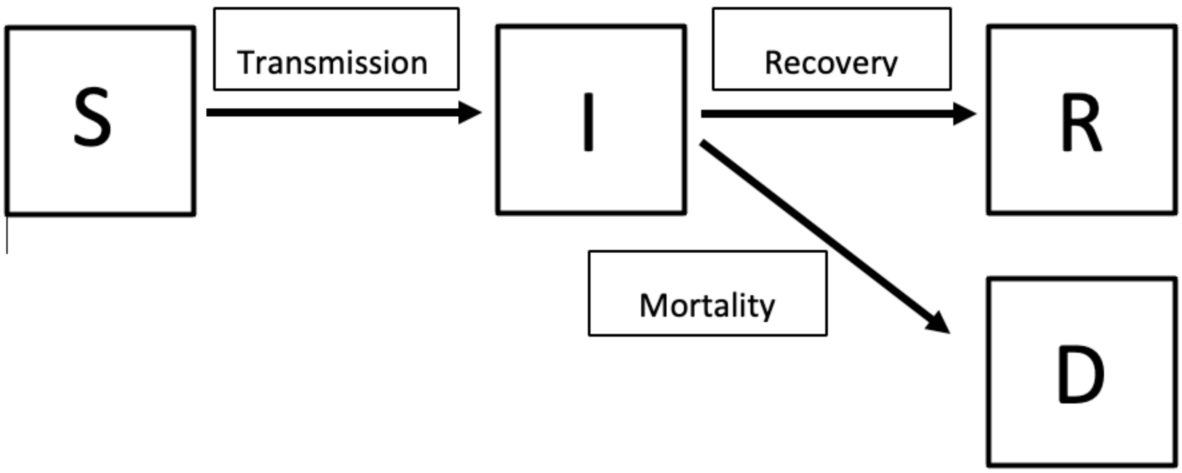
Here are examples of what graphs could look like for each version of the game. Again, results will vary by group but the trends should be relatively similar in each version of the game.





1. Fill in the blanks below with the following terms:

- I (infected)
- D (dead)
- Transmission rate
- S (susceptible)
- Mortality rate
- R (recovered)
- Recovery rate



2. Which day had the highest number of infected fish?

The day with the highest number of infected fish (also known as peak infection day) will vary. In the examples provided here, the peak infection day for version 1 of the game is day 5 when there are 11 infected fish. In game version 2, the transmission probability is lower and so you get a less distinct increase in the number of infected fish (especially because we are only considering a 10-day epidemic with a small fish population of just 30. If we scaled this up to 10,000 fish, you would likely see a more distinct pattern). In game version 2, the number of infected rises to 7 and stays there until day 6.

3. On day 5, what percentage of the fish are susceptible? What percentage of the fish are infected? What percentage of the fish are recovered? What percentage of the fish are dead? Round your answer to the nearest tenth.

In game version 1, there are 11 susceptible fish, 11 infected fish, 3 recovered fish, and 5 dead fish on day 5. The total population size is 30. Proportion of population that is susceptible = 11/30, proportion of fish that are infected = 11/30, proportion of fish that are recovered = 3/30, and proportion of fish that are dead = 5/30. Actual numbers will vary.

4. On day 10, what percentage of the fish are susceptible? What percentage of the fish are infected? What percentage of the fish are recovered? What percentage of the fish are dead? Round your answer to the nearest tenth.

In game version 1, there are 0 susceptible fish by day 10, 2 infected fish, 13 recovered fish and 15 dead fish. Thus, the proportion of the population that is susceptible is 0/30, the proportion of the population that is infected = 2/30, the proportion of fish that are recovered = 13/30 and the proportion of fish that are dead is 15/30. Actual numbers will vary.

5. Why does the number of infected individuals increase and then decrease? Hint: consider the box and arrow diagram from question 1.

The key here is to understand the fundamental premise of the compartmental models: individuals move through each host class (S, I, R or D) and the rate at which this occurs is dependent on the rate of transmission, recovery or mortality (although for this game, rate was replaced with probability). All fish start as susceptible. Once they are infected, they move into the infected class. They then leave the infected class due to mortality (from the virus) or due to recovery. Therefore, the number of infected individuals increases initially as fish become infected but then begins to decline as more and more fish recover (remember that for this model, we assume that recovered fish cannot become re-infected) or die. Eventually the epidemic ends because the susceptible population drops below some threshold value, below which infected individuals are more likely to recover than to infect others. The number of infected individuals increases more rapidly in game version 1 because the transmission probability is very high.

6. What are three kinds of approaches that could be used to reduce the spread of the disease? Consider how public health professionals do this in human populations. Are there approaches that can be used in aquaculture but not in humans?

Several correct answers are possible. These include:

- Culling (the removal of infected fish by killing them) – widely used in aquaculture but cannot be done in human populations. This is one reason why IHNV can be a major financial cost for farmers.
- Vaccines – widely used in aquaculture, can be done in human populations. There are many vaccines that have been developed for IHNV, though only one is commercially available.
- Frequent testing of the fish for virus – widely used in aquaculture, can be done in human populations (although there may be logistical or ethical restrictions to this in humans).
- Quarantining fish that test positive for the virus or appear sick – can be done in human populations (e.g. stay at home orders during the COVID-19 pandemic).
- Monitoring the origin of fish imports to prevent bringing pathogens into US aquaculture from overseas. Newly arrived fish are often quarantined prior to being added to the main fish population. If they develop symptoms, then they are generally discarded. There is an entire international governing body called the World Organization for Animal

Health (WOAH) which is responsible for declaring what pathogens are notifiable. IHN is a WOAH-notifiable disease.
- Using disease resistant fish (fish that are selectively bred to be resistant to the virus) – cannot be done in human populations, although some individuals are more resistant to specific pathogens due to natural genetic variation.
- Sanitary practices – The most widely used disease management approach in aquaculture. Can be used in human populations (wash your hands!). Many aquaculture farms rely on strict biosecurity protocols like using UV-sterilized water, bleach rinses/soaks, careful disposal of dead fish, and sterile practices to prevent disease spread.

7. What are some assumptions that we made with this simulation?

The important thing to understand is that when we use models, **we always make assumptions to simplify the complicated world of biology into a world of mathematical expressions.** This is an incredibly powerful tool, but it is important to understand what assumptions you are making in any model that you use because this will determine how the results are interpreted and directions of future research. There are many different answers to this question, but some are listed below. In this game, we assumed:

1. The population is constant (there are no new fish arriving and no fish are leaving).
2. The dead fish cannot infect other fish (in fact, there is some evidence to suggest that this is not the case with IHNV, but this is an active area of research).
3. Recovered fish cannot be re-infected.
4. Each fish has an equal probability of being infected, recovering or dying. In reality, there may be some fish that are naturally resistant to the virus and thus less likely to be infected.
5. A fish can infect other fish (is infectious) as soon as it becomes infected. In many cases, this is not entirely true. For example, viruses like SARS-CoV2 or influenza have periods where the infected individual is infectious only after a few days of being infected.
6. Mortality is due only to the virus. In order to keep the game simple, I have chosen to ignore the fact that there is also some rate at which fish are dying due to non-virus reasons. For example, they may die of old age, they may be eaten by an eagle, or they may be harvested and sold in your local grocery store *before* they die of IHNV.

8. Imagine that game version 1 is modeling an outbreak of a specific IHNV strain called **220-90**. Game version 2 is modeling an outbreak of another IHNV strain called **SV76** (these are both real IHNV strains). If you detected one of these strains on your fish farm, which strain would you be most concerned about?

The goal of this question is to have the students realize that each viral “species” (e.g. SARS-CoV2 or rabies virus) and even specific viral strains within a “species” (e.g. the different variants of SARS-CoV2) all have different rates of transmission, recovery, and mortality. It is these differences that determine how pathogens spread in host populations (whether they are human or fish). These parameters define whether we expect to see an epidemic, how we can reduce the probability of the epidemic occurring, and how significant the epidemic will be. I would be most concerned if I detected IHNV viral strain 220-90 because according to my example for game version 1, this virus caused a higher level of mortality and resulted in a greater number of infected fish over a 10-day outbreak.

9. CLASS JIGSAW: Now compare your graph with the graphs of your classmates and your answers to questions 3 and 4. Consider: why are their results different from yours?

The key here is that each group's graph is different and that those differences are due mainly to the different parameters that they were given, but also to random chance from the dice rolls. For example, the students could compare how the proportion of fish in each compartment (S, I, R or D) changes depending on which version of the game they played. In game version 1, there will probably be a higher proportion of fish that have died than in game version 2. This is because the death probability (d) = 70% for game version 1 whereas d = 40% for game version 2. In fact, when I played the game myself, I did not get any mortality in game version 2. This is likely because the recovery probability is so high that fish move from infected to recovered faster than they move from infected to dead. Because this game requires the player to determine the number of recovered individuals first, it is possible that game version 2 will result in no mortality.

The students could also look at the way the slope of each line changes. For example, in game version 1, the number of recovered individuals grows at a slower rate than it does in game version 2 (because recovery probability is so much higher in game version 2). Similarly, the number of dead fish rises rapidly in game version 1 because the probability of death is 70%.

Appendices:
All appendices also exist as separate handouts. I suggest making 6 copies (or more if there are more than 6 groups per class) of appendices B, C, and D. These copies can then be laminated for repeated use. To facilitate printing, all items that I recommend printing are on pages 23-25. The teacher may also consider making a laminated copy of the game instructions (appendix A), but only one copy is needed. The Underwater Outbreak Simulation game instructions are also outlined in the last slides of the PowerPoint. The teacher may choose to play the first few rounds as a class with game instructions displayed for the students to follow along.

Appendix A: Game Instructions

Underwater Outbreak Simulation Game: Instructions and Materials

Set-up:

1. Layout the gameboard
2. Assign responsibilities to all group members
    a. Player 1 = Record keeper. Keeps track of the number of S, I, R and D at each turn.
    b. Player 2 = Responsible for the recovered fish.
    c. Player 3 = Responsible for the infected fish.
    d. Player 4 = Responsible for the dead fish.
3. Place one red dot in the center of the square at the top right corner of the gameboard with a red dry erase marker.
4. Place one black dot in the center of all remaining squares with a black dry erase marker.

Gameplay:

The following steps are based on version 1 of the game. The rules are the same for all other versions, but the numbers change based on the version of the game.

1. *Round 1 (day 1): Starting the outbreak*
    a. Determine how many fish get **infected**
        i. Player 3 rolls the 10-sided dice for each fish that neighbors the initially infected fish. A neighboring fish is one that is either directly horizontal, vertical or diagonal to the initially infected fish.
        ii. In version 1 of the game, t = 60%. Therefore, rolling a 1, 2, 3, 4, 5, or 6 results in the fish getting infected (because there is a 60% chance of rolling a 1, 2, 3, 4, 5, or 6 with a 10-sided dice)
        iii. If the fish gets infected, then player 3 will erase the black dot and replace it with a red dot.
        iv. If none of the fish get infected on round #1, keep rolling the dice for each neighboring fish until at least one more fish becomes infected.
    b. Player 1 records the number of S, I, R and D fish in the table
        i. Note: at this point in the game, there should be no recovered or dead fish.
2. *Round 2 (day 2):*
    a. Determine how many fish get **infected**
        i. Player 3 rolls the 10-sided dice for each fish that neighbors any infected fish
        ii. In version 1 of the game, t = 60%. Therefore, rolling a 1, 2, 3, 4, 5, or 6 results in the fish getting infected.
        iii. If a fish becomes infected, then player 3 will circle the black dot with a red line. This indicates a *newly infected* fish.
    b. Determine how many fish **recover**
        i. Player 2 rolls the 10-sided dice for each fish that was infected in a previous round (denoted by a solid red dot)

ii. In version 1 of the game, r = 30%. Therefore, rolling a 1, 2, or 3 results in the fish recovering from the infection. Fish that are *newly infected* (black dot circled with red line) cannot recover.
iii. If a fish recovers, player 2 will erase the red dot and replace it with a blue dot. This indicates that the fish has recovered. For the purposes of this game, we will assume that a fish cannot become infected again after it has recovered.
iv. Player 3 will then fill in the red circles that indicated *newly infected fish*. These are now considered infected fish.

c. Record the number of fish of each color:
   i. Player 1 records the number of S, I, R and D fish on the table

3. *Round 3 (Day 3)*
   a. Determine how many fish get **infected.**
      i. Same as in round 2.
      ii. Remember to use a red circle to denote newly infected fish.
   b. Determine how many fish **recover.**
      i. Same as in round 2.
   c. Determine how many fish **die**.
      i. In practice, a fish could die on any day of the infection. However, for the sake of keeping this game simple, we will assume that fish will only die on days 3, 6 and 9.
      ii. It is also important to remember that fish may die for reasons that are not related to the virus. For example, aquacultured fish might be harvested or wild fish might be consumed by predators before dying of the infection. This is usually accounted for in epidemiological models and is referred to as *background mortality rate*. For the purposes of this game, assume that the death probability (d) accounts ONLY for virus-induced mortality and we will ignore background mortality rate.
      iii. On days 3, 6, and 9, follow these steps to determine how many fish die. Only infected fish can die. By ignoring background mortality rate, we are assuming that susceptible fish cannot die.
      iv. After determining how many fish recover, player 4 will roll the dice for each of the remaining infected fish. Do not roll the dice for *newly infected* fish. We will assume that newly infected fish cannot die.
      v. In version 1 of the game, d = 70%. Therefore, rolling a 1, 2, 3, 4, 5, 6, or 7 will result in the fish dying.
      vi. If the fish dies, player 4 will erase the red dot and replace it with a green dot to indicate that the fish has died.
      vii. After determining how many fish die, fill in the red circles denoting newly infected fish. These fish are now infected.
   d. Record the number of fish of each color
      i. Player 1 records the number of S, I, R, D fish on the table
4. *Round 4 (Day 4):* Same as in round 2
5. *Round 5 (Day 5):* Same as in round 2

6. *Round 6 (Day 6):* Same as in round 3. Remember to determine how many fish die!
7. *Round 7 (Day 7):* Same as in round 2
8. *Round 8 (Day 8):* Same as in round 2
9. *Round 9 (Day 9):* Same as in round 3. Remember to determine how many fish die!
10. *Round 10 (Day 10):* Same as in round 2.

Additional Notes:

- If no new fish get infected, die or recover in one of the rounds, this still counts as one day. Record the number of fish in S, I, R and D even if it is the same as the previous day.
- If a neighboring fish is close to two infected fish, only roll the dice once. Although this is not entirely accurate since a fish that is close to two or more infected fish likely has a higher probability of becoming infected, it avoids overcomplicating the game.
- If there are no more susceptible fish able to become infected before the game reaches 10 rounds, continue to roll the dice to determine how many fish recover or die, but there are no more fish available to be infected.

Appendix B: Recording Table

Version of the game: ___

Turn Number	Day of Outbreak	S (susceptible)	I (infected)	R (recovered)	D (dead)	N (S + I +R +D)
0	0	29	1	0	0	30
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						

Appendix C: Gameboard

Version of the game: ____

	1	2	3	4	5	6
A						
B						
C						
D						
E						

Appendix D: Versions of the game

Each group receives one card. It is ideal for half the class to play version 1 and for the other half of the class to play version 2.

Game Version 1		
Parameter	**What it Means**	
Transmission probability (t) = 60%	Fish is infected	Roll 1, 2, 3, 4, 5, or 6
	Fish is **not** infected	Roll 7, 8, 9, or 10
Recovery probability (r) = 30%	Fish recovers	Roll a 1, 2 or 3
	Fish does **not** recover	Roll 4, 5, 6, 7, 8, 9, 10
Death probability (d) = 70%	Fish dies due to infection	Roll 1, 2, 3, 4, 5, 6, 7
	Fish does **not** die due to infection	Roll 8, 9, 10

Game Version 2		
Parameter	**What it Means**	
Transmission probability (t) = 30%	Fish is infected	Roll 1, 2, 3
	Fish is **not** infected	Roll 4, 5, 6, 7, 8, 9, 10
Recovery probability (r) = 60%	Fish recovers	Roll 1, 2, 3, 4, 5, 6
	Fish does **not** recover	Roll 7, 8, 9, 10
Death probability (d) = 40%	Fish dies due to infection	Roll 1, 2, 3, 4
	Fish does **not** die due to infection	Roll 5, 6, 7, 8, 9, 10

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