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 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 scientists' model infectious disease dynamics in humans, wildlife and agriculture or aquaculture.

Students will demonstrate their understanding of infectious disease dynamics by:

- Describing the impacts of viruses on economically valuable fish species
- 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 with continuous flow of water in which fish (often rainbow trout) are farmed.

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

Bacteria: small living things made of one cell that reproduce asexually.

Virus: smaller than bacteria, cannot reproduce without a host.

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* infecting salmonids (trout, salmon).

Viral strain: a genetic variant of a virus.

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" virus. 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.

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.

SIR Model: a type of epidemiological model called a compartmental model in which a population experiencing an epidemic is divided into four compartments: S (susceptible), I (infected), and R (recovered).

Host: an organism infected by a pathogen.

SIRD Model: a variation of the SIR model that includes a fourth compartment to account for the fact that fish may also die due to the infection. This fourth compartment is denoted D (dead).

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 diseases that can be caused by many kinds of **pathogens**. One of these pathogens is **infectious hematopoietic necrosis virus (IHNV)**, which 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).

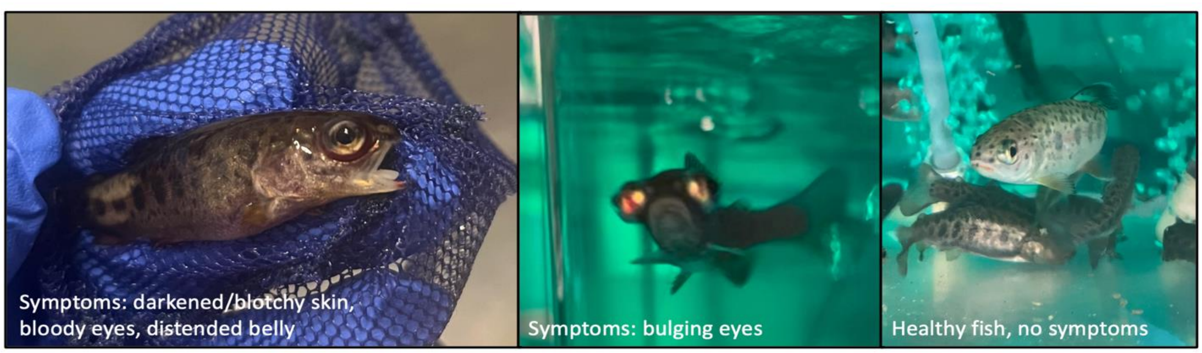
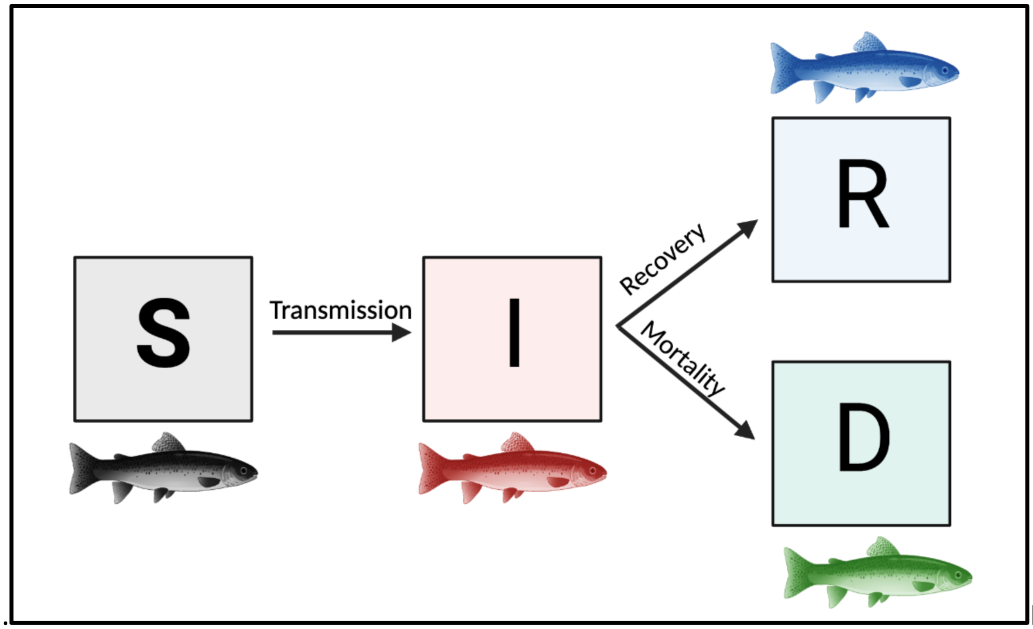


Fig 1: Characteristic symptoms of IHNV include darkened skin, distended bellies, bulging eyes, bloody eyes, and behavioral changes.

Infectious hematopoietic necrosis virus causes disease in members of the Salmonid family, 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 dynamics of a 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. 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. 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. Critically, if the right combination of host, pathogen and environment is not achieved, then the virus will not spread through a population (Dixon et al. 2016).

The global rainbow trout farming industry has been heavily impacted by IHNV. The virus can kill up to 100% 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. In fact, the subject of my research aims to understand how these intervention strategies might be impacting the evolution of the virus.

Scientists work to understand how diseases spread through populations. These approaches can indicate how effective management strategies like vaccination will be. To do this, scientists can build a type of **epidemiological model** called a compartmental model. 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. All members of the population start of 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 may then recover or move into the R (*recovered*) compartment. An extension of the basic SIR model is the **SIRD model**. The only difference here is that individuals in the infected compartment can either move to the R (*recovered*) compartment or they can move to the D (*dead*) compartment (Fig. 3). 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.** The process of calculating the number of individuals moving from one compartment to another is done using calculus. For the purposes of this lesson plan, we will simplify this by using **probability**. In other words, the probability that a fish gets infected, recovers, or dies. These values will be used to complete the IHNV outbreak simulation game.



.Fig 2: Depiction of the fundamental components in the SIRD model.

In this lesson, students will play a board game that simulates the spread of IHNV in a rainbow trout population with a mock SIRD 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 percentage 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 might spread. Each group will receive different parameters (transmission probability, recovery probability and mortality probability) for their game. This will result in groups generating different graphs depending on the parameters that they are given. At the end of the class, students will compare their results to understand how changes in the probability of transmission, recovery and mortality impact the way in which a disease spreads.

Materials & Supplies:

- Worksheet
- SIRD 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)
- Calculator
- Optional: graphing software (e.g., Microsoft Excel or Google Sheets)

- *Link to excel template:* https://masweb.vims.edu/bridge/VASEA/LessonPlanDocuments/VASEA_Danforth_ExcelTemplate_2025.xlsx
- *Link to Google Sheets template:* https://docs.google.com/spreadsheets/d/1Yl4XS2_HUWYJDb28ksEb6jHg2aov6YT-70TiBqH9daY/edit?usp=sharing

- Optional: scratch paper for calculations

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 website: https://flipsimu.com/dice-roller/roll-d10/.

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

1. https://www.youtube.com/watch?v=2hcRFhPgcV4 – introduction to IHNV in rainbow trout
2. https://media.hhmi.org/biointeractive/click/modeling-disease-spread/basics-background.html - video is at the bottom of this page. Note that this model discusses an SIR model, which is functionally the same as the SIRD model but lacks a "death" compartment.

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, It is ideal for all three 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 3 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.

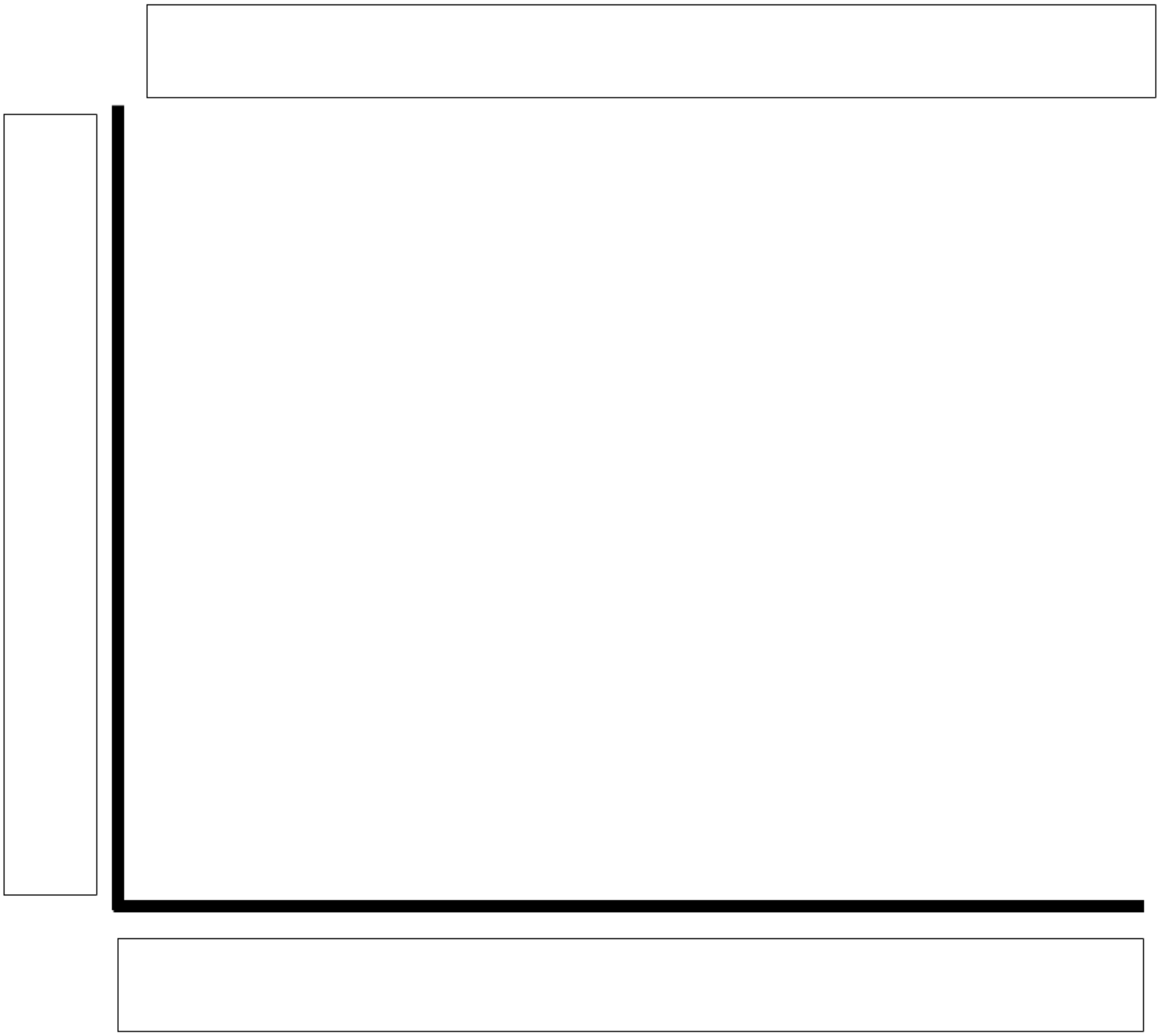
Assessment:

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

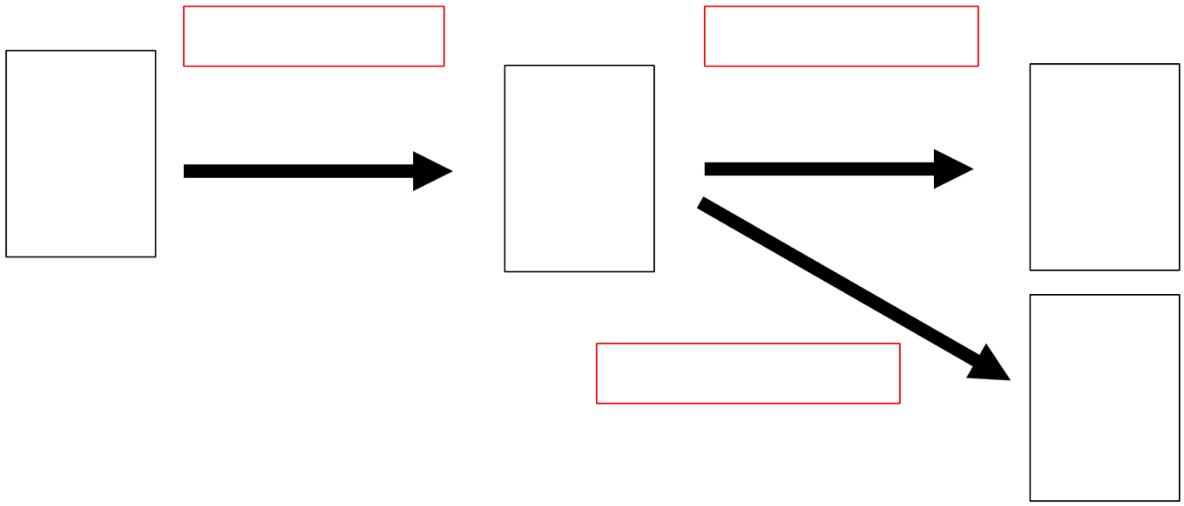
Worksheets:

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

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 infections (peak infection day)?

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.

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.

5. On day 15, 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.

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

7. What assumptions did we make with this simulation?

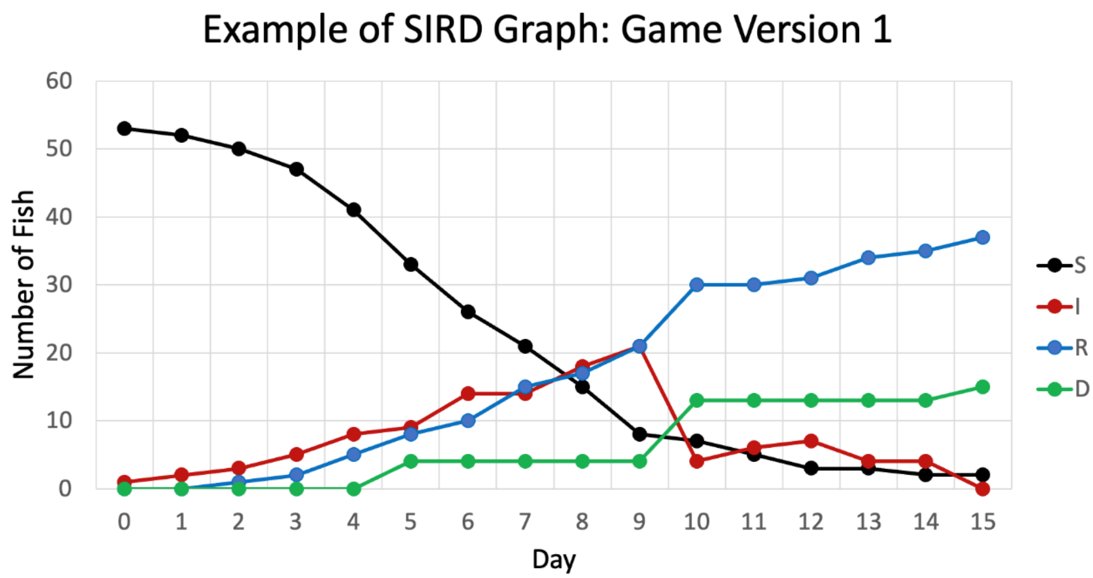
8. Now, compare your graph with the graphs of your classmates. Consider: why are their results different from yours?

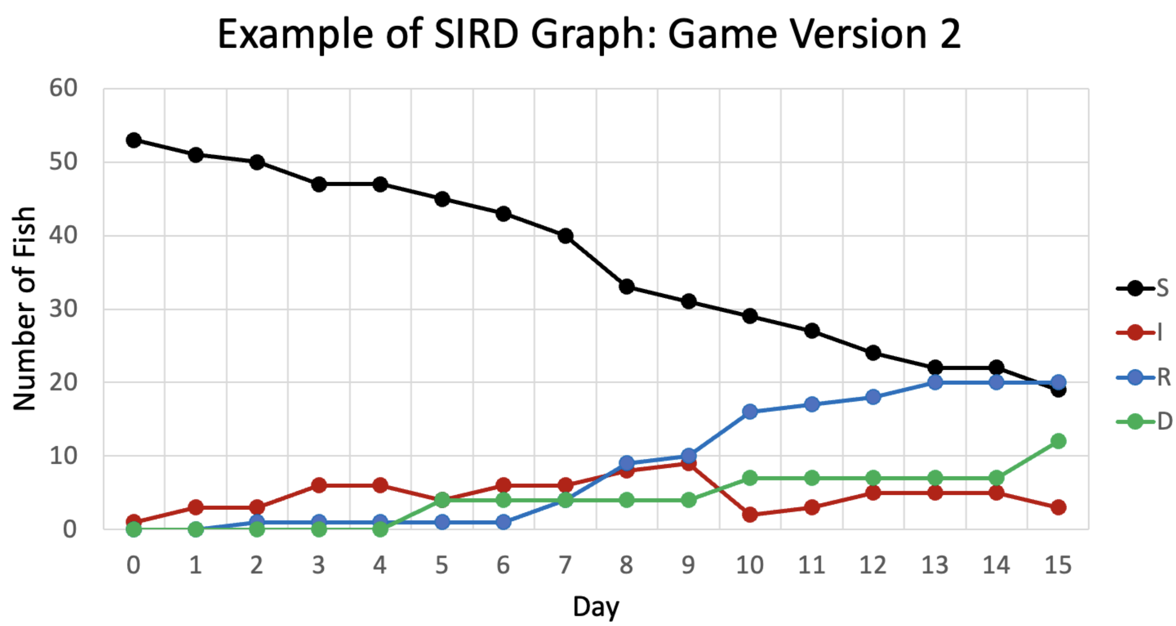
Answer Keys:

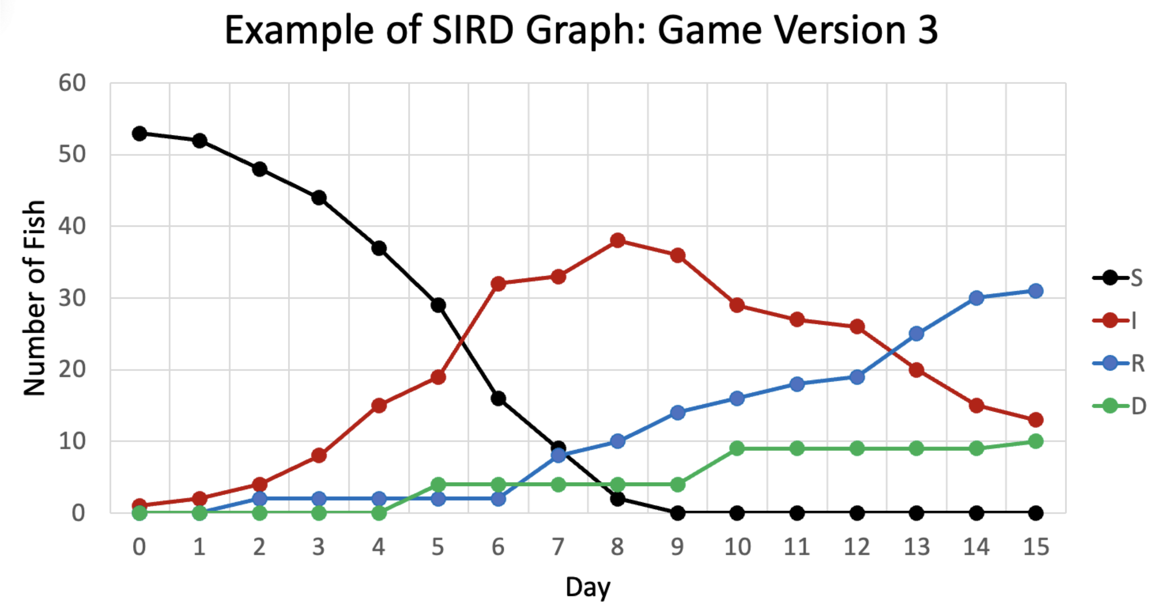
Worksheet: This example is from version 1 of the game. Actual answers may vary by version of the game, but also due to the random chance nature of rolling the dice.

Turn Number	Day of Outbreak	S (susceptible)	I (infected)	R (recovered)	D (dead)	N (total) = S+I+R+D
0	0	53	1	0	0	54
1	1	52	2	0	0	54
2	2	50	3	1	0	54
3	3	47	5	2	0	54
4	4	41	8	5	0	54
5	5	33	9	8	4	54
6	6	26	14	10	4	54
7	7	21	14	15	4	54
8	8	15	18	17	4	54
9	9	8	21	21	4	54
10	10	7	4	30	13	54
11	11	5	6	30	13	54
12	12	3	7	31	13	54
13	13	3	4	34	13	54
14	14	2	4	35	13	54
15	15	2	0	37	15	54

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.

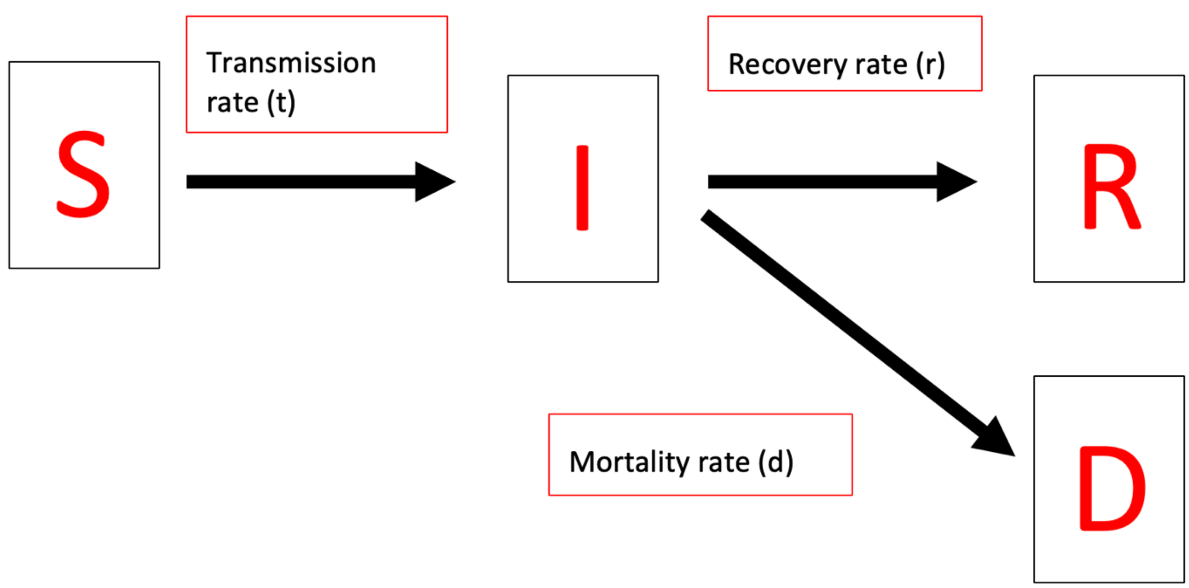






1. Fill in the blanks below with the following terms:

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



2. Which day had the highest number of infections (peak infection day)?

This is the day where the line for "I" is highest. In my example, this would be day 9 where there were 21 infected fish.

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 this example, there are 33 susceptible fish, 9 infected fish, 8 recovered fish and 4 dead fish on day 5. The total size of the population is 54, so 61.1% ((33/54) x 100)) of the fish are susceptible, 16.7% of the fish are infected, 14.8% of the fish are recovered and 7.4% of the fish are dead on day 5.

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.

On day 10, 7 fish are susceptible, 4 are infected, 30 are recovered and 13 are dead. Therefore, 13.0% of the fish are susceptible, 7.4% of the fish are infected, 55.6% of the fish are recovered and 24.1% of the fish are dead on day 10.

5. On day 15, 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.

On day 15, 2 fish are susceptible, 0 fish are infected, 37 fish are recovered and 15 fish are dead. Therefore, 3.7% of the fish are susceptible, 0% of the fish are infected, 68.5% of the fish are recovered and 27.8% of the fish are dead on day 15.

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

Several correct answers are possible. These include:

- Culling (the removal of infected fish) - cannot be done in human populations
- Vaccines – can be done in human populations
- Frequent testing of the fish for virus – can be done in human populations
- Quarantining fish that test positive for the virus or appear sick – can be done in human populations, thought to a lesser extent
- Quarantining any new fish, even prior to testing for the virus
- Using disease resistant fish (fish that are selectively bred to be resistant to the virus) – cannot be done in human populations, although some humans may be more resistant to specific pathogens due to natural genetic variation

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 incredibly complicated world of biology into a world of math. It is important to understand what assumptions you are making in any model that you use because this will determine how you can interpret your results. 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)
3. Recovered fish cannot be re-infected
4. Each fish has an equal probability of being infected, recovering or dying. 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 have latent periods where the infected individual is infectious only after a few days of being infected.

8. Now, compare your graph with the graphs of your classmates and your answers to questions 3, 4 and 5. 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 to the different parameters that they were given. For example, the students could compare how the percent 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 should be a higher percentage of fish that have died than in game version 3. This is because mortality probability (m) = 70% for game version 1 whereas m = 20% for game version 3. Note that if I had decided to have the students determine the number of dead fish on each day instead of on every 5 days, the differences between the number of mortalities in each version of the game would be significantly different. The students could also look at the way the slope of each line changes. For example, the number of susceptible fish decreases very slowly in game version 2 but decreases rapidly in game versions 1 and 3. In game version 3, the number of susceptible hosts begins to decline rapidly as soon as the number of infected hosts begins to increase. This is because the transmission probability (t) for game version 3 is extremely high at 70%. Finally, the students might notice that the number of recovered fish is lowest in game version 2 where the probability of recovery is 20% (higher than the probability of recovery in game version 1). So why might this have happened? This is likely because the probability of mortality was high at 50% and the transmission probability is just 30%. Thus, few fish are becoming infected (hence the very slow decline in susceptible fish), and those that are are more likely to die before they have the chance to recover. The answers to this question will vary depending on the shape of the students' graphs. Because this game relies on probability and rolling dice, no graph will look the same. However, the students should touch on these ideas.

Appendices:

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 18-21. The teacher may also consider making a laminated copy of the game instructions (appendix A), but only one copy is needed. The Underwater Outbreak 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

IHNV 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 any square on the gameboard with a red dry erase marker. These dots should be large.
4. Place one black dot in the center of all remaining squares with a black dry erase marker. Again, these dots should be large.

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. <u>Determine which fish get infected</u>
        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 = 50%. Therefore, rolling a 1, 2, 3, or 5 results in the fish getting infected (because there is a 50% chance of rolling a 1, 2, 3, 4 or 5 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 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. <u>Determine how many fish get infected</u>
        i. Player 3 rolls the 10-sided dice for each fish that neighbors any infected fish
        ii. In version 1 of the game, t = 50%. Therefore, rolling a 1, 2, 3, 4, or 5 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. <u>Determine how many fish recover</u>
    i. Player 2 rolls the 10-sided dice for each fish that is infected (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 2 will then fill in the red circles that indicate *newly infected fish*. These are now considered infected fish.
c. <u>Record the number of fish of each color:</u>
    i. Player 1 records the number of S, I, R and D fish on the table

3. *Rounds 3 and 4: Same as in round 2*
4. *Round 5 (Day 5):*
    a. Determine how many fish get infected
        i. Same as in round 2
    b. Determine how many fish recover
        i. Same as in round 2
    c. Determine how many fish die
        i. Although in reality a fish could die on any day of the infection, that's a lot of dice rolls! For the sake of simplicity, we will assume that fish might only die on days 5, 10 and 15. On each of these days, follow these steps
        ii. After determining how many fish recover, player 4 will roll the dice for each of the remaining infected fish
        iii. 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.
        iv. 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.
    d. Record the number of fish of each color
        i. Player 1 records the number of S, I, R, D fish on the table
5. *Rounds 6-9: Same as in round 2*
6. *Round 10 (Day 10): Same as in round 5*
7. *Rounds 11 – 14: Same as in round 2*
8. *Round 15 (Day 15): Same as in round 5*

Additional Notes:

- If no new fish get infected in one of the rounds, then that 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 has a higher probability of becoming infected, it avoids overcomplicating the game.
- If all fish are either dead or infected before reaching 15 rounds, continue to roll the dice to calculate the number of recovered fish

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	53	1	0	0	
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
11						
12						
13						
14						
15						

Appendix C: Gameboard

Version of the game: ____

Appendix D: Versions of the game

Each group receives one card. If there are more than three groups in the classroom, two groups may receive the same card.

Game Version 1		
Parameter	**What it Means**	
Transmission probability (t) = 50%	Fish is infected	Roll 1, 2, 3, 4, or 5
	Fish is not infected	Roll 6, 7, 8, 9, 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) = 20%	Fish recovers	Roll 1, 2
	Fish does not recover	Roll 3, 4, 5, 6, 7, 8, 9, 10
Death probability (d) = 50%	Fish dies due to infection	Roll 1, 2, 3, 4, 5
	Fish does not die due to infection	Roll 6, 7, 8, 9, 10

Game Version 3		
Parameter	**What it Means**	
Transmission probability (t) = 70%	Fish is infected	Roll 1, 2, 3, 4, 5, 6 or 7
	Fish is not infected	Roll 8, 9, or 10
Recovery probability (r) = 10%	Fish recovers	Roll a 1
	Fish does not recover	Roll 2, 3, 4, 5, 6, 7, 8, 9, 10
Death probability (d) = 20%	Fish dies due to infection	Roll 1, 2
	Fish does not die due to infection	Roll 3, 4, 5, 6, 7, 8, 9, 10

References:

1. USDA *National Agricultural Statistics Service,* USDA, Editor. 2023
2. Dixon Peter, Richard Paley, Raul Alegria-Moran, and Birgit Oidtmann. 2016. "Epidemiological Characteristics of Infectious Hematopoietic Necrosis Virus (IHNV): A Review." *Veterinary Research* 47 (1): 63
3. Keeling, Matt J., and Pejman Rohani. *Modeling Infectious Diseases in Humans and Animals*. Princeton University Press, 2008. *JSTOR*, https://doi.org/10.2307/j.ctvcm4gk0. Accessed 4 Dec. 2024.