SimBio Virtual Labs®: EcoBeaker®

Nutrient Pollution

Introduction

Energy, Nutrients, and Trophic Relationships

The dynamics of all ecosystems revolve around two key processes: energy flow and nutrient cycling. Most energy flow starts with the sun. **Autotrophs** (autos = self + trophe = food), such as plants, use solar energy to generate organic tissue from inorganic chemicals. Autotrophic organisms are considered to be **primary producers**, because they produce the organic molecules that fuel other organisms. **Heterotrophs** (heteros = another + trophe = food) obtain energy for growth and maintenance from the organisms they consume. Organisms that eat primary producers (e.g., herbivores) are known as **primary consumers**. Predators of herbivores are considered **secondary consumers**, and predators of predators are **tertiary consumers**. At each of these trophic levels, some of the solar energy initially converted into chemical energy by autotrophs is passed along, but some is dissipated as heat.

Organic molecules not only store the energy that powers living organisms but are the building blocks with which organisms are constructed. Cells and tissues are made from a diversity of organic molecules like amino acids to make proteins and nucleic acids to form DNA. These specialized molecules require a variety of chemical elements including carbon, hydrogen, oxygen, nitrogen, phosphorus and sulfur, as well as small amounts of elements like potassium and sodium. These required elements are called **nutrients**. The nutrients in an ecosystem come from the air, water, soil, and rocks. In many environments, one or more of the nutrients required by the local primary producers is in short supply, and the lack of such a **limiting nutrient** can limit growth of living things in the area (i.e., if you add that nutrient, growth increases). Many aquatic systems are nutrient limited, usually by phosphorus (P) or nitrogen (N). The natural input of these elements to a body of water, such as a lake, can be a slow process. For example, most P in streams and lakes comes from the weathering of rocks. In places where the rocks contain little P or weather slowly, there may be very little P in the water. For this reason, many bodies of water could support far more life if only they had a bit of fertilizer.

Inadvertently (and occasionally on purpose), humans supply this fertilizer. Every time you flush your toilet, its contents go somewhere, and quite often that somewhere is a nearby body of water. Mixed in with your droppings are food scraps from your kitchen sink, along with the soap you used to wash your dishes (which may contain phosphates). Also mixed in is extra fertilizer from people's lawns, ammonia (which contains nitrogen) from industrial facilities, and all the other odds and ends that find their way into city pipes and storm drains. Wherever this mixture of pollutants ends up receives a large input of nutrients. If the pollution ends up in water, those nutrients usually drive growth of the local primary producers, the phytoplankton (algae and cyanobacteria).

Too Much of a Good Thing? Nutrients and Algal Blooms

If you've ever lived near a lake experiencing an algal bloom, you know it is not pleasant. Good lake water, in most people's opinion, is not green and smelly. It is odorless and clear, which generally means it is nutrient-poor, which limits the growth of phytoplankton. When phytoplankon die, they sink to the bottom of the lake and undergo decomposition, a process which uses oxygen in much the same way you use oxygen when you breathe. When phytoplankton populations are large, the resulting high rate of decomposition can strip the oxygen from the water and turn a lake **anoxic** (i.e., lacking oxygen). Many animals cannot survive if oxygen levels drop too low, generally below about 2 mg/liter. Furthermore, if certain types of cyanobacteria are present, algal blooms can result in increased toxin levels in the water, which can cause human health problems. For all of these reasons, people do not usually like lakes that are overly nutrient-rich.

Here's where you come into the picture. When you initiate the **Nutrient Pollution** laboratory you will be (virtually) transported back in time to the early 1950s, when many cities were experiencing a post-war population boom. With larger populations came increased sewage, and much of the sewage was disposed of in the nearest body of water. A few years prior to your arrival, your city built a sewage system that empties into a lake near your home. You estimate that they will soon be tripling the lake's nutrient input rate. You've started to see changes in the species dominating the lake, and you are worried about this turn of events. Being a concerned citizen, you decide to do some experiments with the goal of trying to predict what's going to happen to your lake if the city keeps dumping raw sewage into it. The nutrient that most often limits growth in lakes is phosphorus, so in your experiments, you'll concentrate on phosphorus. You are also concerned, because you know sewage often contains toxins such as heavy metals that affect animals much more than plants. You want to know if the added toxins might have additional effects on the lake.

You have access to a research station with a set of small lakes just outside of town for your experiments. Using these lakes, you will conduct experiments to determine the effects of adding phosphorus and toxins. You will then use your results to write a letter to the editor of your local paper. Your goal is to tell the public what's likely to happen if they keep increasing the sewage dumped into the lake.

The Lake Model in SimBio Virtual Labs

This lab uses a lake simulation to explore how the addition of nutrients (and toxins) can influence a lake's community and potentially lead to algal blooms. The virtual lake includes five simulated species with the following roles in the community:

SPECIES	TYPE OF ORGANISM
1. Green Algae	Phytoplankton (primary producer)
2. Cyanobacteria	Phytoplankton (primary producer)
3. Bosmina	Zooplankton (primary consumer)
4. Daphnia	Zooplankton (primary consumer)
5. Trout	Fish (secondary consumer)

The two types of phytoplankton in the lake model are green algae and cyanobacteria (sometimes referred to as blue-green algae). Green algae are a diverse group, but the model treats them as one species. Cyanobacteria are photosynthetic bacteria. Many cyanobacteria, including the ones in this model, are also capable of nitrogen fixation. The phytoplankton and zooplankton both have stages in their life cycles in which they go dormant. This means that even if they disappear from the water in the lake, some dormant individuals in the mud at the bottom will eventually emerge and repopulate the lake. The model also includes detritivores that decompose the dead bodies of the organisms in the lake. Lake detritivores are microscopic and not shown in the simulation, but you will know they are there because decomposition uses oxygen, and the dissolved oxygen (DO) level is constantly monitored with a probe at the bottom of the lake.

A few other details about the lake model might be of interest. Phosphorus and nitrogen are two nutrients that commonly limit growth in lakes, so the simulated lake "budget" is primarily based on these two nutrients. Phytoplankton growth not only depends on phosphorus and nitrogen concentrations but also on the amount of light energy available. Light is limited by lake depth and by phytoplankton, which block light when populations are large. The consumers in the lake also need phosphorus and nitrogen to grow, which they get from their prey. Each time a zooplankton or trout encounters a prey item, it has a certain chance of catching it. A certain percentage of the nutrients in the captured prey are taken up, and the rest are excreted back into the lake water. In addition, small amounts of nitrogen and phosphorus are constantly being added to the lake from outside, and a percentage of what's currently in the lake is constantly being lost through the lake's outlet. Finally, you might notice that phytoplankton have different movement patterns at different depths of the lake.

Some Important Terms and Concepts

Ecosystem Ecology

Ecosystems include both the biological and physical components of a community. Ecosystem ecologists study the flow of energy and the cycling of materials through ecosystems.

Eutrophication

Lakes and other bodies of water that have particularly large populations of primary producers are considered to be eutrophic. Eutrophication, or increased primary productivity, occurs when extra nutrients are added to a lake. When eutrophication occurs naturally (e.g., as lakes age), it is typically a gradual process. However, eutrophication can also occur rapidly when people dump fertilizer or sewage into lakes. If nutrient levels become high enough, lake communities can literally be suffocated by huge blooms of phytoplankton. These blooms pose a particular threat to the environment if the phytoplankton include toxin-producing species.

Biological Magnification

Organisms can inadvertently consume toxins by drinking polluted water or eating other organisms that contain toxins. Some of these substances can be metabolized and excreted, but others accumulate in the body. If primary consumers eat primary producers that contain toxins, the toxins will be transferred to the consumers. If the toxins are not excreted, they will accumulate as more and more toxic prey are consumed. Similarly, the toxins that have accumulated in the primary consumers will be passed on to their predators, the secondary consumers. In this manner, accumulating toxins concentrate as they move up the food chain through successive trophic levels. This process of increasing toxin concentration through successive links in a food chain is referred to as biological magnification.

Exercise 1: Starting Up

[1] Before you start playing with the simulation model, you should read the introductory section of the workbook. The background information will help you understand the simulation model and answer questions correctly.

[2] Start the program by double-clicking the **SIMBIO VIRTUAL LABS** icon on your computer or by selecting it from the Start Menu on your computer.

[3] When **SIMBIO VIRTUAL LABS** opens, select **NUTRIENT POLLUTION** from the **EcoBeaker** suite.

You will see a number of different panels on the screen:

– The upper left panel shows a (virtual) lake in the early 1950s that is not yet heavily impacted by people and their pollution; this is where you will begin your investigations by learning a bit about the species in the lake.

– Bar graphs on the right will show the population sizes of all the species in the lake.

– A legend above the graphs shows the species in the lake and their icons.

– You will run the simulation using the **CONTROL PANEL** in the bottom left corner on the screen. To the right of the **CONTROL PANEL** is a set of **TOOLS** that you will use for doing your experiments. These will be described as you need them.

[4] Click on the names in the **Species Legend** in the upper right corner of the screen to bring up library pages for each group of species. Use the library to complete the following questions:

[4.1] Which species in the simulation is capable of nitrogen fixation?

[4.2] Members of which species in the simulation are commonly known as "water fleas"?

[5] Start the simulation by clicking the **GO** button in the **CONTROL PANEL** and watch the action for a bit.

[5.1] Briefly describe what happens in the simulation when phytoplankton die. (Hint: They change color.)

[6] Click the **STOP** button to pause the simulation.

[7] Click the **MICROSCOPE** ("View organism") tool button at the bottom of the screen to activate your mobile "Gut-o-Scope" (patent pending). Then click on individuals in the lake to see what they last consumed. (NOTE: this only works for organisms with guts!)

[7.1] Based on your sampling, what do Bosmina in the lake eat?

[7.2] Based on your sampling, what do Daphnia in the lake eat?

[7.3] Based on your sampling, what do Trout in the lake eat?

[8] When there are not very many individuals of a particular species present, just by chance it is less likely that they will show up in gut content samples. In this lake, Bosmina only eat green algae whereas Daphnia eat both green algae and cyanobacteria. Trout eat BOTH of the primary consumers.

[8.1] After reading the above statement, did you miss any species in your gut content sampling? If so, which ones?

Exercise 2: P in the Water

A research station has a set of small experimental lakes you can alter as you need and a research boat that is outfitted with monitoring equipment. As you recall from reading the Introduction, you are concerned about the risk of algal blooms that might occur with increased phosphorus added to the lake as the town grows. Because green algae tend to outcompete cyanobacteria, algal blooms are usually dominated by green algae. Therefore, your first set of experiments focuses on what happens to green algae when phosphorus (P) is increased. While you're at it, you will record oxygen levels at the bottom of the lake to see any links between anoxia (lack of oxygen) and water pollution.

[1] Select **P IN THE WATER** from the **SELECT AN EXERCISE** menu at the top of the screen.

[2] Click **PHOSPHORUS** in the **Chemical Input** options (to the right of the **TOOLS**). Make sure it is set to 1x (i.e., no extra phosphorus).

[3] Click the **STEP 52 WEEKS** button to run the simulation for one year. (Note: You can adjust the speed of the simulation with the **SPEED SLIDER** tool in the **CONTROL PANEL.**)

[3.1] When the simulation stops, record the population size of green algae (from the graph), and the dissolved oxygen (DO) level (from the graph or from the meter at the bottom of the lake) in the first row of the data table which follows.

HINT: if you click on the colored bars in the Population Size graph, the numbers (population sizes) that the bars represent will pop up!

[4] Click the **RESET** button to start again with a new experimental lake.

[5] Increase **PHOSPHORUS** to 2x (double the starting concentration). Then click the **STEP 52 WEEKS** button to run the simulation for one year.

[5.1] Record your data in the second row of the following data table.

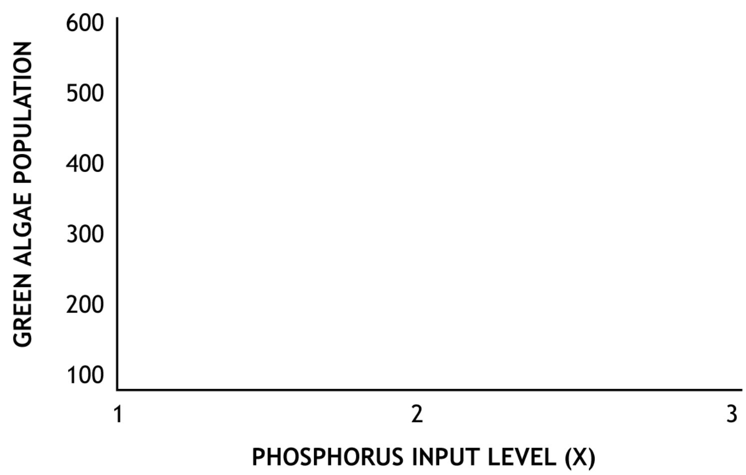
[6] Click the **RESET** button, then increase **PHOSPHORUS** to 3x (triple the starting concentration). Then click the **STEP 52 WEEKS** button.

[6.1] Record your data in the third row of the following data table.

Data Table for Phosphorus Input Experiment

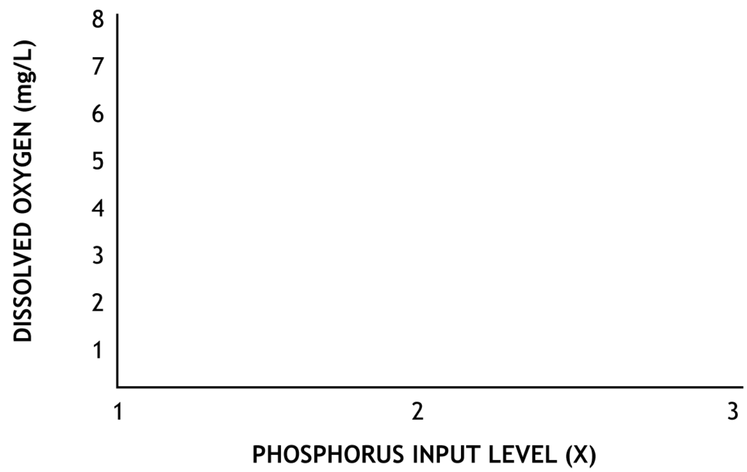
PHOSPHORUS INPUT	GREEN ALGAE POPULATION SIZE	DISSOLVED OXYGEN (Mg/L)
1X		
2X		
3X		

[6.2] **Draw a line graph of your green algae population size data to show how green algae relate to phosphorus input levels. Don't worry about being too precise; you can graph approximate values.**



[6.3] **Does the relationship between green algae population size and phosphorus level indicate that phosphorus was a limiting nutrient for green algae in the lake? Explain.**

[6.4] **You also have recorded data from the oxygen meter at the bottom of the lake. Now draw a line graph showing how oxygen relates to phytoplankton population size. Again, don't worry about being too precise; you can use approximate values of your data.**



[6.5] **What is the relationship between dissolved oxygen and phosphorus in the lake?**

[6.6] **Based on your two graphs, what is the relationship between green algae population size and dissolved oxygen the lake? Provide a biological explanation for your answer.**

[7] Click the **TEST YOUR UNDERSTANDING** button in the bottom right corner of the screen and answer the question in the window that pops up.

Exercise 3: DO or Die

When you added phosphorus to your experimental lake in the previous exercise, the green algae population increased and the dissolved oxygen decreased. But what would happen in a more realistic lake with more species? You will now repeat the phosphorus addition experiment in a lake that is identical to the one in the previous experiment, except that it also includes zooplankton and trout.

[1] Select **DO OR DIE** from the **SELECT AN EXERCISE** menu at the top of the screen. The lake will now include green algae, cyanobacteria, Daphnia, Bosmina, and trout. If you look at the following data table, you will see that you will be collecting the same data as in previous exercises. Before you start these experiments, first make some predictions.

[1.1] Thinking about the trophic relationships of the species, do you think the green algae populations will be smaller, larger, or about the same as in your previous experiments? Explain your reasoning.

[1.2] Do you think the dissolved oxygen concentration will be lower, higher, or about the same as in the previous experiment? Explain your reasoning.

[1.3] Which species do you expect to be impacted the most by increased phosphorus, and why?

[2] Make sure the **PHOSPHORUS** level is set at 1x and, as before, click the **STEP 52 WEEKS** button to run the simulation for one year.

[2.1] When the simulation stops, record the population sizes of green algae and the concentration of dissolved oxygen (DO) in the first row of the data table below.

Data Table for Phosphorus Input Experiment

PHOSPHORUS INPUT	GREEN ALGAE POPULATION SIZE	DISSOLVED OXYGEN (Mg/L)
1X		
2X		
3X		

[3] Compare your new data to the corresponding data in the first row in the data table from Exercise 2.

[3.1] Were your predictions correct? How different are the phytoplankton population sizes and dissolved oxygen levels from the previous experiment?

[4] **RESET** the simulation, increase **PHOSPHORUS to 2x and** click the **STEP 52 WEEKS** button to run the simulation for one year.

[4.1] Record your data in the second row of the data table above.

[5] **RESET** the simulation, increase **PHOSPHORUS to 3x and** click the **STEP 52 WEEKS** button to run the simulation for one year.

[5.1] Record your data in the third row of the data table above. (Do not RESET the simulation.)

[6] You should have found that the dissolved oxygen concentrations in this set of experiments was consistently higher than in the lake without zooplankton and trout even though the lakes and phosphorus inputs were identical. (Since there's some random variability in the underlying model, there's a small chance your data did not show this, but typically this is the pattern that emerges.)

[6.1] Why could having consumers as well as producers present change the amount of dissolved oxygen in the lake?

[7] You may have noticed that the population sizes bounced around more with additional species present. This is due to interactions between trophic levels. For example, when trout eat zooplankton, there are fewer zooplankton around to eat the phytoplankton so the phytoplankton population sizes increases. The additional phytoplankton support more zooplankton, so the zooplankton population increases, which in turn supports additional trout, and so on. The system is much more dynamic than before.

[8] Because the system is so dynamic, it can take longer for patterns to emerge. You know that a dissolved oxygen level below 2.0 is considered to be dangerously low. To see if the dissolved oxygen level at the highest phosphorus addition level might go below 2.0 over time, run the simulation by clicking the **GO** button and observe what happens.

[8.1] Does the dissolved oxygen continue to drop over time?

[8.2] What happens when the dissolved oxygen drops below 2.0? (You might have to be patient …)

[9] Click the **TEST YOUR UNDERSTANDING** button and answer the pop-up question.

Exercise 4: Toxins!

Sewage can contain dangerous toxins. It is known that mercury in lakes can be a major health hazard; toxic effects of mercury poisoning include damage to the brain, kidneys, and lungs. It is also known that many heavy metals are prone to biological magnification (a process described in the Introduction.) You don't know whether your city's sewage will be toxic, but in case it is, you write a grant proposal to study the effects of adding the heavy metal mercury[1] to your experimental lake. Your grant is funded, complete with money for assistants to do the tedious sampling of toxin levels in the body tissues of organisms. You just need to visit the experimental lake once a year for four years to collect and analyze the summarized data.

[1] One objective of your experiment is to determine whether mercury biomagnifies.

[1.1] **If mercury biomagnifies, in which of the below organisms would you expect to find the highest mercury levels in a lake with mercury contamination? (Circle one)**

Algae Zooplankton Trout

[1.2] **Briefly explain your selection.**

[2] Select **TOXINS** from the **SELECT AN EXERCISE** menu at the top of the screen. Before you start the experiment (which causes mercury to be added to the lake), click the **SAMPLE TOXINS** button (the little meter to the right of the microscope). This will pop up a window showing the current average mercury level in each species in the lake water.

1 Mercury is found in different forms in the environment. The most important form for cities concerned about their water resources to track is a compound called methylmercury. For simplicity, throughout this lab, we refer to methylmercury simply as mercury.

[2.1] **Copy the Time = 0 data for mercury levels in the organisms on the following data table. (**The mercury has not yet been added to the lake, so you should be recording a lot of zeros.)

TOXIN ANALYSIS DATA: Time = 0

	POPULATION SIZE	MERCURY
GREEN ALGAE		ng/g
CYANOBACTERIA		ng/g
DAPHNIA		ng/g
BOSMINA		ng/g
TROUT		ng/g

[3] Use the **STEP 52** button to run the simulation for one year.

[3.1] **Record your data below. Then repeat two more times (i.e., run for 3 years total) and record your data in the space provided on the corresponding data tables on the next page. (Since you are tracking what happens over time, do not hit the RESET button between runs!!)**

TOXIN ANALYSIS DATA: Time = 1 year (52 weeks)

	POPULATION SIZE	MERCURY
GREEN ALGAE		ng/g
CYANOBACTERIA		ng/g
DAPHNIA		ng/g
BOSMINA		ng/g
TROUT		ng/g

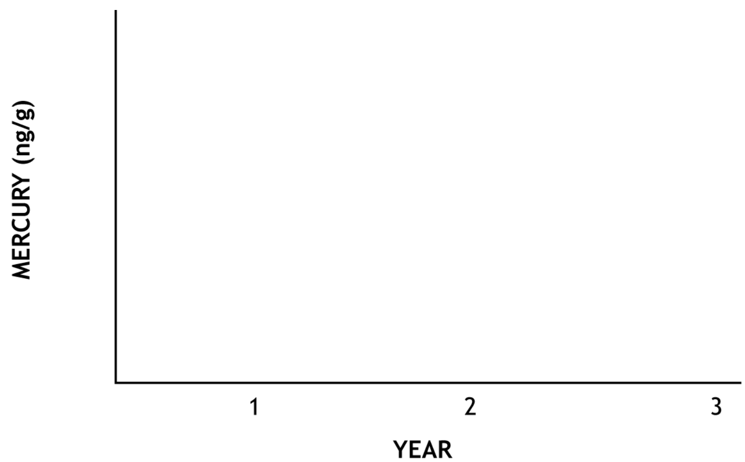
TOXIN ANALYSIS DATA: Time = 2 years (104 weeks)

	POPULATION SIZE	MERCURY
GREEN ALGAE		ng/g
CYANOBACTERIA		ng/g
DAPHNIA		ng/g
BOSMINA		ng/g
TROUT		ng/g

TOXIN ANALYSIS DATA: Time = 3 years (156 weeks)

	POPULATION SIZE	MERCURY
GREEN ALGAE		ng/g
CYANOBACTERIA		ng/g
DAPHNIA		ng/g
BOSMINA		ng/g
TROUT		ng/g

[3.2] **Create a line graph showing mercury concentration over a three-year interval in each species. Your graph will include 5 lines, one for each species; be sure to label which line is for which species. Don't worry about being precise; you can graph approximate values!**



[3.3] **Is there more mercury in the phytoplankton at the base of the food chain or in the fish at the top? Does this change over time?**

[3.4] **Does your graph show evidence for biomagnification of mercury in this lake? Explain.**

[4] Click the **TEST YOUR UNDERSTANDING** button and answer the pop-up question.

Exercise 5: Mystery in the Lake

Not only have you become an expert on nutrient pollution in lakes, you have also learned how to travel through time! You have transported yourself from the lake where you started in the 1950s to the same lake today. It's a mess! Lots of sewage is being dumped in the lake, and there is also a problem with runoff (contaminated water flowing into the lake) from nearby industry. The lake is experiencing a toxic algal bloom because the cyanobacteria in the lake are producing a chemical called microcystin, a liver toxin that can make people sick when they drink the water. It is unusual to find more cyanobacteria in a lake than green algae, as typically green algae are superior competitors. Your challenge is to figure out what is happening in the lake, and in particular, why there are more cyanobacteria than green algae.

[1] Select **MYSTERY LAKE** from the **SELECT AN EXERCISE** menu at the top of the screen. In this more open-ended exercise, you have access to all of the tools and can design your own experiments. You can adjust the **CHEMICAL INPUTS** for both phosphorus and nitrogen, and can now even remove nutrients (i.e., by setting the **CHEMICAL INPUTS** to zero).

[2] In most lakes, green algae are at a competitive advantage over cyanobactera, but in this lake the cyanobacteria dominate. There is something about the chemistry of this lake that is allowing cyanobacteria to prosper while keeping the green algae in check.

[2.1] Is there a difference in the biology of these two phytoplankton that might provide a hypothesis for what is happening in this lake? (Look back at the natural history if you need to.)

[2.2] If a nutrient is limited for a particular species, what happens when you add more of that nutrient to the system?

[2.3] If a nutrient is NOT limited for a particular species, what happens when you add more of that nutrient to the system?

[3] Experiment with chemical inputs to see if you can find evidence to support your hypothesis above for why cyanobacteria may be outcompeting green algae in this lake.

[3.1] Describe your experiments and the results that support your answer. Feel free to describe any other interesting findings as well!

Exercise 6: Letter to the Editor (Optional)

You are back in the early 1950s. Your final task is to write a short letter to the editor of your local newspaper expressing your informed opinion about your city's plans for industrialization. In particular, discuss any concerns you have about sewage or run-off ending up in the lake.

Wrap-up

Sewage is not a new problem. Two thousand years ago, the Romans were building sewage systems, and every town and city before and since has had to deal somehow with what to do with the waste products of its inhabitants (even if the “solution” was just to leave it in the street until rain washed it away). In the late 1800s and early 1900s, scientists in Europe and North America started studying the effects of sewage in water, similar to what you did in this lab.

One of the most famous of these studies happened in Lake Washington, an 18-mile-long lake that forms one border for the city of Seattle, in the northwestern U.S. By the middle of the century, there was an abundance of data on what happened to lakes when nutrients, especially phosphorus, were added to them. Dr. Tommy Edmondson, a limnologist at the University of Washington, along with many of his students, surveyed Lake Washington in 1950 and again in 1955. Although these surveys were not specifically looking for effects of sewage on the lake’s water quality, in 1955 they noticed some of the warning signs for a lake about to go bad—rising phosphorus levels and rising levels of certain algal species. Edmondson raised a warning cry in Seattle and helped spearhead a campaign to move the city’s sewage outflow from Lake Washington to the ocean, where it would do less damage. The lake responded faster than anyone expected. While new sewage lines were being built, sewage continued going into the lake, and the lake began experiencing algal blooms and foul-smelling water. Within three years of completion of the sewage diversion, the water quality was better than it had been even in 1950 when Edmondson first sampled. Similar improvements have now been seen in other lakes around the world after nearby communities changed how sewage and other nutrient sources were processed.

Although most point sources of water pollution (like sewage and industrial by-products) are now fairly well-regulated, non-point sources, such as agricultural run-off and detritus washed down city storm drains, are still a big problem. Most bodies of water that are near human establishments are becoming more and more eutrophic (nutrient rich), and we can anticipate increasing problems with algal blooms, fish poisoning, and other water quality issues in the future. Not only are freshwater lakes and rivers affected, but so are the coasts of our oceans. Red and brown tides, for instance, have been linked to increases in nutrients in coastal waters. Fortunately, among the array of environmental problems currently facing the world, this is one of the most easily solved. Simple things like reducing the amount of fertilizer used on fields (which often is more than the crops can use anyway), reducing the amount of waste products each household disposes of, putting swamps or other natural buffer zones between people and waterways, and making better sewage systems can all substantially reduce the amount of nutrients that get into the water. Hopefully, as was the case with Lake Washington, we’ll start working on the solutions before the problems get too out of hand.

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