Attenuation of Light in Water

Overview:

This lab might take a little while to set up, but can yield some very interesting results. The idea is to stand a piece of PVC pipe on end, fill it with water, and shine a light into the opening at the top. A light intensity logger can then measure the intensity of the light at various depths. The results can be used to get an idea of the quantity of impurities in the water. You can then put the light intensity logger on your Sea Perch to gather data in the field and compare the data to your in-class experiments. This experiment lends itself to some interesting mathematical and physical analysis.

Grades: 9^{th}-12^{th}

Objectives

- To construct a PVC model to hold water
- To understand what happens to light intensity as depth increases
- To understand what factors could influence the amount of light attenuation

National Science Education Standards

Content Standard A - Science as an Inquiry

-□Abilities necessary to do scientific inquiry

Content Standard B – Physical Science

- Conservation of energy and increase in disorder
- Interactions of energy and matter

Content Standard E – Science and Technology

- Understandings about science and technology

Content Standard F – Science in Personal and Social Perspectives

- Environmental quality

Content Standard G – History and Nature of Science

- Nature of scientific knowledge

Lesson
Background Theory

Consider the ideal situation of light as a point source. In this case, light intensity falls off as the square of the distance from the source. Assuming a lossless medium, the light provides energy E, a value the remains the same no matter how far you are from the source. However, as the distance r from the source increases, the energy gets spread out over a larger and larger area. This area can be expressed as $4\pi r^2$, with r representing the distance to the source. So intensity I(r) is given by $E_0/4\pi r^2$. If we let $k_1 = E_0/4\pi$, it follows that $I(r) = k_1/r^2$. Therefore, light intensity varies inversely with the square of the radius.

To simplify the analysis of our results, we will now take the logarithm of both sides of the equation. This will give us a linear relationship, which is much easier to work with. Using the logarithm rules yields:

$$\log(I) = \log(k_1) + \log(r^{-2}) = \log(k_1) - 2\log(r)$$

The HOBO data logger will take measurements in units of log lumens per square meter, so this work had already been done for us. So, given an ideal point source, one would expect a plot of log(I) versus log(r) to be a straight line with intercept log(k_1) and slope –2.

Now consider a tube with perfectly reflecting sides. Energy must still stay the same at all distances, but now intensity will also stay constant, because area is constant. A plot of log(I) versus log(r) in this case would yield a straight horizontal line. Specifically, $\log(I) = E_0/4\pi R^2$, where R is the radius of the tube. Note that I is not a function of r in this situation.

Pre-Lab:

If we measure intensity in air (before we add water to the tube), we expect a combination of these two cases. The inverse square relationship implied by a point source will occur, however reflection from the walls of the tube (which are white) will lessen this effect. As a result, we expect to find a slope between –2 and 0 when we plot the log of intensity against the log of depth. We'll call this slope m and we'll refer to it later.

As a simple test of this reflection property, measure the light intensity at the bottom of the tube and then place the HOBO on the floor outside the tube, move the lamp over, and measure the intensity again. Is the intensity greater at the bottom of the tube?

Adding water to the situation gives us one more factor to consider: the attenuation of light in the water. Attenuation is a combination of absorption and scattering and we assume it to be zero when dealing with air. It is definitely not zero in the case of water however. Assuming again a tube with perfectly reflecting sides, and also assuming a uniform medium, we expect energy to decrease as $E(r) = k_2 r E_0$. Here E_0 is the initial energy, r is distance, and k_2 is another constant. Since the area of the tube is constant, we expect intensity to be related to r in this same manner. So, $I(r) = k_3 r I_o$.

Again we want to take the logarithm of this equation, which gives

$$\log(I) = \log(I_0) + r\log(k_3)$$

If we plot log(I) against r (as opposed to plotting against log(r)), we find a line with intercept $\log(I_0)$ and slope $\log(k_3)$.

Now we put this all together. In our tube filled with water, light is attenuated by the water, but it also decays as a result of the distance and reflection combination. There is also undoubtedly some light lost as a result of the plastic case that holds the HOBO. We want to focus on the attenuation of the water, so we need to eliminate these other effects. We know precisely the magnitude of these effects from our measure of the intensity in air. All we have to do then is add $m\log(r)$ to each of the measured intensities (in water), and the result is the corrected intensity measurement that takes only the attenuation effect into account. Specifically,

$$\log(I_{corr}) = \log(I_{meas}) + m\log(r)$$

We can now find the equation for I as a function of r taking into account only the attenuation affects of the water.

Materials:

Sea Perch
A Stowaway Light Intensity data logger (SLA08)
Submersible case
A piece of PVC pipe (2-3 meters long with cap on one end)
Tap water
Lamp
Fishing line
Weights
Ruler
Waterproof Tape
Buckets (or a hose)

Procedure:

1. Glue a cap firmly to one end of the PVC tube to prevent leaking.
2. Secure the PVC tube vertically.
3. Position the lamp so it is shining straight down into the tube, placing it as close as possible to the opening.
4. Tie one end of fishing line, long enough to reach the bottom of the tube, to the submersible case with weights attached to the case as well.
5. Mark off the testing depths on the line with masking tape, every 20 cm for 2 meters; cover the masking tape with waterproof tape so it won't slip in the water.
6. Tie the other end of the line to something that will float.
7. Launch the HOBO to measure light intensity at half-second intervals.
8. Make sure that the weights are arranged so that the light sensor will be facing up when it is submerged.
9. Turn on the light source.
10. First, with no water in the tube, lower the HOBO to the first depth and hold it there for a minute to gather data.
11. Repeat for all other depths.
12. After all depths are done, pull it out and look at the results. Save the data.
13. Fill the PVC tube with tap water, leaving a few centimeters at the top so it doesn't overflow when the HOBO is submerged.
14. Repeat the testing process. Check and save these results.
15. Go to a local water source and repeat the testing process again using your Sea Perch as the vehicle in which you can deploy your light meter. Check and save the results.