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Research Article

Life Cycle Assessment (LCA) Comparing Disinfection Options for Drinking Water Treatment

—Alexandria Hidrovo

Flint, Michigan's water crisis put my major, environmental engineering, in perspective for the first time. Flint has become one of the main tragedies to shine a light on America's aging infrastructure. It is also a prime example of the type of environmental injustice happening around the country today. Seeing the families and community in Flint suffer made me realize that this type of tragedy could happen anywhere in the United States, but the way it is handled will vary depending on the affected community's socioeconomic status. This realization began my fascination with water quality and environmental justice and is the reason I want to become an engineer. I want to make a positive impact on these issues. As an undergraduate, I was able to explore this passion by conducting research on disinfection methods in drinking water treatment for Bethlehem, New Hampshire, first as a McNair Scholar, and then through a Summer Undergraduate Research Fellowship (SURF) from the Hamel Center for Undergraduate Research.

Alexandria Hidrovo

Drinking water treatment is essential to provide a healthy source of water for a community. There are various methods to disinfect water, and all have tradeoffs regarding public health, costs, and environmental impacts. For example, chemical disinfection methods that use chlorine are simple and inexpensive, but they can produce disinfection byproducts (DBPs) within treated drinking water. The public trusts that the treated drinking water provided to them is clean and safe, which is true for the most part, but more research must be done on DBPs and the negative health effects that they may cause with long-term exposure.

Physical disinfection methods, such as medium-pressure ultraviolet light (MP UV), do not produce harmful byproducts. These systems use UV lamps, which are directly powered by electricity. The lamps produce polychromatic wavelengths of UV light (200–315nm), which disinfect the water. These systems use more energy than traditional chlorination systems, but do not produce DBPs, which is why they are becoming a preferred method for water treatment. The increase in energy use can have a negative environmental impact because of the amount of non-renewable fossils fuels used to produce the electricity. However, more energy-efficient UV technology is developing, and as alternative energy becomes more popular, the impact should decrease.

Public health protection is a main concern when treating drinking water, but so is the maintenance cost of running the treatment system. My SURF research aimed to help the town of Bethlehem better understand which kind of water treatment system would be most beneficial. My research helped inform the public on both UV and chlorination treatment systems, and the tradeoffs of producing DBPs or using more energy. By providing them with my research and analyses, voters can now voice educated opinions and concerns at public meetings about the town's plan for updating their local drinking water treatment facility.

Drinking Water Disinfection Methods

Chemical disinfectants are the most common way to disinfect water in North America (United States Environmental Protection Agency Office of Water [US EPA OW], 2000). Most often, the chemicals used are chlorine gas and sodium hypochlorite. In a drinking water treatment facility, disinfection is one of the last processes to take place because other processes, such as coagulation-settling-filtration, need to occur first to remove particles and natural, organic matter that can interfere with disinfection. A chemical disinfectant, such as sodium hypochlorite, is added to the filtered water and it destroys or damages the cellular structures of the microorganisms (microbes), therefore interfering with their metabolism, biosynthesis, and growth. These microbes can be bacteria, viruses, protozoan cysts, and fungi in the water that can cause serious health effects if ingested (US EPA OW, 2006).

However, using purely chemical disinfectants can pose a potential human health risk as well. Free chlorine, which is produced when sodium hypochlorite dissociates in the water, can react with natural organic matter within the treated water to form disinfection byproducts (DBP). Research has shown that long-term DBP exposure is hazardous to human health because certain DBPs are known to be carcinogenic (Wang, G., Deng, Y., & Lin, T., 2007; Wang, W., Ye, B., Yang, L., Li, Y., & Wang, Y., 2007).

Drinking water treated with a physical disinfection method, such as UV disinfection, does not directly produce regulated DBPs, nor does it impart taste, odor, or color to the water. Furthermore, such methods have the potential to reduce the need for secondary chemical disinfectants used to maintain a residual of the chemical disinfectant in the distribution system. UV light disinfects filtered water in a way distinctly different from chemical disinfectants. Instead of damaging the microbes' cell structure, UV light inactivates the microbes by damaging their DNA and/or RNA, which prevents them from replicating (US EPA OW, 2006). A microbe cannot infect a host if it cannot replicate.

A UV system consists of glass tubes, which generate UV light, submerged in the water to be treated. Voltage (electricity) is applied to a gas mixture within the tubes, which results in a discharge of photons, or ultraviolet light. The UV wavelengths emitted from the lamp tubes are determined by the elemental composition of the gas and the voltage level applied. Most UV lamps use mercury vapor because it emits light at the germicidal wavelength range needed (between 200nm and 300nm). The lamps are always completely submerged in the filtered water (US EPA OW, 2006). (See Figures 1a and 1b.)

The Groundwater Rule established by the Environmental Protection Agency (EPA) in 2006 requires 99.99 percent inactivation of human enteric viruses in drinking water. The challenge facing UV drinking water equipment is the difficulty in demonstrating that they are validated to proving 99.99 percent viral disinfection (US EPA OW, 2009). This difficulty arises because the regulations require the highly UV-resistant adenovirus to be used to demonstrate the 99.99 percent compliance.

Figure 1a: This is a photo of the pilot UV disinfection system placed in Bethlehem. There are four UV lamps shown with black tops sticking out of the left side of the reactor. There are two UV wavelength sensors shown with longer gray columns connected to the black tops.

In order for UV drinking water treatment systems to demonstrate compliance, UV treatment usually must be followed by the addition of residual disinfectants such as chlorine or chloramines (e.g., NH_2Cl). Chloramines produce far fewer DBPs than chlorine because they are less reactive with organic matter and persist longer.

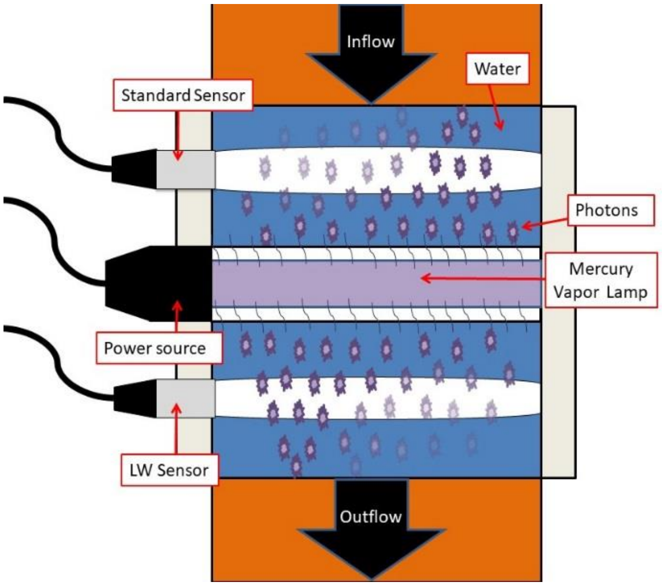

Figure 1b: This diagram shows Figure 1a in more detail. The water being treating is flowing through the reactor. The mercury vapor lamp emits the UV wavelengths (photons) that disinfect the water and are recorded by the sensors. The two sensors shown are both measuring UV wavelengths, but the standard sensor measures the range from 240–300nm and the LW sensor measures the range from 200–240nm.

Recent studies show that low ultraviolet wavelengths (below 240 nm) may be more effective than higher wavelengths at removing the adenovirus from drinking water, but older UV sensors can't detect those lower wavelengths. As a result, UV systems using these older sensors can't cost-effectively prove adenovirus disinfection and meet EPA requirements (Linden, K. G., Wright, H. B., Collins, J., Cotton, C., & Beck, S. E., 2015).

My McNair research showed that new, innovative UV sensors can accurately and precisely read low UV wavelengths (200nm–240nm). The success of the new sensors is the first step in being able to prove that medium-pressure UV treatment can disinfect within that low-wavelength range to meet the EPA requirement. UV systems that take advantage of low wavelengths could potentially lower their energy use by 40 percent, reducing the economic and environmental impacts of medium-pressure UV treatment. The next step for this research was to assess the actual impacts associated with the energy consumption of UV disinfection, and to determine the human toxicity risk posed by the consumption of disinfection byproducts (DBP) from chlorination disinfection currently being used at Bethlehem. I applied for the Summer Undergraduate Research Fellowship (SURF) to explore these new questions.

Disinfection System Options for Bethlehem, NH

Bethlehem's current drinking water treatment system uses slow sand filtration followed by a chlorination system using sodium hypochlorite. Slow sand filtration provides excellent, cost effective particle removal, but was never intended to remove dissolved natural organic matter. Therefore, this system produces quantities of chlorinated DBPs that do not meet the DBP regulatory limits set by the EPA, and Bethlehem has been required by state and federal regulations to adjust treatment processes until they are compliant (US EPA OW, 2010).

Dr. Malley, my mentor, is currently co-principle investigator of a U.S. EPA National Center for Innovation in Small Systems, called DeRISK, co-located at the University of Colorado Boulder and the University of New Hampshire (UNH). One of these DeRISK projects is a pilot study that uses a medium-pressure UV water treatment system for Bethlehem.

The UV system at Bethlehem is sized to treat 400 gallons of water per minute through reactors that each hold four UV lamps. The system includes innovative sensors that can monitor the presence of the important, low wavelengths of UV, which allow a more cost-effective disinfection of adenovirus to meet the EPA's 99.99 percent disinfection requirement (Malley, 2016). The pilot medium-pressure UV system, followed by chloramines, is an alternative that can achieve virus inactivation and lower the levels of DBPs, thereby supplying drinking water in compliance with the EPA regulations, and protecting public health.

Changing disinfection treatment methods is a big decision for Bethlehem. There are public health and cost tradeoffs for any treatment system. The purpose of my SURF research was to evaluate each method individually using a life cycle assessment (LCA). LCA can be defined as an evaluation of all flow inputs for a product while also assessing the potential environmental impacts throughout the product's life cycle. In the case of my LCA, the "product" was the drinking water being treated to meet the EPA standards.

My hypothesis was that Bethlehem's current chlorination process uses less energy, because it involves simply adding chemicals, but has a greater human health risk factor because chemical disinfectants produce more DBPs. Conversely, the medium-pressure UV system being used in the pilot study would consume more energy because of its high electricity demand, but would have a lower human health risk because UV does not directly produce DBPs. The purpose of my LCA was to assess both methods, based on Bethlehem's current conditions, to provide useful information that could help the town make their decision.

Methods

The comparative LCA for the chemical and physical disinfection methods being considered for Bethlehem's water treatment plant was completed over the summer of 2017. LCA methodology assesses all the materials and processes required to make, use, and dispose of a product. This includes the processes and materials that feed that process, all the way up the supply chain of materials starting with the extraction of raw resource inputs (Horne, R. E., Grant, T., & Verghese, K. L., 2011). The life cycle of a product involves the following stages: material extraction, material processing, product manufacturing, product use, and finally, product disposal.

My LCA focused on the manufacturing stage of the life cycle. I compared two main factors within this LCA: energy consumption and human toxicity risk. The LCA on the pilot plant showed the pros and cons of adopting the UV system permanently, as compared to the original chlorination system.

To conduct the LCA, I used the leading LCA software, SimaPro. SimaPro incorporates all inputs and outputs for both disinfection methods: chlorination and UV. The program then calculates all environmental impacts for both methods, making it easy to compare them.

As the main researcher on this project, I spent most of my days doing background research on both disinfection treatment processes and learning how to use the SimaPro software. Research and outreach were required to gather the information on the materials that had been used to construct both the chlorination system and the UV pilot system. When I couldn't find information, I made reasonable assumptions to move forward.

I also calculated cancer risk, to assess human toxicity risk, from total intake estimates of DBPs from onsite studies conducted in 2016 by my mentor. I conducted most of this research independently on a computer. For some complex calculations, I received help from Dr. Malley's graduate student, Tyler Kane, who is working on the Bethlehem project for his master's thesis.

Results

The results for this LCA confirmed my original hypothesis: the UV system uses more energy but presents a lower human health risk compared to the chlorination system, which uses less energy but has a higher human health risk. (See Figure 2.)

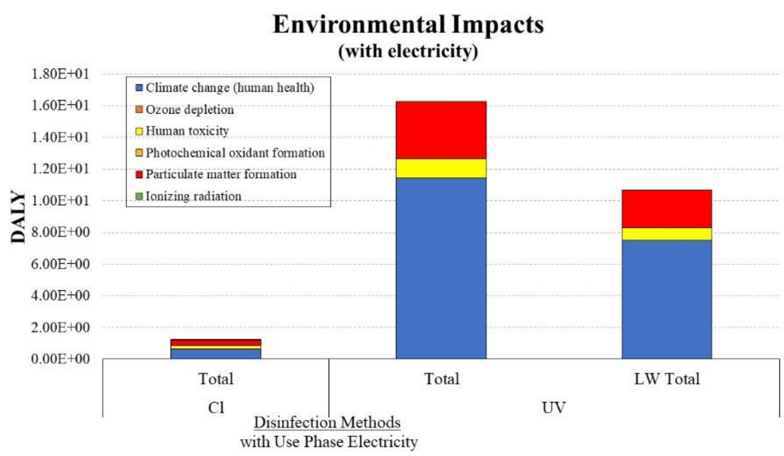

Figure 2: The same three environmental impacts dominate for the chlorination disinfection method (Cl) and the medium-pressure ultraviolet disinfection method (UV) when including the electricity used for both systems in the LCA. The "LW Total" bar for UV refers to the pilot UV disinfection system that takes advantage of low wavelengths. The environmental impacts are measured in DALY (disability adjusted life years) values, which represent an assessment of damage to human health for each category.

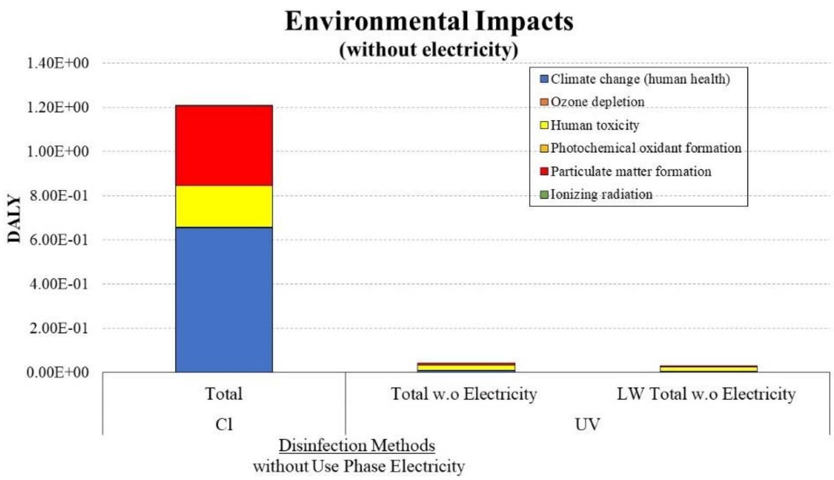

Figure 3: As in Figure 2, the dominant environmental impacts for the chlorination disinfection method (Cl) and the medium-pressure ultraviolet disinfection method (UV) are shown here, but this graph shows impacts without consideration of the electricity used for both systems. The chlorination disinfection method virtually stays the same with or without consideration of electricity use, but the UV disinfection method drastically decreases in DALY (disability adjusted life years) values when electricity use is not considered, showing that electricity is the main factor causing most of the environmental impacts for UV systems.

Electricity required to achieve 99.99% inactivation and removal of pathogens and viruses was estimated using a model created by the UV system engineers. This disinfection capability requires the use of more UV lamps, which in turn leads to more electricity. The model estimated the maximum energy needed for a UV system, which means the amount of electricity used in my LCA calculation is an overestimation, but is still considered representative. The same UV system could potentially lower its energy demand by 40% if it took advantage of low wavelengths. Figure 3 shows what the results would look like if electricity was removed from the disinfection components.

The human health risk for my research focused on the direct risk associated with the amount of DBPs in the treated water distributed from Bethlehem's current treatment plant to the community. Onsite studies conducted in May and October of 2016 measured the amount of DBPs produced by both the chlorination system and the UV system over time.

As mentioned earlier, UV systems require a chemical addition to leave a chlorine residual within the piping infrastructure to confirm adequate disinfection. The pilot UV system in Bethlehem uses chloramines, a chemical compound that has less disinfection capability than free chlorine but produces significantly fewer DBPs, making it less toxic than the existing chlorination system. As expected, I found that the chlorination system shows a much higher amount of DBPs being produced from the chemicals that must be added during the disinfection process. This relationship can be seen in both onsite studies (May and October 2016) that I used to evaluate toxicity risk. (See Figure 4.)

From this data, I calculated a total lifetime cancer risk from DBPs ingested through tap water. The number of people that are at risk of getting cancer is only an estimate, because there is significant uncertainty associated with the assumptions made. The variability in age, sex, nutrition, genetics, and so on makes this calculation impossible to customize for each community member (Wang, W. et al., 2007).

There are multiple exposure paths through which DBPs can enter a person's system, such as ingestion, inhalation, and dermal contact, but my research looked only at oral ingestion, which is the

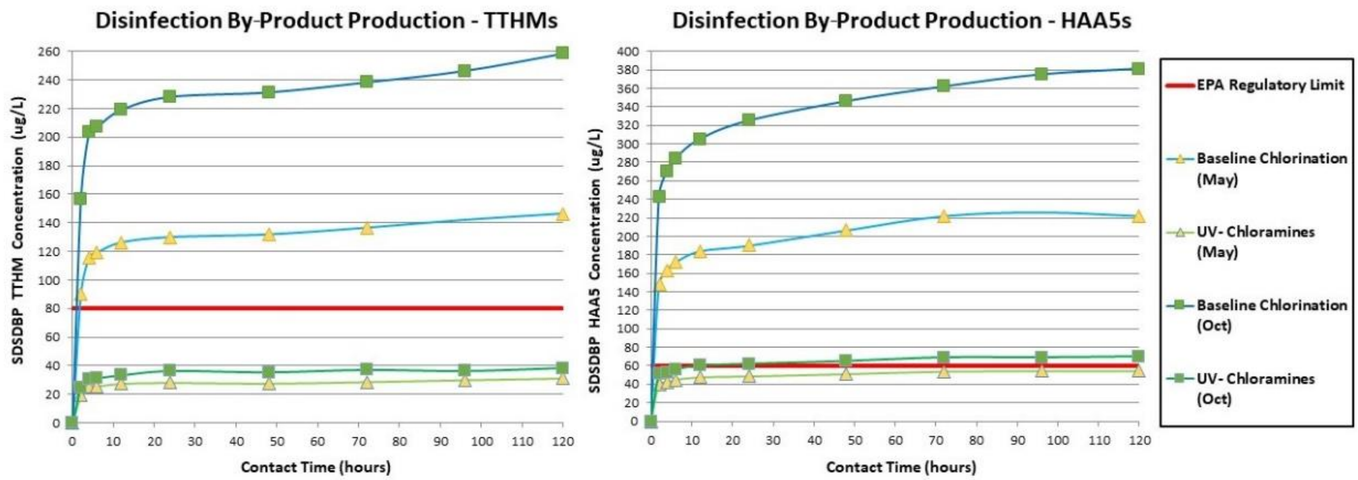

Figure 4: Disinfection byproducts (DBPs) are usually categorized as either total trihalomethanes (TTHMs, left side) or haloacetic acids (HAA5s, right side). The graphs show the different concentrations for the baseline chlorination system and the UV system (which uses chloramines) compared to the EPA regulatory limits of 80 micrograms per liter (µg/L) for TTHMs (left) and 60 micrograms per liter for HAA5s (right). The UV-chloramines disinfection system produces significantly fewer DBPs than a typical chlorination system. The major difference seen between the two studies represented in both graphs is related to the season change. In October the water to be treated contains more natural organic matter, which reacts with the free chlorine in the treated water, producing more DBPs in October than in May for both treatment systems.

most common exposure route for treated drinking water. Based on the October 2016 data, Bethlehem's community could have 2 out of the 3,000 residents at risk of getting cancer if the water treatment plant uses a chlorination disinfection system. If the water treatment plant uses a UV system, then not one person is at risk. My findings represent an 84% decrease in cancer risk when the water treatment plant is using a UV system instead of a chlorination system. The May 2016 DBP data produced a similar result. In this case, 1 out of the 3,000 residents is at risk of getting cancer with the use of a chlorination system. There is a 74% decrease with not one person at risk with when using a UV system. (See Figure 5.)

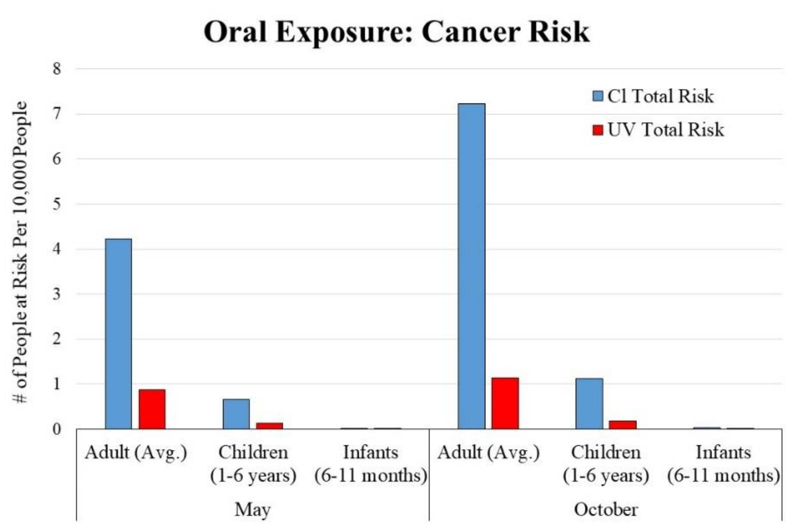

Figure 5: The cancer risk for May (left side) and October (right side) differ due to the season change, as described for Figure 4. Cancer risk is measured as the number of people at risk per 10,000 people (e.g., Cl system, May, Adult = 4.5 people at risk per 10,000 people). These results were converted within the article text to represent the number of people at risk specifically for Bethlehem's 3,000-person population.

Conclusion

The community of Bethlehem, New Hampshire, and the Bethlehem water treatment plant stakeholders can use the findings of my LCA to help inform their decision on whether a UV system as an upgrade option is worth the investment, in light of the cancer risk from using a chlorination system, and the environmental impact and cost associated with a UV system. The LCA can also be a model for other water treatment plants with similar conditions and can provide information on the impacts associated with chlorine and UV disinfection methods. Public health protection is a main priority for water treatment plants, so knowing the pros and cons to both methods will help communities choose appropriate disinfection methods based on their requirements and conditions.

My research on Bethlehem's water treatment plant over the past two years has underlined for me how important it is that stakeholders and the communities served know the tradeoffs for the systems currently being used and potential alternative systems. When communities are not fully informed, missteps and even public health tragedies can occur, as was the case with Flint, Michigan's water crisis. Even though the specifics of Flint's situation are much different from the situation in Bethlehem, in both cases it is important to know all characteristics of the treatment processes and the trade-offs they may have.

In my senior year at UNH, I applied for the dual credit option, which allows me to count eight credits of coursework to simultaneously complete my bachelor of science degree in environmental engineering, and begin my master's degree in civil and environmental engineering. My research on Bethlehem's water treatment situation has made me comfortable conducting independent research and has familiarized me with both LCAs and UV treatment, which are growing fields of interest. This experience showed me that you must be interested in your research topic and committed to answering a question. There are many communities across the U.S. and the world that do not have access to clean drinking water, which is essential and should be a human right. I would like my professional career to start by combining both my passion for environmental justice and water treatment, and my master's degree program will further my progress toward achieving that goal.

I would like to thank the CONNECT Program, TRiO Scholars Program, and McNair Scholars Program for believing in me from the moment I arrived at UNH and pushing me to be a leader for first-generation, low-income, multicultural students like me. Thank you to the Hamel Center for Undergraduate Research for giving me the opportunity to conduct this research through the generosity of the donors for the Summer Undergraduate Research Fellowship (SURF): the Class of 1962 Student Enrichment Fund, the Patricia M. Flowers '45 Scholarship Fund, and Mr. Dana Hamel. Thank you to Tyler Kane and Dr. Weiwei Mo for all your guidance and support through the duration of this research. Lastly, a special thank-you to my mentor, Dr. James P. Malley, for inspiring me to seek out knowledge, so I can one day become a great researcher and engineer just like you are. I appreciate you taking me under your wing for my past two research experiences and providing me the opportunity to grow as a young professional. It takes a village to raise a child and I couldn't have done it alone, so with all heart, I thank all of you for helping me get to this point in my undergraduate career. To my family, I love you and everything I do is for you.

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Author and Mentor Bios

Alexandria Hidrovo grew up in Harrison, New Jersey. She is part of the McNair Scholars Program and TRiO Scholars Program. In May of 2018, she will graduate from the University of New Hampshire (UNH) with a bachelor of science degree in civil and environmental engineering, and will continue at UNH for her master's degree. Alexandria wished to share her findings on water treatment and analysis, a project which was funded by a Summer Undergraduate Research Fellowship (SURF), with *Inquiry*'s broader audience. "This assessment showed me that the obvious 'environmentally friendly' product isn't always that much more environmentally friendly when you look at all aspects of its life cycle," she said. She also realized how important it is to be dedicated and interested in your research subject, because research is a time-consuming process. In reflection, this project gave her a sense of accomplishment; she was able to answer a question that is applicable within her field of interest.

James Malley is a professor of civil and environmental engineering at the University of New Hampshire (UNH). He has a B.S. degree in environmental chemistry from Rutgers University, a second B.S. in civil engineering, and his M.S. and Ph.D. degrees in civil/environmental engineering from the University of Massachusetts, Amherst. Dr. Malley has thirty-eight years of experience in environmental engineering, working on over 100 projects in nine countries. He has served as the director of the UNH Environmental Research Group and the chairperson of the UNH College of Engineering and Physical Sciences environmental engineering B.S. degree program. In 2013, he received the UNH Faculty Excellence Award for Public Service. Dr. Malley was the founding president of the International Ultraviolet Association and a member of the Board of Directors of the American Water Works Association. He also received the International Ultraviolet Association's Presidential Lifetime Achievement Award for outstanding contributions to the field of UV technology in 2007. It remains Dr. Malley's lifetime professional goal to have a positive impact on public health through improving drinking water quality for people.

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