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Overcoming affective and cognitive chemistry challenges in an introductory environmental engineering course using a Flint Water Crisis case study

Prof. Matthew James Scarborough, University of Vermont

Matthew Scarborough is an Assistant Professor in the Department of Civil and Environmental Engineering at the University of Vermont where he teaches courses related to water and wastewater treatment. Dr. Scarborough's research focuses on understanding and controlling microbiomes that protect the environment and public health. Matthew earned his Ph.D. at the University of Wisconsin-Madison in 2019 where he also completed a certificate program in the integration of research, teaching, and learning.

Dr. Katherine D McMahon

Katherine (Trina) McMahon is a Professor at the University of Wisconsin Madison in the Civil and Environmental Engineering Department where she has taught introductory environmental engineering courses since 2003. She is the faculty co-director for the UW-Madison Delta Program whose mission is to prepare future faculty to be effective teachers. She was Dr. Scarborough's mentor for the Delta internship that spawned this paper. Trina co-chaired the Education Innovation Committee for the UW-Madison College of Engineering for two years. Her research interests include water quality, microbiology, and limnology.

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Abstract

An understanding of chemistry is critical for many engineering disciplines. Students taking an introductory environmental engineering course at the University of Wisconsin- Madison (with a typical cohort of 100 undergraduate students) have historically struggled to overcome cognitive and affective challenges related to chemistry. Analysis of historical data confirmed that many students were not able to master certain key chemistry concepts during the course. To improve attitudes towards chemistry and student performance on chemistry problems, we implemented a week-long case study on the Flint Water Crisis. The case study included short on-line videos related to the history of Flint, MI, and the chemistry of lead in distribution systems. The unit also included two lectures: one covering the chemistry and another telling the story of the crisis that unfolded after the water source was switched in Flint. Students used classroom response systems, concept maps, and minute-papers to engage with the material during lectures. We dedicated a 2-hour problem solving session for students to answer quantitative questions designed to assess learning gains. Students also completed a writing assignment to describe the chemistry behind the Flint water crisis and to suggest ways for preventing another "Flint" from occurring.

Based on student assessments of their learning gains (SALG), 98% of students reported good or great gains in their understanding of the Flint Water Crisis. Additionally, 78% of students reported that their understanding of chemistry improved (a fair amount or a great deal) and 75% of students reported that their attitudes towards chemistry improved (a fair amount or a great deal) because of the Flint Water Crisis Case Study. Student writing assignments demonstrated that they met learning outcomes related to the Flint Water Crisis and 91% of students responded that the writing assignment was beneficial to their learning (a fair amount or a great deal). We also compared the performance of the cohort that included the Flint Water Crisis Case Study to a cohort that did not include the case study. On final exam questions, students who were taught the Flint Water Crisis performed significantly better on an acid-base chemistry problem ($p < 0.05$). While the change in mean performance on a redox chemistry question was not significantly different, the number of students who performed poorly on the question decreased. Students also identified the components of the case study that they found to be most beneficial. Based on these results, we propose several modifications for teaching the Flint Water Crisis to future cohorts.

This study demonstrates that high-impact case studies can improve learning outcomes for engineering students. In our study, both cognitive and affective learning outcomes improved for chemistry-related outcomes in an introductory environmental engineering course. Furthermore, this study demonstrates that including writing assignments with case studies can benefit student learning. Case studies may be especially beneficial for motivating students to engage with and learn material that could otherwise be deemed as unimportant for their chosen field of study.

Introduction

Every undergraduate student majoring in civil and environmental engineering at the University of Wisconsin - Madison is required to complete an introductory course in environmental engineering. A major component of this course is applying chemistry to solve environmental engineering problems. The specific problems relate to acid-base chemistry, redox chemistry, the ideal gas-law and Henry's law. For instance, an understanding of acid-base chemistry and Henry's law is necessary to determine the pH of a natural water body; redox chemistry is important for understanding (bio)chemical transformations of pollutants; and the ideal gas law is important for evaluating the partitioning of volatile pollutants. One semester of college chemistry is a prerequisite for the course, though many students actually complete two semesters. Many of the fundamentals covered in the introductory environmental engineering course should have also been covered in these introductory chemistry courses. However, historically, students have not performed well on exams and assignments that require applying chemistry.

The cause of poor performance may be cognitive, affective, or a combination of both. An assessment of students in Fall 2017 showed that less than 25% of incoming students could determine the proportion of a weak acid protonated at a given pH at the beginning of the semester; On the final exam, only 53% of students solved a similar problem correctly. In addition to persistent challenges in the cognitive domain, affective challenges are also expected to be common. While past courses have not specifically evaluated comfort, confidence, or motivation related to applying chemistry to engineering problems, in Fall 2017, several open-ended survey responses from the post-class survey indicate affective challenges, one of which is shown below:

"Chemistry is my kryptonite and will always remain a voodoo black magic to me …"

Learning is not just a cognitive process. Poor performance in chemistry is expected to be, in part, due to a lack of motivation. Many civil engineering majors do not expect to complete an emphasis in environmental engineering. The class includes many students who focus instead on construction, structural, or transportation engineering. These students likely place less value on learning and applying chemistry despite the fact that chemistry is important to several aspects of their disciplines: Construction and structural engineers use chemistry to design corrosion control systems and transportation engineers use chemistry to design concrete and asphalt pavements. Therefore, addressing the underlying factors of student motivation is likely key to improving student performance.

Poor performance in undergraduate chemistry courses is largely the result of affective, motivational challenges [1-4]. There are four factors affecting student motivation: **purpose**, **competence**, **autonomy**, and **community** [5, 6]. To improve student attitudes towards chemistry, all four of these aspects should be addressed. While teaching chemistry to undergraduate students is known to be a challenge, student performance improves when strategies to implement active-learning are used [7, 8]. Case studies are useful tools for engaging STEM students in active-learning [9]. For example, an undergraduate green chemistry course successfully used several case studies (ibuprofen synthesis, atom economy, terta-amido macrocyclic ligand oxidant activators, cellulose processing), group discussions and the construction of concept maps associated with each case study to improve student attitudes towards chemistry. Teaching chemistry to civil engineering students, specifically, is not as well researched. Kimmel and Lambert, 1973 used "practical examples" and open discussions as central components of a physical chemistry course for civil engineers [10]. For example, students were asked to analyze a real-life proposal of using steam from powerplants to heat homes in a local community. Sell, 1982 also used several real-life examples to teach chemistry to civil engineers. Example problems considered multiple industries including iron and steel production, cement manufacture, pulp and paper manufacture, food processing, brewing and chemical production [11].

The question we aimed to address in this study was "will civil engineering students' attitudes towards chemistry and abilities to apply chemistry improve after analyzing a high-profile case study related to environmental problems?" Our hypothesis was that student chemistry performance and self-reported attitudes about chemistry in an introductory environmental engineering course are improved by a thorough analysis of a high-profile and compelling case study, in this case the Flint Water Crisis.

Approach

Past learning outcomes and activities. This project aims to address cognitive and affective challenges associated with solving chemistry problems in an introductory environmental engineering course. Historically, this class has had between 80 and 100 students. Most students in the course are Civil Engineering majors, ranging from sophomore to senior standing. Some undergraduate students from Biological Systems Engineering, Chemical and Biological Engineering, and Mechanical Engineering also take the course as an elective. The course is taught in a blended format in which students are expected to watch a video lesson and complete an on-line formative assessment for each lecture topic. The course includes a weekly group problem solving session in which students work on their assigned problem sets. Each week there are also two one-hour lectures and a weekly in-class quiz related to the problem set, completed by students individually. The course has two midterm exams and a final exam. In the past, the course has also used "Engineering in the News" writing assignments, in which students write about a current topic in the popular press and relate it to concepts covered in the course. The learning outcomes related to acid-base and redox chemistry from past courses are shown in Table 1.

Table 1: Learning outcomes, assessments, and activities related to acid-base chemistry and redox chemistry. Activities added as part of the Flint Water Crisis are underlined and italicized. (G) indicates a group assignment or activity and (O) indicates an optional activity.

Learning Outcomes	Assessments	Activities for Participants
Acid-Base Chemistry		
Calculate the concentrations of an acid and its conjugate base in strong and weak acid solutions.	• Chemistry Pre-Assessment • Final Exam	• Chemistry Review Session • Online Lesson 3.1: Acid-base chemistry • Lecture: Acid-Base Systems • Problem sets (G) • *Online Lesson 13.2: Flint Water Crisis Chemistry* • *Lecture: Flint Water Crisis Chemistry* • *Problem Set: Flint Water Crisis (G)*
Redox Chemistry		
Write and balance oxidation-reduction reactions	• Final Exam	• Online Lesson 2.2: Transformations • Problem sets (G) • Chemistry Review Session • *Online Lesson 13.2: Flint Water Crisis Chemistry* • *Lecture: Flint Water Crisis Chemistry* • *Problem Set: Flint Water Crisis (G)*
Use redox reactions to determine the mass of compounds produced or consumed	• Final Exam	• Chemistry Review Session • Problem Sets (G) • Online Lesson 13.2: Flint Water Crisis Chemistry • Lecture: Flint Water Crisis Chemistry • *Online Lesson 13.2: Flint Water Crisis Chemistry* • *Lecture: Flint Water Crisis Chemistry* • *Problem Set: Flint Water Crisis (G)*

The Intervention. For this project, we built on past course learning outcomes (Table 1) with learning outcomes related to the Flint Water Crisis (Table 2). To address cognitive issues, we used two online videos (Online Lesson 13.1 – Flint Water Crisis Overview and Online Lesson 13.2 – Flint Water Crisis Chemistry) and an online formative quiz for each lesson. We also used three lectures. In the first lecture, we reviewed the chemistry aspects of the crisis, worked through example problems, and completed a concept map activity. In the second lecture, we covered the *story* of the Flint water crisis, discussing the events leading to the water crisis, how the crisis was uncovered, and the failures of government employees to address the crisis. The second lecture ended with a minute paper related to engineering ethics and asked students to submit "muddiest points". During the third lecture, we covered common misconceptions uncovered using student concept maps and addressed student-submitted muddiest points. The students were also assigned a problem set that required application of chemistry to solve problems related to the Flint Water Crisis (**Appendix A**). Problem sets were completed in pre-assigned groups. In addition, a writing assignment developed with input from the UW Writing Center (**Appendix B**) was completed by all students. A timeline of all of the activities implemented for the Flint Water Crisis case study and related assessments is provided (**Fig 1**).

Table 2: Additional proposed learning outcomes, assessments, and activities. (G) indicates a group assignment or activity.

Learning Outcomes	Assessments	Activities for Participants
Redox, Solubility, and Disinfection Chemistry		
R-1. Explain the rationale for Flint switching water sources from Lake Huron to the Flint River	• Writing Assignment: Flint Water Crisis	• Online Lesson 13.1: Flint Water Crisis Overview • Lecture: The Story of the Flint Water Crisis
R-2. Describe the chemical characteristics of the Flint River and compare these to Lake Huron	• Writing Assignment: Flint Water Crisis	• Online Lesson 13.1: Flint Water Crisis Overview • Online Lesson 13.2: Flint Water Crisis Chemistry • Lecture: Flint Water Crisis Chemistry • Problem Set: Flint Water Crisis (G)
R-3. Explain the chemistry that resulted in high levels of lead in Flint's drinking water	• Writing Assignment: Flint Water Crisis	• Online Lesson 13.2: Flint Water Crisis Chemistry • Lecture: Flint Water Crisis Chemistry • Problem Set: Flint Water Crisis (G)
R-4. Explain why additional pathogens were present in Flint's water	• Writing Assignment: Flint Water Crisis	• Online Lesson 13.1: Flint Water Crisis Overview • Online Lesson 13.2: Flint Water Crisis Chemistry • Lecture: Flint Water Crisis Chemistry • Problem Set: Flint Water Crisis (G)
R-5. Describe how adding orthophosphate to Flint's water could reduce lead levels	• Writing Assignment: Flint Water Crisis	• Online Lesson 13.1: Flint Water Crisis Overview • Online Lesson 13.2: Flint Water Crisis Chemistry • Lecture: Flint Water Crisis Chemistry • Problem Set: Flint Water Crisis (G)
R-6. Recommend strategies that can be used to prevent "another Flint" from happening.	• Writing Assignment: Flint Water Crisis	• Online Lesson 13.1: Flint Water Crisis Overview • Online Lesson 13.2: Flint Water Crisis Chemistry • Lecture: Flint Water Crisis Chemistry • Problem Set: Flint Water Crisis (G)
Affective Outcomes		
A-1. Report improved attitudes towards using chemistry to understand and address engineering challenges	• Post-course survey	• All Flint Case study activities

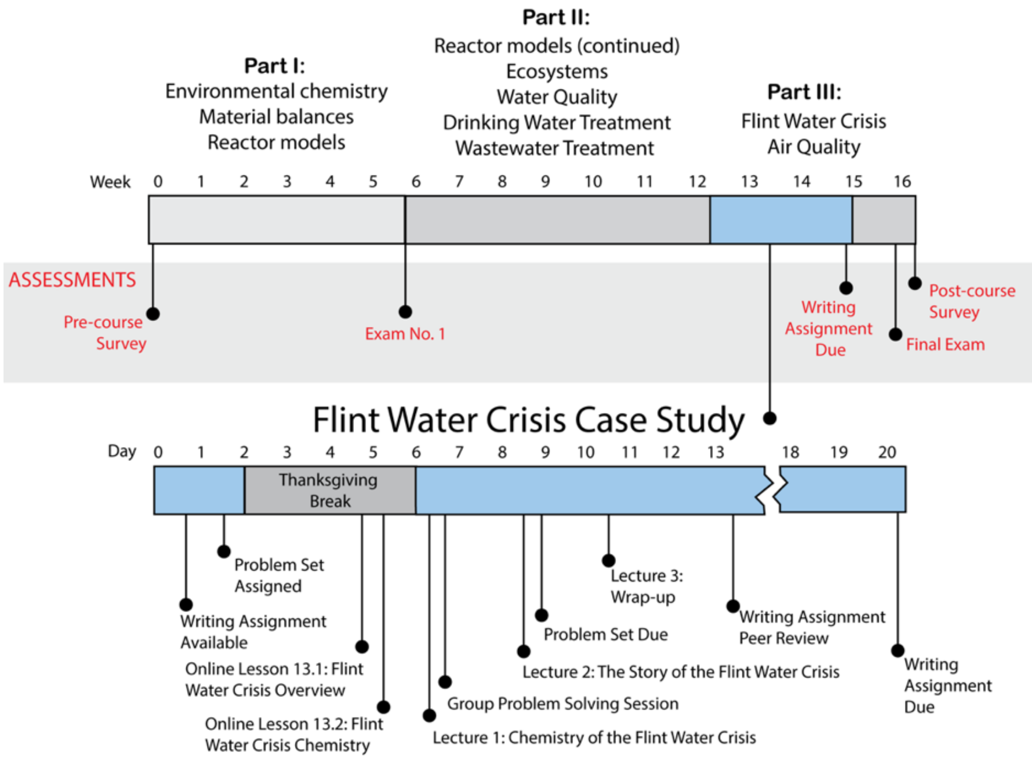

Figure 1: Timeline of an introductory environmental engineering course the Flint Water Crisis case study. The case study was taught late in the semester, after covering environmental chemistry, material balances, reactor models, ecosystems, water quality, drinking water treatment, and wastewater treatment.

To address affective issues surrounding chemistry performance, we aimed to address the four factors of intrinsic motivation: purpose, competence, autonomy, and community [5, 6]. The use of a high-impact, well-known case study was expected to help students see the purpose for understanding and applying chemistry. To address competence, problem sets associated with each case-study were assigned and problem sets were scaffolded so that students could arrive at solutions to complex problems through the step-wise application of principles learned earlier in the course. To allow for student autonomy, individual, open-ended writing assignments were used. These writing assignments asked students to not only explain the causes of the Flint Water Crisis, but also to propose strategies to prevent another crisis like the one experienced in Flint. Lastly, to provide a sense of community, the problem sets were solved in pre-assigned student groups and writing assignments underwent a process of peer-review.

Integrating teaching-as-research, learning communities, and learning-through-diversity. Teaching-as-research was used to develop this report. Throughout this report, we aim to determine if our intervention (a Flint Water Crisis case study) benefited student learning. We collected and analyzed data to test our hypothesis, and we make recommendations for future cohorts based on evidence. To encourage the development of *productive learning communities*, the problem set and writing assignment were conducted in student groups. Group work was already an integral part of the course, and students worked in groups throughout the semester to solve eleven problem sets. To facilitate group work, the course includes weekly two-hour group problem-solving sessions. During the first session, students created and signed group contracts indicating expectations of members within the group. A mid-semester "group check-in" was also conducted to ensure groups were functioning well and that the contracts were being adhered to. Students worked in the same groups throughout the semester, and the group work was monitored by the instructor and two teaching-assistants. In addition to working on problem sets, students used a peer review process for completing the writing assignment. To encourage *learning through diversity*, students were given the opportunity to discuss the Flint water crisis in their assigned groups. In addition to understanding the chemistry, the writing assignments allowed students to consider some of the social justice issues involved with the crisis. The proposed discussions occurred after students had been working together for 12 weeks and after mid-semester group "check-ins" indicated that groups were functioning well. Expectations of mutual respect were explicitly stated during the first group problem solving session. These expectations included understanding that others may have different views and skills; listening when others are speaking; supporting statements with evidence and rationale; and sharing responsibility for including all voices in a conversation. In addition, the case study offered a wider diversity in assessment strategies by offering a writing assignment worth 10% of the final course grade. Lastly, the Flint Water Crisis lectures highlighted contributions of individual from diverse backgrounds, including economically disadvantaged individuals; a water expert of Hispanic descent; and a daughter of Iraqi refugees.

Evaluation

Our hypothesis resulted in two key questions to evaluate: (1) Did the Flint Water Crisis case study improve attitudes towards chemistry, and (2) Did the Flint Water Crisis case study improve chemistry performance? To address the first question, we used questions from a post-course student assessment of their learning gains (SALG) survey. These surveys were conducted as part of the full course survey using the SALG online tool (www.salgsite.net). Question specific to affective improvements included:

- HOW MUCH did the Flint Water Crisis Case Study IMPROVE your ATTITUDE towards chemistry?
- As a result of your work in this class, what GAINS DID YOU MAKE in the following: Confidence that you can use chemistry to solve engineering problems?

To evaluate if students in the Fall 2018 cohort achieved the cognitive learning outcomes related to the Flint Water Crisis (**Table 2**), we used the grades they achieved for each component of the writing assignment. To evaluate if students thought they made gains in overcoming cognitive challenges related to chemistry, we evaluated responses to the following SALG questions:

- HOW MUCH did the Flint Water Crisis Case Study IMPROVE your UNDERSTANDING of chemistry?

- As a result of your work in this class, what GAINS DID YOU MAKE in the following SKILLS: Applying chemistry to solve engineering problems

To evaluate if chemistry performance improved, we compared assessments from Fall 2018 (Flint Water Crisis Case Study included) to Fall 2017 (no Flint Water Crisis case study). We compared the performance on a chemistry pre-assessment as well as performance on two final exam questions: one related to acid-base chemistry and another related to redox chemistry (**Appendix C**). For both cohorts, the acid-base chemistry problem asked students to calculate the proportion of a weak acid protonated given the system pH. For the redox question, students were asked to calculate the theoretical oxygen demand of an organic compound containing carbon, hydrogen, and oxygen atoms.

In addition to our main questions, we also evaluated how much students thought they gained from the Flint Water Crisis unit compared to other course units. Additionally, we evaluated how the addition of the Flint Water Crisis may have impacted other learning outcomes by comparing results from various course topics from Fall 2017 to Fall 2018. Lastly, to inform future modifications to the case study content, we asked students to identify how much they gained from individual components of the case study.

Results

Overcoming affective challenges. Students reported improved attitudes toward chemistry and confidence in applying chemistry to solve engineering problems (**Fig 2**). Based on SALG results, 75% of students reported their attitudes towards chemistry improved either a fair amount or a great deal (**Fig 2A).** Open-ended responses for the SALG also indicate improved attitudes towards chemistry (**Appendix D)**. Reported confidence in using chemistry to solve engineering problems was high (**Fig 2B**), with 63% reporting good or great gains in confidence. These results indicate that the Flint Water Crisis case study improved student attitudes towards chemistry and that, overall, the course made students more confident in applying chemistry.

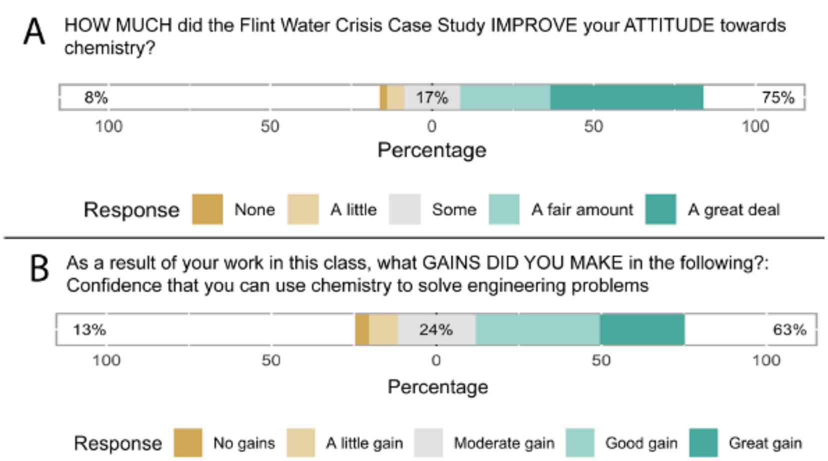

Figure 2: Student assessments of gains related to affective chemistry outcomes. The data summarizes results of responses to the end of semester SALG survey (n=93). Numbers in the rectangles represent the total percentage responding “None” or “A Little”; “Some”; and “A fair amount” or “A great deal”.

Overcoming cognitive challenges. Students reported improved understanding of chemistry and gains in the ability to apply chemistry to solve engineering problems (**Fig 3**). 78% reported that the Flint Water Crisis case study improved their understanding of chemistry either a fair amount or a great deal, while only 9% reported that their understanding was not improved or only improved a little (**Fig 3a**). Similarly, 80% of students reported good or great gains in applying chemistry to solve engineering problems. Evaluation of student writing assignments (**Fig 4**) indicated that learning outcomes related to the Flint Water Crisis were achieved. Students performed very well at comparing and contrasting the chemical characteristics of the Flint River and Lake Huron (mean = 97%). Nearly all of the students correctly identified that the high levels of chloride in the Flint River contributed to the crisis. Students also performed well at explaining the chemistry that resulted in high lead levels in Flint homes (mean = 92%), with most students accurately describing the redox, corrosion, and solubility chemistry aspects contributing to the crisis. Students performed worse (mean = 82%) at explaining the chemistry that resulted in a Legionnaire's outbreak. While most students correctly identified that the oxidation of lead pipes consumed chlorine, most students failed to consider the consumption of chlorine due to the iron pipes in the distribution system (because iron pipes were much more abundant in Flint's distribution system, oxidation of chlorine by iron pipe material was likely responsible for oxidizing more chlorine than the lead pipes). Lastly, students were able to explain how adding orthophosphate prevents lead leaching (mean = 91%), however most students did not mention

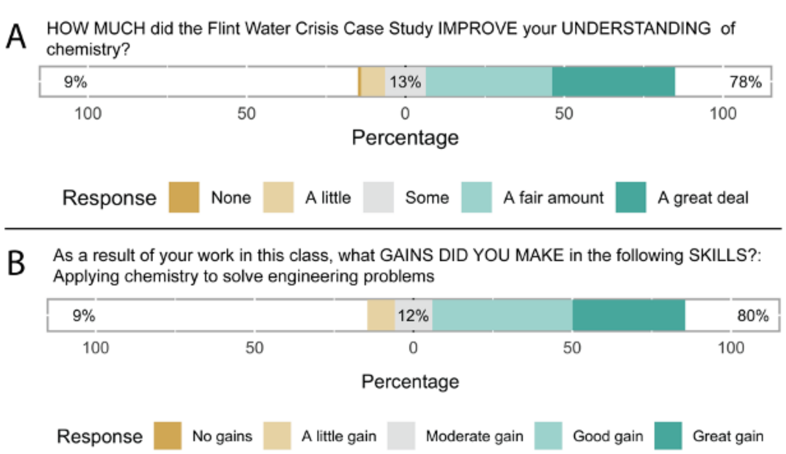

Figure 3: Student assessments of learning gains related to cognitive chemistry outcomes. The data summarizes results of responses to the end of semester SALG survey (n=93). Numbers in the rectangles represent the total percentage responding "None" or "A Little"; "Some"; and "A fair amount" or "A great deal".

that phosphate is part of a triprotic acid system and that the pH impacts the relative amounts of phosphate species and that certain phosphate species are more desirable than others for maintaining a passivation layer. In total, the results from the writing assignment showed that students can explain the chemistry underlying the Flint Water Crisis.

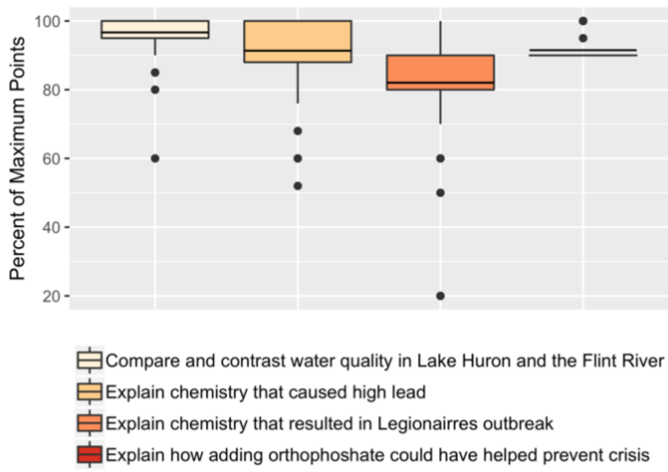

Figure 4: Performance on the Flint Water Crisis Writing Assignment. Results are shown for each of the four learning outcomes related to chemistry (n=93). A copy of the writing assignment and detailed grading rubric is included in Appendix B. Boxes represent the middle 50% of scores, and horizontal lines within the boxes represent the mean scores. Vertical lines (whiskers) represent the top and bottom 25% of scores and outliers are indicated by closed circles.

We also compared the performance on chemistry-related problems for the 2018 cohort and the 2017 cohort (the 2017 cohort was not taught with the Flint Water Crisis case study). The 2017 and 2018 cohorts performed comparably on a chemistry pre-assessment (**Appendix E**) taken during the first week of the semester. In both cohorts, less than 20% of students correctly calculated the amount of a weak acid that is protonated given the pH of an aqueous solution. Less than 70% of students in each cohort could correctly wrote an equilibrium equation given a chemical reaction, and less than 70% of students calculated the concentration of hydrogen ions given the pH of a solution.

While cohorts performed similarly on the chemistry pre-assessment, the 2018 cohort performed slightly better than the 2017 cohort on the final exam at calculating the amount of a weak acid that is protonated given the pH of the aqueous solution (**Fig. 5**; $p = 0.047$). While the mean was also higher for the scores on a redox chemistry question, the difference is not significant ($p = 0.054$). However, as indicated by the presence of outliers **(Fig 5)**, the 2018 cohort had less poor-performing students on the redox question.

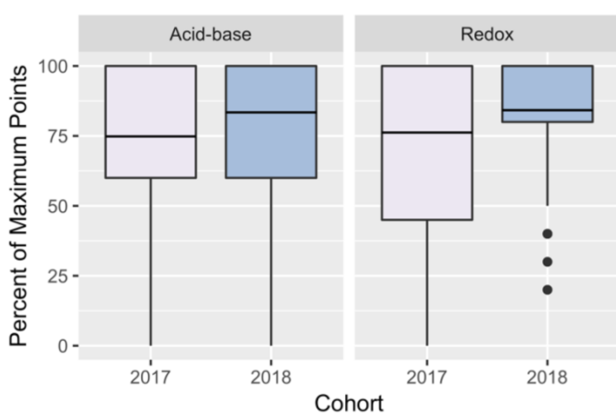

Figure 5: Performance on final exam questions related to acid-base and redox chemistry. The Flint Water Crisis case study was taught for the 2018 cohort (n=93) but not for the 2017 cohort (n=89). Boxes represent the middle 50% of scores, and horizontal lines within the boxes represent the mean scores. Vertical lines (whiskers) represent the top and bottom 25% of scores and outliers are indicated by closed circles.

Impacts on other course topics. In addition to assessing chemistry attitudes and performance, we also investigated self-reported gains in other course topics for the 2018 and 2017 cohorts (**Fig. 6**). In the Fall 2018 cohort, 98% of students reported good or great gains in their understanding of the Flint Water Crisis. In addition, the reported gains in understanding environmental chemistry were higher in 2018 (89% reporting good or great gains) than in 2017 (76% reporting good or great gains). Gains for other topics (excluding ecosystems) were all lower in 2018 than in 2017. While there was reduced time spent on wastewater treatment and air quality because of the addition of the Flint Water Crisis case study, the lower reported gains for other topics (drinking water treatment, water quality, material balances, reactor models) are not due to less time spent on the topics.

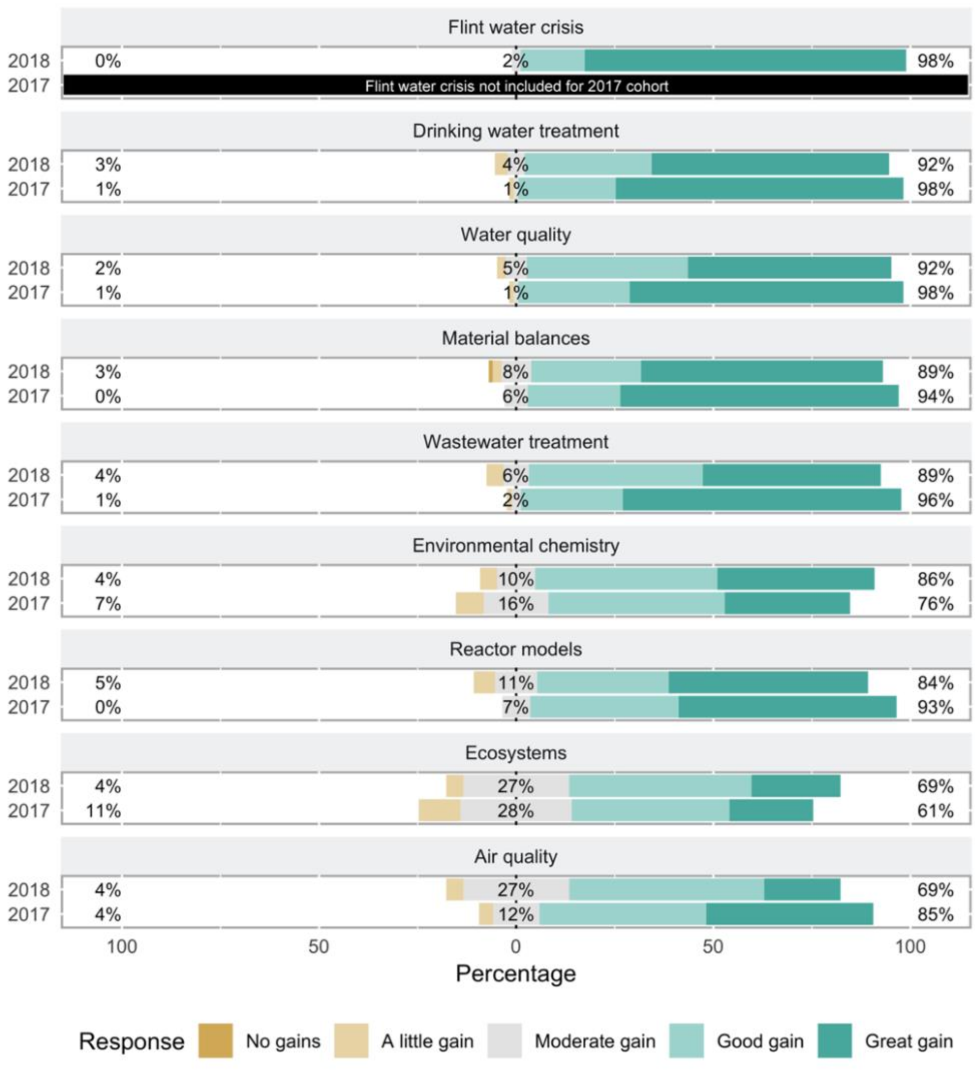

Figure 6: Student assessments of gains in their understanding of course topics in 2017 and 2018. The data summarizes results of responses to the question: "As a result of your work in this class, what GAINS DID YOU MAKE in your UNDERSTANDING of each of the following?" The Flint Water Crisis case study was taught for the 2018 *cohort* (n=93) but not for the 2017 cohor*t (n=89)*.

Impacts of individual case study components. To inform potential improvements to the Flint Water Crisis case study, we also asked students to report how individual components of the case study helped their learning (**Fig. 7**). Students identified the lectures as being the most helpful components, with 98% reporting that the lecture telling the story of the Flint Water crisis was the most beneficial component. 91% of students identified the writing assignment as helping their learning a fair amount or a great deal.

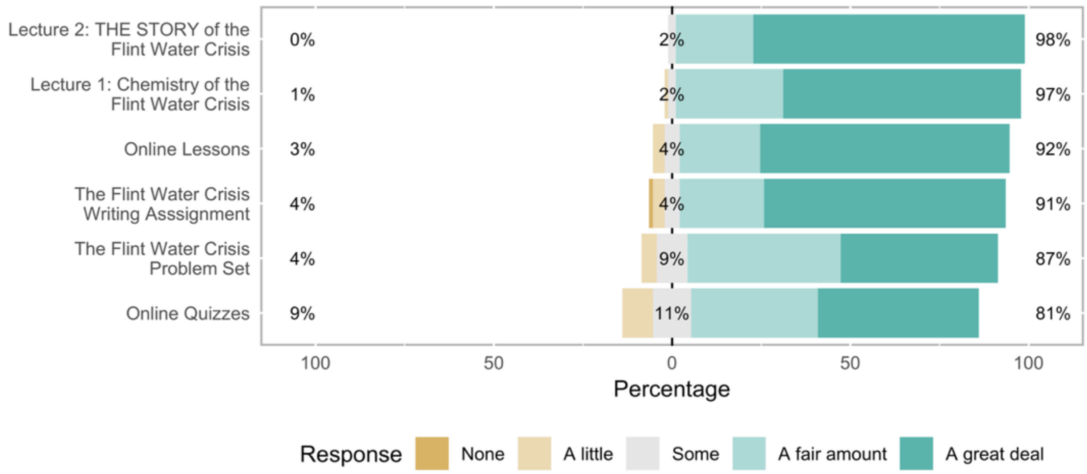

Figure 7: Student assessments of individual Flint Water Crisis case study components. The data summarizes the Fall 2018 SALG results for the question "HOW MUCH did each of the following components of the Flint Water Crisis Case Study HELP YOUR LEARNING?"

Discussion

The addition of a Flint Water Crisis case study to an introductory Environmental Engineering course was made in an attempt to answer the question: "Will civil engineering students' attitudes towards chemistry and abilities to apply chemistry improve after analyzing a high-profile case study related to environmental problems?" Reported improvements in attitudes and confidence (**Fig. 2**) indicate that the Flint Water Crisis case study helped students overcome affective challenges related to applying chemistry. Students reported improved understanding of chemistry as a result of the Flint Water Crisis case study (**Fig. 3**). This is supported by student performance on a final exam question. Whereas only 17% correctly calculated the amount of a weak acid protonated on the chemistry pre-assessment (**Appendix E**), 70% of students correctly solved a similar problem on the final exam. In comparing student performance across cohorts, the Fall 2017 cohort (no Flint Water Crisis case study) and Fall 2018 cohorts (included Flint Water Crisis case study) performed comparably on a pre-course chemistry assessment (**Appendix E**). Students in the Fall 2018 cohort only saw slight improvements in their performance on final exam chemistry questions compared to Fall 2017 (**Fig 5**). Overall, students met the learning outcomes of the Flint Water Crisis case study (**Fig 4)** and 98% of students reported good or great gains in their understanding of the Flint Water Crisis (**Fig 6**).

One concern is that students in the Fall 2018 cohort reported less gains in other topics covered in the course compared to the Fall 2017 cohort (**Fig 6**). It may also be beneficial to investigate responses from additional cohorts to ascertain if the responses are outside of typical year-to-year variations. In total, the Flint Water Crisis case study required three lectures and 1.5 problem solving sessions (one for the problem set and another half of a session for peer review of the writing assignments). This took away from covering additional material related to wastewater treatment and air quality. One way to reduce the time spent on the Flint Water Crisis case study would be to only include the components that students found to be the most helpful. At the very least, we recommend that introductory environmental engineering courses include lectures for the "Story" of the Flint Water Crisis and the underlying chemistry.

We should also consider the timing of the Flint Water Crisis case study within the course. It was taught near the end of the semester (**Fig 1**). Teaching the case study earlier may motivate students to embrace chemistry earlier in the course. Incorporating aspects of the case study into the Environmental Chemistry section of the course (during the first month) may be a good approach. One advantage to teaching the case study later in the course, however, is that students are primed to more readily understand the chemistry underlying the crisis. Also, students have had more time to work within their groups and build learning communities prior to the Flint Water Crisis problem set and writing assignment.

The writing assignment was a major activity and assessment tool. Going into this project, I was reluctant to combine two things engineering students are known to dislike: writing and chemistry. To ensure a successful assignment, we worked with the UW writing center to develop the prompt, a detailed grading rubric, and examples of good and bad peer review feedback (**Appendix B**). The detailed rubric also eased the burden of grading and assessing the writing assignments. While the writing assignment was not identified as one of the most helpful aspects of the case study (**Fig. 7**), 91% of students reported that the assignment helped their learning a fair amount or a great deal. Given the general dislike for writing among undergraduate engineering students (and audible groans when I announced the assignment to the class), students largely seemed to enjoy the writing assignment.

Several themes emerged from the case study related to student misconceptions. First, students struggled early on to recognize the difference between "chlorine" and "chloride." Both played a role in the Flint Water Crisis, but the roles they played were quite different. While "chloride" increased the corrosivity of the water in the distribution system, "chlorine" (as hypochlorite or hypochlorous acid) is a disinfectant that oxidized iron and lead in the pipes. Also, students correctly explained that lead pipes consumed the chlorine residual, but many failed to explain the iron pipes would also corrode and consume chlorine. Lastly, students largely did not explain that orthophosphate (a corrosion inhibitor) participates in acid-base chemistry and that the least protonated form is ideal for forming a passivation layer and preventing corrosion. These themes were identified through the muddiest point, and concept map activities, as well as evaluation of the writing assignments.

Another possible addition to the Flint Water Crisis case study would be to discuss trihalomethane (THM; a class of carcinogenic disinfection byproducts) formation that resulted in the City of Flint exceeding THM limits. Several students attempted to address THM formation in their writing assignments and several students incorrectly stated that the THMs came from the Flint River. The THMs increased partly due to high organic matter in the Flint River, but also because the City began adding more and more chlorine to deal with the higher pathogens (the addition of more chlorine created THMs and also resulted in release of more lead). While formation of disinfection byproducts was covered in an online lesson during the drinking water treatment unit, it would be good to reinforce these concepts and how they played a role in the Flint Water Crisis.

Conclusions

In this study, we implemented a Flint Water Crisis case study and assessed if the case study improved chemistry-related attitudes and performance. Evaluation of student learning gains through survey questions and final exam performance showed that both attitudes and performance improved compared to a cohort that was not taught using the Flint Water Crisis case study. Nearly all students in the case study cohort (98%) indicated that they achieved good or great gains in their understanding of the Flint Water Crisis. The combination of online lessons, lectures, a problem set, and a writing assignment allowed students to access and explore content in various ways, and most students reported that all components contributed to their understanding of the material. Students in the cohort with the case study, however, reported lower gains in understanding of other course topics. Prioritizing desired learning outcomes and time allocated to topics remains a challenge in this broad introductory environmental engineering course, but this study demonstrates that a high-impact case study improved learning outcomes for a subject area often deemed unimportant by civil engineering students. High-impact case studies may be especially beneficial for helping students gain an appreciation for topics often deemed “uninteresting” or “voodoo black magic” by students, and the engineering education community should continue to develop, share, and assess the impacts of case studies.

List of Appendices

Appendix A: Flint Water Crisis Problem Set

1. **SHOULD WE WORRY ABOUT CORROSION?** A small town has hired you as a consultant to expand their drinking water treatment system. Due to an increasing population, they are evaluating two different new water sources. Data for the two potential sources are given below.

Constituent	Well No. 22	Watson Creek
Ca^{2+} (mM)	68	11
Mg^{2+} (mM)	12	3.6
Cl^- (mM)	2	12
SO_4^{2-} (mM)	1.1	4.2
HCO_3^- (mM)	120	12
CO_3^{2-} (mM)	0.14	0.011

Calculate the Larson-Skold Index (LSI) for each potential water source and comment on the corrosiveness of each source (indicate if the water is likely non-corrosive, corrosive, or highly corrosive). **In Flint, there is no indication that the LSI was ever calculated for the Flint River prior to switching sources.**

2. **AN EXAMPLE OF A LEAD COMPLEX: PLATTERNITE.** Lead pipes are made of Pb^0. This form of solid lead is readily oxidized to many lead compounds, including plattnerite ($PbO_{2(s)}$). When lead pipe is stored above ground, a layer of $PbO_{2(s)}$ can form before the pipe is installed. When exposed to water, $PbO_{2(s)}$ can be reduced to Pb^{2+} which is soluble in water.

   (a) Write the redox half reaction for the reduction of $PbO_{2(s)}$ to Pb^{2+}.

   (b) Write the redox half reaction for the oxidation of H_2O to O_2.

   (c) Write the overall chemical reaction for the conversion of $PbO_{2(s)}$ to Pb^{2+} in the presence of H_2O.

3. **PREVENTING LEAD LEACHING WITH ORTHOPHOSPHATE**. Orthophosphate can (and should!) be added to water distribution systems to prevent corrosion. Orthophosphate prevents corrosion by building a physical barrier between the lead pipe and the drinking water. This barrier is sometimes referred to as a "passivation layer." **Orthophosphate was added to the water that Flint received from Lake Huron, but no corrosion inhibitor was added after the water source was switched to the Flint River.**

Orthophosphate (PO_4^{3-}) reacts with Pb^{2+} to form a very insoluble solid ($Pb_3(PO_4)_2$). As a weak base, phosphate can also accept protons to form HPO_4^{2-}, $H_2PO_4^-$ and H_3PO_4 ($pK_{A,1}$ = 2.16, $pK_{A,2}$ = 7.21, and $pK_{A,3}$ = 12.32).

(a) Write the dissolution reaction for $Pb_3(PO_4)_2$

(b) Based on the problem statement, draw a diagram that shows the interaction between lead and phosphate species in the pipe. Also include the reaction between lead and OH^-.

(c) In order to form a passivation layer, water and orthophosphate are added to an existing distribution system. No water is added or removed from the system during this period (In other words, the distribution system is a batch reactor allowed to reach equilibrium). The initial concentration of Pb^{2+} is 150ppb (10 times the limit!). Write a system of equations to solve for the resulting lead concentration and pH after 100 mg/L of Na_3PO_4 (MW = 164 g/mol) is added to the system and the system reaches equilibrium. Na_3PO_4 completely dissolves and reacts with Pb^{2+} to form $Pb_3(PO_4)_{2(s)}$. Assume the pK_{sp} for $Pb_3(PO_4)_{2(s)}$ dissolution is 54 and that a layer of $Pb_3(PO_4)_{2(s)}$ has formed on the interior walls of the pipe. Assume the lead also reacts with OH^- to form $PbOH^+$ with an equilibrium constant of $10^{7.6}$. Assume that the system is closed to the atmosphere.

(d) You use an equation solver to solve this system of equations and learn that the pH at equilibrium is 9.78. At this pH, you determine that 0.29% of the phosphate added ends up in the completely unprotonated form, PO_4^{3-} What is the concentration of Pb^{2+} (**in ppb**) at equilibrium? (*Hint: You're welcome to try using solver from scratch, but it will likely give you errors; some of the values are too small for EES to handle with ease (pun intended)… also, this problem is more representative of what you would see on an exam)*

(e) If the pH decreases, how will the lead concentration (Pb^{2+}) be impacted? Will it increase, decrease, or stay the same?

4. IS THAT WATER SAFE? LEAD AND CHLORINE IN A DISTRIBUTION SYSTEM.
Hypochlorous acid (HOCl) is a strong oxidant that inactivates pathogens, but it also oxidizes lead Pb^0 to produce Pb^{2+}. In lead pipes, HOCl not only causes Pb^{2+} to enter the water, but it also can be consumed by the lead, resulting in inefficient disinfection of pathogens. **This is one of the suspected reasons for the outbreak of Legionnaire's disease in Flint that killed 12 people and made many more sick.**

(a) HOCl is a weak acid that dissociates to H^+ and OCl^- with a K_a of 2.9 x 10^{-8}. The molecular weight of NaOCl is 74.44 g/mol. 7 mg/L of NaOCl is completely dissolved in water. After dissolving, the final pH is 7.5. How much HOCl is present (in mg/L)?

(b) Write the overall chemical reaction for the oxidation of Pb^0 to Pb^{2+} with HOCl being converted to Cl^-. (*Hint: Write two half reactions, then add them together*)

(c) Pb^0 present in the pipes reacts with HOCl according to a first-order reaction with respect to HOCl. This will cause the HOCl concentration to decrease as the water moves through the distribution system. Write a mass balance equation for HOCl in a pipe (assuming the pipe acts as an ideal plug flow reactor). You can ignore the impacts of any other reactions occurring in the pipe.

(d) A water treatment plant adds HOCl to its water as it leaves the water treatment plant. If the flow rate from the water treatment plant is 2,500 m^3hr^{-1} and the distribution pipe is a lead pipe with a cross sectional area of 0.5 m^2, what will be the approximate HOCl concentration at a home 20 km from the water treatment plant? The rate constant (k) is 0.40 hr^{-1}. Assume the initial HOCl concentration is equal to the concentration calculated in part (a) and ignore impacts of changing pH. No corrosion inhibitor is added to the distribution system.

(e) State law requires that the HOCl concentration remains above 1 mg/L (as HOCL) at all points in the distribution system. Is the water treatment plant meeting this requirement?

(f) Assuming all of the HOCl consumption is due to reactions with lead, what is the lead concentration (Pb^{2+}) at a home 20km from the water treatment plant and how does this value compare to the allowable concentration in drinking water of 15 ppb?

Appendix B: Flint Water Crisis Writing Assignment

Overview

On April 25, 2014, Flint Michigan officially switched their drinking water source from Lake Huron to the Flint River. This switch in water supply resulted in a public health crisis that continues to this day.

The Town of Streeter-Phelps has hired you as an environmental engineer to address concerns resulting from the Flint Water Crisis. Like Flint, Streeter-Phelps' water distribution system contains several stretches of lead pipes. Concerned citizens have asked the Town Council to replace the lead pipes immediately. At your first meeting to discuss the project with the Town Council, they voiced several questions and comments:

- "Why would Flint change from a pristine water source to a river containing a bunch of lead?"
- "If they would have just added phosphate, then the lead would have been transformed to a non-toxic form."
- "Lead pipes aren't the culprit, it was the acidity of the new water source that caused the problem."
- "It was the Legionella in the Flint River that made everyone sick."

You left the meeting concerned that the Town's leaders did not really understand what occurred in Flint. You now must prepare a report to better explain the Flint Crisis to the Town's leaders and make suggestions on preventing a Flint from occurring in Streeter-Phelps.

Learning Outcomes

- Explain the rationale for Flint switching water sources from Lake Huron to the Flint River
- Compare and contrast the chemical characteristics of the Flint River and Lake Huron
- Explain the chemistry that resulted in high levels of lead in Flint's drinking water
- Explain why additional pathogens were present in Flint's water after the switch
- Describe how adding orthophosphate to Flint's water could reduce lead levels
- Recommend strategies that can be used to prevent "another Flint" from happening

Instructions

Your essay should include five paragraphs and be up to three single-spaced pages long total, with 12pt times new roman font and 1 inch margins. You should also include a cover page that includes (1) the course number; (2) the title of the assignment; (3) the date; (4) your group number; and (5) the name of your peer reviewer. You can assume that the audience for this report is a group of people who have completed an introductory environmental engineering course. The report should be organized as follows:

- In the first paragraph, explain the rationale behind the City of Flint switching water sources.
- In the second paragraph, describe the chemical characteristics of the Flint River and contrast with Lake Huron
- In the third paragraph, explain the chemistry that resulted in high levels of lead in Flint's drinking water. Also, explain how the switch in water supply may have resulted in an increased number of pathogens in Flint's drinking water.
- In the fourth paragraph, describe how adding orthophosphate to Flint's water could have reduced lead levels.

- In the final paragraph, summarize your essay and sign-off by suggesting a way that the Town of Streeter-Phelps might prevent “another Flint.”

References

You should also include a list of references which will not count towards your length limit. You may use the citation format of your choice.

While we will discuss the Flint Water Crisis in class, you are expected to use additional references to reply to the specific questions above. Several potential sources are listed below:

American Chemical Society, “The Flint Water Crisis: What’s Really Going on?”

https://www.acs.org/content/acs/en/education/resources/highschool/chemmatters/past-issues/2016-2017/december-2016/flint-water-crisis.html

NOVA Documentary, “Poisoned Water” https://www.pbs.org/video/poisoned-water-jhhegn/

PBS Article, “Study confirms how lead got into Flint’s water”

https://www.pbs.org/newshour/science/study-confirms-lead-got-flints-water

Atlantic Article, “Who Poisoned Flint?” https://www.theatlantic.com/politics/archive/2016/01/who-poisoned-flint/425454/

New York Times Article, “Unsafe Lead Levels in Tap Water Not Limited to Flint”

https://www.nytimes.com/2016/02/09/us/regulatory-gaps-leave-unsafe-lead-levels-in-water-nationwide.html?rref=collection%2Fnewseventcollection%2Fflint-water-crisis&action=click&contentCollection=us&region=rank&module=package&version=highlights&contentPlace

Environmental Science & Technology Article, “Flint Water Crisis: What Happened and Why?”

https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5353852/

Peer Review

As part of this assignment, you are required to review and provide feedback for one of your group members’ assignments. You are expected to hand in a copy of your written feedback with your assignment. Your peer review will account for 10% of your assignment grade according to the rubric provided below. In your review, you should use the rubric as a guide and provide your feedback with the attached form. Two example peer review forms are also provided at the end of this document.

Grading

For this assignment, we will be looking for evidence that you understand the chemistry that lead to Flint’s water crisis and that you can explain the chemistry to others. We are also assessing your holistic understanding of the Flint water crisis, including how engineering decisions were made that lead to the crisis. Lastly, we are assessing your ability to review the work of your peers. A detailed rubric is provided on the following page

Rubric

	Maximum	100 %	85%	70%	60 % or less
Explain the rationale behind switching water sources from Lake Huron to the Flint River	10 pts	Explains the multiple drivers that lead to the decision and the historical context of these decisions	Explains one of the major drivers leading to the decision	Explains one of the minor drivers that resulted in the decision	Does not explain an actual driver for making the switch
Compare and contrast the chemical characteristics of the Flint River and Lake Huron	20 pts	Describes all of the key water parameters that differed between the water sources and provides reasons for why the parameters were different	Describes many of the key water parameters that differed between the water sources	Describes many of the parameters that differed between the water sources but does not include key parameters	Does not describe any important parameters that differ between the two sources
Explain the chemistry that resulted in high levels of lead in Flint's drinking water	25 pts	Accurately explains all of the key chemistry principles	Explains key chemistry principles	Explanations of chemistry involved are not accurate	No explanation of the underlying chemistry provided
Explain why additional pathogens were also present in Flint's drinking water	10 pts	Accurately explains all of the key chemistry and disinfection principles	Explains key chemistry and disinfection principles	Does not accurately explain the impacts on disinfection	No explanation related to pathogens provided
Describe how adding orthophosphate to Flint's water could reduce lead levels	10 pts	Accurately describes all of the key chemistry principles	Describes key chemistry principles	Descriptions of chemistry involved are not accurate	No description of the underlying chemistry provided
Recommend strategies to prevent "another Flint" from occurring	10 pts	Suggests a solution that considers economics, sustainability, and public health	Suggests a solution that considers public health	Suggests a solution that does not consider public health	Does not suggest any solutions

Meet the required style and format	5 pts	Essay has a cover sheet and is 3 pages or less in length. A list of references is included. Grammar and spelling errors are minimal (< 5)	Essay has a cover sheet and is 3 pages or less in length. A list of references is included. There are many spelling and grammar errors (> 5)	Essay does not meet page requirements or does not have a cover sheet.	Essay does not meet page requirements or does not have a cover sheet. There are many spelling and grammar errors (> 5)
Provide a review of a peer's work	10 pts	The review provides specific, thoughtful comments to improve the technical content of the report in multiple sections.	The review comments are specific and helpful, but the reviewer missed major issues with the manuscript.	The review comments do not address technical aspects of the report and instead focus on grammar, punctuation, etc.	No "Peer Review Feedback Form" included with Assignment
Total	100				

The Flint Water Crisis – Peer Review Feedback Form

Reviewer Name: ______________________________________

Reviewee Name: ______________________________________

1. Describe a feature of the paper that stands out as a strength (1.5 pts)

2. Indicate the section of the paper that can be most improved and suggest a way to improve the section (1.5 pts)

3. Using the rubric provided with the assignment, give a score for each item indicated below and suggest a way to improve each item (7 pts).

	Maximum	Score	Suggested Improvements
Explain the rationale behind switching water sources from Lake Huron to the Flint River	10 pts		
Compare and contrast the chemical characteristics of the Flint River and Lake Huron	20 pts		
Explain the chemistry that resulted in high levels of lead in Flint's drinking water	25 pts		
Explain why additional pathogens were also present in Flint's drinking water	10 pts		
Describe how adding orthophosphate to Flint's water could reduce lead levels	10 pts		
Recommend ways to prevent "another Flint" from occurring	10 pts		
Style and Format	5 pts		
Total Pts	90		

The Flint Water Crisis- Peer Review Feedback Form

EXAMPLE OF FEEDBACK THAT NEEDS IMPROVEMENT

Reviewer Name: ____

Reviewee Name: ____

1. Describe a feature of the paper that stands out as a strength (1.5 pts)
   The discussion about lead was really good

2. Indicate the section of the paper that can be most improved and suggest a way to improve the section (1.5 pts)
   Nothing. This paper will likely win a Pulitzer, if not the Nobel prize for literature.
3. Using the rubric provided with the assignment, give a score for each item indicated below and suggest a way to improve each item (7 pts).

	Maximum	Score	Suggested Improvements
Explain the rationale behind switching water sources from Lake Huron to the Flint River	10 pts	10	The rationale is really good.
Compare and contrast the chemical characteristics of the Flint River and Lake Huron	20 pts	20	None
Explain the chemistry that resulted in high levels of lead in Flint's drinking water	25 pts	23	There was an extra semi-colon in the sentence about corrosion.
Explain why additional pathogens were also present in Flint's drinking water	10 pts	8	The section seems incomplete.
Describe how adding orthophosphate to Flint's water could reduce lead levels	10 pts	10	Good job!

Recommend ways to prevent "another Flint" from occurring	10 pts	9	There was one run-on sentence for this entire paragraph.
Style and Format	5 pts	5	
Total Pts	90	85	

The Flint Water Crisis- Peer Review Feedback Form

EXAMPLE OF GOOD FEEDBACK

Reviewer Name: _______________________________________

Reviewee Name: _______________________________________

1. Describe a feature of the paper that stands out as a strength (1.5 pts)
   The author clearly explained the rationale behind Flint deciding to switch water sources from Lake Huron to the Flint river. This discussion included other alternatives considered by the City and how cost ultimately drove the City to use the Flint River.

2. Indicate the section of the paper that can be most improved and suggest a way to improve the section (1.5 pts)
   The discussion of the differing water characteristics between the Flint River and Lake Huron is incomplete. The author should expand this to more than a statement that the Flint River was "more polluted" than Lake Huron. What chemical characteristics made it "more polluted"?

3. Using the rubric provided with the assignment, give a score for each item indicated below and suggest a way to improve each item (7 pts).

	Maximum	Score	Suggested Improvements
Explain the rationale behind switching water sources from Lake Huron to the Flint River	10 pts	10	I have no recommended improvements for this section. The author has thoroughly researched the decision making process and the drivers that lead to the decision to switch water sources.
Compare and contrast the chemical characteristics of the Flint River and Lake Huron	20 pts	12	As mentioned above, this section lacks details. The author should include additional information about the chemical composition, especially as it relates to corrosivity. "More polluted" can mean many different things.
Explain the chemistry that resulted in high levels of lead in Flint's drinking water	25 pts	22	While this section explains lead leaching in detail, it does not adequately explain how the corrosive water also broke down chemical barriers protecting the pipes.
Explain why additional pathogens were also present in Flint's drinking water	10 pts	7	While it is true that there may have been more pathogens in the Flint River, the paragraph does not explain how the chlorine residual was impacted by lead and the Flint River water. The author should explain why so much HOCl was

			consumed by other compounds in the Flint River water.
Describe how adding orthophosphate to Flint's water could reduce lead levels	10 pts	10	This section thoroughly explains how phosphate prevents lead from leaching into drinking water. The author has demonstrated that they understand the chemistry involved with corrosion prevention.
Recommend ways to prevent "another Flint" from occurring	10 pts	8	While the author recommends a solution (removing all lead pipes), it neglects considerations of the costs involved with this approach. I suggest the author add additional recommendations for Cities that cannot afford to immediately replace all of their lead service lines.
Style and Format	5 pts	4	There are several typos that I have corrected in the hard-copy I reviewed.
Total Pts	90	73	

Appendix C: Examples of “acid -base” and “redox” chemistry questions used for evaluation[1]

Example “Acid-Base” Problem:

Acetic acid is a weak acid that can lose a proton to form acetate as its conjugate base (pKA = 4.75). If a solution of sodium acetate has a pH of 5.2 at equilibrium, what proportion of the acetate added is present as acetic acid in the solution?

Example “Redox “Problem:

Glucose ($C_6H_{12}O_6$; FW = 180 g mol^{-1}) is oxidized by microorganisms that perform denitirifcation (convert NO_3^- to N_2). Estimate the mass of glucose required to convert 1 g of NO_3^- (FW = 62.0 g mol-^{1}) to N_2 (FW = 28 g mol^{-1}) .

[1]The actual questions are not included in this report because they will be used for future student assessments and this report will be made available to the public.

Appendix D: Selection of student responses to the question "Please describe how the FLINT WATER CRISIS CASE STUDY has CHANGED your ATTITUDES towards chemistry."

Adding the Flint unit was an integral part to my liking CEE 320. It incorporated many aspects of topics we had already learned, and added new topics as well (especially within chemistry). The main attitude change caused by learning about Flint is the importance of a comprehensive understanding of water chemistry and the complexity and vastness of chemical reactions.

In my past experience in chemistry (102,103), no real world connections were made. It's nice to see a real world application of the chemistry I thought would be useless to me.

I have gained more understanding for why chemistry is important in engineering and how it can affect many types of engineers, basically anyone who works with any types of materials will have to worry about some sort of chemistry and reactions to different materials.

Writing the paper on the Flint Water Crisis changed my views of chemistry thoroughly.

I've learned that chemistry actually serves a purpose in my life. I also love that I can now use my knowledge to describe a difficult time in America and how to prevent it.

The Flint Water Crisis case study actually helped me see the importance of understanding all aspects of chemistry to make sure everyday life will run as smoothly as possible.

I wished I would have taken general chemistry more seriously.

Learning how thousands of people were harmed by the negligence of a city and how applying simple chemistry could've prevented that has further motivated me to pursue a career in environmental engineering.

Learning about the Flint Water Crisis gave me a greater appreciation for the importance of understanding chemistry because it literally can save lives of people.

Appendix E: Performance of 2017 and 2018 Cohorts on a Chemistry Pre-Assessment

Responses were coded as "No attempt made," "Minor attempt made," "Attempted bit error made," or "Problem solved correctly." Student performance on the pre-assessment was similar across the six questions.