Using Geographic Information Systems (GIS) in high school chemistry: Three case studies of socio-environmental science instruction

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Paper presented at the 2024 Association for Science Teacher Education (ASTE) Annual Meeting in New Orleans, LA. USA

Program Abstract
Introducing GIS within diverse academic settings provides authentic applications for science. Three sites [PA/DE, TX, WA] implemented geospatial socio-environmental chemistry activities with high school students as part of a NSF-supported project. This paper set describes how GIS was used to integrate technology with different chemistry topics.

Full Abstract:
This paper set describes geospatial socio-environmental chemistry learning activities developed and implemented in three U.S. states. Because each setting and socio-environmental issue were unique, units varied while holding true to the NSF project goals.

Paper 1: This case examines how a chemistry teacher incorporated his new knowledge and skills to enhance a chemistry lesson on the periodic table. Students investigated metals and metalloids by first mapping where the metals were mined, processes of mining and extraction, and potential impacts on the local environment. Although he did not intentionally plan for students to make connections with economics, human rights, and global political issues, students quickly saw broader implications for learning about chemical elements. Having students see chemical elements as a socio-scientific environmental issue made the chemistry topic authentic and relevant to their everyday lives.

Paper 2: In this case, we focus on Kimberly, a high school agriculture education teacher who developed proficiency in ArcGIS Online during summer professional development. Kimberly designed and executed an activity for her 10th-12th grade students, exploring pH levels in soil. This case provides an overview of the project, Kimberly's professional development, the soil sampling lesson, and her reflections on using technology to engage students. The challenges are discussed, including technical issues and data display adjustments. Kimberly aimed to provide authentic experiences with GIS technology, emphasizing its

relevance in agriculture and spatial data analysis. Based on the insights gained, the paper concludes with Kimberly's reflections and future implementation plans.

Paper 3: This case describes how a polonium-210 (P-210) murder mystery functioned to familiarize students with ArcGIS tools and interface prior to the first full SESI investigation. The teacher focused on the case of Alexander Litvinenko, a former Russian intelligence agent who fell ill with radiation poisoning due to P-210. Students engaged in this case through a series of maps which documented segments of this real-life event and ultimately discovered that Litvinenko was murdered by two former KGB agents. The teacher built upon this activity in later more intensive uses of GIS (e.g., data collection, display, manipulation, and analysis) as they addressed subsequent SESI investigations and related topics in their enacted chemistry curriculum.

Note:

This manuscript is the product of an NSF-funded collaborative research project (awards 1949388, 1949393, and 1949400) across three universities working with a total of six partner high schools. Each university team presents a case from one of their respective partner high schools in which a teacher integrates geospatial tools into classroom instruction during a chemistry unit.

Introduction

Despite accelerating industry growth and congruence across STEM fields, few school-based programs integrate geospatial technology within their curricula. The call for students to graduate from high school with the skills necessary for a robust national STEM-related workforce requires teachers who are prepared to implement a curriculum that can provide students with geospatial thinking and reasoning (GTR) skills. GTR skills are essential for occupations in which there is a heavy reliance on cognitive thinking skills that include knowledge about geospatially-referenced data and their relationships (Goodchild & Janelle, 2010; National Research Council, 2006). These skills involve important scientific practices highlighted in the Next Generation Science Standards [NGSS] (NGSS Lead States, 2013), and include data manipulation, analysis, data mining, computational thinking, and modeling that provoke and require critical thinking and problem solving that are connected to data referenced to Earth's surface or to the Earth's representation through map and globe visualizations (Huynh & Sharpe, 2013). Curricula that engage students to collect and analyze data, and solve problems provide important skills that help prepare students for career opportunities and lifelong learning (National Research Council, 2011; National Science Board, 2015).

To address this issue, a collaborative group of teacher educators across three universities were awarded an NSF grant to work with high school teachers to implement socio-environmental science investigations into their curriculum. Teachers from eight high schools in rural, urban, and suburban settings began a professional development (PD) project across various content areas to promote the use of geospatial tools and to create interdisciplinary, environmentally-focused curriculum-embedded learning activities using a geospatial curriculum approach. The teachers, with the help of university faculty, identified topics that both align with existing curricula and involve understanding geospatial patterns and relationships in real-world data. The teachers identified opportunities for students' hands-on use of geospatial data and analysis tools to master the curriculum-specified content through inquiry-based learning. During the third year of the grant, teachers implemented multi-disciplinary units that involved decision-making based on the analysis of scientific data connected to relevant social science content, and having implications for social equity. The learning activities provided opportunities for students to collaborate, seek evidence, problem-solve, master technology, develop GTR skills, and practice communication skills, all of which are essential in the STEM workplace.

Conceptual Framework

Socio-environmental science investigations (SESI) focus on social issues related to environmental science. SESI involves inquiry-based investigations that are open-ended with students engaging in data collection and geospatial analysis. SESI activities are multi-disciplinary and involve decision-making based on the analysis of georeferenced geospatial data, examination of relevant social science content, and consideration of social equity implications. SESI are based on the pedagogical frameworks of place-based education and socio-scientific issues-based instruction. Place-based education focuses on local or regional investigations, is designed around engaging students in examining local problems (Sobel, 2004), and utilizes fieldwork to gather evidence in that local setting (Semken, 2005; Semken et al., 2017). SESI investigations can provide opportunities to empower students to address important socio-scientific issues in their community. Socio-scientific issues are socially relevant, real-world problems that are informed by science and often include an ethical component (Sadler et al., 2007), such as human impact on the environment, climate change, and questions related to economic and racial repercussions of urban development. These issues require the use of evidence-based reasoning and provide a context for understanding scientific information using an active approach to learning, placing science content within a social context in a way that fosters motivation for, and the ownership of, learning by the student (Sadler et al., 2006; Zeidler & Nichols, 2009).

SESI curriculum design incorporates the following elements:

1. Focus on socioscientific issues: socially relevant, real-world problems that are informed by science (Zeidler & Nichols, 2009).
2. Design place-based education (Gruenewald & Smith, 2014; Sobel, 2004), grounding all curricular concepts in students' local environment.
3. Use inquiry-driven learning: students seek to answer driving investigative questions about their local environment.
4. Require students to collect authentic data within the local environment to answer these questions.
5. Require students' hands-on use of geospatial technologies to promote GTR skills—specifically ArcGIS Online and its associated mobile data collection app—for data collection and analysis to make inferences about the geospatial patterns and relationships in the collected data.

In designing SESI-informed curriculum, we use a teacher-partnership model: teachers are design partners in conceptualizing, designing, developing, and refining any geospatially-enhanced science instruction. This collaborative design strategy allows us to draw upon the strengths of both the university-based teacher educators and researchers and the in-service teachers with whom we partner. Each member of a SESI design process, whether a teacher or professor or GIS specialist or graduate student, brings their own relative strengths with geospatial technologies, curricular concepts, instructional design, and knowledge of students and the local environments for which we are designing the lessons.

This collaborative design process has been a cornerstone of our work, more than a decade of research and development of geosptially-enhanced high school science education. This paper presents three outputs from this work, three chemistry education lessons from classrooms across our current partner schools. Each case embodies different aspects of the SESI design principles, but all emerge from the same design process. The cases are presented below, with cross-case discussions and conclusions following.

Case 1 (Texas): Mapping the Periodic Table

The Texas site consists of a private university in an urban setting and two public high schools. Over the last three years, a small cohort of teachers from science, social studies, and STEM areas have been working with the university researchers in long-term PD to learn how to incorporate geospatial technologies including ArcGIS online into their existing curriculum. Gill was an original member of the cohort who joined the PD group with the rest of his STEM department. He is an experienced science teacher who has mainly taught physics and chemistry over the last several years of his career. Gill also served as the technology coordinator for his campus and was responsible for managing a variety of devices and technology applications used at his new school. The school is in its fifth year as a STEM and Fine Arts magnet academy which serves students from across the metropolitan area.

Gill's students are generally highly motivated to be at school and are interested in STEM majors and careers. This year, Gill is teaching an integrated physics and chemistry course with honors students. Like many chemistry teachers, Gill struggles with keeping his periodic table unit engaging for students. How could geospatial tools help make the periodic table authentic for students so they are aware of how chemical elements are used in their everyday lives?

Professional Development

Across the first three years of the grant, the research team worked with teachers during in-person summer PD sessions and monthly after-school meetings. This PD work addressed a variety of goals: technical training on GIS, identification and development of ideas for curriculum integration, managing project logistics, and more. After three years of PD with GIS technologies, Gill had the idea to have students map out the elements from the periodic table. He brought his activity plans to his monthly PD meeting with university researchers and his other cohort teachers. Although the cohort group helped him brainstorm some of the technical aspects that would be needed for the activities, Gill used his own understanding of his chemistry curriculum and geospatial tools to create activities independently once he was back at school.

Gill uses a variety of technology applications with his students on a regular basis so he felt comfortable introducing ArcGIS as a new technology during the last six weeks of school. Unlike other teachers in the PD cohort who had the university researchers set up student accounts and create supporting materials in ArcGIS, Gill was proficient enough with instructional technology to set up the activities on his own. Because his students had used a variety of technology applications in his course, Gill was able to trust his students to set up their own usernames and passwords in the school's ArcGIS site. While this may sound like a simple task, this was the first time one of our teachers allowed students to set up their own accounts and request to be part of the teacher's course group in ArcGIS. Students choose an element from the periodic table, researched their element, decided where the element is found on earth, and then placed their element on a map in ArcGIS. In order for each student to experience using ArcGIS, they worked independently to place their element on a map and include details about the element in a Map Note. Gill encouraged the students to talk with their peers as they worked, allowing them to learn from each other as they navigated the new technology platform.

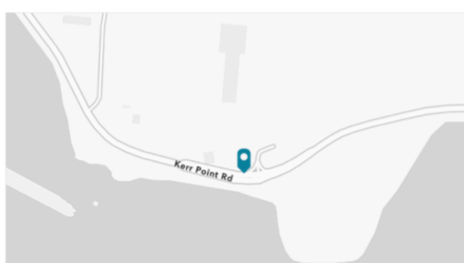
Implementation: Instructional Adaptations

In his original plan for the activity, Gill envisioned students would address most of the elements from the periodic table: organic and inorganic elements, both radioactive and stable elements, both metals and non-metals. However, as the activity unfolded with the students, Gill decided that focusing on metals and metalloids made the most sense for his instructional purposes; mapping where elements are found in abundance on Earth. Students were surprised to find where different metals were mined, the processes of mining and extraction, and potential impacts on the local environment. Using the ArcGIS maps allowed students to visualize the sources of the elements that are used in everyday products they take for granted like their cell phones and lithium batteries. Although Gill did not intentionally plan for students to make connections with economics, human rights, and global political issues, the students quickly saw broader implications for learning about chemical elements. For example, one small group was allowed to spend time discussing the impacts of mercury poisoning in young children who work in gold mines in South America and another group examined alumnium mining in Austrailia (see Figure 1). Having students see chemical elements as a socio-scientific environmental issue made the chemistry topic authentic and relevant to their everyday lives.

Figure 1

Aluminum Mining Story Map

Aluminum products (https://www.hnkyal.com/en/media/aluminum-application-industries-and-daily-life-2568)



Weipa Mine, Australia - largest aluminum mine in the world

Although students were not out physically collecting ArcGIS data points, they did use their own internet research to locate their elements and place a map point on a map. This gave their element a geospatial reference and made the periodic table more than a poster on the wall in their classroom. After they had all learned how to place a point on a map and add data to the map, then they were ready to use additional features in ArcGIS Online. The next step was for students to work in groups and share what they had learned about their metal or metalloid element. Without any prior instruction or tutorials, students were introduced to the ArcGIS StoryMap platform and were asked to create a StoryMap to explain what they had learned about their element, where it is sourced, and how it is used in industry. Students collaborated in small groups to create a StoryMap about one of their elements and share what they had learned about the element. Several groups presented their information about Lithium because they were fascinated with the possibility of a lithium battery shortage. They used their StoryMaps to trace origins of Lithium mining and extraction, factories that produce lithium batteries for products such as electric vehicles, and concerns for the disposal and recycling of the lithium batteries after they reach their end of life. Finally, the students shared their StoryMaps with their peers during in-class presentations.

Reflection

When the research team debriefed with Gill after the activities were complete, Gill was pleased with how easily students were able to use ArcGIS online and StoryMaps. Since this was his first time using the technologies with his students, he was convinced that there are some meaningful ways to incorporate required science content with geospatial technologies such as ArcGIS online. Because these activities were done at the end of the school year and after state testing, there was more time to let students explore the technology and spend time researching somewhat tangential issues associated with their element. He also knew the students' levels of technology proficiency and felt comfortable asking students to navigate a new technology platform and to present their learning using a StoryMap than a more traditional slideshow.

The university researchers hoped that each teacher in the cohort would be ready to implement their geospatial technology activities within the first year of the PD; however, they found that each teacher worked on their own timeline. Although it took Gill three years to try using the PD in his own classroom, his implementation was successful and he was ready to try more activities the following school year. Previous research suggested that teachers should gradually implement geospatially activities within the curriculum with the support of university researchers co-planning (Hammond et al., 2019). In this case, Gill had been participating in PD without using any of his newly gained knowledge in his classroom. Toward the end of the third year, he jumped into a full set of activities that he planned all on his own for his integrated physics and chemistry course. Not only did he demonstrate his understanding of the geospatial technology and its applications, but he also managed to teach a required chemistry topic in a rigorous and authentic way.

Case 2 (Washington): Soil Sampling in Agricultural Science

The project team at the Washington State University site consisted of three faculty members, a doctoral student, a program coordinator, and ten teachers from three local high schools. The high schools include a small project-based alternative school and two large comprehensive schools serving large numbers of Latinx and low-income students. The teachers participating in the Washington State project included science, mathematics, environmental science, earth science, geography, agriculture, and special education instructors. In this case, we describe how the high school agriculture education teacher in the project, Kimberly, gained an understanding of ArcGIS Online during the summer PD experiences, planned and implemented an activity with her 10^{th}-12^{th} grade students, and reflected on her use of technology to engage students in learning chemical properties, such as pH.

Kimberly teaches in one of the largest comprehensive high schools with around 3200 students in the state of Washington. At this school, 20% of students are English learners, 65% are Latinx, 65% are low income, 58% passed all their ninth-grade classes, and 84% regularly attend school. This school enrolls students from urban as well as rural regions, where agricultural activities take place in the nearby vicinity. Kimberly manages an active Agricultural program that sees varying enrollment each year, catering to a diverse student body. Kimberly stated that she wanted to expose the students to authentic experiences using GIS technology to highlight how agricultural production uses this technology to collect, analyze, and manage spatial data related to farming operations.

Professional Development

Before implementing this activity, the project's teachers met at the university campus during the summer to learn about designing and implementing SESI investigations to be integrated into their curricula during the upcoming academic year. This PD was centered on introducing teachers to ArcGIS Online through experiences as students themselves, followed by planning time where they designed SESI activities and investigations that could be embedded into their existing curricula. During the PD sessions, this planning was conducted with the project teams' and peer teachers' assistance and feedback. Teachers were also permitted to practice their lessons with the whole group during the final day of the PD. Kimberly had little prior experience using the geospatial tools in her classroom. Still, she had considered incorporating them for some time because she knew the importance of understanding ArcGIS for her students' future agricultural careers. For example, Kimberly had started an ArcGIS organization for her school in hopes of having her students engage with the technology, but she lacked the proper school support and training in ArcGIS to continue. SESI reintroduced Kimberly to ArcGIS Online, and she spent time during the PD sessions planning for lessons in which she would introduce her students to navigating and accessing data within various layers on a map.

As a sample activity during the summer PD, Kimberly created a lesson in which students would map the cultivation of crops in the contiguous United States. By using maps with additional data layers, students can visually examine prevalent agricultural produce grown in the country while identifying optimal production environments. Furthermore, Kimberly intended for students to utilize this information to construct a StoryMap, showcasing their comprehension of spatial relationships regarding crop production and environment type. Kimberly also spent time with the other teachers learning to manipulate maps in ArcGIS Online, collect data with the ArcGIS Field Maps app, and design an ArcGIS StoryMap. From her summer experiences, Kimberly gained the knowledge and confidence to start integrating ArcGIS online into her existing curricula with her students when the school year began.

Using GIS

Despite encountering challenges in integrating ArcGIS Online into the classroom before her experience in the PD, Kimberly developed a strong proficiency in handling administrative responsibilities within the platform. These tasks included establishing student accounts, generating StoryMaps and feature layers, and forming groups within the school's organizational structure. Kimberly's determination led her to master the technological aspects of ArcGIS Online, empowering her to take charge of essential administrative functions within the platform.

Kimberly's difficulties prior to the PD sessions were rooted in the initial adoption of certain GeoInquiries that failed to generate enthusiasm among herself and her students. She implemented these lessons without any assistance or guidance from the university personnel involved in the grant, leaving her without any support throughout the process. It was only during the summer PD sessions in 2021 that Kimberly conceived a plan to engage students in an investigation of the soil surrounding their campus, aiming to identify the crops that would flourish most successfully. Through these conversations, university personnel were able to assist Kimberly in creating materials and readying them for classroom implementation.

The soil chemistry curriculum for her agricultural students begins following the exploration of fundamental soil attributes, including sand, silt, clay, organic matter, soil profile layers, and more. The focus then shifts to the chemistry of soil, particularly soil pH and soil salinity. Kimberly ensures her students understand how to measure these critical parameters, what leads to non-ideal situations in soil chemistry, and the solutions commonly used in agriculture to address them. She emphasizes the direct impact of soil pH on nutrient availability, underscoring its significance in crop production, as certain essential elements become unavailable to plants at specific pH levels.

Kimberly continued refining the Soil Sampling lesson after the summer PD sessions. She independently developed her own feature layer, devoid of any aid from the university team, which led to issues during the debrief on the data described below. The feature layer encompassed data fields for collection, including the student group names, location numbers (i.e., location of sample denoted by flags with numbers around campus), and pH of the soil. Kimberly prioritized investigating pH as the initial focus point while also contemplating the inclusion of additional data collection on soil characteristics such as nitrogen and phosphorus at a later date; this choice was made in hopes of not overwhelming herself or her students while engaging in their first data collection activity using ArcGIS.

Kimberly dedicated a day before the data collection day to help the students as they logged into their ArcGIS accounts. They used their personal computers, provided by the school, and downloaded the Field Maps app on their personal devices (e.g., cell phones) for data collection in the field. A few students faced limitations on their phones and couldn't download the app, so Kimberly paired them with a student who had the app installed, ensuring everyone had an opportunity to understand the software's functionality. Kimberly's proactive approach ensured that students were well-prepared to leverage modern technology for their fieldwork. Given the widespread usage of geospatial technologies in the farming industry, Kimberly emphasized the significance of exposing her students to ArcGIS, underlining its relevance in their future agricultural careers.

Once students successfully accessed their ArcGIS Online accounts on both their computers and personal devices via the Field Maps app, Kimberly proceeded with the technical aspects of data collection. She provided a demonstration of utilizing the Vernier pH sensor and explained the significance of the storage solution. Furthermore, she instructed the students to detach the pH probe and determine the pH of various solutions. Students conducted tests with their probes in known pH solutions to ensure accurate readings, effectively integrating technology into their hands-on learning experience.

Kimberly provided detailed instructions on the correct procedure for obtaining and preparing a soil sample for pH testing, seamlessly integrating technology into the hands-on process. In the absence of soil sample corers, Kimberly provided each pair of students with a large plastic cup, deionized water, and a clean garden trowel. She adeptly directed the students to remove any significant debris from the area, such as rocks and leaves. Using the garden trowel, students dug a hole approximately 6 inches deep, collecting the soil in their plastic cups and thoroughly mixing the sample to obtain a well-blended representation of the soil's composition. They combined the soil sample with deionized water and mixed the material once more before employing the pH probe.

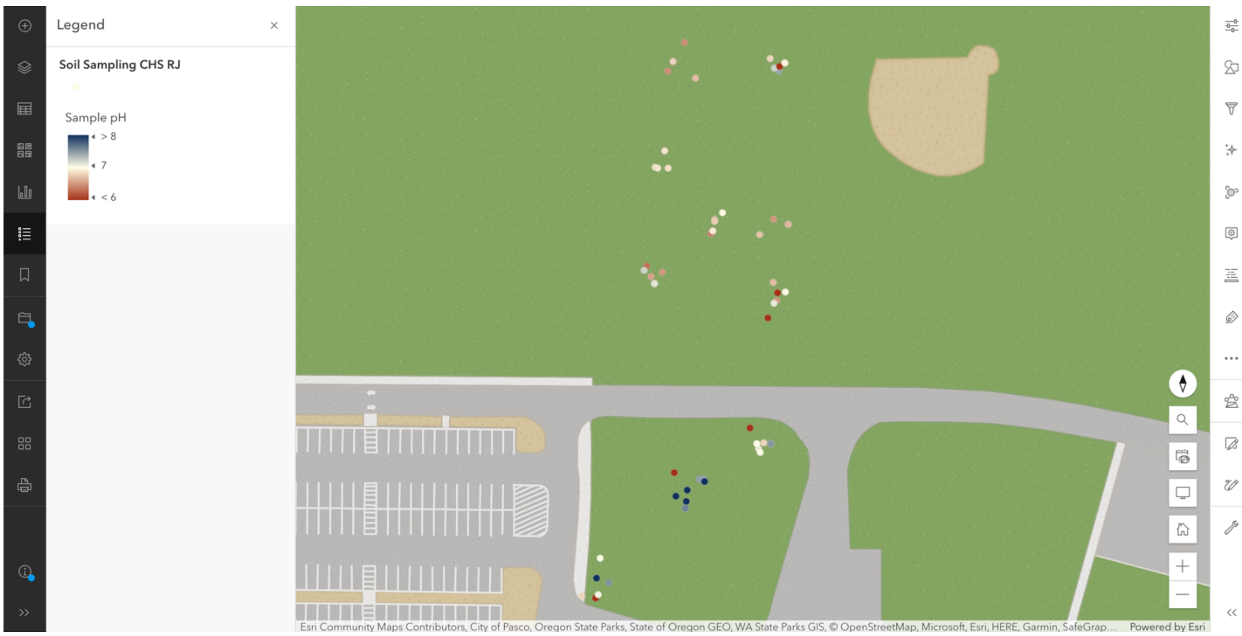
On the subsequent day, students ventured to different accessible areas on campus to gather soil samples. Working in pairs, one student utilized the Field Maps app, while the other employed the pH probe. The technology seamlessly facilitated this collaborative effort in collecting and preparing the samples. What made the process engaging was that students could instantly observe the data they collected appearing on the map, showcasing the real-time integration of technology into their fieldwork. Collecting data consumed the entire class period on both days, with technology playing a pivotal role in streamlining the data gathering process. On the final day, Kimberly led a discussion of the results, demonstrating how technology enhances data collection and facilitates in-depth analysis and understanding. In lessons following this data collection, Kimberly encouraged her students to choose two crops of interest. They were tasked with determining the soil chemistry requirements for their selected crops, mirroring the activities often performed by agronomists in agriculture.

Reflection

After the students had collected all the data, Kimberley planned to explore the findings with her students. However, she encountered a minor challenge when she discovered that the color gradient display option for the data points was temporarily unavailable. Though a slight setback, this aspect did not hinder the students' ability to discuss their valuable findings. Despite the temporary limitation in the color gradient display, the students continued their discussion, showcasing their adaptability and analytical skills. They addressed potential human errors during field data collection, such as the inadvertent failure to remove the probe from the storage solution. As they organized the data points by pH and examined them individually, they astutely observed that one group consistently recorded the same pH for each section. Through collaborative problem-solving, they realized they had inadvertently kept the probe immersed in the storage solution instead of correctly inserting it into their testing samples. Additionally, the students observed during their analysis that one location had an average pH slightly above seven, the highest among the surrounding areas. This discovery sparked engaging conversations and hypotheses about the relationship between the slope of the ground, water drainage, and the likelihood of a pH closer to seven in that area.

Kimberley's proactive response to the temporary display issue demonstrated the value of technology as a tool for enhancing the learning experience. Seeking assistance from the university team to resolve the color display, she promptly shared the corrected color gradient display with the class, ensuring that technology continued to facilitate their exploration and understanding of the data. By utilizing this display, Kimberley and her students could quickly identify the area of land that consistently measured above a neutral pH and the data points that consistently showed acidic measurements for each plot. This display confirmed the students' previous conversations about water drainage and its impact on the pH of the soil, as well as the human error in data collection, such as forgetting to remove the pH probe from the storage solution (see Figure 2). Though the lesson may have briefly lost momentum, Kimberley embraced the experience as a valuable learning opportunity, paving the way for even more effective future implementation of this technology-driven activity. Soil sampling and testing, along with the use of technology for testing and mapping, provide students with a tangible experience that prepares them for potential careers in agriculture, equipping them to tackle real-world challenges and opportunities in the field.

Figure 2
Soil Sampling Map



Note. The display represents the data as a color gradient indicating "above or below" a pH of 7.0.

Case 3 (Pennsylvania): Polonium-210 - How to get away with murder

Our partner site in Philadelphia is a magnet high school, drawing students from across the entire city. Accordingly, the participating teachers at the school are mindful of how to begin the academic year: how to bring students together from across different neighborhoods and middle school backgrounds, how to introduce them to the culture at the school, and how to introduce them to their curriculum and the novel geospatial integrations that students will encounter throughout their course. Through the first three years of the grant, the collaborating teachers at this site had developed several innovative ideas for using GIS in this beginning-of-year context, such as a social use of GIS (mapping out a get-to-know-you survey) or campus exploration (scavenger hunts and inquiries to take students around different parts of the school property).

From the first year of the project, Louis stood out as a highly innovative, ambitious teacher. His courses ranged from STEM to Natural Resources Management to Anatomy &

Physiognomy, along with more common curriculum areas such as Chemistry. Throughout our time working together, Louis has generated numerous ideas for novel geospatial integrations into his curricula: a unit addressing endangered species and sustainable energy (see Leeson et al., 2022), several designs for geospatial lab activities in which students would design and conduct their own data collection, and adaptations of watershed activities into the immediate local context of the school. Unsurprisingly, then, Louis identified an innovative opportunity for starting his students' experience of his geospatially-enhanced chemistry curriculum: How could he start the school year with an engaging activity that used GIS and introduced chemistry concepts without requiring any previous knowledge?

Professional Development

Our PD work with our teachers employed the commonly-used 'ghost map' example of John Snow's investigation of a cholera outbreak in Victorian London (Johnson, 2006). This topic is often referenced in introducing GIS and geo-referenced data to new users. (For examples, see https://www.youtube.com/results?search_query=cholera+GIS or https://learn.arcgis.com/en/projects/map-a-historic-cholera-outbreak/). Louis appreciated the way this activity allowed for immediate engagement with a topic (cholera), a geo-referenced dataset (cholera cases by house), and the use of a GIS to understand, investigate, and reach a conclusion. If he were teaching Biology, this cholera example would make perfect sense as an introduction to the curriculum. For a chemistry class, however, the ghost map did not provide an entry point to any curricular concepts. Inspired by this example from his PD experience, Louis wanted to find a topic that could make a powerful connection to chemistry.

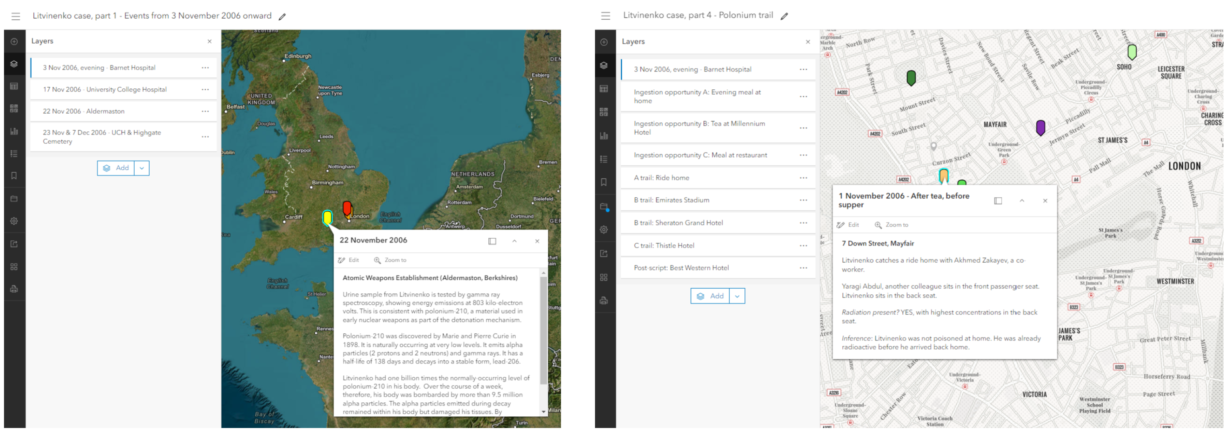
Louis identified forensic investigations of poisoning attempts (and murders) by the Russian government as a topic that would be highly engaging, involve geospatial tools for data analysis, and introduce curriculum-specified chemistry topics as students retraced steps in the investigations. Working with a university partner, Louis focused on the case of Alexander Litvinenko, a former Russian intelligence agent who applied for asylum in the United Kingdom in 2000. In 2006, he fell ill with symptoms that initially suggested a severe case of gastroenteritis. However, the symptoms soon cascaded well beyond the scope of what could be explained by bacteria or even by thallium poisoning—his white blood cell count plummeted and he experienced multiple organ failure. After sending blood and urine samples out for testing at Aldermaston, the research hub of Great Britain's nuclear weapons program, they determined that Litvinenko was suffering from radiation poisoning after having been dosed with a massive, lethal dose of polonium-210, which had been ingested as part of something that he had consumed on November 1, 2006 (Owen, 2016). An inquest by the British government (Owen, 2016) identified two former KGB agents as the poisoners: they had met Litvinenko for tea on the day he fell ill and had placed the radioactive substance in his drink.

Development & Implementation

Louis and his university collaborator used the information from the inquest and other sources to build a sequence of GIS maps, each annotated with the movements of Litvinenko, his assassins, and other figures in the case. These maps documented different segments of the event, beginning with Litvinenko's admission to a London-area hospital on November 3, 2006; his increasingly fraught medical symptoms and initial (erroneous) diagnoses; the identification of polonium-210 in his tissues; and his death on November 23, three weeks after the poisoning. From there, the maps worked backwards in time, showing Litvinenko's movements and interactions prior to November 3, as well as the movements and interactions of possible poisoning suspects. (See Figure 3, below, for selections from this sequence of maps.) We bundled these maps and a supporting guided notes sheet into a StoryMap (https://storymaps.arcgis.com/stories/39271e4128024723a262364cb8bdca79). This StoryMap provided the instructional frame for working from whole-class instruction (introducing the case and the functionality of the maps) into individual or small-group interaction (debating possible suspects, identifying what investigative steps should take place next), and back into whole-class discussion to connect these events to specific concepts in chemistry: looking at the periodic table to identify polonium; discussing isotopes, radioactive decay, and half-lifes; tracking what transmutation takes place after alpha decay, and so on.

Figure 3

Selected maps from the polonium poisoning investigation.



Note. Each map has layers that organize events in time; each placemarker has embedded details from the investigation as well as related chemistry information.

During the implementation of this activity, the students were highly engaged, calling out answers and suggestions of who the culprit might be. Arguments tended to break out among students as some leaped to the conclusion that his wife was the poisoner while others pointed out that this hypothesis was both unsupported by the evidence and based on misogynistic assumptions. Some students evinced genuine shock and surprise upon learning that this was a real case—Alexander Litvinenko was a real person, murdered by his former compatriots, with his wife widowed and son left fatherless. They had assumed that the maps and details were made up for the purposes of teaching chemistry rather than compiled from an actual forensic investigation. The final step in the case, uncovering the fact that the poisoners, two former KGB associates of Litvinenko, had dosed him not once but twice, was literally a jaw-dropping realization for some students.

Louis felt that the activity was such a success that he elected to use it not only in his chemistry classes but also in his Anatomy & Physiology class. In this curricular context, he preserved all of the chemistry-related concepts within the narrative but went deeper on the specific biology involved, such as discussing the organ systems involved in the medical pathology (digestive, circulatory, bone marrow). These more biology-related discussions brought out additional details in the radiation chemistry: for example, the alpha particles can only penetrate a very short distance within organic tissue, about ten cell diameters. Because of this short range, the assassins repeatedly handled massive doses of polonium without killing themselves; Livinenko, on the other hand, had swallowed the polonium. As his digestive and circulatory system carried the polonium throughout his body, the alpha particles were released at close range into sensitive tissues throughout his body—the initial vomiting was due to damage within his stomach, the diarrhea was from damage to his intestines, and so on. The cross-curricular context of human anatomy and radiation chemistry further enhanced the students' engagement with the science of the case.

Reflection

The sequence of conceiving, designing, developing, and implementing the polonium poisoning activity highlighted both existing and new themes to our geospatial work. First, this case reinforced our curriculum design strategy of working with teachers as co-designers of geospatial curriculum. The creative leaps that Louis made were the catalyst for the entire activity, bridging from our example (John Snow's work during the 1854 cholera epidemic) into his curricular context (what might be a similar activity look like in a chemistry class?) and then identifying the crucial, aligned details in the Russian government's chemical assassinations. The university team, despite both our greater experience (having done geospatial curriculum development for more than a decade) and our own breadth of content-area expertise (chemistry, biology, environmental science, and more), did not see the opportunity that Louis had seized. We have seen and used the ghost map example for years; it had become ossified in our minds. Louis, with a fresh perspective, was able to point the way to a new and innovative geospatial integration into his chemistry curriculum.

Second, the polonium poisoning case brought a new pedagogical frame into our typical pattern of inquiry-driven learning: the use of narrative. While narrative is employed in science education—consider, for example, the typical sequences of introducing Malthusian views of evolution as an introduction to Darwin's insights, or the succession of atomic models (Aristotle, Thomson, Geiger-Marsden, Bohr, and so on)—it is not a signature pedagogy. Inquiry learning, given its alignment with the scientific process and goals of science, is the dominant pedagogical theme in both the broader field of science education and in our own curriculum design and development work. The polonium poisoning activity, however, is built around a narrative frame, a story with a beginning (Litvinenko first appearing at a hospital), a middle (the forensic investigations that followed from the medical diagnosis of polonium poisoning), and an end (the dramatic revelations of the multiple attempts to murder Litvinenko and the denouements for his family, the British government, and the other persons in the narrative). The narrative is composed in a non-linear fashion, moving forwards from 3 November 2006 then backwards as the forensic investigation yields new information, to allow for moments of inquiry within this arc: students identify possible poisoners and are invited to debate their various theories of the case. This use of a composed narrative as a frame for a geospatial instructional activity was a departure from our previous practice and expectations for geospatial curriculum design. Similar to other educational learning experiences that situate learning with a narrative, emotionally appealing storylines can serve to motivate and engage learners and have potential to increase learning (Hapgood et al., 2005).

Finally, this activity served its intended purposes as identified by Louis: engage students with the chemistry curriculum, introduce them to geospatial tools, and establish the themes of spatial relations as essential to the study of chemistry and geospatial tools as one way to represent these spatial relations and understand their significance when solving certain problems.

Louis built upon this introduction in later activities that brought students into more intensive uses of GIS, such as data collection, display, manipulation, and analysis as they addressed subsequent SESI investigations and related topics in their enacted chemistry curriculum.

Louis' comment on his geospatial chemistry instruction is that these activities, as initiated by the polonium poisoning case, brought chemistry "off the bench," outside the classroom and into more recognizable activities. In his view, the geospatially-integrated instruction allowed him to shift the context of chemistry concepts and practices into the world of people and their movement, their meals, their politics, and even their deaths.

Cross-Case Discussion & Implications

Looking across the three cases presented in this manuscript, we see teachers using geospatial tools in a highly novel context, chemistry education, and in a variety of ways. In Louis' classroom, students viewed and interacted with maps and geo-referenced datasets. In Gill's classroom, students annotated maps and providied text and media to build StoryMaps. In Kimberley's classroom, students were engaged in the full SESI model of hands-on data collection, analysis, drawing conclusions, and making decisions. The challenge of bringing geospatial tools into the chemistry classroom required both the creative input of the teachers and a flexible approach for translating the SESI curriculum design principles for specific points during a curriculum implementation sequence and for specific geospatial skill development. For example, Louis' Polunium mystery served as an intial learning activity in the beginning of the school year to initially hook students into learning about chemistry while at that same time learning the ArcGIS interface and some basic map exploration skills. Gill's students conducted independent research and presented their findings geographically on a shared map while learning some basic map development skills. Kimberly's students used a SESI investigation to focus on spatial data patterns and geospatial reasoning about pH soil values.

The three cases also highlight the power of collaborative work across institutions. Kimberley had instituted an ArcGIS Online organizational account well before our geospatial project started, but she needed the connection with her local university team before she could bring GIS into her classroom instruction. The periodic table activity from Gill's classroom spurred a longer sequence of activity for Louis and his collaborators, beginning with on-campus scavenger hunts (identifying organic elements such as carbon), spiraling into locally-observable inorganic elements (silicon, for example), and then duplicating Gill's strategy of taking a global lens to explore and document remote elements (such as uranium) through StoryMaps. The soil chemistry activities in Kimberley's classroom were created following a less agriculturally-focused soil lab in Louis' chemistry classes. Louis' polonium poisoning activity is being shared with other teachers of Anatomy & Physiology for potential use in their classrooms. Without these connections and collaborative practices, the work of each teacher and each university team would proceed far more slowly and be less successful for their students.

Finally, while only Louis used the exact words "off the bench", all three cases present an example of chemistry moving out of the laboratory and into a specific geographic context. For Gill's students, the connection was between the periodic table and the locations where certain metals and metalloids are mined or refined. For Kimberley's students, the connection was between ions and the soils (which they often forget contain water) around the school and the crops grown in their local region. For Louis' students, the connection was between radiation chemistry, the periodic table, and forensic investigations, albeit in a new-to-them context of Russia-sponsored assassination in post-Cold War London. In all three cases, students were connecting and applying their academic understandings of chemistry topics to identifiable places, people, events, and/or decisions in the world.

Conclusion

As described in the introduction, this research is the product of years of collaboration, both across groups of science teacher educators and with groups of science teachers. While all of this work fits under a single umbrella of "science education," it also demonstrates that different scientific disciplines come with their own imperatives. Chemistry education demands spatial thinking on a very small scale, from molecules down to sub-atomic particles; environmental science engages spatial thinking on larger scales as students consider watersheds or migration routes. As science teachers and teacher educators integrate geospatial technologies into science education, they must consider the affordances of the technology relative to the demands of the specific scientific discipline or topic being addressed in addition to the availability of georeferenced data and other resources that can be used for the design of specific curriculum-embedded investigations or learning activities. In some cases, the alignment will be obvious; GIS, for example, is a relatively clear fit with environmental science in which much data is georeferenced to the Earth. In other cases, however, creative thinking and collaboration can find new connections, which may significantly enhance students' classroom experiences. Thanks to Gill, Kimberley, Louis, and the many other science teachers we have worked with, we have found places where the unlikely pairing of geospatial tools and chemistry education create opportunities for students to bridge the classroom and the world, and provide a model for continued design and development of geospatially-integrated chemistry education.

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