“Off the Bench”: Three Case Studies of Geographic Information System (GIS) Integration in High School Chemistry Instruction

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Abstract

Across Texas, Washington, and Pennsylvania, three university teams worked with teachers at three high schools to integrate geographic information systems (GIS) and other geospatial tools into chemistry lessons as part of a larger, multi-disciplinary teacher professional development initiative. Each university followed a specific design model of socioenvironmental science investigations (SESI) in their professional development and curriculum development processes. Each teacher’s work is presented as a case with distinct school contexts, professional development experiences, classroom implementation outcomes, and reflections after implementation. Cross-case findings include variability in teachers’ adoption processes, the importance of cross-site collaboration, and the ability of geospatial tools to bring chemistry topics “off the bench” and into students’ thinking about their world. These cases present an advance in the curricular reach of GIS, which to date has not been broadly used in high school chemistry instruction. Further, the cases illustrate examples of the teachers’ geospatial science pedagogical content knowledge.

Introduction

Effectively teaching science topics with a geospatial dimension requires both specialized technological pedagogical content knowledge (TPACK) (Mishra & Koehler, 2006) and support for implementing geospatial technologies in the classroom. Integrating geospatial technologies into science education involves a distinct form of TPACK known as geospatial science TPACK, or Gs-TPACK (see Bodzin et al., 2012). Educators possessing Gs-TPACK demonstrate a comprehensive understanding of the intricate relationship between science pedagogy and geospatial technologies. As a result, they can employ suitable pedagogical methods and geospatial technologies to teach science and related disciplines.

Developing geospatial science pedagogical content knowledge entails grasping how to model geospatial data exploration and analysis techniques (Hammond et al., 2018). It also involves effectively scaffolding students' geospatial thinking and analysis skills. The concept of GsTPACK extends beyond disciplinary boundaries, as geospatial technology can interact with specific subject-based content that crosses these boundaries, such as demography in a history lesson or geologic substrata in a geography lesson. This interaction has the potential to create effective teaching and learning opportunities for students.

There is a notable absence of geospatial technology integration in school-based programs. Meeting the demand for high school graduates equipped with skills essential for a robust national STEM workforce necessitates educators who can implement curricula that foster students' geospatial thinking and analysis skills. Geospatial thinking and analysis skills are crucial for professions that heavily rely on cognitive abilities related to geospatially-referenced data and their interconnections (Goodchild & Janelle, 2010; National Research Council, 2006). These skills align with key scientific practices emphasized in the Next Generation Science Standards (NGSS Lead States, 2013) that encompass data manipulation, analysis, and mining. These practices stimulate critical thinking and problem-solving linked to data referenced to the Earth's surface or visualized through maps and globes (Huynh & Sharpe, 2013). Curricula that engage students in collecting and analyzing data while solving problems provide crucial skills, preparing students for science career opportunities and lifelong learning (National Research Council, 2011; National Science Board, 2015).

An Integrated Professional Development and Curriculum Development Model for Geospatial Teaching

To tackle this challenge, a collaborative team of teacher educators spanning three universities partnered with local high school teachers to integrate geospatial technologies into their curriculum. Eight US high schools in diverse rural, urban, and suburban settings engaged in an integrated professional development (PD) and curriculum development initiative spanning subject areas such as Environmental Science, Biology, Chemistry, Physics, Geography, Robotics, Computer Science, and Agriculture. The project goal was both to advance participating teachers' Gs-TPACK and to support their development and implementation of curriculum-aligned, geospatially-integrated instruction. To date, more than three dozen teachers have participated in this project and applied our geospatial curriculum approach to their classroom instruction.

Our work uses a design partnership model in which teacher educators and teachers work together to identify topics within their existing curricula that connect to geospatial data and spatial patterns (see Hammond et al., 2019). We then explore opportunities for students to engage with geospatial data and analysis tools directly, using tools such as ArcGIS Online (https://www.arcgis.com/), as teachers address this curriculum-specified content through hands-on use of GIS and other geospatial tools. Once we have settled on a curricular topic and a geospatially-integrated instructional strategy, the teachers and teacher educators collaborate to develop materials, implement them in the classroom, and examine student outcomes. This collaborative design strategy allows us to draw upon the strengths of both the university-based personnel. Each member in the design process, whether a teacher, professor, 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.

The curriculum development work focused on the socio-environmental science investigation (SESI) design model (Hammond et al., 2018 & 2019; see also Zeidler & Nichols, 2009). SESI learning activities address curriculum-specified content through localized geospatial inquiries. These activities typically begin with a driving question, involve hands-on geospatial data collection, analysis of patterns and relationships both within the collected data and across external datasets, construct explanations, and culminate in decision-making to enhance the local community. (For examples of SESI learning activities, see Carrigan et al., 2019; Leeson et al., 2022; and Morrison et al., 2023.)

Each university site location collaborated with local teachers to develop a framework for geospatial PD and SESI curriculum development activities. The main goals of the process were to develop teachers' geospatial thinking and analysis skills, promote their Gs-TPACK growth, and help them apply these skills to integrate new student GIS learning experiences into their existing curricula. The development activities included exploring different freely available geospatial applications, such as ArcGIS Online for analysis and the Field Maps mobile app for data collection, various data collection procedures, displaying and navigating maps, annotating maps, analyzing data using different tools for pattern recognition and examining outliers, and constructing new data displays and visualizations. Each session featured hands-on experiences with learning activities that could be incorporated into an instructional sequence of a science curriculum unit. For example, data collection activities were introduced as teachers learned how to use the Field Maps Designer to create a mobile data collector for students to use in hands-on local geo-inquiry investigations. Esri Storymaps were introduced as a simple way to integrate ArcGIS Online maps alongside supporting text, images, and links to other relevant materials.

The Challenges of Integrating Geospatial Technologies into High School Chemistry Curricula

In the grant's third year, our project team began working with three collaborating teachers at three different sites to develop geospatial materials for chemistry education. Integrating geospatial technologies into the basal high chemistry curriculum is more challenging than integrating GIS into other science disciplines such as earth science or environmental science (for examples, see Kerski, 2014; Nolan et al., 2019). The latter disciplines contain geospatially referenced topics, such as geomorphology, watersheds, or ecosystems; consequently, Esri's GeoInquiries collection (https://www.esri.com/en-us/industries/k-12-education/geoinquiries; see also Baker, 2015; Miller, 2022) includes dozens of activities for earth science and environmental science. Chemistry, on the other hand, has zero GeoInquiries. One reason for this absence may be because of scale: while the Next Generation Science Standards cover some topics at a geographic scale, such as the role of nuclear power in understanding matter and its interactions (NGSS Lead States, 2013), the typical high school chemistry curriculum focuses primarily on content knowledge at the molecular level and below. Another reason may be a lack of available georeferenced chemistry data that can easily be used in the high school chemistry classroom.

However, some topics in the chemistry curriculum present opportunities for geospatial technology integration if georeferenced data is available. For example, geospatial technologies can be used to study the distribution of pollutants by mapping and visualizing pollution patterns or tracking the dispersion of chemicals in the environment. The distribution of elements in rocks and soils can be analyzed to examine differences in geographical regions. Geospatial technologies can be used to investigate atmospheric composition over time to understand how greenhouse gases vary across different locations and over time. Geospatial tools can aid in water quality investigations, tracking the movement of pollutants in streams, rivers, or lakes, and assessing the impact of chemical processes on aquatic ecosystems. Geospatial technologies can also be used to analyze soil composition, map nutrient distribution, and evaluate the impact of fertilizers and pesticides on agricultural land. Each of these examples provides an opportunity to apply chemistry concepts—chemical vs. physical changes, gas laws, pH, titration, and so on—to a real-world phenomenon.

While each of these geospatial integration ideas may help high school students gain a more comprehensive and applied understanding of chemistry concepts and foster connections between chemical processes and the real-world environment, many barriers exist for chemistry teachers to readily implement such learning activities and investigation. If the investigations use student-collected data, specific data collection equipment may be required, and this equipment will need to be calibrated and maintained. In addition, available georeferenced data must be located, validated, and imported into a GIS mapping application such as ArcGIS Online to examine spatial data patterns. This calibration and validation is a time-consuming process, and chemistry teachers may not have the background knowledge to assemble the data in a GIS mapping application. Furthermore, teachers may not have the GsTPACK to implement such learning activities.

Due to our collaborative design partnership with our three teachers, we were able to address these many challenges to produce three cases of successful geospatial integration into high school chemistry lessons. Each case highlights how geospatial technologies were implemented within a curricular context and how students learned geospatial thinking skills. 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 personnel to learn how to incorporate ArcGIS Online and other geospatial technologies into their existing curriculum. Gill joined the project in its first year and was entering his third year of geospatially integrated teaching. 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. Gill currently teaches 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 project, the Texas-based teacher educator/researcher team (two faculty members and a doctoral student) 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 other cohort teachers. Although the cohort group helped him brainstorm some of the technical aspects needed for the activities, Gill used his understanding of his chemistry curriculum and geospatial tools to create activities independently once he returned to 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 Online, Gill was proficient enough with the instructional technology to set up the activities on his own. Because his students had used various technology applications in his course, Gill could trust them to set up their own usernames and passwords on 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 Online.

During PD sessions, Gill was introduced to Esri's StoryMaps, part of the suite of webbased tools that inter-operate with ArcGIS Online. StoryMaps allow users to embed their GIS displays within accompanying media, such as headers, text, images, videos, and Web links. The model StoryMap presented during an after-school PD session was light-hearted and not curriculum-aligned ("Songs About Texas"; https://arcg.is/ynnnT). This exposure prompted Gill to explore the StoryMaps platform, making a similarly non-curriculum-aligned StoryMap of places he had traveled. Not until the following school year, however, did he return to StoryMaps and begin thinking about their curriculum-aligned uses. He created a partial draft of a StoryMap about nuclear energy, which prompted a new idea: Why not have students build StoryMaps about selected elements in the periodic table?

Implementation: Instructional Adaptations

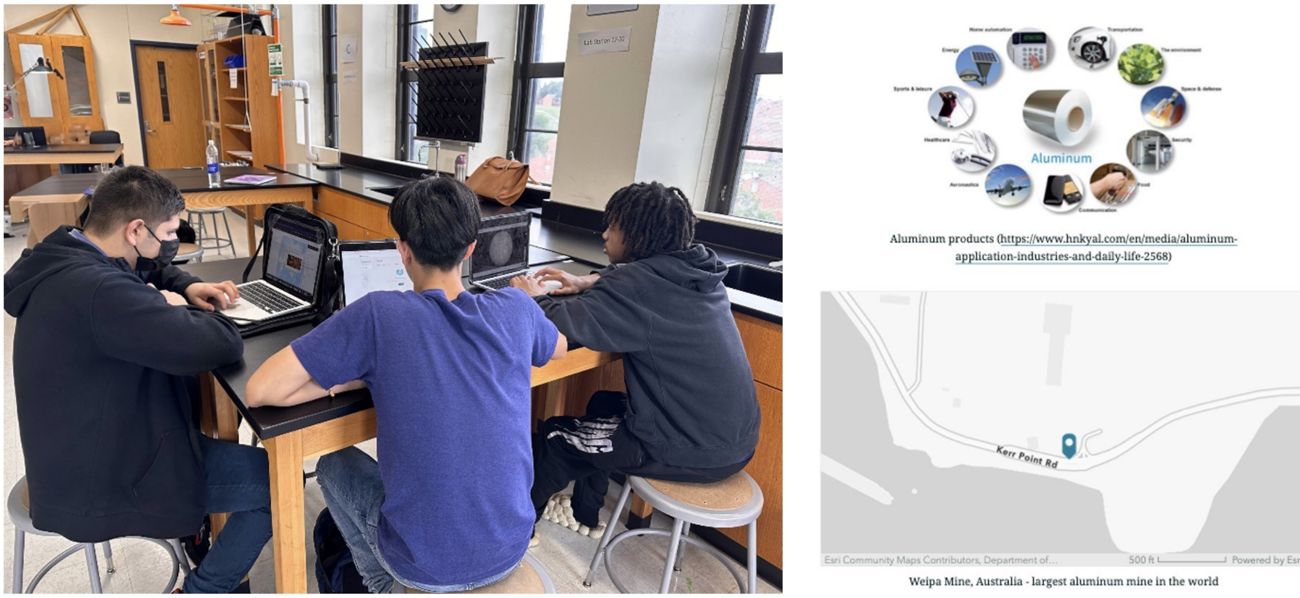
In his original plan for the activity, Gill envisioned that students would address most of the elements from the periodic table: organic and inorganic elements, radioactive and stable elements, and metals and non-metals. However, as the activity unfolded with the students, Gill decided that focusing on selected metals and metalloids made the most sense for his instructional purposes. Some metals and metalloids are concentrated within specific geologic features, such as ore veins; accordingly, they can be geo-located and mapped in ways other elements are not. For example, the copper deposits in the Atacama Desert are distinct from the surrounding areas, while the oxygen and silicon within the desert's sands are more ubiquitous elements.

After introducing the assignment, Gill showed students how to add place markers on an ArcGIS Online map and integrate contextual data within the placemarkers' pop-up data field displays. Students worked in groups to research a selected metal or metalloid, identifying where it is sourced and how it is used in industry. Each group then synthesized their research in a StoryMap to share what they had learned. As they researched and built their ArcGIS Online maps, students learned about the elements present in familiar, everyday items, such as their cell phones and rechargeable batteries, and created visualizations tracking the sources of the elements. Students were surprised to learn where different metals and metalloids were mined, the processes of mining and extraction, and their potential impacts on the local environment. The activity made the periodic table more than a poster on the wall in their classroom; it gave elements a geospatial reference and connected them to students' lives.

Although Gill did not intentionally plan for students to make connections with human rights, economics, and global political issues, the students quickly saw broader implications for learning about chemical elements. For example, one student group began investigating the impacts of mercury poisoning on young children who work in gold mines in South America. Another group examined aluminum mining in Australia (see Figure 1 below). 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 the 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.

Figure 1

Student Group Work; Sample Story Map (Aluminum Mining)



Reflection

When the teacher educator/researcher team debriefed with Gill after the activities were completed, Gill was pleased with how easily students could 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 instead of using a more traditional slideshow.

The university teacher educators/researchers hoped that upon learning of a new geospatial tool during PD, the collaborating teachers would be motivated to integrate this tool quickly into their classroom instruction. While some teachers did make rapid introductions of geospatial tools into their teaching routines, Gill took a slower route—an entire academic year passed between his first exploration of StoryMaps in PD and his first forays into their curriculum-connected use. Gill's adoption pathway was also distinct in his level of independence: he designed and implemented his periodic table activity without input from the university team. Previous research suggested that teachers should gradually implement geospatial activities within the curriculum with the support of university collaborators (Hammond et al., 2019). However, Gill provides an example of a teacher working on his own timeline and in his particular curriculum development process. While the journey from PD to the classroom differed from what was anticipated, Gill nonetheless demonstrated his understanding of geospatial technologies and mastery of instructional integration, rigorously and authentically teaching a required chemistry topic.

Case 2 (Washington): Soil Sampling in Agricultural Science

The project team at the Washington state site consisted of three faculty members, a doctoral student, a program coordinator, and ten teachers from three local high schools. The high schools included a small project-based alternative school and two large comprehensive schools serving a high number of Latinx and low-income students. The teachers participating in the Washington project included general science, mathematics, environmental science, earth science, geography, agriculture, and special education instructors. In this case, we describe how the project's high school agriculture education teacher, 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 Washington's largest comprehensive high schools with around 3200 students. At this school, 20% of students are English learners, 65% are Latinx, 65% have free and reduced lunch, 58% passed all their ninth-grade classes, and 84% regularly attend school. This school enrolls students from urban and rural regions where agricultural activities occur in the school's vicinity. Kimberly manages an active agricultural education program that sees varying enrollment each year. 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. Kimberly is unique among our collaborating teachers in that she had prior experience with both geospatial PD and using GIS in her classroom. In a previous PD session, independent of our project, Kimberly had learned about ArcGIS Online and set up an organizational account for her school. She planned to use it with her agriculture students and even tried using several of Esri's GeoInquiries in her classes. However, these activities failed to generate enthusiasm with her students, and Kimberly felt uncertain about how or even whether to continue to integrate GIS into her teaching. Consequently, the ArcGIS Online account she had set up remained dormant until her work with our project began.

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, planning was conducted with the project teams' and peer teachers' assistance and feedback. Teachers practiced their lessons with the whole group during the final day.

During these sessions, Kimberly deepened her mastery of ArcGIS Online and began engaging in her curriculum development process. She created a lesson in which students would map the cultivation of crops in the contiguous United States, seeing the prevalent agricultural produce grown in the country while identifying optimal production environments. She also identified an opportunity for hands-on data collection by her students: sampling and then testing the soil on the school campus, aiming to identify the crops that would flourish most successfully within these soil conditions. Finally, students could construct a StoryMap, showcasing their comprehension of spatial relationships regarding crop production and environment type. All of these instructional strategies involved far more intensive use of ArcGIS Online and its related tools than Kimberly's previous uses of GeoInquiries. From the summer PD experiences, she gained the knowledge and confidence to plan and implement these novel and ambitious uses of geospatial tools as her students investigated crop production and soil chemistry.

Using GIS in the Classroom

The soil chemistry curriculum for Kimberly's agricultural students begins with exploring 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 ensured that her students understood 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 emphasized 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. To keep this initial data collection activity as simple as possible and not overwhelm herself or her students, Kimberly limited her focus to just one chemical parameter, pH. She could then return to the soil sampling activity at a later date to introduce additional aspects of soil chemistry, such as nitrogen and phosphorus levels or salinity.

Kimberly built a data collector to be used in Esri's Field Maps app. In the class session prior to this data collection, she addressed the required logistics, including helping students download the app onto their cell phone, log into their ArcGIS Online account within the app, navigate to the shared map for soil sampling, and understand the data collection protocols and data entry process. A few students faced limitations on their phones. They 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. Kimberly also emphasized the significance of GIS as an important tool for the farming industry and, therefore, the activity's relevance to students' future agricultural careers.

Next, Kimberly instructed students on the data collection procedures. She demonstrated 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. She modeled the soil sampling process: at a designated location, remove any significant debris from the area, such as rocks and leaves. Using the garden trowel, dig a hole approximately 6 inches deep, collect the soil in a plastic cup, and thoroughly mix the sample to obtain a well-blended representation of the soil's composition. Combine the soil sample with deionized water and mix the material once more before employing the pH probe. Then, enter the observed pH into the shared soil sample map in ArcGIS Online.

On the subsequent day, students ventured to different accessible areas on the school's campus to gather soil samples at Kimberly's identified locations. 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 the GIS technology playing a pivotal role in streamlining the data gathering process.

On the final day, Kimberly led a discussion of the results, demonstrating how GIS technology enhances data collection and facilitates in-depth understanding and analysis of soil pH. 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 sleeve before gathering their data reading. 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.

In lessons following this data collection and analysis, 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. Due to their own experiences with the challenges of accurate data collection and interpretation during the soil sampling lesson, they had a renewed appreciation for the complexity, scope, and significance of data in agriculture.

Reflection

Kimberly's experience demonstrates several important themes in teachers' learning about GIS and geospatially-integrated instruction. To start, Kimberly's first experiences with GIS were unsuccessful; her initial PD sessions about ArcGIS Online and her first forays into using GeoInquiries in class did not lead her to repeat or expand her use of GIS. For Kimberly and other teachers to successfully bring GIS into their teaching, sustained PD and support are required. A second theme is the centrality of curriculum development: once Kimberly had identified a curricular topic that could be enhanced by using GIS, she was able to design, develop, and implement a complex, hands-on sequence of data collection, analysis, and then presentation of findings. In particular, she persisted despite the challenges in the data collection process and structuring the map color display for geospatial analysis. This persistence contrasts sharply with her prior use of GeoInquiries, in which she felt disappointed by students' engagement and abandoned any further use of GIS. Having designed her own instructional sequence with GIS integration, Kimberly was motivated to keep working through the challenges and even to refine her instructional design further. After the soil sampling lessons were finished, she enlisted the university team to help resolve the color display problem. With their assistance, she was able to re-set the color ramp in the GIS to match the pH scale appropriately (see Figure 2 below). Kimberly's previous experience with GeoInquiries did not involve curriculum development since they are designed to be used off-the-shelf. When these lessons felt unengaging in her classroom, she did not persist with GIS implementation with her students. Once Kimberly had designed her soil chemistry lessons, however, she was motivated to persist through the challenges of data collection and data display, and she brought in additional support from the university team when she needed technical help. As a demonstration of Kimberly's persistence, she has (as of this writing) created more than 100 data layers, maps, and StoryMaps in her ArcGIS Online organizational account, including iterative versions of her soil sampling lessons.

A third theme presented in the soil sampling lesson is the teaching opportunities created by data collection and, in particular, the errors made during the collection. Once the students spotted the errors made during data collection, such as forgetting to remove the pH probe from the storage solution, Kimberly could build upon this tangible experience, discussing the importance and limitations of agricultural data. Accordingly, the data collection process, including the errors and their discovery, provided a powerful teaching opportunity to equip students to tackle real-world challenges in the field, prepare them for potential careers in agriculture, and understand important concepts relating to the nature of science and the roles of data and interpretation in scientific understanding.

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 – Radiation Chemistry and Assassination

The Pennsylvania-based teacher educator/researcher team worked with a chemistry teacher at our partner site in Philadelphia, a magnet high school that draws students from across the entire city. Accordingly, the participating teachers at the school are mindful of how to begin the academic year: to bring students together from across different neighborhoods and middle school backgrounds, introduce them to the culture at the school, and introduce them to their curriculum and the novel geospatial integrations that students will encounter throughout their course. Through the first three years of the project, the collaborating teachers at this site developed several innovative ideas for using GIS in this beginning-of-year context, such as social use of GIS (mapping out a get-to-know-you survey) or campus exploration learning activities (for example, scavenger hunts and classification activities 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 Natural Resources Management to Anatomy & Physiology to an integrated STEM class, along with core sciences such as Chemistry. Throughout our time working together, Louis 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, Louis also 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 content knowledge?

Professional Development

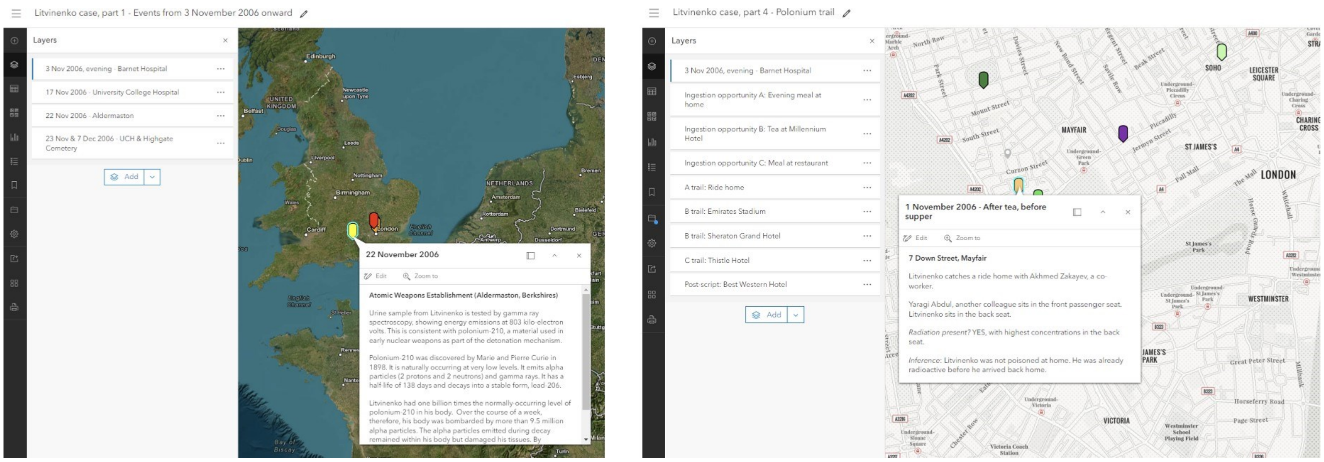
Our PD work with teachers employed the commonly-used ‘ghost map’ example of John Snow’s investigation of a cholera outbreak in Victorian London (Johnson, 2006). This topic is often referenced when introducing GIS and georeferenced data to new users. (For an example, see Esri’s *Map a historic cholera outbreak*, n.d.). Louis appreciated the way this activity allowed for immediate engagement with a topic (cholera), a georeferenced dataset (cholera cases by house), and the use of a GIS to understand, investigate, and reach a conclusion to an authentic historical mystery. 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, Litvinenko 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, the medical team determined that Litvinenko was suffering from radiation poisoning after having been dosed with a massive, lethal dose of polonium-210. Given the damage to multiple organ systems, he must have ingested the radioactive substance as part of something that he had consumed on November 1, 2006. 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 tea.

Development & Implementation

The development of classroom materials required extended, close collaboration between Louis and his university colleagues, collating information from the inquest and other sources to develop a timeline of key details, identify geographic reference points, and then 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 backward 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 (see Hammond, 2022). 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-life; tracking what transmutation takes place after alpha decay; and so on.

Figure 3

Selected Maps from Polonium Poisoning Investigation



Note. Each map's layers organize events in time; each placemarker embeds relevant details.

Once Louis brought the activity into his classroom, 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. One student expressed that she had assumed the maps and details were made up for the purpose of teaching chemistry rather than compiled from an actual forensic investigation, stating, "Wait, this is real life?" 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 a jaw-dropping realization for some students.

Louis felt that the activity was such a success that he elected to use it in his chemistry and Anatomy & Physiology classes. In this curricular context, he preserved all of the chemistry-related concepts within the narrative but went deeper into 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 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; Litvinenko, on the other hand, had swallowed the polonium and, therefore, experienced accumulating, irreversible effects over time. Once his digestive and circulatory systems had carried the polonium throughout his body, the alpha particles were released at close range into sensitive tissues, causing disruptions and eventual organ failure —the initial vomiting was due to damage within his stomach, the diarrhea was from damage to his intestines, the drops in blood cell counts were due to damage to bone marrow, and so on. The crosscurricular 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 in 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 a similar activity look like in a chemistry class?) and then identifying the crucial, aligned with details in the Russian government's chemical assassination case. Despite our lengthier 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), the university team was blind to the cross-curricular opportunity that Louis saw within the PD materials. We 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 inquirydriven 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, etc.)—it is not a signature pedagogy. Given its alignment with scientific processes and goals of science, inquiry-based learning is the dominant pedagogical theme in both the broader field of science education and in our 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: from the starting point of November 3, 2006, we first work forward in time to examine the medical case until Litvinenko's death and burial; we then work backward from that starting date as the forensic investigation yields new information. The second part, the reversed chronology of the investigation, allows for moments of inquiry: 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 the potential to increase learning (Habgood et al., 2005).

Finally, this activity served its intended purposes as identified by Louis: it engaged students with the chemistry curriculum, introduced them to geospatial tools, and established the themes of spatial relations as essential to the study of chemistry, with geospatial technologies as one tool 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 commented on his geospatial chemistry instruction 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, meals, politics, and even their death and legacy.

Cross-Case Discussion & Implications

Looking across the three selected cases in this study, we see teachers using geospatial tools in a highly novel context of chemistry education to address a variety of curricular topics and instructional modes. In Louis' classroom, he used GIS at the start of his curriculum: the maps and datasets were an engaging introduction to chemistry, specifically radiation chemistry and the periodic table. Gill used GIS and

StoryMaps to enhance his periodic table instruction. This activity was an extension, not an introduction of the topic, and some students further extended their learning by engaging with the economic, political, and social justice implications of resource extraction. In Kimberly's classroom, she enhanced her previous use of GIS and level of detail in teaching soil chemistry, using a hands-on data collection activity to anchor lessons about soils and agricultural planning. In all three cases, students were engaged with core chemistry concepts from the curriculum and tasked with understanding spatial relationships and engaging in spatial reasoning.

Another common feature across the three cases is the broad variation and unpredictability in conducting geospatial PD with teachers. At the start of our project, we presented our design model for classroom instruction (e.g., localized geospatial inquiry with hands-on data collection culminating in decision-making), and we moved through our integrated PD and curriculum development process to bring GIS into the classroom. Among the three cases, only Kimberly's implementation fit our anticipated model. Drawing upon her PD experiences, she was able to design and implement a sequence of lessons in which her students collected data to address a driving investigative question, analyzed the data, considered explanations, formulated conclusions, and made decisions. In the other two cases, however, the teachers employed different—but highly successful—instructional approaches to bring GIS into their classrooms. Gill's students gathered information and annotated maps, synthesized their research, and presented their findings, but they did not engage in hands-on data collection. Louis' students, given the context of an introductory lesson to begin the year, had minimal hands-on use of GIS.

Furthermore, Gill and Louis worked on very different timelines and workflows. Gill took over a year to find the curricular connection between his PD experience with StoryMaps and the curriculum-aligned topic of the periodic table, specifically metals and metalloids. Once he had the connection in mind, he worked completely independently, preparing materials and organizing students' work with no required assistance from the university team. On the other hand, Louis had a much more rapid connection between his PD experience of the ghost map and the inspiration to bring a poisoning case into his introduction to chemistry. The workflow, however, was much more deeply connected to his university collaborators as they worked through the inquest and developed maps together. To meet the challenge of successfully bringing GIS and geospatial tools into chemistry lessons, we needed both the creative input of the teachers and a flexible approach for conducting our geospatial PD and curriculum development.

The three cases also highlight the power of collaborative work across institutions using a design partnership—geospatial integration is enriched and sustained when teachers can connect with other, geospatially-engaged teachers and developers. As noted, Kimberly had instituted an ArcGIS Online organizational account well before our geospatial project started. Still, she needed the connection with her local university team before successfully bringing GIS into her classroom instruction. The polonium poisoning activity in Louis' classroom similarly required close collaboration with the university team. In subsequent work in these classrooms, we also saw diffusion and exchange across sites: The periodic table activity from Gill's classroom spurred a longer sequence of activities for Louis and his teacher 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 Kimberly's classroom helped inspire a similar soil sampling lesson in Louis' chemistry classes. Louis' polonium poisoning activity has been used by other Anatomy & Physiology teachers 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 Kimberly'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 newto-them context of government-sponsored assassination in post-Cold War London. In all three cases, students connected and applied their academic understandings of chemistry topics to identifiable places, people, events, and/or decisions in the world.

In sum, the three cases highlight the three teachers' Gs-TPACK for teaching chemistry. Each teacher used an appropriate geospatial application with applicable pedagogical instruction for chemistry learning in their curriculum sequence. In these cases, the teachers made disciplinary connections to other disciplines outside of chemistry, resulting in valuable teaching and learning experiences for the students.

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 many datasets 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, Kimberly, 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 creates 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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