INNOVATIONS IN REMOTE AND ONLINE EDUCATION BY HYDROLOGIC SCIENTISTS

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PUBLISHED IN: Frontiers in Education, Frontiers in Environmental Science and Frontiers in Water

frontiers Research Topics

ISSN 1664-8714
ISBN 978-2-83250-844-2
DOI 10.3389/978-2-83250-844-2

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INNOVATIONS IN REMOTE AND ONLINE EDUCATION BY HYDROLOGIC SCIENTISTS

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Citation: Mulvey, B., Ward, A. S., Jefferson, A. J., Bales, J., eds. (2022). Innovations in Remote and Online Education by Hydrologic Scientists.
Lausanne: Frontiers Media SA. doi: 10.3389/978-2-83250-844-2

Table of Contents

frontiers | Frontiers in Environmental Science

TYPE Editorial
PUBLISHED 09 November 2022
DOI 10.3389/fenvs.2022.1074801

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OPEN ACCESS

EDITED AND REVIEWED BY
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SPECIALTY SECTION
This article was submitted to Freshwater Science,
a section of the journal
Frontiers in Environmental Science

RECEIVED 20 October 2022
ACCEPTED 25 October 2022
PUBLISHED 09 November 2022

CITATION
Mulvey BK, Jefferson AJ, Ward AS and Bales J (2022), Editorial: Innovations in remote and online education by hydrologic scientists.
Front. Environ. Sci. 10:1074801.
doi: 10.3389/fenvs.2022.1074801

Editorial: Innovations in remote and online education by hydrologic scientists

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KEYWORDS

hydrology education, water science education, remote education, online education, educational resource platforms, educational innovation, open access educational resources

Editorial on the Research Topic
Innovations in Remote and Online Education by Hydrologic Scientists

1 Introduction

Hydrologic science is essential for sustainability and resiliency on a changing planet, and educational innovations to support instructors and students in this area are critical to ensuring future professionals are ready to tackle the world's environmental challenges (Ruddell & Wagener, 2015). This research topic was motivated by the educational adaptations and innovations that emerged during the early days of the COVID-19 pandemic. When faced with an abrupt shift to remote instruction, instructors quickly identified, modified, and developed remote content, activities, and instructional strategies. Given the importance of hydrology-related teaching and learning, there is a great need for continued iterative development and sharing of evidence-based open-access curricular materials, models, applications, and more. This open-access collection of papers will increase findability and accessibility of effective and well-documented pedagogical tools. In doing so, we advance the goal of ensuring that all students, independent of their individual circumstances or institutional resources, receive the highest quality educational programming, even in exceptional times.

The research topic contributions illustrate just how far the hydrologic science community has come in collaborating to develop, share, and test educational resources since the beginning of the COVID-19 pandemic. Together, the papers promote broader use and continued development of these supports for science education overall and hydrology education in particular well beyond the pandemic. The articles address the following themes: 1) visualizations and models for aquifers and water balance; 2) field experiences; 3) coordinated, collaborative resource development and sharing efforts; and 4) educational activities and strategies with broad applications. These articles share strengths in collaboration and visualization while highlighting areas in need of additional growth.

2 Research topic themes

2.1 Visualizations and models of hydrological concepts

One theme in this special issue emphasizes the power of visualizations and models as tools for teaching and learning, as represented by three papers. Lowry et al. present folded-paper aquifer models as an inexpensive way to support lower-scoring learners' ability to physically rotate aquifer models to support visualization and interpretation associated with three-dimensional problem solving. Another low-cost alternative is L. Gallagher et al. open-source interactive, gamified computer simulation, the ParFlow sandtank, which offers a variety of setup options compared to physical aquifer models. Illustrative outcomes for middle school and undergraduate science settings included that learners visualized and/or tested different scenarios to understand key hydrologic concepts and make decisions about water use. Gannon and McGuire highlight a web application and related activities involving user manipulation of model parameters to investigate water balance using NOAA climate stations. Student users in higher education hydrology classrooms reported that the application and activity promoted concept learning better than a spreadsheet or hand calculations. Overall, these articles offer suggestions for how to engage learners in reasoning through complex scenarios.

2.2 Field experiences

Three articles underscore the importance of engaging learners with outdoor and field experiences in hydrology courses, regardless of course delivery as in person, hybrid, or online/remote. Saup et al. adapted to the shift to remote instruction for a large-enrollment general education course by offering the choice for students to engage in either an in-person field-based lab activity or an online version. Students who opted for the in-person version scored better on the lab activity, compared to those who completed the online version, and increased enjoyment in learning about water whereas the online completers reported a decrease in their enjoyment. The authors note the importance of mitigating these disparities through enhanced interactions of teaching assistants and students in the online version. Schwarzenbach et al. migrated to a more accessible and flexible smartphone-based self-guided excursion, "Water in the City," compared to the pre-pandemic class trip. Built-in learner supports such as immediate feedback on question responses and ability to return to the locations and thus be reminded of the excursion may support stronger learner outcomes. Whether with instructors or application-based support, students benefit from connections with others during field experiences. Hinckley and Fendorf structured hands-on, small group collaborative learning about soil texture and color using kits that could be deployed in person or remotely. By integrating conceptual learning, hands-on experiences, and synthesis and interpretation, students gained both skills and interest in soil properties.

2.3 Coordinated, collaborative resource development and sharing platforms

Four articles explored instructor perspectives and student understanding using HydroLearn (www.hydrolearn.org), an open-access online platform for instructors to identify existing learning modules, adapt them, and collaborate to develop new modules. Recommendations for module development include instructor pairs co-creating modules, intensive training and use of curriculum design principles, consistent feedback, applicability to instructors' own course, and peer-review (M. Gallagher et al.). Instructors wanted accessible and adaptable shared curricular resources, yet there is a need for consolidation into one platform with the potential to test and iteratively improve resources and use workshops to bring instructors together to collaborate (Spackman Jones et al.). Roundy et al. and Byrd et al. shared meaningful improvements in students' conceptual understanding related to a snow and climate modeling module and 15 modules involving authentic, high-level tasks.

2.4 Educational activities and strategies with broad application

A final set of articles highlight educational activities, strategies, and courses that engage learners in authentic scientific and coding practices, with crucial support embedded in the learning materials and through interactions with instructors. This set of articles establishes evidence-based ways to support learners' enculturation into science and science communication. Thompson et al. highlight a shared constructivist, flipped classroom approach involving supportive, inclusive online instructional strategies used across four courses to promote diverse student engagement. The approach involved authentic learning and assessment that engaged students with the natural environment. Special attention was paid to development of supportive relationships with the instructor and other students. Kelleher et al. offer evidence-based recommendations for the effective incorporation of coding into hydrology courses across delivery methods. The main recommendations include making explicit the importance and benefits of coding early; going slowly; articulating each step; normalizing errors and seeking help, including explanations; and asking questions to promote student reflection. Jefferson et al. present faculty perspectives about an online, collaborative, multi-institutional graduate training course in hydrology, showing that it is perceived to widely benefit students, but that institutional administrative barriers may slow its growth within and beyond the hydrologic sciences.

Weaver et al. present an asynchronous online poster symposium–with substantial scaffolds over time to support quality posters and presentations–in a large introductory undergraduate environmental science course. Students identified the poster-related assignments as the course aspect through which they learned the most, and a large majority expressed confidence in their abilities to create a scientific poster. Informed by a community of inquiry framework, Gareis et al. share Wikipedia page-editing assignment guidelines and instructor-based outcomes involving support from a faculty mentoring network. Instructors considered the assignments to improve student motivation and scientific source reliability awareness while promoting STEM diversity, equity and inclusion discussions.

3 Conclusions and recommendations

Overall, this research topic documents important lessons learned regarding science teaching and learning, which we hope will promote long-term educational advancement in the hydrologic sciences and beyond. The scientific community in general and the community of hydrologic scientists in particular are poised to further develop flexible, accessible, and effective educational resources, activities, and assessments. We echo the call from a recent *Earth and Space Science* commentary to continue to foster integrated, coordinated, and networked open-science approaches to strengthen evidence-based, socially just teaching and learning (Fortner et al., 2022).

Additional professional development and peer-learning support will be critical to human resource development and the promotion of equity and justice in teaching and learning, especially as more learning is occurring *via* virtual platforms. More differentiated support for learners in needed, with stronger support for more novice learners and more flexible support for learners with higher initial knowledge and skills. Sustained structural and institutional support for collaboration and resource development can improve inclusive capacity building.

Another key need is the sustainment and continued development of online educational resource collections and databases with attention to accessibility. HydroLearn and other platforms offer an important start to collaborative curriculum development and sharing. Yet sustaining these platforms beyond the lifetime of the grants that supported their creation will require creativity and new resources. Also, much remains to be done to improve searchability and accessibility.

We call for substantial additional funding for these structural supports and continued development. In this way, the innovations identified and developed for use during the COVID-19 pandemic may act as a catalyst for future innovations. These educational innovations will help to prepare learners to address complex local and global problems.

Author contributions

All authors contributed to the conceptualization and writing of this article. BKM developed the first draft. AJJ developed the second draft, with ASW, JB, and BKM providing final edits.

Funding

Origins of this special issue were supported in part by NSF award EAR- 2028737.

Acknowledgments

We dedicate this collection to the memory of Thomas Meixner, whose contributions to hydrology education and research were magnified by his generosity of spirit.

Conflict of interest

JB was employed by Consortium of Universities for the Advancement of Hydrologic Science, Inc.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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CURRICULUM, INSTRUCTION, AND PEDAGOGY
published: 12 April 2022
doi: 10.3389/feduc.2022.873196

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An Interactive Web Application Helps Students Explore Water Balance Concepts

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The concept of a water balance is a foundational topic in hydrology classrooms. While understanding and applying this concept is crucial to the introduction of more advanced topics, students often struggle to develop a thorough understanding of the relationships between components, assumptions, and limitations of a water balance. To aid students in developing a working understanding of a water balance, we developed a web application that runs a one dimensional Thornthwaite-type water balance at any of thousands of NOAA climate stations across the continental United States using the local soil-water storage capacity at the station location. Within the app, students can manipulate the soil-water storage capacity, latitude, temperature, and precipitation to better understand how it works and explore scenarios of land use, extreme weather, and climate change. The application is free and will run on any device that can open an internet browser window (laptops, chromebooks, smartphones, etc). Here we present the details of the model, functionality of the application, and link to several ready-made classroom activities. Finally, results from student surveys in two hydrology classrooms show that students may learn water balance concepts more effectively than traditional methods such as spreadsheet computations.

Keywords: water balance, water budget, web app, teaching, hydrology

OPEN ACCESS

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Specialty section:
This article was submitted to specialty of Frontiers in Education, a section of the journal Frontiers in Education

Received: *10 February 2022*
Accepted: *11 March 2022*
Published: *12 April 2022*

Citation:
Gannon JP and McGuire KJ (2022) An Interactive Web Application Helps Students Explore Water Balance Concepts. Front. Educ. 7:873196. doi: 10.3389/feduc.2022.873196

INTRODUCTION

A water balance of a soil pedon or watershed is a core concept in many introductory hydrology and hydrogeology courses and texts (e.g., Hendriks, 2010; Fitts, 2013; Hornberger et al., 2014; Dingman, 2015; Bedient et al., 2019; Davie and Quinn, 2019; Hiscock and Bense, 2021). It is a useful and powerful context through which to discuss core hydrology concepts like soil water storage, groundwater recharge, potential and actual evapotranspiration, and runoff. Additionally, the conceptual model of a water balance can then be used to examine the impacts of change on a hydrologic system, such as development, land use conversion, or climate change.

The ability to explain hydrologic concepts and explore impacts to a hydrologic system, however, is predicated on having a solid understanding of how a water balance works and how it responds to changing inputs or parameters that describe the system. This is often a challenge for students who are learning hydrology for the first time. While activities like hand calculations and water balance spreadsheets are helpful, students can spend more time and energy learning how to perform the calculations or manipulate a spreadsheet or graph a variable than working to understand the concepts behind the water balance. Furthermore, we found hand calculations and spreadsheet-based activities were even more difficult to run effectively after the shift to online learning in the COVID-19 pandemic. In the online environment, it was challenging to provide adequate troubleshooting and help to students having trouble. This was especially problematic in introductory classes where effective use of spreadsheets is not a learning goal, but a conceptual understanding of a water balance was an important fundamental learning goal. For these reasons, we saw the need to create a way for students to explore a water balance in a variety of ways, both graphically and with tabular data, without having to perform calculations or work with a spreadsheet.

Importantly, we also wanted to create a way to introduce students to the water balance that maintained the active learning approach of traditional hand calculations or spreadsheets. Active learning, where students do not simply sit and listen to an instructor, has been shown again and again to be an effective pedagogical practice (Freeman et al., 2014) and one that can reduce achievement gaps between advantaged and disadvantaged groups (Haak et al., 2011). It was also a goal to develop something that would foster inquiry-based learning. Inquiry-based practices promote learning by inviting students to ask their own questions and then work to develop answers (Bransford et al., 2000). This is a powerful technique, but especially for an online-based activity, we felt students needed to be able to explore concepts without getting overwhelmed or encumbered by technical errors or procedural confusion.

Interactive web applications are one way to provide students with an inquiry-based learning experience that may aid their understanding of course concepts without overburdening them with the operational aspects of the calculations involved. These web applications are growing in popularity. They can be developed using common scientific coding languages (R, Python, Matlab) and hosting them continues to become easier and less expensive. In fact, the Consortium for the Advancement of Hydrologic Sciences, Inc. (CUAHSI) has resources for hosting several types of web applications (more info at: www.cuahsi.org/education/). Furthermore, multiple studies found web applications benefit student learning (e.g., Hagtvedt et al., 2007; Azman and Esteb, 2016).There is such strong evidence for enhanced learning with web applications that the American Statistical Association recommends their use in statistics instruction (Franklin et al., 2007).

For these reasons, we developed a web-application that allows students to explore and better understand the water balance. The flexibility of a web application allowed us to add functionality that would be cumbersome, if not impossible, in a spreadsheet or by-hand activity in a hydrology classroom. Students can easily manipulate inputs and parameters in the water balance and load data from thousands of sites across the contiguous United States, choosing from two periods of monthly climate normals (1981–2010, 1991–2020) (Arguez et al., 2012). This allows for exploration of a variety of concepts at a range of levels of complexity, from an early activity in an introductory class to an upper level undergraduate hydrology or hydrogeology course.

In the following sections, we explain in detail how the app calculates a water balance and what data is used. We then explain the functionality of the app and results from a survey of students who used the app in an in-class activity. Finally, we provide information about how to access several ready-to-use activities and an instructional video about using the app.

METHOD: WATER BALANCE MODEL

The app runs a Thornthwaite-type monthly water balance model following the approach described by Dunne and Leopold (1978) and Dingman (2015). Thornthwaite-type monthly water-balance models (Thornthwaite and Mather, 1955, 1957; Dunne and Leopold, 1978; Black, 2007), are lumped conceptual models that estimate climatic average or continuous hydrologic budgets (Dingman, 2015). Thornthwaite-type models have been applied to variety of settings (e.g., Alley, 1985; Willmott et al., 1985; Steenhuis and Van der Molen, 1986; McCabe and Markstrom, 2007; Westenbroek et al., 2010) and have proven to be useful tools in water resource assessment (e.g., Taylor et al., 2006; Tillman et al., 2017). Inputs for these models typically consist of monthly values of precipitation and temperature for a watershed or region of interest. Here we use mean monthly values to represent the climatic average. Thornthwaite-type models typically have a single parameter, the soil-water storage capacity, S_C, or the available water storage of the soil in the watershed. S_C is defined as:

$$S_C = (\theta_{fc} - \theta_{pwp}) \cdot Z_r, \quad (1)$$

where θ_{fc} is the field capacity, θ_{pwp} is the plant permanent wilting point, and Z_r is the depth of the root zone (often assumed as 1 m). The difference between θ_{fc} and θ_{pwp} is the (plant) available water capacity, which is expressed as a fraction of total volume of soil (cm^3 of water per cm^3 of soil) and is the water available for transpiration. The average available water capacity (i.e., $\theta_{fc} - \theta_{pwp}$) for watersheds in this app is the Available Water Storage measure for the upper 100 cm of soil from the Natural Resource Conservation Service (NRCS) gNATSGO (Gridded National Soil Survey Geographic Database) database (Soil Survey Staff, 2020). Runoff estimation is not included in this version of the water balance in the model. Instead, runoff can be considered part of the surplus water term. Runoff values can be separately estimated from the monthly water surplus and/or by applying a direct runoff coefficient as a fraction of monthly precipitation (e.g., see McCabe and Wolock, 2011).

Monthly precipitation, P, is partitioned into rainfall, $RAIN$, and snowfall, $SNOW$, using a factor, F, that is multiplied by total monthly precipitation to determine the amount of rainfall in that month. If monthly air temperature is below 0°C, precipitation is considered snowfall and F is zero. If the monthly air temperature is above 0°C, but below 6°C, F is computed based on the linear temperature relationship shown in **Figure 1** and the rainfall fraction of the precipitation is $0 \leq F \leq 1$ (Dingman, 2015). Therefore, $RAIN = F \cdot P$ and $SNOW = (1 - F) \cdot P$.

The factor, F, is also used to estimate monthly snowmelt following a degree-day or temperature-index approach. Here, F is multiplied by the sum of the snow water equivalent on the ground, $PACK$, for the previous month and the current month's

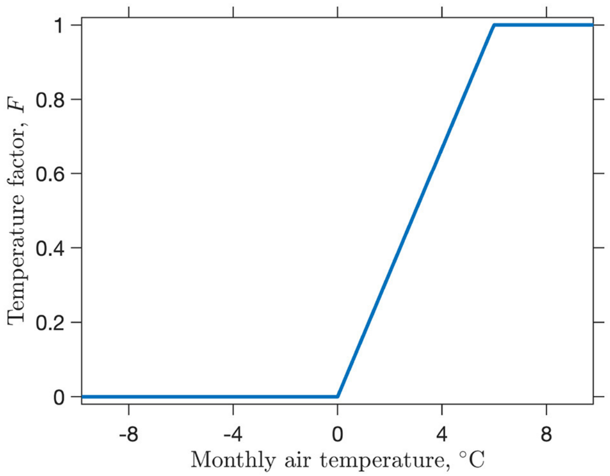

FIGURE 1 | Monthly temperature factor for rainfall/snowfall partitioning or snowmelt estimation based on air temperature. Slope of the line between 0°C and 6°C is 0.167°C^{-1}.

snowfall, *SNOW*, to estimate snowmelt, *MELT*. The result is the amount of snow that will melt and be considered part of water input to the soil, *W*. Water input, *W*, to the soil storage is therefore the sum of rainfall and snowmelt. The snowpack at the end of month is then computed following Dingman (2015) as the proportion of precipitation that fell as snow and contributed to that month's snowpack, plus the previous month's snowpack that did not melt.

Potential evapotranspiration, *PET*, in this model is calculated using the Thornthwaite (1948) equation; however, other approaches that use air temperature (e.g., Hamon, 1961) could be used as well. The model assumes that if monthly water input exceeds monthly *PET*, then actual evapotranspiration, *ET*, takes place at the *PET* rate and the soil-water storage, *S*, increases or, if it is already at soil-water storage capacity (S_C), it remains constant. The Thornthwaite (1948) equation for *PET* depends on monthly temperature and latitude, which is used to account for the varying number of days per month and hours of daylight (Criddle, 1958). When water input for a month is less than *PET*, *ET* is equal to the sum of water input and the amount of soil-water that can be removed from the soil storage for month *i* depending on the following exponential drainage function (Alley, 1984):

$$S_i = -S_{i-1} \cdot \left[1 - \exp\left(-\frac{PET_i - W_i}{S_C}\right)\right] - S_{i-1}. \qquad (2)$$

The app provides a table of monthly values (e.g., **Table 1**) and five graphs for any given location defined by a NOAA observing station location. The graphs display monthly water inputs to the soil-water storage that are divided into snowmelt and rainfall contributions, soil-water and snowpack storage, monthly temperature, and the snow and rain monthly fractions of precipitation. **Table 1** is the monthly water balance output for Blacksburg, Virginia, at 37.2 °N latitude. The onset of snow inputs and snowpack occur in December and the snowpack reaches its peak in February, and melts in March. For the months when there is adequate supply of soil-water storage for the evaporative demand (October-May), *ET* is equal to *PET*. Recharge of the soil-storage begins in October and reaches its capacity the following month. The depletion of soil-water storage begins in June and continues into September as the evaporative demand is satisfied by removing water from the soil-water storage, *S*. The average monthly water surplus ($W - ET - \Delta S$), i.e., water available for recharge and runoff, are the monthly inputs that are in excess of monthly *ET* and soil-water storage changes.

RESULTS: APP IMPLEMENTATION AND FEATURES

The water balance app is a Shiny web application (https://shiny.rstudio.com/) and is hosted by CUAHSI. The web application can be run on any common internet browser on a computer, tablet, smartphone, or chromebook. Use of the app is free and does not require the user to download any special software. Source code for the app can be found at https://github.com/jpgannon/Water-Balance-App.

The app, shown in **Figure 2** has six tabs which support a variety of functions. The landing page for the app is the "Output Plots" tab. Here students see five plots rendered from the results of the water balance function: soil inputs, soil storage, soil output, temperature, and precipitation. The plots will resize if the user changes the size of their browser window, and they can copy and paste the plots or save them by right-clicking on them. This facilitates saving the plots for activity write-ups. The plots will update automatically if the user makes changes to any of the settings on the left side of the app.

On the left panel, the user has several options. The first dropdown allows the user to select one of several thousand NOAA climate monitoring sites by either scrolling through the available options or typing to search. Next, the climate normal period can be switched between 1991–2020 and 1981–2010. The next slider down automatically starts at the soil water capacity of the site, which is the Available Water Storage measure for 100 cm of soil from the Natural Resource Conservation Service (NRCS) gNATSGO database (Soil Survey Staff, 2020). Moving this slider will change the water holding capacity in the model. The latitude slider similarly updates depending on the site chosen, and if moved, changes the latitude in the PET calculation in the model. The following two sliders, precipitation and temperature, always start at zero. If the user moves these sliders, they will add or subtract the value of the slider from each monthly value for the site chosen. For example if the temperature slider was moved to +1, it would add 1°C to the temperature data for each month at the site. Finally, if the user selects a climate normal period in the dropdown at the bottom of the column, those data will be added as a separate dataset to the plots. This can be used to compare the two climate normals, or if the user selects the same climate normal period for both, they can more clearly see how the water

TABLE 1 | Output of Thornthwaite-type monthly water balance for Blacksburg, VA.

	P	T	F	RAIN	SNOW	PACK	MELT	W	PET	W - PET	S	ΔS	ET	W-ET-Δs
Jan	78.2	-0.3	0	0	78.2	130.3	0	0	0	0	140	0	0	0
Feb	71.4	1.2	0.2	14.5	56.8	149.0	38.1	52.7	2.6	50.1	140	0	2.6	50.1
Mar	92.5	5.3	0.9	82.2	10.3	17.7	141.6	224	19.3	204	140	0	19.3	204
Apr	88.4	10.4	1	88.4	0	0	17.7	106	46.5	59.6	140	0	46.5	59.6
May	110.0	15.2	1	110	0	0	0	110	82.2	27.8	140	0	82.2	27.8
Jun	101.6	19.8	1	102	0	0	0	102	114	-12.7	128	-12.1	114	0
Jul	108.2	21.8	1	108	0	0	0	108	130	-22.1	109	-18.6	127	0
Aug	91.2	21.1	1	91.2	0	0	0	91.2	118	-26.7	90.3	-19.0	110	0
Sep	78.7	17.3	1	78.7	0	0	0	78.7	81.8	-3.0	88.4	-1.9	80.7	0
Oct	70.6	11.3	1	70.6	0	0	0	70.6	45.1	25.5	114	25.5	45.1	0
Nov	72.9	6.3	1	72.9	0	0	0	72.9	19.3	53.6	140	26.1	19.3	27.5
Dec	74.9	1.0	0.2	12.5	62.4	52.0	10.4	22.9	2.0	20.9	140	0	2.0	20.9
Annual	1039		831	208		208	1039	661				648	390	

Temperatures, T, in °C, water-balance terms in mm. $S_C = 140$ *mm.*

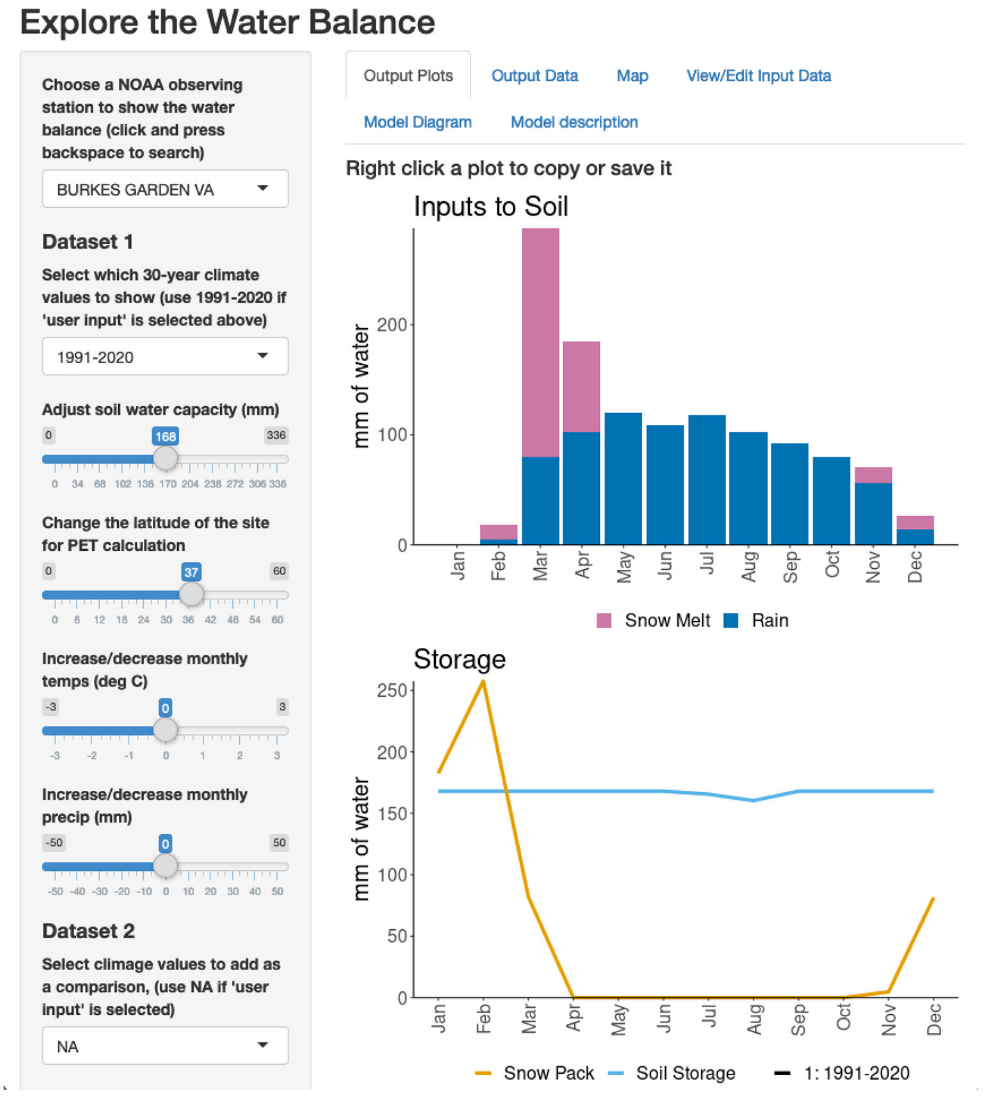

FIGURE 2 | App interface showing two of the five plots, available inputs, and the tabs with additional functionality.

budget changes when they manipulate the sliders, as the second dataset is unaffected by user inputs.

The second tab at the top of the app is titled "output data" this tab shows all the output from the water balance model. This can be used to explore more quantitative differences between outputs, such as PET and AET. The data can also be downloaded using a download button at the bottom. This produces a comma-separated value (CSV) of the model output, which a user could then use to create their own visualizations, perhaps for an upper-level class or for custom figures for a lecture.

The third tab is the map tab. Here the user can zoom and pan around the contiguous US and see all available places for which they can calculate the water balance. If the user clicks a marker, that site will be selected in the left panel. If the user selects a site using the drop-down menu in the first tab, it will be highlighted on the map in the map tab.

The fourth tab allows the user to view or edit the input data for the model. When a site is chosen, its data populates this table. If the user double clicks on any value, they can enter a new value in its place, and the app will recalculate the water balance with the new data. This could be used to simulate a large flood or a drought, for instance. This tab has the additional functionality of allowing the user to put in a custom dataset from somewhere not included in the available data. If the user selects "User Input", the first option in the dropdown menu for sites on the left panel, the view or edit input data becomes all zeros. The user can then enter their own temperature and precipitation values and use the sliders to change the available soil water capacity and latitude of the site.

Finally, the fourth and fifth tabs of the app offer a diagram of the model used, and a detailed description of the functionality of the app and the Thornthwaite soil water balance.

DISCUSSION: EFFICACY IN A CLASSROOM ENVIRONMENT

We used the app to introduce the water balance in two classes at Virginia Tech. One class was an introductory watershed hydrology class taught in the department of Forest Resources and Environmental Conservation and the other was an upper level undergraduate/introductory graduate level hydrology methods class taught in the Biological Systems Engineering department. The introductory class had around 60 students and the advanced class about 20. Both classes were taught in-person. After a short slideshow presentation introducing the water balance and a demonstration of the functionality of the app, students were provided with an activity. Both the lecture introduction and activity are included in the resources linked below. In both cases, these were individual activities in an in-person class. However, the application and included activities are likewise suitable for group-based activities and virtual or hybrid modalities, as no specific computing resources are required. After the activity, we asked the students to respond with how much they agreed with two statements to help determine if the students felt the app helped them understand the water balance, and if they enjoyed it more than previous activities using other methods,

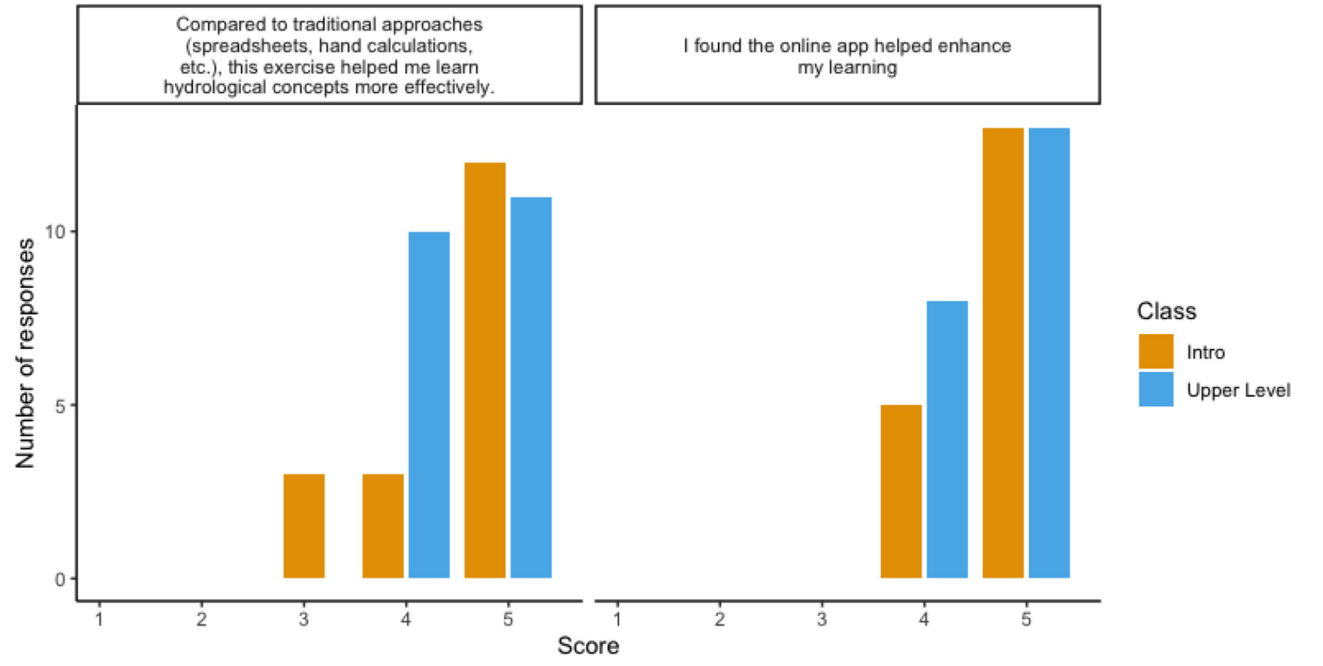

FIGURE 3 | Responses to questions asked after water balance app activity. The x axis shows the score students marked for each question, where 1 was strongly disagree and 5 was strongly agree. The orange bars show responses of the students in the introductory level class and the blue bars show the responses of an upper level undergraduate/introductory graduate level class.

such as spreadsheets or hand calculations. The exact statements posed were:

"Compared to traditional approaches (spreadsheets, hand calculations, etc.), this exercise helped me learn hydrological concepts more effectively."

"I found the online app helped enhance my learning."

Students responded to each of the statements on a scale of 1–5 where 1 was "strongly disagree", 3 was "agree", and 5 was "strongly agree." **Figure 3** shows that students uniformly agreed that the app enhanced their learning and that the exercise helped them understand the material more effectively than a spreadsheet or hand calculation. For both courses, the most frequent response was "strongly agree" for both questions.

While the student response was positive, there are some drawbacks to using this web application as a sole replacement for other types of activities, depending on the learning goals for the class. For instance, exploring the app alone would not be appropriate if the topic is introduced in a class with the dual purpose of developing a conceptual understanding of the water balance and developing/practicing spreadsheet skills, graphing, unit conversion, or basic budget calculations. However, this app can also be used to facilitate these more advanced activities. For example, students could use the app to explore water balance concepts across the US and then export the data for a site of their choosing as a comma separated values (csv) file *via* the "output data" tab to perform further analysis by hand or in a spreadsheet program.

READY-TO-USE ACTIVITIES

To facilitate use of this app in hydrology and earth science classrooms, we created three activities that can be used in a classroom after a short introduction to the water balance and the app. The questions addressed in these activities are as follows:

1. What controls how water is partitioned in a water balance?
2. What controls the amount of actual evapotranspiration at a site?
3. What is the difference between a water limited and energy limited system?
4. How can climate change affect the water balance?

The complete activities are available *via* CUAHSI's hydroshare, along with Powerpoint slides that introduce the water balance, a link to a video showing how to use the app, and a link to the app itself (https://www.hydroshare.org/resource/0ecadff374aa4a2b84e41f146d39f48c/).

CONCLUSIONS

The water balance is a crucial concept for students of hydrology to understand thoroughly, but is often confusing due to numerous interactions between parameters. Common methods used to explore the water balance can leave students bogged down in calculations or spreadsheet operations, taking away from their opportunity to become more comfortable with the core concepts. Interactive web-applications offer a solution, as they are a platform-agnostic and easy to use way for students to explore hydrologic concepts in the classroom.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

Both authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

FUNDING

The publication of this article was supported by the Virginia Tech Open Access Subvention Fund.

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frontiers | Frontiers in Environmental Science

ORIGINAL RESEARCH
published: 03 May 2022
doi: 10.3389/fenvs.2022.875712

Self-Guided Smartphone Excursions in University Teaching—Experiences From Exploring "Water in the City"

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Like many other university teachers, we were faced with an unprecedented situation in spring 2020, when we had to cancel *on-site* teaching and excursions due to the Covid-19 pandemic. However, we were in the fortunate position that we had already started to develop a smartphone-based self-guided excursion on the topic of "Water in the City". We accelerated this development and used it to replace the traditional group excursion in our Bachelor level introductory course in Hydrology and Climatology. The excursion of this course is visited by around 150 students each year. Because the student feedback was overall very positive, we used the self-guided excursion again in 2021 and plan to continue to use it in the coming years. In this paper, we describe the excursion, discuss the experiences of the students and ourselves, and present recommendations and ideas that could be useful for similar excursions at other universities.

Keywords: field trip, undergraduate teaching, hydrology, mobile phone, treasure hunt, student evaluation

Edited by:
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Kent State University, United States

Reviewed by:
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Specialty section:
This article was submitted to Freshwater Science, a section of the journal Frontiers in Environmental Science

Received: *14 February 2022*
Accepted: *05 April 2022*
Published: *03 May 2022*

Citation:
Schwarzenbach FM, Seibert J and van Meerveld HJ (2022) Self-Guided Smartphone Excursions in University Teaching—Experiences From Exploring "Water in the City". Front. Environ. Sci. 10:875712. doi: 10.3389/fenvs.2022.875712

INTRODUCTION

By being out of the classroom and in the real world, excursions and field trips are unique experiences and are often among the most memorable days of a study (Djonko-Moore and Joseph, 2016). The new or unconventional site for learning and teaching has a motivating effect on the students (Hasse and Colvard, 2006; Herrick, 2010; Gašparová and Kyseľová, 2020; Holgersen, 2021). Excursions and field trips, furthermore, provide students with the possibility to make observations on their own and to strengthen their understanding by seeing—in real life—what they learned in theory in the classroom (Jonasson, 2011; Kingston et al., 2012; Krakowka, 2012; Djonko-Moore and Joseph, 2016). This can provide them with an idea of the value of their newly acquired knowledge. Thanks to the authentic learning context and examination of real-world problems, the knowledge obtained during excursions can be applied to new tasks that students are subsequently confronted with. This makes excursions and field trips especially valuable and effective (Brickell and Herrington, 2006; Fränkel et al., 2020).

However, excursions and field trips, especially large group excursions, also have disadvantages. Especially in loud environments or windy areas, students standing in the back of the group may have difficulties hearing the instructor and, thus, may miss parts of the content (Moore et al., 2011; Wissmann, 2013). Moreover, it is not possible to adjust the speed of the excursion to the individual needs of students (Larsen et al., 2020). This applies to both the content (some students need more background information or more detailed explanations than others) and physical speed (some students walk faster than others). Students who learn at a slower pace, students for whom the contents of the excursion are very new, and students who are not native speakers may need some extra time to think about the contents of the excursion and to understand them. For others, the pace may be too slow, so that they become bored and distracted. Furthermore, the different levels of fitness among students may result in a walking speed that does not fit everyone, so that the excursion becomes a physical challenge for some and is too slow for others.

Excursions also require significant time for preparation, to be carried out, and, in some cases, grading. Thus, the workload for instructors can be relatively large. The time requirement for instructors becomes especially large if large classes have to be split into smaller groups to keep the group size reasonable and the excursion has to be repeated multiple times, or when excursion reports have to be graded. Although the time commitment for each excursion is smaller if the excursion is repeated several times, this time benefit is limited. In addition, there are costs related to excursions, e.g., transportation and lodging, so the number of students that can be taken on an excursion is often limited. Due to these financial costs and time constraints, the number of excursions that are part of a curriculum has decreased for many university programs (Herrick, 2010; Larsen et al., 2020), even though they are considered important for learning, especially in geography and earth and environmental sciences (Jonasson, 2011).

Excursions with out an instructor to lead the group and explain the contents may remedy some of the issues for large group excursions described above. Different approaches and new technologies can be used to support excursions and field trips, e.g., a web interface with additional information on a real-world problem (Brickell and Herrington, 2006), or podcasts to support learning in the field (Jarvis and Dickie, 2010). Mobile guides (Moore et al., 2011; Fränkel et al., 2020) or a combination of mobile guides and paper workbooks (Wissmann, 2013) allow students to visit the sites of an excursion on their own, without an accompanying instructor.

Audio tours (Wissmann, 2013) and self-guided visits of sites close to campus (Moore et al., 2011) ensure that each student hears and sees the information taught during the excursion. Students are more independent and can experience the excursion at their own pace if they do an excursion individually or in small groups (Herrick, 2010). This means that they can look up terms that they do not understand, access background information, or repeat some parts if needed. Furthermore, it is easier to implement theoretical aspects into the written descriptions of self-guided excursions than to talk about these during a normal group excursion. Thus, the important connection between theory and practical experience may be more easily achieved with self-guided excursions (Holgersen, 2021). Finally, self-guided excursions are usually more flexible so that students can do them when it fits their schedule and the timing can more easily be adapted (e.g., to avoid bad weather conditions) than for large group excursions (Larsen et al., 2020; Thönnessen and Budke, 2021).

The results of studies that have evaluated different types of excursions are mixed (e.g., Costabile et al., 2008; Ruchter et al., 2010; Crawford et al., 2017). In a study with small groups of adult participants, the overall experience was similar for an excursion with a human guide, a mobile guide, and a brochure as a guide (Ruchter et al., 2010). However, in another study, it was found that participants had more fun during the excursion when using a mobile phone guide (Crawford et al., 2017). Among other reasons, this may be due to the sense of modernity and innovation that such an excursion offers. Apart from the fun factor, mobile technologies also offer other benefits, such as GPS functionality for simplified orientation and navigation (Medzini et al., 2015) and a broad palette of options to present learning contents (Costabile et al., 2008; Jarvis and Dickie, 2010; Schneider and Schaal, 2018), such as pictures, videos, or audio recordings. Above all, the solutions to questions and exercises can be given directly so that the students immediately know whether they solved an exercise correctly or need to revise their solution. Another advantage is that no reports need to be written and graded after the excursion. The workload for instructors is, thus, not directly tied to the number of students. In other words, for excursions that are visited alone, in pairs, or in small groups, the participation of individuals increases, but the workload for instructors does not increase considerably. Once the rather time-intensive implementation of an excursion is done, the required efforts for running the excursion may get smaller with each realization (Kingston et al., 2012; Thönnessen and Budke, 2021).

However, preparing a self-guided excursion and carrying out such an excursion involves several challenges. Because the instructor is not present in person during the excursion and thus cannot support the students in their learning process, the contents of the self-guided excursion need to be clear and well-designed (Schultz and DeMers, 2020). The area where the excursion takes place needs to be known even better than in the normal case (Krakowka, 2012) because one cannot react to special circumstances, such as potentially dangerous locations, or adjust the route after the students have started the excursion. Therefore, the descriptions and instructions given to the students need to be clear and well thought through. As mentioned earlier, smartphones provide valuable tools that can overcome (some of) these challenges, and thanks to the availability of these devices among students, these tools can be brought into the curriculum without a major logistical challenge (Medzini et al., 2015).

We have used a self-guided excursion based on a smartphone app in an introductory Hydrology and Climatology course at the University of Zurich. Our one-day excursion focuses on water in the city of Zurich. As the development of the excursion had started just before the beginning of the Covid-19 pandemic, we were able to provide the first-year students in Geography and Earth System Sciences at the University of Zurich with a replacement for the usual large group excursion when our university switched completely to online teaching in spring 2020. Based on the students' feedback, we made a few adjustments before carrying out the excursion again in spring 2021.

This paper aims to describe and evaluate the self-guided excursion. First, we describe how the contents of the excursion were implemented in the scavenger hunt application (app) "Actionbound" (www.actionbound.com). Afterwards, we

TABLE 1 | Overview of the topics covered in the Water in the city of Zurich excursion and example activities. The section and number indicate the section (A–D) of the excursion and the stop number.

Subject area	Topic	Activities	Section and number
Water in lakes and rivers	Discharge estimation	Estimation of the discharge in a small creek using the stick method and the Manning-Strickler formula	A2
	Temporary streams	Determination of the state of a temporary (i.e., intermittent) stream (flowing, standing water, dry)	A3
	Lake	Read information text and graphics about the temperature- and water level dynamics in a lake during different seasons	B1
	Hydrometry	Read information text, pictures and graphics about hydrometric methods, compare measurements to direct estimate of the discharge	D2
	Characteristics of different rivers	Comparison of two rivers (discharge, specific discharge, sediment concentration, color) at their confluence	D4
Natural hazards	Sediment transport	Explanation of an underground sediment retention basin	A1
	Flood protection measures I	Watch a video about flood risks and flood protection measures; case study: How would the students react to a specific situation if they were responsible?	B4
	Flood protection measures II	Listen to a radio report about a bridge that has to be replaced to improve flood protection	C4
Sanitation	Emergency wells	Visit of an emergency well, read about their importance for the city, drink the water and smell the taste the difference in the water from different sources	C2
	Groundwater and drinking water	Walk along the "water way" and read the information boards in the area where the city has a groundwater well field and around the water and wastewater treatment facilities, answer questions	D1
History	Canal as part of the city defense system	Walk along the canal and read about its history and characteristics	B2
	Perception of rivers in a city	Listen to a literary text about how an inhabitant of the city perceives the river and how the city and the river affect each other	B5
	History of wells	Visit different wells and fountains and read about their history	C1
	Roman bath culture	Visit an archeological site with information boards about Roman baths	C3
Economy	Fish ladder	Look at pictures and read text about different types of fish ladders; estimation of the length of the largest possible fish that can use the fish ladder	B3
	Hydropower plant	Visit of a hydropower plant, read information about its history, its economic importance, and its influence on the natural ecosystem	D3

evaluate the experiences of the students based on a survey held directly after the excursion, and another one held in fall 2021 (i.e., several months to more than 1 year after the excursion) about what they remembered from the excursion and its contents. Finally, we discuss the advantages and disadvantages of this kind of excursion and provide tips and tricks for implementing a similar excursion in other places. Because every city and excursion is different, our excursion can only serve as an example. We give examples of what could be included in an excursion about water in a city and hope that this description may inspire other university teachers to develop smartphone-based self-guided excursions as well.

DESCRIPTION

Background of the Excursion

The excursion about water in the city of Zurich, Switzerland, is part of the course Physical Geography II, Introduction to Hydrology and Climatology, at the Department of Geography at the University of Zurich. The course is a compulsory course for Bachelor students in Geography and Earth System Sciences. Most students take the course in their second semester at university. The excursion is visited by about 150 students each year. The teaching language is German; thus, the language of the excursion also German. While most students taking the course are native speakers, German is the second or third language for some students; students from the Italian-speaking canton of Ticino form the largest group of non-native German speakers.

Zurich is the largest city in Switzerland, with 430,000 inhabitants and more than a million people living in the larger urban area (agglomeration). The excursion was divided into four sections (A–D), each covering one geographic region of the city. We aimed to have a balanced selection of topics to show the different facets of water and its use, while ensuring that they were all somehow connected. Thus, in each section, the excursion passed by natural watercourses and human-made water structures (**Table 1**). Each section consisted of multiple stops, where the students were asked to answer questions or do some other activity. All stops within a section were located reasonably close together, so that they could be visited by foot. The different sections could be reached by foot, public transport or bike. The entire excursion (i.e., all four sections) could be completed within 1 day. Students were allowed to choose with which section they wanted to start, and had to complete the other sections in

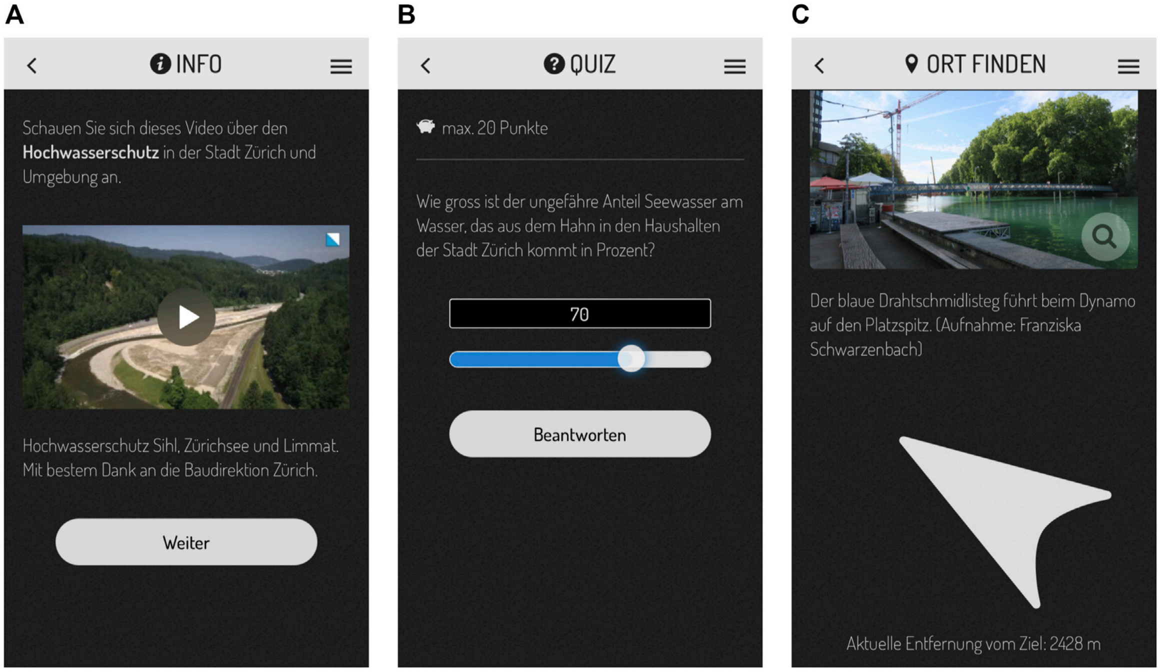

FIGURE 1 | Screenshots of the Water in the city of Zurich excursion in the Actionbound app. **(A)**: video about flood protection measures in the city of Zurich (translation: "Watch this video about flood protection in the city of Zurich and the surrounding area."). **(B)**: "Number slider" for a question about drinking water (translation: "What is the approximate percentage of lake water that comes out of the tap in households in the city of Zurich?"). **(C)**: Picture, arrow and distance to the next stop on the excursion (translation: "To reach the 'Platzspitz', cross the blue 'Drahtschmidlisteg' close to the 'Dynamo' club.")

alphabetic order to avoid large groups of students visiting the excursion together.

There was already a self-guided excursion about water in the city of Zurich, which we used as the starting point for the new smartphone-guided excursion. For this "pen and paper" version of the excursion, the students obtained a workbook with information, directions and maps, and questions and assignments. The students afterwards handed in a report that contained the answers to the questions and assignments, which was then graded. Similar to other studies (Moore et al., 2011), we found it very useful to use an existing excursion or template for the development of the self-guided excursion. The use of this existing excursion as a starting point mainly reduced the amount of time that was needed to identify interesting places in the city that could be visited by the students. However, we had to make many changes to the structure of the excursion, mainly to take advantage of the new possibilities provided by using smartphones, e.g., the inclusion of audio and video material. The students no longer had to write a report but received immediate feedback on their answers, which meant that the questions and tasks had to be restructured. Compared to a "pen and paper" excursion, an excursion with a smartphone does not provide suitable options to include questions that require essay-like answers. The small screen of a smartphone is also not ideal for providing a lot of text. We tried to keep the texts short, but also created an additional pdf file containing all the longer texts included in the excursion. This allows students to read the longer texts already before they start the excursion, or they can make print-outs and read the texts on paper during the excursion.

Implementation of the Excursion

After reviewing several smartphone options, we decided to use "Actionbound" for the implementation of the excursion because it offered a complete package and, therefore, was a time-efficient and convenient solution compared to designing something on our own [as was, for example, done by Pang and Weatherley (2016)]. Actionbound is developed by Actionbound GmbH in Berlin. Actionbound offers an online user interface to create indoor and outdoor scavenger hunts, called "bounds". Implementing a smartphone-based excursion using Actionbound does not require any programming skills. The online user interface is designed to be intuitive and interactive. After half an hour of playing around, all the functionalities can easily be used. There is a user forum in which many questions have already been answered. New questions are usually answered by the development team within a few hours.

Actionbound offers different types of licenses. The lecturer license fits our needs best. For a flat rate of 99 Euros per year, an unlimited number of bounds can be created. These bounds can be used by all students visiting a course from one lecturer. The use of the app is free for the students. There are also other solutions, for example, faculty licenses or licenses that allow a bound to be used a certain number of times, e.g., for outreach events. Actionbound can be tested for free for 14 days. The use of Actionbound for private purposes is free.

TABLE 2 | Media types that can be used in the excursion and examples from the Water in the city of Zurich excursion.

Media	Examples
(Short) texts	– History of different wells – History, use and environmental impact of the hydropower plant – Text about the regulation of the water level of the lake
Pictures and graphics	– Pictures of high flow or low flow situations of a river – Photos of an exceptionally cold period when the lake was frozen – Pictures of the underground sediment collector – Visualization of the "positive rheotaxis" (of fish and how that can be used for fish ladders) – Graph showing the stage-discharge-relationship of the Limmat at the gauging station in Zurich
Videos	– Video explaining the stick method for discharge estimation – Video about the flood risk in Zurich and the measures taken to protect the city from these risks – Video of a discharge measurement in the Limmat using a current meter
Audio	– Short audiobook of a literary text about the Sihl, the wilder river in Zurich – Radio report on the renewal of a bridge as part of the flood protection measures
Information boards elsewhere	– Information boards from the local authorities about the drinking water supply – Information boards from the local authorities about the Roman baths
Objects in the city	– Physical staff gauge in the Limmat and the Schanzengraben to read the water level – Fish ladder

TABLE 3 | Question types and examples from the Water in the city of Zurich excursion.

Question type	Examples of questions
Multiple choice	Multiple correct answers: – Which flood protection measures were mentioned in the video? – What factors contribute to the exceptionally high flood risk for Zurich? One correct answer: – What is the reason for the higher specific mean discharge of the Limmat than the Sihl? – What is the mean residence time of the water in the lake of Zurich?
Enter free text	– What is the name of the street that follows the route of the former Sihl channel? – How many lake waterworks does Zurich have?
Number slider	– How much bigger is the environmental burden of 1 L of bottled water compared to 1 L of tap water? – Under the assumption that the fish ladder in the Schanzengraben meets the legal requirements for its length, how long (in cm) is the longest fish that you can expect here?
Sort list	– Put the four pictures showing the temperature distribution in the lake in the following order: winter—spring—summer—autumn.
Survey	– If you were responsible for the safety of the city of Zurich, how would you react to the flood risk in May 2013? – Which flow class did you observe in the temporary stream?
Upload picture	– Upload a picture showing where you estimated the discharge using the stick method. – Upload a selfie with the emergency well. If you don't feel comfortable with uploading a selfie, take a picture of your shoe.

Students can access a bound (i.e., the excursion) with the app using a QR code or the title of the bound. The full bound can be downloaded at once, so that cellphone coverage is not necessary during the excursion. The app then guides the students to the places of interest, provides information in various formats, and gives assignments to complete and questions to answer (see screenshots in **Figure 1**). The students collect points by finding the right locations, answering questions correctly, and completing assignments. The results are uploaded as soon as a student has finished the excursion. The user interface of the instructors then shows the answers to the questions, the files that were uploaded by the student, the number of points obtained for each step or question, and the time used to complete each individual step and the complete bound. In our case, the students needed to complete the bound and obtain a minimum number of points to pass the excursion. There was no competition among the students regarding the number of points obtained, but this element can potentially be used to motivate students. It has been shown that, in general, students tend to respond well to some added pressure with a point collection system (Krakowka, 2012).

The locations that the students need to visit during the excursion are stored in the bound. This can be done by either clicking on the corresponding point on a map or by entering

TABLE 4 | Time investment for the development of the smartphone-based self-guided excursion.

Task	Approximate time used
Implementation of the original structure of the "pen and paper" excursion into Actionbound	8 h
Updating the excursion material, search for additional information	20 h
Re-structuring of the excursion, implementation of new contents, adjustments after feedback and tests	50 h
Test runs	20 h
Create information files for students	5 h
Communication with students, verification of student visits	15 h

the coordinates. These components serve as a guideline throughout the entire excursion: all the sites that the students should visit are stored this way. To make it easier for the students to find the correct locations, we also added pictures that indicated the correct way and the points of interest. These pictures were meant to be helpful, especially for students who had issues with the GPS on their smartphones.

The bound can be filled with different media, such as texts, pictures, videos, or audio recordings (**Table 2**). These can be uploaded in the most common formats (e.g., jpeg, png, mp3, mp4) to a media library. Thus, no special file formats are needed, which was the case some 10 years ago (Moore et al., 2011). In addition to providing information and waypoints, there are many possibilities to design quizzes and exercises for the students (see examples in **Table 3**). The responses of the students were automatically graded, except for the survey questions or the upload of a picture (because there is no right or wrong answer in these cases). To keep the students motivated, the level of difficulty was chosen in such a way that the questions were not trivial but also not too difficult. As a result, the students could answer the questions correctly if they tried to solve them conscientiously and, thus, collect many points. In multiple-choice type questions, points were given for partially correct answers as well. When entering a free text, different ways of expressing the answer were accepted, and for the number slider, we gave partial points for values that were close to the correct one. To improve the learning experience, the correct answer was shown directly after the question if it was not answered correctly. For more complex concepts (e.g., the influence of changes in the riverbed on the stage-discharge-relationship), an additional explanation that included an explanatory graphic was shown if the question was not answered correctly.

Realization of the Excursion

Table 4 gives an overview of the approximate time investment for the realization of the self-guided excursion. This started with the decision to use Actionbound and ended with the implementation of the feedback from the students after they visited the excursion. Of course, the time required strongly depends on how much time needs to be invested in finding interesting sites (and thus how familiar someone is already with the area), as well as the scope and length of the excursion, and the time required to get to the start of the excursion for the test runs. Implementation of the structure of the original pen and paper-based excursion was done within one workday. Implementing the new contents and the new structure took the most time.

Before the students went on the excursion, we tested the different sections several times to ensure that the stored locations were correct and everything worked. These tests were also valuable for taking the pictures that were used as descriptions or illustrations. Additionally, one student visited the excursion before the other students and provided us with detailed feedback and comments that we implemented before the entire class took the excursion.

Although the primary time commitment was the initial implementation, some effort was still required during the excursion time to ensure that everything worked out fine and that the students received help if they faced difficulties. We tried to be available for the students *via* e-mail and provide them with instant help and answers when they had problems with the app or the GPS on their smartphone.

As mentioned before, the students collected points during the excursion by passing by specific locations, correctly answering the questions, or completing certain assignments, and needed to collect a minimum number of points to pass the excursion. We checked the number of points that each student collected, as well as the time that it took them to complete the bound to ensure that they visited the entire self-guided excursion. In the first year, it was rather time-consuming to check if all the students completed the excursion. For the second year, extensive testing and attendance behind the scenes were not needed to the same extent, and many tasks could be delegated to student assistants. Thus, the effort required from the instructors in this second year was significantly smaller than for the traditional group excursion, especially because the group excursion was usually repeated multiple times due to the large number of students in the course. We assume that we can continue to use the self-guided excursion in the coming years without significant additional efforts. Some minor updates and changes as well as double-checking that all points can still be reached may be required to keep the excursion up to date. If this is done on a regular basis, we see no reason why the excursion would be outdated after a few years.

EVALUATION

We gave the students the option to provide feedback after each section of the excursion and asked them to complete a survey about their experiences after they had completed the entire excursion. We received answers from 86 of the 162 students who completed the excursion in 2020 (53%), but after the 2021 excursion we only received answers from 21 of the 136 students

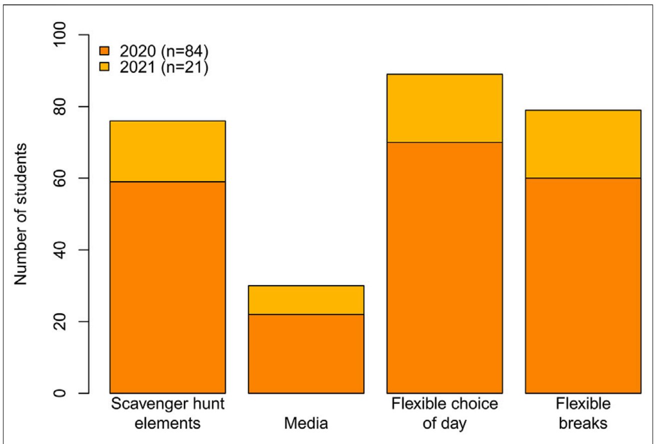

FIGURE 2 | Elements of the self-guided excursion that students rated as especially valuable. Most students appreciated the flexibility and scavenger hunt elements of the self-guided excursion (results from the survey sent out directly after the excursion).

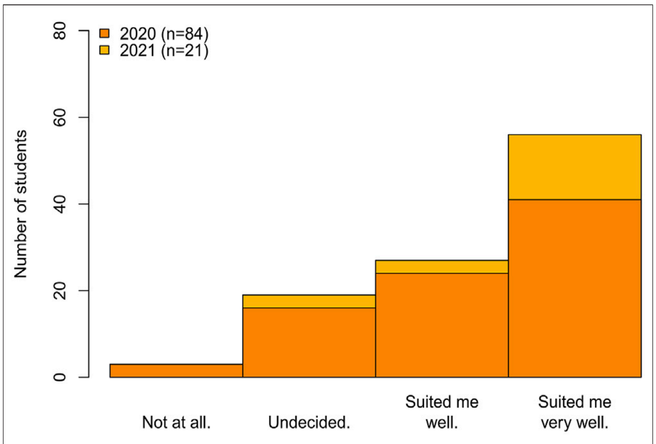

FIGURE 4 | Answers to the question "How well did it suit you that the excursion took place in Zurich?". It suited the majority of the students well or very well that the excursion took place in Zurich (results from the survey sent out directly after the excursion).

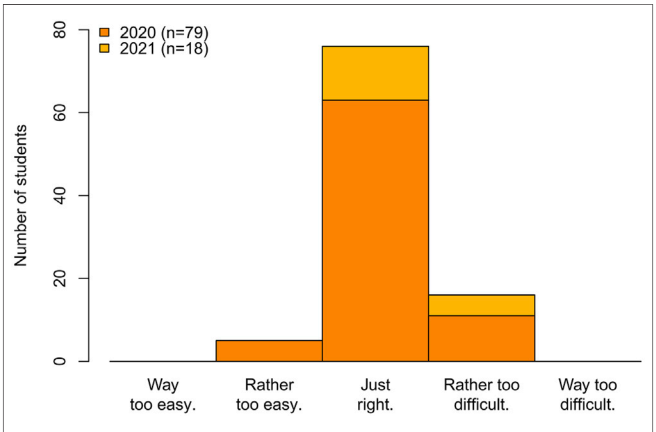

FIGURE 3 | Answers to the question "How would you rate the difficulty of the excursion?". Most students considered the level of difficulty to be just right. Only a few students found it rather too difficult or rather too easy (results from the survey sent out directly after the excursion).

who completed the excursion (15%). As we were more reliant on the students' feedback in the first year, we had a raffle (free cinema tickets) for helpful feedback, which we did not have in the second year. This may explain a large part of the difference in response rates for the 2 years. A follow-up survey was sent out in fall 2021 (i.e., five, respectively, 17 months after the excursion), which was answered by 92 students: 43 students did the excursion in 2020 and the other 49 in 2021. However, some of the students did not answer all the questions. Because only a small portion of the students filled in the survey, the answers are not fully representative but provide more of an indication of how the excursion was perceived. The information from these surveys was nevertheless valuable to improve the excursion. For instance, the additional pdf file containing all the longer texts of the excursion and the additional pictures showing the path that the students need to follow originated from the students' feedback. The option to upload a photo of the visited site if the GPS did not work as an alternative for getting the points to find the site was also implemented after the first use of the excursion.

Impressions of the Students Directly After the Excursion

Directly after the excursion, most students indicated that they appreciated the flexibility that a self-guided excursion offers (**Figure 2**). The flexible choice of the excursion day was rated even higher than the flexibility to take breaks during the excursion. Several students mentioned in the open comments that they appreciated the ability to choose the speed of the excursion on their own. Thus, the flexibility during the day seems to have been very valuable too. Most of the students also indicated that they liked the scavenger hunt elements that the self-guided excursion offers because they made the day more fun. The different types of media that were included in the excursion were not mentioned as one of the most valuable features, but they were also not considered a negative aspect. In 2020, 87% of the students who completed the survey thought that the different question types made the excursion varied and did not think that certain question types were not so suitable; 95% of the students answering this question in 2021 shared this opinion.

Most students indicated that the level of difficulty was appropriate and that they were neither over- nor under-challenged (**Figure 3**). About a sixth of the students had some issues with understanding the contents or solving specific tasks and therefore rated the excursion as rather too difficult. A few students would have wished for some more challenging exercises and found the excursion contents rather too easy for the level of studies. None of the students considered the level of difficulty to be completely off.

Most students appreciated that the excursion took place in the city of Zurich, where many of them live (**Figure 4**). They mentioned that the travel distances, and thus travel time and

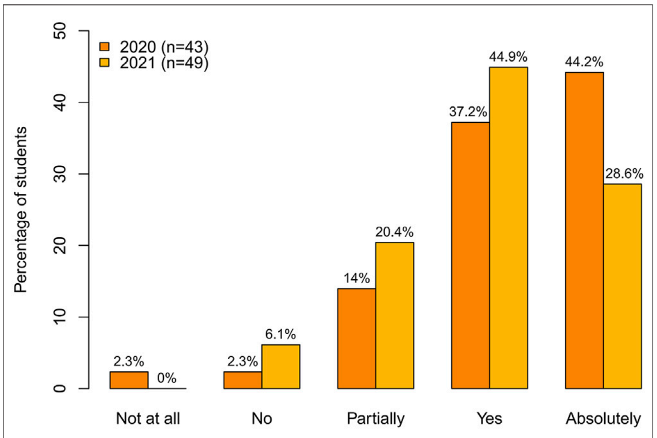

FIGURE 5 | Agreement with the statement "I had fun on the excursion". Most students enjoyed the excursion but students who completed the excursion in 2020 rated the fun factor higher than the students who completed the excursion in 2021 (results from the survey sent out in fall 2021, 5 and 17 months after the excursion, respectively).

costs, were kept low this way and that they liked getting to know the city where they are studying better, and in a different way. They frequently mentioned that they had been living in or around Zurich for many years but never realized all the different facets of water in their city and, thus, enjoyed this new focus. They also appreciated that—thanks to the relatively short distances between the different stops, more environmentally friendly modes of travel (i.e., public transport, bicycle, or walking) could be chosen than the bus for a typical group excursion. However, despite these advantages of an excursion in the city of their university, some students mentioned that they would have preferred an excursion to a mountainous area or a more remote area without so many people and noises. This was mainly mentioned by students who did the excursion in 2020 when an excursion to the Alps was planned and announced at the beginning of the term but had to be cancelled. In 2021, this alternative was never mentioned to the students.

The main criticism from the students was that the excursion was too long or that it took them more time than the 6–7 h that we had assumed. However, we calculated the average time that students needed to complete the excursion in 2021, and it was 6 h (standard deviation: 1.4 h), including breaks. The additional comments to this question indicate that this impression was related to the walking distances. Many students commented that walking through the city for several hours on a hot summer day or while it was raining was too long. Students perceived the walking distances to be exhausting and were potentially not adequately prepared, e.g., they were not wearing appropriate shoes or did not expect any physical effort because the excursion took place in a city. If public transport is used where it is recommended, the total walking distance is ~11 km. If public transport is only used for the longer distances between the four sections, the walking distance is almost 16 km. Related to the duration of the excursion, some students mentioned that the battery consumption of the app was too high or that they forgot to bring a power bank. A handful of students also mentioned that their GPS did not work.

The students also mentioned that they could not socialize with their classmates or get to know more people during the excursion. We also see the lack of a social aspect as a downside of a self-guided excursion. In the first year, we requested that the students complete the excursion on their own to ensure safe distances with regard to Covid. We did not say that the students have to do the excursion on their own in the second year but they still had to sign up for a time window (to keep potential group sizes small). As a result, many students visited the excursion in pairs or small groups in 2021. They mentioned in their feedback that they enjoyed solving problems together, helping each other when difficulties occurred, discussing their ideas and impressions, and having fun during the day.

Impressions of the Students Several Months After the Excursion

The survey that was completed about 1.5 years after the excursion suggests that the students who took the excursion in 2020 had a lot of fun, even though many of them visited the excursion alone. The students who took the excursion in 2021 also enjoyed the excursion, but overall did not rate the fun aspect quite as high (**Figure 5**) when answering the same survey about 5 months after completing the excursion. However, in the surveys completed directly after the excursion, the percentage of students considering the excursion fun or very fun was similar (about 77%; but note that far fewer students returned the survey in 2021 than in 2020). The selfies that we asked the students to upload at one of the stops included a lot of smiling faces in 2020 and 2021, which may also indicate that the students had fun on the excursion in both years. The evaluations of the course of which the excursion is a part were better in 2020 than for any other year before. This suggests that many students valued the extra efforts of the instructors during the unexpected situation and that they were happy that the excursion was not cancelled completely but that an alternative smartphone-guided excursion

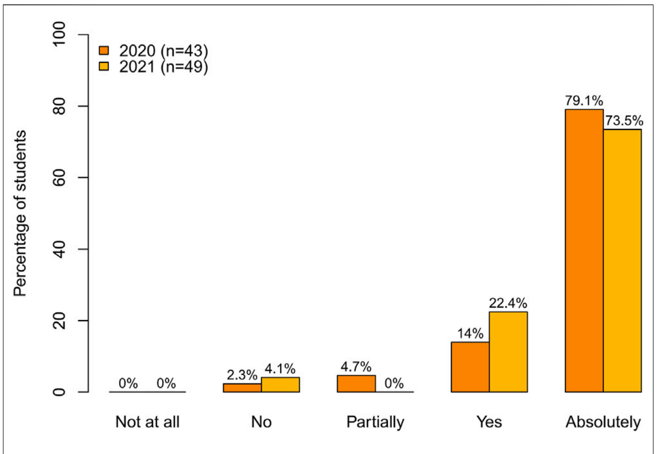

FIGURE 6 | Agreement with the statement "The excursion felt different to our normal studies". Almost all students considered the excursion to be very different from the usual study setting (results from the survey sent out in fall 2021, 5 and 17 months after the excursion, respectively).

was offered. Alternatively, it could be that after the lock-down in 2020, the students were very happy to be outside again.

For all the other questions, such as how different the excursion felt to their normal studies (**Figure 6**), if the students found the smartphone-guided excursion innovative, if they felt that they learned something during the excursion, and questions regarding the organization of the excursion, there were no clear differences between the responses of the students from the 2 years. Overall, the feedback was very positive in both years. There was also no clear preference for one excursion type: 21% of all the students who answered the survey recommended a self-guided excursion instead of a group excursion for other courses as well, 38% were undecided between a self-guided excursion and a traditional excursion, 25% would rate a traditional excursion slightly higher if they had the choice, and 16% would prefer a traditional excursion over a self-guided excursion.

Potential for Learning

Because we never held the "Water in the City of Zurich" excursion as a group excursion, we cannot compare how much the students learned on the self-guided excursion to what they learned on a traditional excursion. However, from the survey that we asked the students to fill out several months after the excursion, we can still make a statement about the potential for learning during the self-guided excursion. Based on the answers to the question about what comes to their mind first when they think about the excursion (two exemplary answers shown below), we can infer that many students thought that they learned something or that the excursion was informative and diverse:

– "*neue Einblicke in bekanntes Gebiet, heisser Tag, anstrengend, aber lehrreich*" ("new insights into a known area, a hot day, exhausting, but informative")
– "*Ich fand sie* (die Exkursion) *super spannend. Zum einen lernte ich viel über Wasser aber mit den Spaziergängen auch viel über die Stadt Zürich.*" ["I found it (the excursion) super-interesting. On the one hand I learned a lot about water but with the walks also a lot about the city of Zurich."]

About 55% of the students said they could remember the contents equally well or even better than for a typical group excursion. More than 75% of the students answered that they still think about the contents of the excursion when they walk through the city and more than 60% already told someone else about something that they learned during the excursion. From the comments, it appears that the exceptionalities taught during the excursion were most firmly anchored in the students' memories. For example, the students seem to best remember the existence of the more than 80 emergency wells that deliver fresh water to the city in case of an emergency in the water supply system, and that the river Sihl flows through the main train station and that this increases the flood risk considerably. The answers to the specific knowledge questions that we asked in the survey several months after the excursion reflect the same. Questions about specific facts were mainly answered correctly, while the quality of the answers for more technical questions differed a lot. For example, the question about the purpose of the enrichment basins in the groundwater well field was only answered correctly by 30% of the students, while 20% chose one of the two wrong answers and 50% said that they did not remember the answer to this question. Even though the hydrological details were forgotten, the students indicated that they remembered the stops where they learned these contents very well and thought about the excursion when they passed by these places at a later time.

DISCUSSION

Benefits of Self-Guided Excursions

Mobile technologies can be useful in learning settings and support the conceptualization of new content and scaffolding processes (Brickell and Herrington, 2006; Lai et al., 2007). A smartphone based self-guided excursion combines a field trip, a teaching method that is generally liked by students (Krakowka, 2012), with innovative smartphone applications for learning, which are also highly appreciated by students (Kingston et al., 2012). Our results confirm these previous findings and show that the students enjoyed visiting the self-guided excursion and the scavenger hunt elements and gamification aspects because they make learning more fun. We see a lot of advantages of self-guided excursions, especially for large student groups. The students are no longer passive listeners but need to be engaged and complete individual assignments, which may help them to understand the concepts taught during the excursion. The students receive immediate feedback and there is no grading of reports. One could argue that with increasing group size, the advantages of a self-guided excursion outweigh the disadvantages, such as the lack of the group experience and the lack of possibilities to directly ask questions. An excursion with a small group of students and an expert may offer better learning opportunities than a self-guided excursion using smartphones due to the intensive student-teacher interaction. However, this is for many courses not feasible and the average student-teacher interaction during traditional large group excursions is marginal. For these courses, a self-guided excursion using a smartphone may improve individual learning. However, more research about the effectiveness of excursions using mobile technologies compared to that of traditional group excursions is needed.

Another big advantage of a self-guided excursion compared to a traditional group excursion is the flexibility and independence in terms of schedule. Because the excursion is individual, students can more easily fit the excursion in their schedule and if they cannot join on the day that they planned to do it (e.g., due to illness), it is much easier to complete the excursion on a different day. This flexibility was highly appreciated by the students (**Figure 2**) and agrees with the experiences of other university teachers (e.g., Wissmann, 2013). One can assume that the demand for flexible and individual approaches may be even higher in the post-pandemic world because students became used to a flexible learning environment (e.g., asynchronous lectures) during the pandemic. Aside from the flexibility for the students, the organization of a self-guided excursion is also more flexible for the instructors because they do not need to reserve a particular timeslot to accompany the excursion.

Benefits of an Excursion in the City

Our excursion is certainly not the first physical geography or geosciences excursion to take place in a city. There are, for example, geology excursions that guide students to different buildings to look at different rocks. However, most excursions in physical geography and geosciences take place in mountainous areas or other places where it is possible to observe natural processes or human-nature interactions. Students who are used to being outdoors, e.g., because they are used to go camping or hiking, have an advantage over students for which this terrain is unfamiliar. It also means that students need to have appropriate gear and a certain level of fitness to be able to participate in these types of excursions. This requirement for gear and outdoor experience contributes to the geosciences not being inclusive (e.g., Wechsler et al., 2005; Huntoon and Lane, 2007; Gates et al., 2019). A smartphone-based excursion taking place in a city can reduce these inequalities and thus help to make excursions more inclusive.

It is also much easier to implement a self-guided excursion in a city. Compared to a remote area, there are usually fewer safety concerns (although new issues may arise, such as risks due to traffic or crime). A well-connected and central city is easier to reach than remote sites. This applies not only to the students but also for the test runs that need to be done during the development of the excursion. Furthermore, a diverse range of topics may be found within a shorter distance in a city than in a natural area. Additionally, one can expect a better and more continuous cellphone reception in a city, which is valuable for safety reasons and to look up additional information (the full bound can be downloaded in advance).

Our decision for an excursion in the city of the university meant that many of the students had already been to some of the places of the excursion and that it is likely that they will pass by these places again after the excursion. Our surveys suggest that students do indeed return to these places and that they are then reminded about the excursion and its contents. Many students also used this as a teaching moment and explained what they learned to others. In other words, there may be long-time learning beyond the excursion day itself. Moore, Kerr and Hadgraft (2011) showed that it is valuable to revisit sites again after the excursion. It has been suggested that by already being familiar with some of the sites, the "novelty space" is reduced and the working memory can focus on the new content (Orion and Hofstein, 1994), so that it is easier to assimilate new information than in a completely new environment.

Recommendations for Developing a Smartphone-Based Self-Guided Excursion

Self-guided smartphone excursions are a valuable tool in geography education and make use of the new opportunities that mobile technologies offer. Even if a traditional group excursion is possible, this new kind of excursion should be considered as well. If for some reason, a group excursion must be cancelled or is no longer feasible, e.g., because the student numbers are too high, a self-guided excursion should be considered instead of cancelling the excursion completely. We can recommend such an excursion in the city of the university or, more generally, in a place more unusual for an excursion in physical geography. Students appreciate this kind of replacement, especially if they can complete the excursion in pairs or small groups. In contrast, the replacement of the excursion with an online assignment in a similar case was not liked by the students (Gašparová and Kyseľová, 2020). When repeating the excursion for multiple years, the efforts required to implement the excursion in the beginning (**Table 4**) are small.

We recommend that instructors who consider developing a similar excursion plan enough time for preparation and, if possible, to build the self-guided smartphone excursion based on previous material, such as an existing excursion or route along interesting spots. We also recommend using various media to keep the excursion as interesting as possible. Question types should be varied as much as possible as well to avoid different tasks getting boring. However, not too much typing should be required to answer the questions. It will be frustrating for the students if a correct answer is graded wrong because of an auto-correction algorithm (which is often the case for jargon) or typos that are not recognized as typos by the mobile application.

There are different reasons to keep the level of difficulty rather low. First, students will be more motivated when they realize that they can solve the questions (and vice versa get frustrated if they answer too many questions wrong). Furthermore, there is no possibility to ask questions directly if something is unclear. An appropriate (or somewhat low) level of difficulty reduces the risk that students are lost and struggle to understand any of the contents during the excursion. We considered a large range of answers correct, and many answers could be found directly on information boards or in the media that were included in the bound, so that it was rather easy to collect points on the excursion. The main goal of using the app was to guide the students along interesting places in the city and not to create a test or let them answer challenging questions. The majority of the students considered this level of difficulty appropriate (**Figure 3**). Therefore, we can assume that the excursion was still not perceived as trivial. Additionally, the survey results showed that it is not the more complicated details that students remembered after a few months, but the interesting facts. To reach the ultimate goal that students remember as much as possible from the excursion, it is thus advantageous to also include relatively easy but interesting (or surprising) content.

Since our target group are first-year undergraduate students, it was acceptable to include very few quantitative and higher-level questions in the excursion. For the estimation of the different components in the Manning-Strickler formula, we asked the students to enter the intermediate steps of the calculation as an answer to a free text question. We considered all estimates within a reasonable range as correct and provided the students with some guidance if they needed to adjust their numbers. The students had to enter the calculated discharge also as a free text question. This answer had to be within a reasonable range to be counted as correct. For upper-level or graduate-level classes, more quantitative questions and demanding tasks may be required. One option to include these types of assignments is to ask the students to solve a certain task on a piece of paper (e.g., to write down their calculations or to make a sketch (e.g., a geologic map)) and have them upload a picture of it in the app. Alternatively, one can also ask for a text, a video or an audio submission. Automatic grading is not possible in these cases and the instructor will thus have to review the solution after the excursion is finished. If this is only the case for a few assignments, and the number of students is not too high (which is usually the case in graduate-level courses), this may be a reasonable workaround to not being able to grade a question directly in the app.

The students' feedback showed that if an excursion takes too long or is longer than expected, the fun aspects of the smartphone-based excursion fades. Even though the self-guided excursion does not take as long as the previous full-day group excursion (6 instead of 10–12 h), it seemed that for some students this type of excursion feels more exhausting than a group excursion. This may be due to the higher effort that is required of the students. On a self-guided excursion, students are mentally engaged the entire time. In contrast, group excursions often include more downtime (such as during transport, walking, waiting for other group members to arrive, etc.). To avoid the excursion taking longer than expected, we suggest to provide the students with a schedule that assumes a slow pace, so that they will be happy if they are faster than expected and not frustrated that it takes them longer than planned. To ensure that students are mentally and physically prepared for the excursion (e.g., wear appropriate shoes and clothing), the duration of the excursion and the walking distances should be announced clearly. To avoid the drop in the fun-factor (and probably also engagement), a self-guided excursion can also be split into several parts that can be visited on different days (as suggested by Wissmann (2013)).

We recommend sending students in small teams because no direct teacher-student interaction is possible on a self-guided excursion. This way, students have the possibility to discuss the contents with each other and to help each other to understand the assignments. Furthermore, students seem to enjoy being on the road with each other. Small groups of two to four students seem to be a good compromise between individual engagement and the social aspect of an excursion.

There are more options to cheat on a self-guided excursion than on a traditional group excursion that is not graded and where you are either present or absent. Technically, one student could visit the excursion with the smartphones of several other students. Moreover, there are ways to pretend that a smartphone is in a certain location, and thus all stops could be "visited" while sitting at home in front of a screen. Although these risks cannot be eliminated entirely, they are reduced if students are asked to upload a picture at some point during the excursion. As mentioned before, we checked the time that the students needed to complete the excursion and the points they achieved, prior to giving them the mark that they passed the excursion. These checks are easily possible with tools like Actionbound. We did not find any indication that cheating was a problem. As excursions are generally well-liked by students, one can expect that most students will not try to cheat in this part of a course.

Finally, we recommend to prepare a document with all the information that the students require before they visit the excursion, such as clear instructions on what they can expect, an indication of the time needed to complete the excursion, walking distances, as well as the equipment needed on the excursion and technical preparations (e.g., to download the required app, the bound, and further materials). It is also helpful to tell the students to take a power bank (or charger) with them as they are heavily dependent on their smartphones during the excursion. Moreover, factors reducing the experience, such as long texts that are hard to read on a small display or due to sunlight on the screen, or a non-functioning GPS should be reduced as far as possible, or alternatives should be given (Ruchter et al., 2010; Kingston et al., 2012).

CONCLUDING REMARKS

Smartphone-based self-guided excursions provide an interesting and useful new opportunity to organize excursions in university teaching. With higher student numbers and limited resources and an increasing number of possibilities on how to use smartphones for learning, smartphone-based excursions may gain importance in the coming years. Students seem to like the new way of exploring their surroundings and learning at their own pace. Furthermore, this kind of excursion offers excellent opportunities for direct feedback, which makes learning more effective and reduces the efforts of instructors to grade excursion reports. Compared to a traditional large group excursion, where there are always students standing in the back and cannot hear what the instructor is saying, self-guided excursions bring learning down to an individual level and potentially increase the mental engagement of each student. In addition, the students appreciate the flexibility that it provides during the day and the possibility to choose an excursion day that fits their schedule.

We hope that the excursion about water in the city of Zurich presented in this paper inspires other instructors to create similar excursions. New self-guided excursions may help to curb the trend of having fewer and fewer excursions in geography and geoscience-related study programmes. However, not every traditional excursion can be replaced by a self-guided smartphone excursion. For example, dangerous sites such as glaciers cannot be explored using a smartphone excursion. Thus, one should carefully consider suitable sites for a self-guided smartphone excursion. This may be an unconventional site that would not be visited during a traditional group excursion. Water in the city can be an interesting topic for such an excursion because there are a lot of possible places to explore. If the chosen city is the hometown of the students or close to where they live, they are likely to pass by the places of the excursion again. They are then reminded about the contents of the excursion, and may also tell others about what they learned during the excursion.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

JS and HvM had the idea for the self-guided smartphone excursion and acquired the funding. FS implemented the excursion in Actionbound. HvM and JS tested the excursion and gave feedback for improvement. FS sent out the surveys to the students and analyzed the answers. FS wrote the first draft of the manuscript. All authors reviewed and edited the manuscript.

FUNDING

The conversion of the former "pen and paper" excursion into a self-guided smartphone-based excursion was funded by the Competitive Teaching Fund of the University of Zurich (Project Number 15 in the year 2019). More information can be found here: https://www.lehrkredit.uzh.ch/en/competitive/projects-2019/2019_15.html

ACKNOWLEDGMENTS

We thank the students who took GEO121 in the spring semesters of 2020 and 2021 for filling out the surveys and providing us with their valuable feedback. Hannah Maria Luck was the first student to test the excursion and provided extensive feedback. Sandra Pool created the original "pen and paper" version of the self-guided excursion. Leonie Schäfer and Joshua Haas helped with the organization of the excursion in spring 2021. We thank the two reviewers for their valuable comments.

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frontiers | Frontiers in Environmental Science

ORIGINAL RESEARCH
published: 16 May 2022
doi: 10.3389/fenvs.2022.877327

On-Campus Field Experiences Help Students to Learn and Enjoy Water Science During the COVID-19 Pandemic

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OPEN ACCESS

Edited by:
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Reviewed by:
Christos Troussas,
University of West Attica, Greece
J.P. Gannon,
Virginia Tech, United States

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Specialty section:
This article was submitted to Freshwater Science, a section of the journal Frontiers in Environmental Science

Received: *16 February 2022*
Accepted: *06 April 2022*
Published: *16 May 2022*

Citation:
Saup C, Lamantia K, Chen Z, Bell B, Schulze J, Alsdorf D and Sawyer AH (2022) On-Campus Field Experiences Help Students to Learn and Enjoy Water Science During the COVID-19 Pandemic.
Front. Environ. Sci. 10:877327.
doi: 10.3389/fenvs.2022.877327

Online modes of teaching and learning have gained increased attention following the COVID-19 pandemic, resulting in education delivery trends likely to continue for the foreseeable future. It is therefore critical to understand the implications for student learning outcomes and their interest in or affinity towards the subject, particularly in water science classes, where educators have traditionally employed hands-on outdoor activities that are difficult to replicate online. In this study, we share our experiences adapting a field-based laboratory activity on groundwater to accommodate more than 700 students in our largest-enrollment general education course during the pandemic. As part of our adaptation strategy, we offered two versions of the same exercise, one in-person at the Mirror Lake Water Science Learning Laboratory, located on Ohio State University's main campus, and one online. Although outdoor lab facilities have been used by universities since at least the 1970s, this research is novel in that 1) it considers not only student achievement but also affinity for the subject, 2) it is the first of its kind on The Ohio State University's main campus, and 3) it was conducted during the COVID-19 pandemic, at a time when most university classes were unable to take traditional field trips. We used laboratory grades and a survey to assess differences in student learning and affinity outcomes for in-person and online exercises. Students who completed the in-person exercise earned better scores than their online peers. For example, in Fall 2021, the median lab score for the in-person group was 97.8%, compared to 91.7% for the online group. The in-person group also reported a significant ($p < 0.05$) increase in how much they enjoyed learning about water, while online students reported a significant decrease. Online students also reported a significant decrease in how likely they would be to take another class in water or earth sciences. It is unclear whether the in-person exercise had better learning and affinity outcomes because of the hands-on, outdoor qualities of the lab or because the format allowed greater interaction among peers and teaching instructors (TAs). To mitigate disparities in student learning outcomes between the online and in-person course delivery, instructors will implement future changes to the online version of the lab to enhance interactions among students and TAs.

Keywords: hydrogeology, geoscience education, pandemic, laboratory, groundwater

INTRODUCTION

The COVID-19 pandemic forced a shift towards online teaching and learning, where educators at every level initially operated in "triage mode" (Kilpatrick et al., 2021). Large numbers of faculty who had never taught online (and/or had never taken classes online) were suddenly responsible for teaching students exclusively online. Moreover, most students were also unfamiliar with the administration of classes in an online setting. This sudden shift in online learning exacerbated systemic barriers for students (e.g., students with weaker academic backgrounds learn better in face-to-face classes, and internet/technology access is not evenly distributed). The lack of instructor and peer interaction and feedback also resulted in sharp decreases in student satisfaction (Kanetaki et al., 2021; Sahu 2020; McCarthy 2020; Zhai and Xue 2020). Although in-person teaching restrictions eventually eased with the development of university health and safety protocols, online education will remain a component of educational models for the foreseeable future. It is therefore critical to understand the implications for student learning and their interest in or affinity towards the subject matter.

It is well documented that students are more likely to master course content when they are active participants in their learning. Experiential learning theory suggests that active participation and outcome observation lead to greater conceptual understanding and longer-term retention of course content (Kolb 2015). These learning experiences often include multisensory integration, which allows the brain to process and integrate new information more effectively to facilitate longer-term learning (Persellin and Daniels 2015). Of note, inquiry-based exercises enhance learning by fostering critical thinking and problem-solving skills (Duran and Dökme 2016). Furthermore, field-based exercises provide effective opportunities for students to integrate course material with hands-on field experiences (Trop et al., 2000; Salvwage et al., 2004; Dripps 2019). These types of exercises are especially important in STEM classes, where poor teaching methods are the primary reason that students abandon STEM majors within their first 2 years of higher education (Seymour and Hewitt 1997).

Since at least the 1970s, college campuses have created and used outdoor laboratory spaces as a strategy for providing students with field-based training in STEM subjects (Lawrence, 1975), and their use has continued to grow (Berman et al., 2008; Schwartz 2013). In water sciences, a subject that deals almost exclusively with outdoor processes, instructors have gravitated toward the chance to move teaching from traditional indoor classrooms to outdoor spaces (Hakoun et al., 2013; Van Loon, 2019). In ideal scenarios, outdoor lab spaces are located within walking distance of classrooms, providing easy access within the relatively short lecture and laboratory periods (e.g., (Oliver et al. 2018). The myriad learning benefits these facilities offer students are well-documented and remain a potential socially distanced option for instructors to grant students hands-on learning experiences.

The Mirror Lake Water Science Outdoor Laboratory is a multi-use outdoor training facility for earth science and hydrology students in the heart of The Ohio State University (OSU) main campus (**Figure 1**). It occupies the South Oval and areas around Mirror Lake, a recently restored lake that has been an iconic recreational space for almost 150 years. The outdoor laboratory facility includes a network of wells and two telemetered sensors that continuously stream water quality data for the lake and groundwater (**Figure 1**). Thanks to its central location on campus and outdoor setting, the Mirror Lake Water Science Outdoor Laboratory was one of the few sites where earth science students could develop new field skills during the pandemic, particularly early in the Fall 2020 (FA20) semester. Our motivation for this research is to enhance learning and engagement for introductory earth science students. Specifically, the goal of this paper is to share our experiences following an adaptation of a field-based laboratory activity at Mirror Lake to accommodate over 700 students in our largest-enrollment general education course during the pandemic. Although the benefits of hands-on, field-based training have been well-documented, this research is unique in that 1) it considers both student achievement and affinity for the course subject, 2) it is the first of its kind on The Ohio State University's main campus, and 3) it was conducted during the COVID-19 pandemic, enabling us to assess student performance and

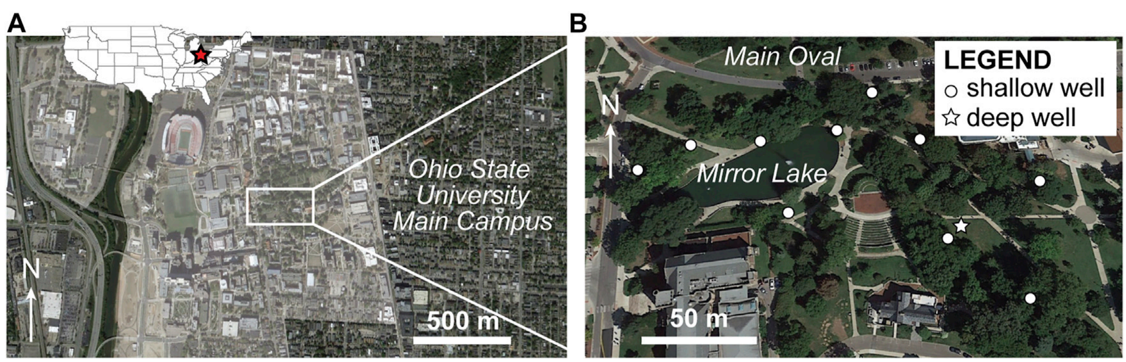

FIGURE 1 | (A) Map of Ohio State University Main Campus in Columbus, Ohio. **(B)** Location of the Mirror Lake Water Science Learning Lab, which hosts ten shallow wells and one deep well for educational activities.

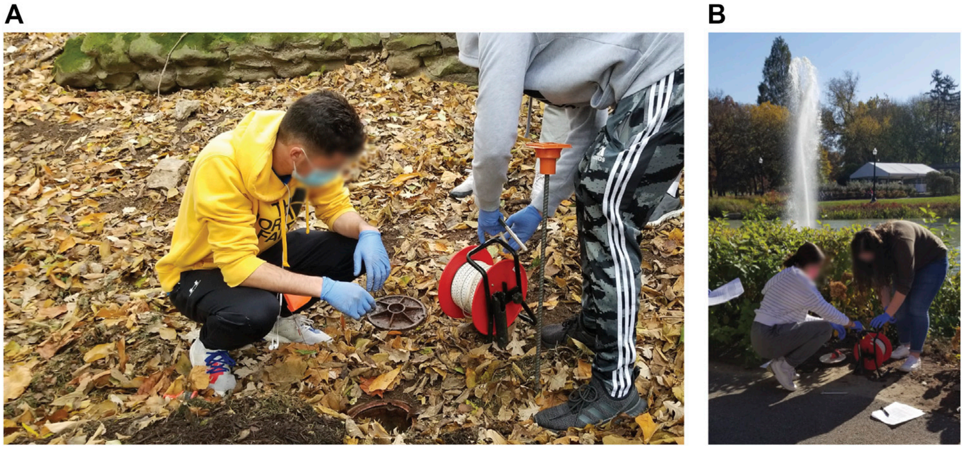

FIGURE 2 | (A, B) Students in general education class ES 1200: Introductory Earth Science Lab used a beep tape to measure depth to water in shallow wells during the pandemic. Masks were required for participation, and laboratory gloves were provided. Photographer: Rowan McLachlan.

perceptions in response to laboratory adaptations made during a pandemic. As part of our adaptation strategy, we offered two versions of the same laboratory exercise, one in-person and one online. Below, we begin by describing the outdoor laboratory facility and the laboratory exercise, including our health and safety adaptations. Next, we examine scores on the in-person and online laboratory exercises to compare learning outcomes for both instruction modes. We then evaluate the impact of both instruction modes on students' affinities for water science using surveys that were conducted in Fall 2021 (FA21). Finally, we offer lessons learned and recommendations for pandemic teaching in similar outdoor laboratory facilities.

MATERIALS AND METHODS

Mirror Lake Water Science Learning Laboratory

The Mirror Lake Water Science Learning Laboratory (**Figure 1**) was established in 2018 to provide more accessible space where students could learn hands-on field skills in hydrology and hydrogeology. An additional goal of the space is to connect students with professionals who can share their experiences in the geoscience workforce. Guest lecturers from local consulting firms and government agencies regularly co-lead laboratory activities with Ohio State University faculty and teaching assistants (TAs).

The Learning Lab is used by almost 1,000 students each semester in general education, major-specific, and graduate-level earth science classes. Students in general education exercises learn to make water level measurements in wells (**Figure 2**) and contour the results to interpret directions of groundwater flow. They also measure water quality, including dissolved oxygen and nutrient levels, in both lake water and groundwater. Students in upper-level and graduate classes use the site for aquifer testing, borehole logging, and ground-based geophysical surveys. Because the Learning Lab is a multi-use space in the heart of the main campus, it is accessible for short lecture demonstrations as well as full-length laboratory exercises. No vans are needed for transportation, and all the wells are accessible from walkways.

The space includes a network of 10 shallow wells with 2″ casing ranging in depth from approximately 5–9 m (**Figures 1**, **2**). A deeper, 8" well was also drilled to an approximate depth of 36 m. The deep well and the lake are both equipped with telemetered sensors that monitor pressure, temperature, and fluid electrical conductivity every 15 min (https://mirrorlake.byrd.osu.edu/). A campus rain gauge also records daily rainfall totals approximately 600 m from the site.

Laboratory Design and Pandemic Modifications for a General-Education Exercise

The introductory groundwater laboratory exercise at Mirror Lake is taught as part of ES (Earth Science) 1,200: Introductory Earth Science Laboratory, a 1-credit course that satisfies OSU's general education requirements for natural science. The goals of the exercise are to introduce students to basic concepts of groundwater as a resource, groundwater flow, and contour mapping. Students first complete a pre-lab exercise with a short reading and video about groundwater resources and several questions that are intended to reinforce their comprehension. They then measure water levels in 10 piezometers in Mirror Lake and use measurements to produce a contour map of the water table near the lake. The students interpret whether lake water is recharging the aquifer or groundwater is discharging to the lake based on their contour map. Laboratory materials are available through CUAHSI HydroShare (https://www.hydroshare.org/resource/7f6295a88f2743a58e3447db650df0d2/).

Prior to the COVID-19 pandemic, ES 1200 was an in-person class, and all laboratory exercises were taught in small sections of up to 30 students. In response to the pandemic, two versions of ES 1200 were offered to students in the autumn semester of 2020

TABLE 1 | Study structure, including relevant questions, data sources, semesters, and numbers of participants.

How do in-person versus online lab experiences affect student academic performance and learning outcomes?			
Test	**Semester**	**# Online**	**# In-Person**
Control: Pre-Lab Quiz (overall grade, % correct on 1 multiple-choice question)	FA 20	171	205
	SP 21	0	781
	FA 21	36	491
Experiment: Lab Activity (overall grade, % correct on 2 multiple-choice questions)	FA 20	171	205
	SP 21	0	781
	FA 21	36	491

How do in-person vs. online lab experiences affect student affinity for earth and water science?			
Test	**Semester**	**# Online**	**# In-person**
Control: Pre-Lab Affinity Survey	FA 21	16	306
Experiment: Post-Lab Affinity Survey	FA 21	22	264

(FA20): online and in-person. Laboratory exercises that could not easily be adapted for both formats were replaced. The groundwater laboratory exercise remained and was the only exercise that offered in-person participants a field experience that semester. We designed this study to assess differences in learning outcomes and affinity for water science between the two groups that completed the in-person and online versions of the groundwater exercise, using the study structure in **Table 1**.

To adapt the in-person version of the lab for the pandemic, the following modifications were made. Students feeling ill or in quarantine/isolation were permitted to complete the lab online with no penalty. Students able to attend the lab in-person met in a socially distanced indoor classroom and were required to wear laboratory gloves and face masks. Students were provided with a brief introduction to the topic and the lab activity by an in-class TA. Following the introduction, students ventured outside to locate the groundwater wells and measure groundwater levels. Measurements were recorded on printed datasheets. Upon completion of the activity (~ 30–45 min), students returned to the indoor classroom to complete the contour map and answer questions. In FA20, most in-person students completed printed handouts of the lab questions during the assigned lab time, but they also had access to the questions through OSU's online Learning Management System (LMS) if they desired to continue working on the exercise after their assigned lab time.

The online version of the exercise was offered asynchronously. Online participants were assigned a Teaching Assistant (TA) who was available for questions through email contact and online office hours. In the online exercise, students were asked to watch a short video of another student measuring depth to water in one of the Mirror Lake wells. Students were provided with photographs of each well showing where the measuring tape intersected the well casing on a previous date. Students were then asked to read the depth-to-water for each well from the photographs. They then used these measurements to make a contour map and answer the same interpretive questions as the in-person participants, submitting their answers through the online Learning Management System. Online students had the same assignment deadline as in-person students (the end of the lab week). They were encouraged to reach out to a TA *via* email or during office hours if they encountered difficulties completing the exercise. Both online and in-person groups also had access to an "Additional Resources" page with helpful links and hints to aid in the completion of the lab.

In the spring semester of 2021 (SP21), all ES 1200 lab sections were online due to a variety of considerations associated with limitations in TA staffing and the increasing COVID infections on campus. No students completed the in-person version of the groundwater lab exercise that semester. In the autumn semester of 2021 (FA21), all ES 1200 lab sections were in-person due to ample TA staffing and encouraging COVID trends. However, students who needed to quarantine or had other extenuating circumstances that prevented them from safely participating in the groundwater lab exercise were offered the online version of the exercise for full credit. As before, both the in-person and the online students were provided with the same deadline and submitted their exercises through the online LMS.

Assessing Learning Outcomes Through Lab Scores

We analyzed pre-lab questions to identify whether the in-person and online groups were statistically similar in terms of their groundwater knowledge before participating in the lab (**Table 1**). In FA21, in-person groups completed the pre-lab questions in front of TAs before taking their field measurements, so they may have benefitted from extra TA support. We therefore only compared pre-lab performance for the FA20 semester. We discarded one open-ended question from the analysis because the scores were influenced by the individual grading style of each TA. We analyzed the percentage of correct answers for the combined remaining 5 multiple-choice questions. We also examined the fraction of students who correctly answered one multiple choice question that we deemed representative of pre-lab concepts. This question was related to a news segment in a video and asked, "How long does it typically take for a deeper aquifer to recharge?" Chi-square tests were conducted to determine statistically significant differences between the percentage of correct answers in online and in-person groups.

To assess comprehension after the lab exercise (**Table 1**), we examined the distributions of total lab exercise scores and performed a Welch's t-test to test for statistically significant differences between scores. Due to the unequal variances between compared means, Welch's t-test was used rather than

Student's t-test. We also examined two specific questions that targeted students' comprehension of their contour maps: "Is hydraulic head generally greater in the piezometers (wells) or the lake (overlook)?" and "Is groundwater discharging to the lake or is lake water infiltrating into the ground?" These questions were multiple choice. Students could not receive partial credit. Chi-square tests were conducted to test statistically significant differences between percentage correctness.

Assessing Affinity Outcomes Through Surveys

During FA21, students were provided a pre- and post-lab survey through the online Learning Management System to gauge their affinity for the topic of groundwater (**Supplementary Appendix SA**). The pre-lab survey acted as a control to gauge initial interest (**Table 1**) and asked for basic student information, including their major and class rank (i.e., first-year, second-year). The post-lab survey repeated the same questions on interest and posed additional open-ended questions including "What did you enjoy most about this lab" and "What would you do to improve this lab?"

The four affinity questions used a Likert scale (i.e., Strongly Disagree—Strongly Agree) to assess identical ideas before and after the lab activity, including: 1) how much they thought about groundwater in the past (pre-lab) and how much they might think about it in the future (post-lab); 2) how much they enjoyed learning about water (pre- and post-lab); 3) how interested they were in taking another earth or water science class (pre- and post-lab); and 4) whether they saw themselves in a water-related or earth science-related career (pre- and post-lab). Likert scale data was scored from 1 (Strongly Disagree) to 5 (Strongly Agree) for statistical analysis. Differences in lab experience were assessed using a Welch's t-test between mean scores for each of the four survey questions between 1) pre- and post-lab online surveys, 2) pre- and post-lab in-person surveys, and 3) post-lab online and in-person surveys. Multiple variances between compared means were >1, leading to the use of the Welch's t-test rather than the Student's t-test for evaluating the statistical significance of the Likert scale questions. Additionally, to assess whether pre-existing differences in the online and in-person student populations (rather than lab experience) affect our results, pre-lab surveys for online and in-person students were separated for comparison.

To analyze what students most enjoyed about the labs, responses were reviewed and grouped into 8 distinct categories. The number of responses that fell under each category was then tallied.

RESULTS

Learning Outcomes

In FA20, 205 students completed the in-person assignment, while 171 students completed the online assignment. In SP21, 781 students completed the online assignment. In FA21, 491 students completed the in-person lab assignment, while 36 students completed the online assignment. In FA20, TAs were highly encouraged to reward participation and grade for completion to alleviate some of the stress on students during the pandemic. As a result, total lab scores for in-person and online students both had a median of 100% (**Figure 3A**). The variability was greater for in-person students, but this variability can be explained by differences in TAs (each TA had a unique interpretation of what it meant to grade for participation and completion). To account for these differences, we compared scores among groups of in-person and online students who had the same TA (**Figure 3B**). For most TAs (10/12) with an in-person and online section, the in-person students scored better. In FA21, the TAs were not asked to grade only for participation and completion, and the differences in lab grades were clear, irrespective of TAs. In-person students out-performed online students ($p < 0.001$), with a median of 97.78% compared to that of 91.67% for online students (**Figure 3A**).

In the pre-lab control, students performed similarly well, regardless of the delivery mode, suggesting there were no initial differences in knowledge or performance between in-person and online groups. In FA20, average cumulative pre-lab scores on the five multiple-choice questions were 94.79% for in-person students and 94.24% for online students ($p > 0.05$). Students performed similarly on the question "How long does it typically take for a deeper aquifer to recharge?" In FA20, the rate of correct answers was 97.34% in-person group and 97.12% in the online group (a difference of <1%) (**Figure 4A**).

In comparison, the performance gap was greater for the two interpretative questions at the end of the lab (**Figure 4B**). For the first question ("Is hydraulic head generally greater in the piezometers (wells) or the lake (overlook)?") in FA20, 78.54% of in-person students and 74.85% of online students had the correct answers ($p > 0.05$). In FA21, 98.78% of in-person students and 97.22% of online students had the correct answers ($p > 0.05$) (**Figure 4B**). The same conclusion was drawn for the second question "Is groundwater discharging to the lake or is lake water infiltrating into the ground?" In FA20, 78.05% of in-person students and 74.27% of online students had the correct answers ($p > 0.05$). In FA21, 96.13% of in-person students and 86.11% of online students had the correct answers ($p < 0.05$) (**Figure 4C**). It is worth noting that incorrect answers came mostly from students who had both incorrect measurements and inconsistent interpretations of those measurements. Less than <10% of students who answered wrong on the first question (**Figure 4B**) had simply misinterpreted good measurements. Another 20% had interpretations that were wrong but consistent with their (incorrect) measurements.

Affinity Outcomes

Pre-lab affinity surveys were completed by a total of 306 in-person students and 16 online students. Post-lab affinity surveys were completed by 264 in-person students and 22 online students. Responses to Likert scale questions in these surveys suggest in-person and online students had different experiences during the lab exercise. While in-person respondents' average affinity (i.e., average levels of agreement to questions) for learning about water significantly increased ($p < 0.001$) following the lab exercise, online students' average affinity significantly decreased (**Figure 5**). Specifically, online students' interest in taking another

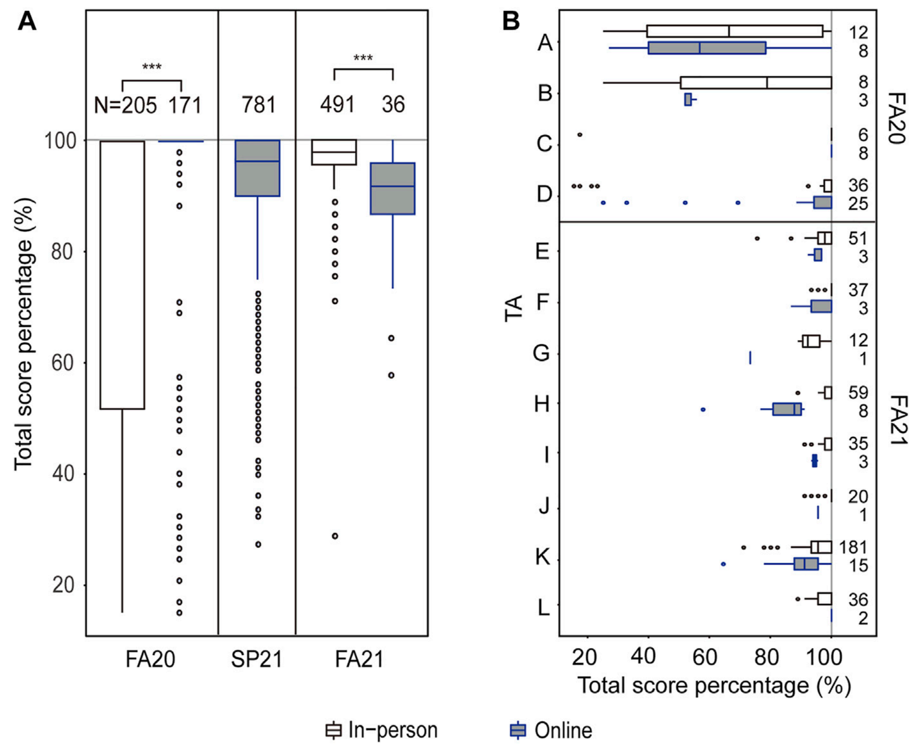

FIGURE 3 | (A) Total lab score percentages by semester, regardless of TA. **(B)** Total lab score percentages by TA, only for those TAs who instructed students using in-person and online modes.

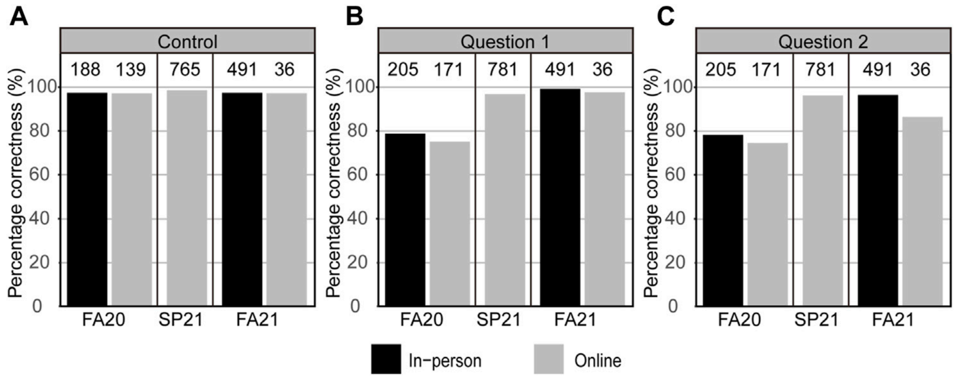

FIGURE 4 | Percentage of students with correct answers for three representative questions **(A)** Pre-lab Control: How long does it typically take for deeper aquifer to recharge? **(B)** Question 1: Is hydraulic head generally greater in the piezometers (wells) or the lake (overlook)? **(C)** Question 2: Is groundwater discharging to the lake, or is lake water infiltrating into the ground?.

class in earth or water science significantly decreased, and they expected they would think significantly less about groundwater in the future (**Figure 5**). Though not statistically significant ($p > 0.05$), more in-person students envisioned themselves in a water- or earth science-related career after participating in the lab, while fewer online students did (**Figure 5**).

Conclusions about online students may be limited by the small sample size, both for pre-lab and post-lab surveys. In FA21, students were only approved for an online version of the exercise if they were absent due to sickness, quarantine, or other reasons that their instructor felt prevented them from attending a different in-person section. As a result, online students may have had personal factors that limited the time and energy they were able to devote to the lab assignment when compared to in-person students. Although online students report slightly lower affinity levels than in-person students in

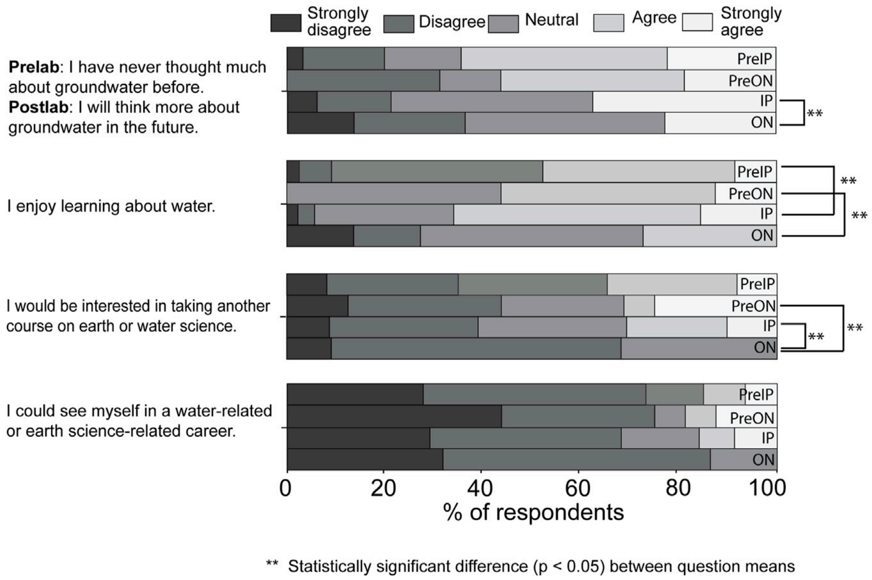

FIGURE 5 | Comparison of responses to Likert-scale questions on affinity from the pre-lab survey of in-person students (PreIP, $n = 306$), the pre-lab survey of online students (PreON, $n = 16$), the post-lab survey of in-person students (IP, $n = 264$) and the post-lab survey of online students (ON, $n = 22$). Statistical significance at the 95% confidence level was evaluated using a Welch's t-test (allowing for unequal variances) between the mean Likert score among responses for each survey question.

the pre-lab survey, the difference is not statistically significant (**Figure 5**). Therefore, we attribute differences from the pre- and post-lab surveys primarily to differences in lab experience. For example, although the online and in-person students were given similar instructional text in the lab assignments, many online students (~ 59%) indicated that they felt the lab assignment needed more information and instructions, suggesting a major difference in perception of the exercise. In comparison, only 31 of the 264 (~ 12%) in-person students offered similar feedback.

Eighteen of the 22 online students provided detailed information about what they enjoyed most in the lab exercise. Eight respondents (~ 44%) enjoyed the "subject covered," 4 respondents (~ 22%) provided negative feedback to the question, and 6 respondents (~ 33%) had diverse answers scattered throughout the remaining categories. Two-hundred-fifty-three of the 264 in-person students offered responses to this question. One-hundred-eighty respondents (~ 71%) enjoyed the "outside and hands-on" aspect of the lab activity. Of the remaining 84 respondents, 43 (~17%) enjoyed the "subject covered," 19 (~ 7%) enjoyed the "group work," and 11 (~ 4%) had diverse answers scattered throughout the five remaining categories, all with three responses or less (**Figure 6**). It is worth noting that ~ 70% of respondents were non-STEM majors, ~ 28% were STEM majors, and 2% were undecided. 23% of respondents were first-year students, 36% were second-year students, 36% were third-year students, and 5% were fourth-year students.

DISCUSSION

Our results suggest that hands-on learning activities with in-person peer and instructor feedback can improve grades for students in earth and water sciences and can increase their affinity for the subject. This is consistent with literature demonstrating that experiential learning in earth sciences improves student engagement and academic performance (Olcott 2018). Providing this hands-on experience was possible due to the existence of accessible outdoor laboratory space. The benefits of outdoor learning spaces, particularly those which facilitate hands-on, inquiry-based learning are well documented (Trop, Krockover, and Ridgway 2000; Salvage, Graney, and Barker 2004; Dripps 2019). This study provides further evidence that by investing in multi-use outdoor laboratory spaces, universities can inspire students' enthusiasm for STEM and make it easier for them to grasp difficult scientific concepts. The importance of outdoor lab spaces was particularly illustrated during the pandemic when classes could not access more distant field sites due to restrictions on group transportation. The Mirror Lake Water Science Learning Laboratory's on-campus location and proximity to lecture buildings make it an ideal outdoor learning space for students to gain experience in the water sciences. The space also addresses sustainability goals stated in the university's Sustainability Goals Project Report, to "integrate teaching, research, and operations through learning-by-doing approaches, including project-based service-learning, utilizing campus as a testbed and other research activities to expand sustainability efforts across and beyond campus."

It is possible that the hands-on activity itself was not the reason for greater comprehension and increases in affinity, but rather the structured access to TAs and peers in the in-person sections. As an example, a consistently challenging task for many students in this lab activity was contour mapping. From an instructor's perspective, the concept can be difficult to explain in a "one-size-fits-all" way during lecture since the steps required

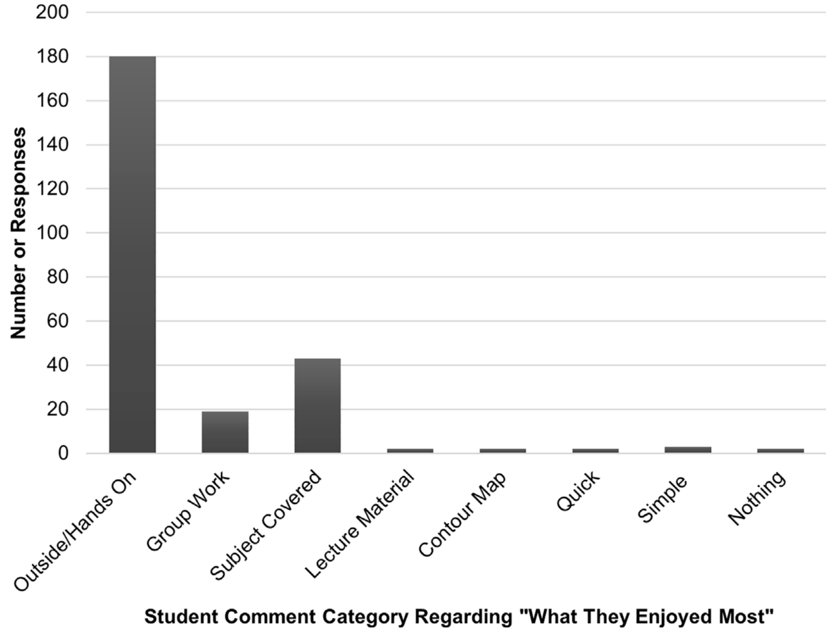

FIGURE 6 | Tally of students' answers to the question "What did you enjoy most about this lab?" Open-ended responses were placed into one of the 8 categories shown.

(i.e., where to draw first and next lines) vary situationally depending upon the data and students' individualized interpretations. The difficulty of instructing students is compounded in an online setting, where students may not have the same opportunity to check their maps one-on-one with an instructor or with other students during an in-person class, and must seek these opportunities themselves (i.e., *via* online office hours or email). Receiving instructor feedback early and often and working in small teams are known to improve student learning, particularly in STEM. Group discussions require students to integrate individual ideas into joint observations (Warfa, Nyachwaya, Roehrig 2018) and allow students who are more familiar with discipline-specific terms and concepts (such as contouring in earth science) to teach their peers (Airey and Linder 2009). A lack of structured working groups in the online delivery mode may help explain why 59% of online students recommended providing "more/better information" to complete the lab, despite having access to a sample recorded lecture, pre-lab documentation, and other additional resources. Although group discussions of field and mapping concepts are not easy to reproduce in an online delivery mode, online teaching strategies can be implemented to help (Kanetaki et al., 2021; Kanetaki et al. 2021a; Kanetaki et al. 2021; Kanetaki et al. 2021b; Kaup et al., 2020; Kreijns et al., 2004). For example, TAs of online sections could host synchronous sessions to facilitate group discussion and inquiry between students. However, synchronous sessions have the downside of placing additional burdens on students with family and work obligations, particularly in a pandemic. To address this, students could be allowed to sign up for time slots that best fit their schedules, or TAs could replicate the discussion experience asynchronously through online discussion boards. Teaching contouring in a more successful way may require additional resources to help students internalize the principles of the activity (rather than just follow a set example) and, where possible, be able to understand and "self-check" where their own work or the work of their peers may violate the principles of the contouring activity (Kanetaki et al., 2021; Krouska et al., 2021).

We also note opportunities to improve the in-person version of the activity. One challenge was how to allocate measurement equipment among student groups. Due to equipment limitations, students worked in groups of up to 10–15. Certain students tended to gravitate towards operating the meters, limiting participation by others. In the post-lab surveys, 7% of in-person students wanted smaller groups and said they were not able to work "hands-on" with the equipment. This was notable since the "hands-on" nature of the lab was by far the most well-liked aspect (**Figure 6**). Rotating group members through assigned roles (such as data recording, opening the wells, operating the beep tape, etc.) at each well could be a potential improvement for teaching this lab with larger classroom sizes and/or limited equipment. This could also facilitate better social distancing, which was difficult in both the SP21 and FA21 labs, by allowing smaller groups to visit more wells simultaneously. In future semesters, concomitant labs will be rotated through the groundwater lab over a 2-week period to increase the availability of physical space and equipment during the exercise and reduce the group size to 4-7 students.

In summary, this comparative study reveals that hands-on field experiences during the COVID pandemic had extensive benefits over online alternatives. Students in the hands-on activity performed better in the lab assessments, enjoyed being outdoors and expressed greater enthusiasm for taking water-related classes and pursuing water-related careers. In future semesters, we hope to reduce the gap in student learning outcomes between online and in-person participants by implementing simple changes to the online labs, such as adding a working session on contouring principles. It is possible that these changes will also positively impact online participants' affinities for water science by enhancing student-TA interactions, student confidence in the material, and feelings of being connected and belonging in the earth science learning community. Even with these improvements, online activity cannot simulate the quality of being outdoors, which was one of the favorite aspects of the exercise for in-person participants. We, therefore, emphasize the value of university investments in multi-use, accessible outdoor laboratory spaces within walking distance of classrooms. Establishing and maintaining these spaces requires support from faculty, administrators, landscape architects, and groundskeeping staff, but the reward is a measurable improvement in student learning experiences, particularly during a pandemic.

DATA AVAILABILITY STATEMENT

The educational materials generated for this study can be found in the CUAHSI HydroShare database: https://doi.org/10.4211/hs.7f6295a88f2743a58e3447db650df0d2

AUTHOR CONTRIBUTIONS

AS and JS conceived the study idea. ZC compiled the lab score dataset, analyzed statistics, and interpreted the results. KL prepared and distributed the FA21 affinity surveys, and BB and KL compiled, analyzed, and interpreted responses. All authors contributed to writing and editing.

FUNDING

This study was supported by NSF Award EAR-1752995. The well network at The Mirror Lake Water Science Learning Laboratory was made possible by generous donations from alumni of The Ohio State University School of Earth Sciences, including Mike and Cindy Morgan and Bruce Hulman, and through the donations of Jamison Well Drilling, Inc.

ACKNOWLEDGMENTS

We thank Stephen Volkmann, Landscape Architect at The Ohio State University, for accommodating drill rigs on campus and for supporting the development of the Mirror Lake Water Science Learning Laboratory. We thank Jason Cervenec for assistance with lab design and Michael Gravina for providing a web-based data viewer. We especially thank the teaching assistants of ES 1121 for their tremendous efforts in adapting laboratory activities in a pandemic and supporting their students. We are grateful to Christopher Atchison for helpful feedback on an early version of the affinity survey. Finally, we thank the many professionals who have donated their time to training students in the laboratory space, including employees of Eagon and Associates, the U.S. Geological Survey, Ohio Department of Natural Resources, and Ohio Environmental Protection Agency.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.877327/full#supplementary-material

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ORIGINAL RESEARCH
published: 10 June 2022
doi: 10.3389/feduc.2022.906995

Implementation of an Online Poster Symposium for a Large-Enrollment, Natural Science, General Education, Asynchronous Course

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OPEN ACCESS

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Specialty section:
This article was submitted to STEM Education, a section of the journal Frontiers in Education

Received: *29 March 2022*
Accepted: *23 May 2022*
Published: *10 June 2022*

Citation:
Weaver EM, Shaul KA and Lower BH (2022) Implementation of an Online Poster Symposium for a Large-Enrollment, Natural Science, General Education, Asynchronous Course. Front. Educ. 7:906995. doi: 10.3389/feduc.2022.906995

Asynchronous online courses are popular because they offer benefits to both students and instructors. Students benefit from the convenience, flexibility, affordability, freedom of geography, and access to information. Instructors and institutions benefit by having a broad geographical reach, scalability, and cost-savings of no physical classroom. A challenge with asynchronous online courses is providing students with engaging, collaborative and interactive experiences. Here, we describe how an online poster symposium can be used as a unique educational experience and assessment tool in a large-enrollment (e.g., 500 students), asynchronous, natural science, general education (GE) course. The course, Introduction to Environmental Science (ENR2100), was delivered using distance education (DE) technology over a 15-week semester. In ENR2100 students learn a variety of topics including freshwater resources, surface water, aquifers, groundwater hydrology, ecohydrology, coastal and ocean circulation, drinking water, water purification, wastewater treatment, irrigation, urban and agricultural runoff, sediment and contaminant transport, water cycle, water policy, water pollution, and water quality. Here we present a is a long-term study that takes place from 2017 to 2022 (before and after COVID-19) and involved 5,625 students over 8 semesters. Scaffolding was used to break up the poster project into smaller, more manageable assignments, which students completed throughout the semester. Instructions, examples, how-to videos, book chapters and rubrics were used to accommodate Students' different levels of knowledge. Poster assignments were designed to teach students how to find and critically evaluate sources of information, recognize the changing nature of scientific knowledge, methods, models and tools, understand the application of scientific data and technological developments, and evaluate the social and ethical implications of natural science discoveries. At the end of the semester students participated in an asynchronous online poster symposium. Each student delivered a 5-min poster presentation using an online learning management system and completed peer reviews of their classmates' posters using a rubric. This poster project met the learning objectives of our natural science, general education course and taught students important written, visual and verbal communication skills. Students were surveyed to determine, which parts of the course were most effective for instruction and learning. Students ranked poster assignments first, followed closely by lectures videos. Approximately 87% of students were confident that they could produce a scientific poster in the future and 80% of students recommended virtual poster symposiums for online courses.

Keywords: online, general education, scientific posters, asynchronous, natural science, STEM—science technology engineering mathematics, large enrollment, virtual poster session

INTRODUCTION

General Education (GE) Natural Science Courses introduce students to different disciplines and topics within the natural sciences and provide an overview of fundamental concepts, methods of inquiry, principals, and theories. These courses are designed to engage students (majors and non-majors) in empirical and theoretical study, help students understand the relationship between fundamental and applied sciences, enable students to recognize the potential impacts of scientific and technological discoveries, and prepare students to be scientifically competent and engaged citizens. Expected learning outcomes for GE Natural Science Courses includes scientific literacy, finding and critically evaluating sources of information, recognizing the changing nature of scientific knowledge, methods, models and tools, understanding the application of scientific data and technological developments, and evaluating the social and ethical implications of natural science discoveries.

This paper describes how an online poster symposium can be used as a unique educational experience and assessment tool in a large-enrollment (e.g., 500 + students), distant education (DE), asynchronous, natural science, GE course. The title of the GE course is "Introduction to Environmental Science" (ENR2100) and it is a 3-credit Natural Science GE course. All undergraduate students at The Ohio State University (Ohio State) are required to take coursework in the Natural Sciences. ENR2100 covers a variety of topics in environmental science including hydrological processes. We spend 6 weeks (approximately 40% of the semester) focused on water science. The water science topics that we cover include surface water, aquifers, groundwater hydrology, ecohydrology, distribution and movement of water, the water cycle, the interaction of water with biological, ecological and geological systems, precipitation, streamflow, coastal and ocean circulation, soil erosion and sediment, agricultural runoff, irrigation, urban runoff, soil water, water purification, water pollution, water policy, and wastewater treatment.

As a GE course, ENR2100 is a prerequisite for many upper-level water science courses at Ohio State. As a prerequisite, ENR2100 challenges students to learn and develop skills that are important to a scientist (e.g., find, download and read journal articles, use reference management software, use Microsoft PowerPoint, write an abstract, create a figure and table, conduct peer review). Prerequisites also help students become more comfortable with the subject matter (e.g., water science) and helps build confidence so that students can be successful in their upper-level water science courses and labs. Many upper-level water science courses at Ohio State require students to give oral presentations and/or poster presentations. The posters assignments students complete in ENR2100 are intended to give them valuable experience so that can be successful in their future water science coursework.

Each year, we have approximately 200 undergraduate students who take ENR2100 in order to fulfill a course requirement for their B.S. degree in Biology, Chemistry, Earth Science, Ecology, Engineering, Environmental Science, Geography, or Public Health. Many of these students plan to go into careers in water science. In the School of Environment and Natural Resources (the home school of the authors), ENR2100 is a required course for students earning an Environmental Science, Water Science B.S. degree. Approximately 30% of our student poster presentations (150–250 posters per semester) are focused on water science. Our virtual poster symposium offers a unique opportunity for these students, who come from different colleges and departments, but have similar career goals to interact with one another and plant the seeds for future collaborations. Many of our past students have gone onto careers in engineering hydrology, hydroecology, hydrogeology, natural resource management, water treatment, or water policy. The class poster project is designed to broaden the skills, knowledge and understanding of the natural sciences for these students, as well as the other students who are enrolled in ENR2100.

Distance education (DE) is one of the fastest growing trends in higher education, particularly since 2020 with the impacts of COVID-19 on all colleges and universities (Barnett, 2014; Greenland and Moore, 2014; Ginder et al., 2018; De Brey et al., 2021; Stevens et al., 2021; U.S. Department of Education, 2021, National Center for Education Statistics Trend Generator). The U.S. Department of Education estimated that in, 2019 over 7.3-million students were enrolled in DE courses at degree-granting post-secondary institutions in the United States and this number is expected to grow in the future (National Center for Education Statistics, 2018; De Brey et al., 2021, IPEDS Data). In the United States, during the fall of 2020, approximately 73% of all students were enrolled in distant education courses in postsecondary institutions (U.S. Department of Education, 2021, National Center for Education Statistics Trend Generator; National Center for Education Statistics, 2018, IPEDS Data). DE can increase student access to college because it is more affordable than traditional education (e.g., no need to live on campus, no transportation costs), provides greater flexibility (e.g., lectures, assignments, exams can be completed from anywhere), allows courses to be self-paced (e.g., asynchronous courses), and accommodates Students' busy lives (e.g., family, work, extracurricular activities) (Akdemir and Koszalka, 2008; Means et al., 2009; Tucker and Morris, 2012; Barnett, 2014; Broadbent and Poon, 2015; Andrade and Alden-Rivers, 2019;

Müller and Mildenberger, 2021). These are the major reasons why DE has become so popular among students, faculty, and administrators at institutions of higher education.

Online courses can be asynchronous (self-paced participation) or synchronous (real-time participation) and while there are pros and cons for each style of instruction, this paper is focused on asynchronous online learning. Asynchronous DE courses can be particularly challenging for both the instructor and student. For instructors, it can be difficult to design and teach engaging course content that provides for active learning and meaningful student-student and student-instructor interactions in an asynchronous setting. For students, self-paced courses can be challenging if course content is not accessible, activities and assignments are poorly organized, and engagement is not properly structured to foster enriching educational experiences.

Expectations and experiences for teaching and learning in an asynchronous course are likely different because participation and engagement in a self-paced course will look different to what is traditionally observed in a synchronous course (Broadbent and Poon, 2015; Müller and Mildenberger, 2021; Stevens et al., 2021). Similarly, student and instructor expectations and experiences in DE vs. in-person courses are also different (Waschull, 2001; Akdemir and Koszalka, 2008; Means et al., 2009, 2013; Broadbent and Poon, 2015; Caliskan et al., 2017; Daniel and Kamioka, 2017; Stevens et al., 2021). Therefore, in an asynchronous DE course it is important for instructors to anticipate student needs, create accessible content, ensure that learners understand content and are able to apply what they learned, and design active learning experiences that are structured in a way to connect students across different time zones, countries, schedules, obligations (e.g., family, work), learning styles, and technologies (Means et al., 2009, 2013; Barnett, 2014; Daniel and Kamioka, 2017; Andrade and Alden-Rivers, 2019; Orr et al., 2020; Müller and Mildenberger, 2021; Stevens et al., 2021).

College general education (GE) curriculum is designed to explore a breadth of topics, teach essential skills, introduce fundamental ideas and concepts, and develop knowledge, perception and understanding. GE courses are particularly well suited for DE because GE courses are required by all students enrolled in traditional 4-year programs at accredited academic institutions. Typically, students of all majors are required to complete a core set of GE courses in arts, humanities, social sciences and natural sciences in order to graduate. The ability to take GE courses online offers students an affordable and flexible option to complete their coursework. Post-COVID, countless colleges and universities have transitioned GE courses to both asynchronous and synchronous DE options (U.S. Department of Education, 2021, National Center for Education Statistics Trend Generator).

Students enrolled in our asynchronously taught online ENR2100 courses consisted of approximately 18% freshman, 34% sophomores, 26% juniors, and 22% seniors (**Table 1**; total number students = 5,625). The approximate distribution of students from the various colleges at Ohio State were as follows: 29% from the College of Arts and Sciences, 42% College of Business, 2% College of Education and Human Ecology, 5% College of Engineering, 7% College of Food, Agriculture and Environmental Sciences, 8% Exploration and 7% Other. Approximately 78% of students (n = 5,625) took ENR2100 to fulfill a GE requirement and 22% took the course to fulfill a course for their major, minor or as a free elective.

TABLE 1 | Student enrollment by class rank in ENR2100, introduction to environmental science.

Semester ENR2100 taught	Number of students enrolled in ENR2100 by rank				
	Freshman	Sophomore	Junior	Senior	Total
Sp17	67	168	148	135	518
Sp18	53	172	135	174	534
Sp19	76	186	150	144	556
Sp20	85	216	244	196	741
Sp20	125	168	81	39	413
Au20	253	275	179	126	833
Sp21	138	232	160	134	664
Au21	146	220	173	123	662
Sp22	100	237	201	166	704
Total **%**	1,043 18%	1,874 34%	1,471 26%	1,237 22%	5,625 100%

All courses listed in table were taught as asynchronous, distant education courses. ENR2100 is a 3-credit natural science, general education course taught at The Ohio State University. Spring semester, Sp. Autumn semester, Au. Semesters are 15-weeks. Two-digit year provided (e.g., Sp17 means course was taught in 2017 during the Spring semester). Of these 5,625 students, approximately 78% took ENR2100 to fulfill Natural Science GE credits.

We used poster assignments to provide an online classroom environment and activities that were grounded in the constructivist theory of education, where learners construct new knowledge and understanding through experience and incorporating new information with their prior knowledge (Richardson, 2003). ENR2100 has 2 Goals and 6 Expected Learning Outcomes (ELOs) that are provided in **Table 2**. Poster assignments were designed to be linked to Goal 1 and ELO 1.3 (**Table 2**), as well as Goal 2 and ELO 2.2 and ELO 2.3. Scientific posters allow students to engage in higher order learning during their analysis, synthesis and evaluation of scientific research, they are able to demonstrate that they have achieved specific course learning outcomes, they create a scholarly and professional product, and they develop skills for effective written, oral and visual communication.

Here we demonstrate how academic units that confer degrees in hydrology (e.g., Earth Sciences, Environmental Science, Geological Sciences, Natural Resources) could utilize a student poster symposium in the DE courses that they teach. We show how student scientific posters can be used as a particularly effective writing assignment that includes an interactive online poster symposium and peer review. We also describe how online technology (e.g., learning management systems) permits an instructor to incorporate a scientific poster symposium in an asynchronous, large-enrollment, natural science course. The methods presented here can be easily adapted for synchronous DE courses as well as upper-level undergraduate and graduate DE courses and courses that are taught in-person.

TABLE 2 | Course goals and expected learning outcomes (ELOs) for introduction to environmental science (ENR2100).

GOAL 1. Successful students will engage in theoretical and empirical study within the natural sciences, gaining an appreciation of the modern principles, theories, methods, and modes of inquiry used generally across the natural sciences.		
	ELO 1.1	Successful students are able to explain basic facts, principles, theories and methods of modern natural sciences; describe and analyze the process of scientific inquiry.
	ELO 1.2	Successful students are able to identify how key events in the development of science contribute to the ongoing and changing nature of scientific knowledge and methods.
X	ELO 1.3	Successful students are able to employ the processes of science through exploration, discovery, and collaboration to interact directly with the natural world when feasible, using appropriate tools, models, and analysis of data.
GOAL 2: Successful students will discern the relationship between the theoretical and applied sciences, while appreciating the implications of scientific discoveries and the potential impacts of science and technology.		
	ELO 2.1	Successful students are able to analyze the inter-dependence and potential impacts of scientific and technological developments.
X	ELO 2.2	Successful students are able to evaluate social and ethical implications of natural scientific discoveries.
X	ELO 2.3	Successful students are able to critically evaluate and responsibly use information from the natural sciences.

Poster assignments linked to ELOs shown with X.

MATERIALS AND METHODS

General Education Natural Science Course and Students

The poster assignment was implemented in the course Introduction to Environmental Science (ENR2100), which is taught at The Ohio State University as (1) an entirely online, asynchronous course or (2) an in-person, synchronous course. The work presented in this paper is focused entirely on asynchronous online courses. ENR2100 is a 3-credit General Education Natural Science Course for undergraduate students. ENR2100 is designed to give students an introduction to environmental science, the ecological foundation of environmental systems, the ecological impacts of environmental degradation by humans, and strategies for sustainable management of environment and natural resources.

The course was taught using the Canvas Learning Management System (Canvas LMS)[1]. There were no required sessions when students had to be logged into Canvas at a scheduled time. ENR2100 was taught over a 15-week semester (autumn or spring) and divided into 15 weekly modules. Student questions were answered by email, Canvas discussion boards, or during office hours that were conducted online using Zoom[2].

Students were expected to keep pace with weekly deadlines (e.g., Fridays at 11:59 p.m.) but were permitted to schedule their efforts freely within the 7-day time frame. Students were instructed and expected to spend 3 h per week on direct instruction (i.e., watching lecture videos and taking notes) and an additional 6 h per week working on out-of-class work (e.g., studying, readings, poster assignments). Of these 6 h, students were instructed to spend approximately 3 h per week working on their poster assignments. Students were able to submit assignments online from anywhere and thus enrollment in ENR2100 consisted of both domestic and international students. A total of 9 asynchronous online ENR2100 courses have been taught at Ohio State over the past 6 years to 5,625 students. Class sizes each semester ranged from approximately 400 to 825 students, with an average class size of 625 students.

Poster Assignment Timeline and Asynchronous Online Poster Event

The first asynchronous online poster symposium took place in 2017 and since then we have hosted a total of nine online poster events during the autumn and spring semesters at Ohio State. Multiple asynchronous online poster events were also successfully held during the COVID-19 pandemic. Each online poster symposium was scheduled and organized within Canvas LMS and open for about 1-week to allow for student participation from all over the globe. Each poster symposium consisted of between 400 and 825 individual posters, with the average poster event consisting of 625 individual poster presentations. Students also completed poster peer reviews during the online poster symposium, with each student completing 2 reviews, for a total of 800–1,650 individual poster peer reviews per symposium.

A Student's overall poster project was scaffolded into 6 smaller assignments, which students completed throughout the semester. Detailed instructions, How-To videos and examples were also provided for each assignment (**Table 3** and **Supplementary Material**). Starting in 2019 a free open textbook "Scientific Posters: A Learner's Guide" was used to help students complete their poster assignments (**Table 3**)[3]. The six poster assignments were worth 25% of a Student's overall course grade. Early assignments were worth fewer points (e.g., Poster Assignment 1 was worth 10 points) compared to assignments that students completed later in the semester (e.g., Poster Assignment 5 was worth 40 points). A detailed grading rubric was provided to students for each poster assignment (**Supplementary Figures 1–3**).

Students were surveyed in order to evaluate the quality of instruction and learning with regards to scientific posters, to determine if poster assignments were meeting learning objectives, to understand if a virtual poster symposium was a rewarding educational experience for students, and to gauge student comfort with and preference for using technology in our course (**Figure 1**). Survey data for ENR2100 was collected over 8 semesters for 9 course sections of ENR2100. A total of 3,167 students from six distinct asynchronous, online ENR2100 courses participated in the survey. All student responses were

[1] https://carmen.osu.edu

[2] https://osu.zoom.us/

[3] https://ohiostate.pressbooks.pub/scientificposterguide/

TABLE 3 | Free resources (i.e., books, how-to videos, downloadable files) for instructors and students.

Free educational resource	Type	Link
Environmental ScienceBites, Volume 1	Open book	https://ohiostate.pressbooks.pub/sciencebites/
Environmental ScienceBites Volume 2	Open book	https://ohiostate.pressbooks.pub/sciencebitesvolume2/
Scientific posters: A learner's guide	Open book	https://ohiostate.pressbooks.pub/scientificposterguide/
Using web of science to find journal articles	Video	https://youtu.be/s8Poqum6s8M
Tips for reading a journal article	Video	https://youtu.be/Bn023GXHwug
Creating an original figure for a poster	Video	https://youtu.be/EqEVHN67s4A
Giving a poster presentation	Video	https://youtu.be/zlt7PwEyjMA
Virtual poster symposium in canvas	Video	https://youtu.be/49GDNepo4uI
PowerPoint poster templates	Files	https://u.osu.edu/introenvironmentalscience/course-assignments/environmental-science-project/scientific-poster/

These resources are intended to help instructors organize and host a virtual poster symposium and manage online poster peer reviews. Resources are also provided for students so that they understand how to produce an organized, high-quality poster and give a professional and informative presentation. All resources are completely free.

anonymous. Enrollment in each of the six courses ranged from 400 to 725 students. Students completed the survey at the end of the semester (i.e., Week 15), after they had completed their poster assignments and participated in the online poster symposium. Surveys were conducted within Canvas during the following semesters: Spring 2017, 2018, 2019, 2020, 2021 and Autumn 2020 and 2021 (**Table 1**).

RESULTS

Poster Assignments and Virtual Poster Symposium

All students at Ohio State are given free access to Microsoft Office products (i.e., PowerPoint, Excel), therefore, students used this software to create their scientific posters. At the beginning of the semester, Microsoft PowerPoint poster templates (36-inches × 48-inches) were provided to all students on Canvas. Students were instructed to download and use one of the poster templates to create their poster (**Table 3**). Poster templates were already formatted (e.g., proper font type, font size, color, organization) and contained detailed instructions about designing a high-quality scientific poster (e.g., how to properly insert a figure or table, scaling, resolution, cropping, moving objects). Each student enrolled in ENR2100 was required to create their own poster (e.g., if 500 students were enrolled in ENR2100, then we had 500 individual poster presentations).

Students worked on their poster presentations throughout the semester and received regular feedback from the instructor and teaching assistants (**Figure 2**). The online poster symposium itself was held at the end of the semester over a period of 6 days during week 14 (a semester is 15 weeks long). During the first 3 weeks of the semester, students were introduced to scientific posters, learned about primary and secondary sources, learned how to utilize library resources to find and download journal articles, newspaper articles, documentaries and books, shown examples of scientific posters and asked to select a topic that is related to environmental science (**Figure 2**). Students were given the ability to choose their poster topic. To ensure that posters were focused, students were instructed to concentrate their poster on one species, one environmental issue, and one location. Students were instructed that in terms of location, the area should be limited to a maximum size of about 100 km × 100 km. Students selected a wide range of environmental topics for their posters. Poster themes included, but were not limited to air pollution, biodiversity, climate change, ecology, food production, mining natural resources, natural resource management, renewable energy, urban design, water pollution, water resources, waste management, wildlife management.

During Week 3 of the semester, students completed Poster Assignment 1, which was a 10-point quiz designed to examine their understanding of scientific posters and scientific communication, their ability to find, download and read journal articles, and their proficiency to critically evaluate and use primary and secondary sources of information (**Figure 2**). The quiz was open-book and students were permitted to use online resources and our class' free open textbook "Scientific Posters: A Learner's Guide" (**Table 3**, see text footnote 3). Students were given multiple attempts and the highest score between attempts was kept. Quizzes were graded and students were provided with written feedback to ensure that they understood fundamental concepts and skills required to write and present an impactful scientific poster.

In Week 5, students completed Poster Assignment 2, which was worth 10-points (**Figure 2**). For this assignment, they were asked to pick their poster topic (i.e., one species, one environmental issue, one location), write a poster abstract and provided 10 references that they would use in their poster. Students are given examples and suggestions but are free to pick their poster topic as long as the research is related to the field of environmental science. Seven references were required to be primary source journal articles, the other 3 could be journal articles or secondary sources. This assignment was open-book and completed on Canvas as an untimed quiz. Poster Assignment 2 was graded using a rubric, and individual feedback was provided to each student regarding their poster topic, 10 references and abstract.

In Week 8, students completed Poster Assignment 3, which was worth 15-points (**Figure 2**). For this assignment, students were required to complete two sections of their scientific poster (e.g., Introduction and Materials and Methods) Students used one of the poster templates (**Table 3**) that were provided on Canvas to complete Poster Assignment 3. The poster templates contained detailed instructions (e.g., writing text, creating figures

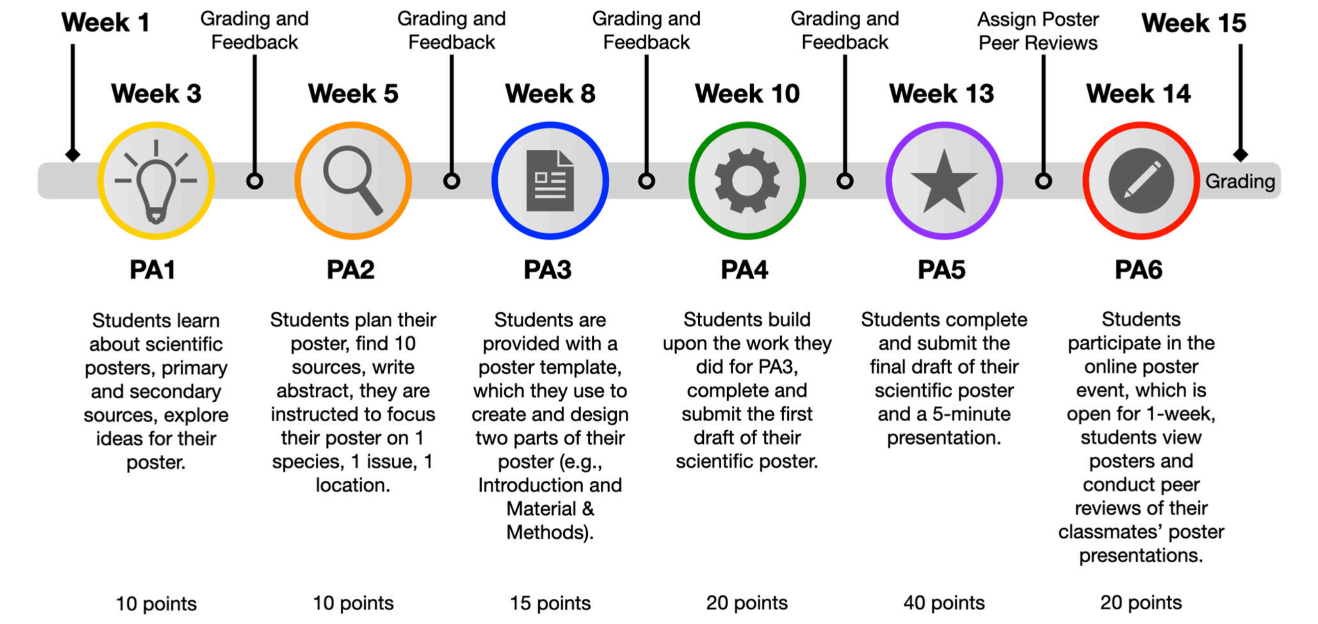

FIGURE 1 | Students were surveyed about their experience with poster assignments and asynchronous online poster event. Students responded to each question by selecting 1 of 5 responses: strongly agree (blue), agree (green), neutral (yellow), disagree (orange), strongly disagree (red). A total of 3,167 students from six different asynchronous, online courses participated in surveys. Class sizes ranged from approximately 400 students to 725 students. Students completed surveys at the end of the semester (i.e., Week 15) after they had completed all poster assignments. Surveys data collected during the following semesters: Spring 2018, 2019, 2020, 2021 and Autumn 2020 and 2021. All student responses were anonymous.

and tables) and were already formatted (e.g., organization, font style, font size, color) to help students produce an organized and professional poster. Students submitted their poster as a PowerPoint file (or PDF file) on Canvas. All student poster files uploaded to Canvas were automatically screened for original content by Turnitin software[4]. Students were encouraged and permitted to utilize Turnitin software prior to each poster assignment submission to ensure that their work was original. Posters were graded by the instructor and teaching assistants using a grading rubric (**Supplementary Material**) and feedback was provided to each student *via* Canvas.

Students continued to work on their posters through week 10 of the semester using the feedback they received from the instructor and teaching assistants on Canvas. At the end of Week 10, students submitted one PDF file, which was the first draft of their poster. Their first draft contained Title, Name, University Address, Abstract, Introduction, Materials and Methods, Results, Discussion, 10 References, 4–6 Figures and/or Tables, and Figure Captions. Students uploaded their poster file to Canvas, and it was automatically screened for original content by Turnitin software (see text footnote 4). Posters were graded by the instructor and teaching assistants using a grading rubric (**Supplementary Material**) and addition feedback was provided to each student using Canvas.

Students continued to work on their posters through week 13 of the semester using the feedback they received from the instructor and teaching assistants on Canvas. At the end of week 13, each student was required to upload their final poster (PDF file) and presentation (5-min audio or video recording) to Canvas within a discussion board (**Figure 2**). Canvas automatically screened for original content using Turnitin software (see text footnote 4) and randomly generated and assigned poster peer reviews for each student. Each student was randomly assigned two posters for peer review. Students were able to see the posters they were assigned to review on Canvas in their "To-Do List" and complete the reviews through Canvas discussion board using a rubric and guided instructions.

Our asynchronous, online poster symposium started on Sunday at 12:00 a.m. of Week 14 and was open to all students for a total of 6 days (**Figure 2**). Students were permitted to login to Canvas at any time and as many times they liked during Week 14 to view the posters and poster presentations posted to the discussion board and complete their assigned peer reviews. Students completed their peer reviews through Canvas and were provided with instructions and a rubric, which they used to complete their peer reviews (**Supplementary Material**). In total, each online poster symposium consisted of approximately 400–825 poster presentations and 800–1,650 peer reviews. Poster grades and peer reviews were provided to each student using Canvas during week 15, which was the final week of the semester.

Student Learning Experience

Students were asked three questions about their experience completing their poster assignments as part of an asynchronous, online course. Student responses to these questions are shown in **Figure 1**. When students were asked if they were provided

[4]https://turnitin.com

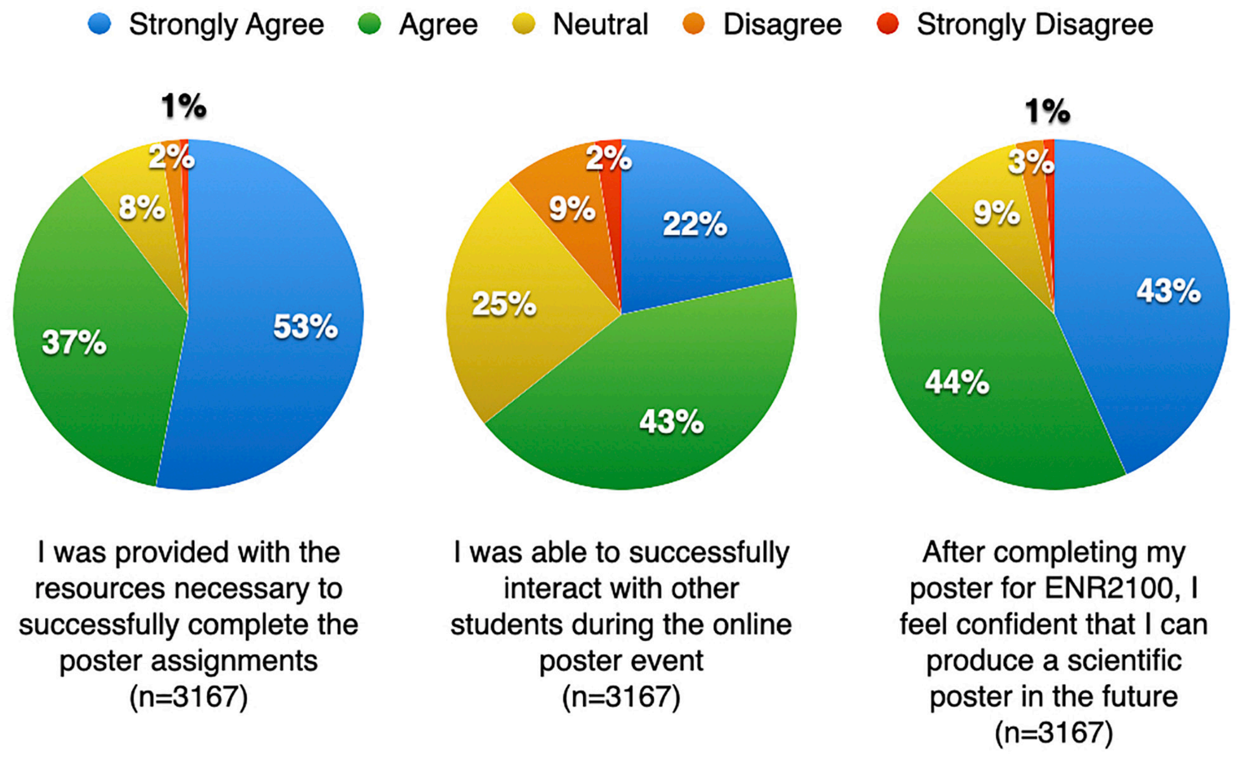

FIGURE 2 | Timeline of poster assignments. Students completed a total of 6 poster assignments during a 15-week semester. PA1 and PA2 were a short-answer quizzes. Students submitted a poster PDF file for PA3 and PA4. Students submitted a poster PDF file and 5-min audio (or video) presentation for PA5. For PA6, each students completed 2 poster peer reviews during the online poster symposium. The online poster symposium was open for 6 days during Week 14 of the semester. All poster assignments were open book. Students were given 7–21 days to complete each poster assignment. Students completed and submitted all poster assignments using Canvas Learning (https://carmen.osu.edu). Poster files submitted for PA3, PA4, and PA5 were uploaded to Canvas and automatically screened for original content by Turnitin software (https://turnitin.com). Each poster assignment was graded using a rubric and feedback was provided to each student through Canvas. The point value for each poster assignment is provided at the bottom. PA, Poster Assignment.

with the resources necessary to successfully complete their poster assignments, student responses were as follows: 90% (2,839 of 3,167) strongly agreed or agreed, 8% (246 of 3,167) neutral, and 2% (82 of 3,167) disagreed or strongly disagreed (**Figure 1**). When students were asked if they were able to successfully interact with other students during the Virtual Poster Symposium, student responses were as follows: 68% (2,154 of 3,167) strongly agreed or agreed, 22% (697 of 3,167) neutral, and 10% (316 of 3,167) disagreed or strongly disagreed (**Figure 1**). When students were asked if they were confident that they could produce a scientific poster in the future, student responses were as follows: 87% (2,755 of 3,167) strongly agreed or agreed, 9% (285 of 3,167) neutral, and 4% (127 of 3,167) disagreed or strongly disagreed (**Figure 1**).

At the end of the semester, students were also surveyed within Canvas to determine which parts of the course were most effective for instruction and learning. Students were asked to rank five modes of content for our course based on which they learned the most: Poster Assignments, Lecture Videos, Lecture Slides, Quiz Materials, Additional Resources (**Figure 3**). A total of 1,788 students from three distinct asynchronous, online courses participated in the rankings during the Autumn 2020, Spring 2021, and Autumn 2021 semesters. Enrollment ranged from 500 to 700 students. Rankings were completed at the end of the semester (i.e., Week 15) by students after they had completed all lectures, quizzes and poster assignments. All student responses were anonymous.

Figure 3 shows that Poster Assignments were most frequently ranked #1 (595 first-place votes) by 1,788 students when asked to identify the part of the course where they learned the most. The number of 1st-place votes (**Figure 3**) were as follows: Poster Assignments (595 votes), Lecture Videos (507 votes), Lecture Slides (332 votes), Quiz Materials (320 votes), and Additional Resources (88 votes). The number of 2nd-place votes (**Figure 3**) were as follows: Lecture Slides (496 votes), Lecture Videos (475 votes), Quiz Materials (481 votes), Poster Assignments (253 votes), and Additional Resources (108 votes).

Students (n = 1,788) from these same three asynchronous, online courses were asked the following three questions at the end of the semester as part of an anonymous online survey:

1. Would you encourage other online courses to consider similar scientific poster assignments and virtual poster symposium?
2. Did presenting your poster in an audio or video clip add to your understanding of your poster topic?

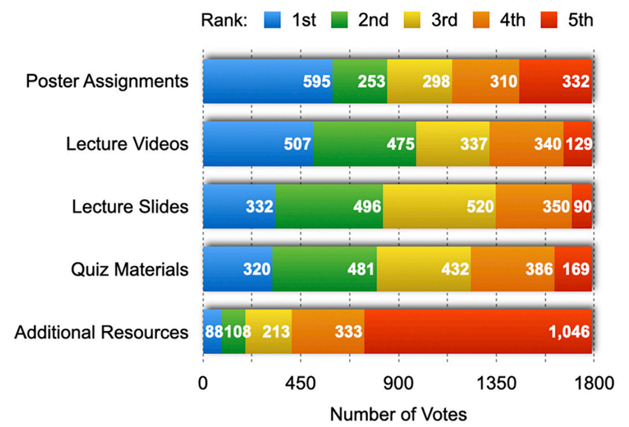

FIGURE 3 | Students ranked five course components (Poster Assignments, Lecture Videos, Lecture Slides, Quiz Materials, Additional Resources) based on which component they learned the most (1st) to least (5th). Total number of votes that each component received is shown as blue (1st-place), green (2nd-place), yellow (3rd place), orange (4th-place), red (5th-place). A total of 1,788 students from three different asynchronous, online courses participated. Students completed rankings at the end (i.e., Week 15) of the Autumn 2020, Spring 2021, and Autumn 2021 semesters after they had completed all lectures, quizzes and poster assignments. All student responses were anonymous.

3. Do you have any comments, ideas or suggestions about the Poster Assignments or the Virtual Poster Symposium?

Approximately 80% of students answered "Yes" to question 1 and 90% answered "Yes" to question 2. The Top 5 Comments to question 3 are provided in **Table 3**.

DISCUSSION

Goals and Learning Outcomes

Poster presentations are an especially effective assignment for teaching science literacy and information literacy in a Natural Science GE course for several reasons. First, presenting a poster to a mixed audience of student peers, teaching assistants, and instructors encourages students to prepare for and effectively communicate with a real audience (Sisak, 1997; Hobson, 2008; Brownell et al., 2013; Feliú-Mójer, 2015; Pedwell et al., 2017). In order to produce a high-quality poster and give an impactful presentation, students must learn how to find, read, evaluate and effectively use information. Faced with the prospect of presenting their work to dozens of their peers, students will confront questions by an audience as integral to the assignment more so than is possible when the only audience is an instructor who grades their work (Huxham et al., 2012; Menke, 2014; Rouser, 2017). Science and information literacy empowers students to become engaged citizens in local, national and global communities, which is a major learning objective for Natural Science GE courses.

Second, the genre of the scientific poster is both more easily comprehensible and imitable by early students than other types of professional scientific outlets (e.g., peer-reviewed journals, professional meetings). The fully fledged research paper or lab report are particular forms of communication, which require detailed instruction and guidance. A meaningful research paper may likewise require more substantial work and time than students are able to commit in a general education course (Huxham et al., 2012). Research papers and lab reports are typically reserved for upper-level courses and labs taken by students (e.g., majors and minors) who have the educational background and training for this level of difficulty. Posters, by contrast, make intuitive sense as a method for abstracting crucial information about a topic, and even introductory posters can function as useful educational tools (Menke, 2014; Navarro et al., 2021). In our Natural Science GE courses, we have observed that all students (e.g., science major, non-science major, freshman, sophomores, junior, senior; **Table 1**) are able to produce organized and professional-looking posters and give polished and informative presentations. We did observe that students who did well on early poster assignments (e.g., Poster Assignments 1–3) and used TA feedback to improve subsequent poster assignments, were much more likely to produce a high-quality poster presentation at the end of the semester. We also noted that students who were more engaged in our online course (as judged by Canvas analytics, which permitted us to see the number of page views, number of downloads, number of discussion posts, number of emails) were more likely to do well on their poster assignments.

Third, research posters encourage multiform representation (e.g., tables, graphs, maps, photographs) and, as research shows, encountering ideas in multiple forms increases the likelihood that students will gain a conceptual understanding and learn to apply what they learn to understand and solve real-world problems (Miller, 2014; Rodríguez-Estrada and Davis, 2015; Rouser, 2017; Murchie and Diomede, 2020; Perra and Brinkman, 2021). Effective communication both requires and inculcates understanding of the science about which students communicate (Brownell et al., 2013; Feliú-Mójer, 2015). Stiller-Reeve et al. (2016), note that climate science and geoscience are increasingly interdisciplinary, and it is therefore important for scientists to write clearly and communicate effectively. They argue that the key to improving the writing and communication skills is to target early career scientists through peer learning (Stiller-Reeve et al., 2016). They show how an online writing program called ClimateSnack can be used to connect young scientists online who can then share manuscripts, receive peer feedback and improve their writing before its published (Stiller-Reeve et al., 2016). To be clear, it is not a choice between teaching students to understand the findings of science, on the one hand, and on the other hand, focusing on the skills of communicating those ideas, facts, theorems, experimental models, and so forth. Effective communication both requires and inculcates understanding of the science about which students are communicating to their audience.

Fourth, the poster presentation assignment makes it feasible to incorporate effective writing and communication instruction in a course with hundreds of students (Hobson, 2008; Navarro et al., 2021). Here we used our virtual poster symposium to serve as interactive online space for students to communicate with their peers by taking part in collaborative learning and discussion (Knapp, 2018). Knapp (2018), found that virtual poster sessions mimic the interaction patterns of in-person conference poster sessions. Teaching scientific literacy and communication is crucial, both for those who plan to become scientists and for those pursuing other professions (Hobson, 2008; Feliú-Mójer, 2015). It promotes deeper learning and understanding of the methods and findings of scientific endeavors, while also promoting enjoyment and ongoing engagement within the practices of research. Perhaps most important, poster presentations train students to participate in conversations about scientific findings, as well as the implications of those findings in society, politics, healthcare and other areas of life. These are important learning objectives for Natural Science GE courses.

We would like to point out that our students created their posters based on research presented in published journal articles. Our students did not conduct the research themselves, mainly because it would be challenging for an undergraduate student to complete laboratory and/or field-based research as part of a 3-credit, 15-week, Natural Science GE course. Students did not have the training, time, funding, and resources to conduct such work. Rather, the main objectives for this poster project were to accomplish the goals and learning outcomes for a Natural Science GE Course: teach scientific literacy and scientific communication, promote a deeper learning and understanding of the methods and findings of natural science research, describe and analyze the process of scientific inquiry, engage in theoretical and empirical study within the natural sciences, and evaluate the social and ethical implications of natural science discoveries. For an online undergraduate honors course or an online graduate-level course, original student data could definitely be presented during an asynchronous online poster symposium similar to what we describe here.

Instruction, Grading, and Student Feedback

Management of Poster Assignments

Careful planning and organization is required by the instructor to make tasks easy to understand and to ensure that expectations are clear for students. Integrating rubrics throughout the course aids in this endeavor so that students know how their work will be graded, ensure that grading is accurate and fair, helps to provide students with timely feedback, and reduces grading errors and to avoid student mistakes (**Table 3** and **Supplementary Material**). An online Learning Management System (LMS), like Canvas, is essential for the management and implementation of an online poster symposium, especially in a large enrollment DE course that is being taught asynchronously. In addition, the Canvas LMS allows for frequent instructor-student communications (e.g., email, discussion posts, assignment comments) and convenient anytime, anywhere access to scientific posters for both students and instructors. Joyner et al. (2020) did observe what they described as a "synchronicity paradox" in online education where students wanted synchronicity to form peer communities, but yet the chief appeal of online education was the asynchronicity. The solution, they argue, it to provide synchronous activities centered around existing patterns of interactions such as lecture co-watching, study groups that select from and meet during specific time slots (Joyner et al., 2020). For our class, we will sometimes group posters according to topic (e.g., water science, climate change, renewable energy) because we found this to be an effective way to encouraged peer-to-peer interactions among students with similar educational interests and career goals (e.g., water science) but who may be from different colleges and departments.

During poster development and composition, the defined scope and structure of the assignment lends itself to a step-by-step process with repeated early feedback (**Figure 2**). Students proceed through a quiz, a bibliography, an abstract, and two preliminary drafts of their poster (**Figure 2**). Likewise, grading can be accomplished more effectively with the same or fewer resources because instructors can see the work in real-time and clarify questions by communicating with students directly. The instructors' and teaching assistants' (TAs) assessments can also be supplemented by peer-review, which increases the effectiveness of the assignment by deepening its resemblance to the actual work of scientists.

While it may be apparent that a scaffolded poster project can simplify the grading process, especially when compared to other written assignments (i.e., research papers), it is not to say that grading posters does not demand a significant dedication of time as well. An assignment of this type requires the compilation and combination of multiple grades for an individual student (e.g., feedback from instructor, teaching assistant, peers) in order to calculate a final grade. The time-demands of these processes are exacerbated when course enrollment is several hundred students and compiled student grades are derived from multiple types of assessments.

Poster Feedback and Grading

In terms of instructor-student ratio, we found that 1 teaching assistant can effectively handle the grading and poster feedback for 40–50 students, meaning that students receive their poster grade and feedback within 7–10 days of submitting an assignment. To allow for smoother workflow and timely and detailed feedback, our teaching assistants utilize rubrics (**Supplementary Material**) for grading Poster Assignments 2–6 (**Figure 2**). Rubrics allowed teaching assistants to consistently assess assignments from student to student. We found that assigning the same TA to the same group of 40–50 students for the entire semester worked best for poster grading and providing feedback. Our TAs preferred grading the same 40–50 students throughout the semester and we found that when same TA worked with the same 40–50 students throughout the semester, that poster grading and feedback was much more likely to be completed and that poster feedback was more detailed and constructive. Students also preferred working with the same TA throughout the semester (as opposed to using a different TA throughout the semester) because they were able to build a working relationship with the TA and become more conformable communicating and interacting with one TA. If students wanted to interact with a different TA, they could easily do so during weekly TA Office Hours that were held over Zoom. We would like to point out that Poster Assignment 1 isn't graded by hand because it is set up as a self-grading, multiple-choice quiz.

All poster submissions, grading, feedback and communication (e.g., instructor-student) was accomplished online using the Canvas LMS. Teaching assistants were able to use Canvas to directly annotate poster files (e.g., add comments, highlight, mark up, draw), grade posters using rubrics and provide detailed comments to students (**Table 3** and **Supplementary Material**). Students were able to see grading rubrics before they started each assignment, presenting expectations and components of each poster assignment. Students were also able to receive timely and detailed feedback through the rubric so that they could improve their work before continuing onto the next poster assignment. Students who had a question could email the instructor using Canvas or post a question within the Canvas discussion board for the instructor to answer.

These strategies allowed teaching assistants to provide students with specific and timely information for each poster assignment, so that students were able to quickly identify and correct mistakes before continuing to the next poster assignment. By scaffolding poster assignments, the instructor was better able to ensure student success because instruction and learning was broken up into manageable tasks. In addition, with the completion of each poster assignment, students built a stronger foundation on which to build their poster. With each step in the process students acquired new skills and new understandings that helped advance them toward their ultimate goal of producing a high-quality poster and presentation.

In addition to poster grading and student feedback, poster peer reviews must be accounted for when hosting an online poster symposium. The "Virtual Poster Symposium in Canvas" video (link to video provided in **Table 3**) provides detailed instructions on how to assign, manage and conduct online poster peer reviews using Canvas. With the traditional pencil-paper peer-review, a workflow is created where student reviews need to be sorted not only by the reviewer but also the instructor. This process places the reviews in the hands of the instructor for an extended period of time, increasing the time between which the student delivers their presentation to when the student receives feedback. This may result in students receiving feedback days or even weeks after their presentation by which time the feedback may be less useful to the learner. Therefore, it is important to provide meaningful and timely feedback to students during the relatively short period of time (i.e., 15 weeks) that they are enrolled in the course. A turnaround time of around 7–10 days, from the time a student submitted their poster to the time the instructor provided feedback, seemed to work best for student success. If grading and feedback couldn't be provided within 10 days, we extended the deadline of the next poster assignment by 1 week. If we didn't extend the deadline, students weren't able to complete their work on time. This is why its important to have an adequate number of teaching assistants to assist with grading and feedback (e.g., 1 TA per 40 students). The Canvas LMS can automatically facilitate many of these logistical tasks that would have traditionally been done by the instructor with pencil-paper peer-reviews, therefore dramatically reducing the time frame of the peer-review process. These tasks include automatically and randomly assigning students their peers to review, reminding students to complete peer-reviews by automatically placing on item on the Student's Canvas "To-Do List," providing immediate access to the peer's work, providing an online space to conduct and submit peer-reviews, sharing back to poster presenters their peer's feedback immediately after reviews are completed (**Table 3**).

Poster Resources and Student Accommodations

Over the past 8 years, we have developed several educational resources that have been particularly effective at helping our students design and give professional poster presentations (**Table 3**). Detailed instructions, examples and How-To videos are also provided to students before they begin an assignment (**Table 3**, videos and **Supplementary Material**). In 2019, we published a free open textbook (**Table 3**, Scientific Posters: A Learners Guide) that we now use for our poster assignments. This book has been particularly helpful to our students. In addition, we published two open textbooks with chapters that were written by our ENR2100 undergraduate students (**Table 3**, Environmental ScienceBites, Volume 1 and Environmental ScienceBites, Volume 2). These two open textbooks have provided our students with examples of writing, figures and tables that they could use to guide them as they created their own scientific posters. These materials are freely available and provided in **Table 3**. Anytime a student has a question about a particular part of a scientific poster we can direct them to a book chapter, poster example or instructional video to answer their question (**Table 3**). These resources are also convenient for students because they are free and can be retrieved online on demand.

Some of our students receive accommodations (e.g., accessible media, assistive technology, deadline modifications) and we found that running our virtual poster symposium asynchronously through the Canvas LMS allowed us to provide accommodations to all our students. Arcila Hernández et al. (2022) came to a similar conclusion when examining poster sessions at professional science conferences from March 2020 to March 2021. They recommended incorporating an asynchronous virtual poster session into in-person poster sessions to improve accessibility, provide greater flexibility, increase engagement, and allow for a greater diversity of feedback (Arcila Hernández et al., 2022).

Some students did find it difficult to create and design their scientific posters. We observed that students who had little to no previous experience using Microsoft PowerPoint found it more difficult to create and design their scientific poster compared to students who had previous experience using PowerPoint (**Table 4**). To help these students we provided free 36-inch × 48-inch PowerPoint poster templates that all students were able to download and use (**Table 3**). We also provided poster examples, instructional videos and book chapters about creating and designing scientific posters (**Table 3**). The other issue we observed for our students was the type of computer they used to create their poster (**Table 4**). Not surprising, students who used a laptop or desktop computer were better able to complete their poster assignment compared to students who used a tablet.

TABLE 4 | Top 5 student responses to the end-of-semester survey question "Do you have any comments, ideas or suggestions about the Poster Assignments?" A total of 1,788 students from three different asynchronous, online courses participated.

Top 5 Student comments regarding poster assignments
1. Students appreciate seeing examples of scientific posters to help them design their own posters. Providing large-format (e.g., 36-inch × 48-inch) PowerPoint poster templates helps students produce professional-looking posters.
2. It is important for the instructor and/or teaching assistants to provide frequent and detailed feedback between poster assignments.
3. Students liked being able to pick their own poster topic because it allowed them to focus on a topic that was important and interesting to them.
4. Students who had little to no previous experience using Microsoft PowerPoint found it more difficult to create a scientific poster compared to students who had previous experience with the PowerPoint software. Laptop and desktop computers, with their larger screens and higher processing power, are better for working on large-format (e.g., 36-inches × 48-inches) posters compared to tablets.
5. Primary source journal articles can be difficult for students to understand.

Students completed rankings at the end (i.e., Week 15) of the Autumn 2020, Spring 2021, and Autumn 2021 semesters after they had completed poster assignments. All student responses were anonymous.

The larger screens and higher processing power of laptop and desktop computers made for a much better experience when working on large-format (e.g., 36-inches × 48-inches) posters. **Supplementary Table 1** provides additional recommendations for poster assignments based on our long-term study.

Asynchronous virtual poster symposiums were part of our classes both before and after the -19 pandemic (**Table 1**). We observed a 30% increase in enrollment in our DE course after COVID-19 (**Table 1**), which resulted in 30% more poster presentations and 30% more peer reviews. In terms of using the Canvas LMS to run and manage the virtual poster symposium (e.g., instructions, poster submissions, video, audio, grading, peer review) nothing changed after the COVID pandemic. We did have to hire more teaching assistants to help with the increased numbers (e.g., to hold Zoom office hours, provide poster feedback and assist with grading). The other difference that we observed after the COVID pandemic, was that students became more independent and proficient when using technology. Students were better prepared to record audio, record video, use Microsoft PowerPoint and Excel, and use databases to find and download journal articles. As a result, we observed that posters were more detailed and organized, figures and tables were higher quality, video and audio recordings became more polished and professional. We also observed that online student interactions were often more frequent and meaningful (e.g., back and forth discussions between students) and peer reviews were more detailed, specific to the research presented in the poster, clear and constructive. Instructors and teaching assistants also experienced a significant decrease (about 50%) in the number of emails from students who had questions related to technology.

Student Educational Experience

Our scientific poster project was designed to provide students with an engaging and rewarding educational experience in a Natural Science GE course that had a large enrollment of diverse students and was being taught as an asynchronous DE course. To obtain and analyze evidence of student learning with scientific posters we conducted student surveys (**Figures 1**, **3**). These data indicated that students were provided with the resources necessary to complete their scientific poster (**Figure 1**). Students viewed the poster assignments as valuable and impactful parts of the course (**Figure 3**) and approximately 90% of our students stated that they gained an understanding and appreciation for theoretical and empirical studies within the natural sciences. After completing the poster assignments, students were confident that they could successfully produce a scientific poster in the future (**Figure 1**) and approximately 80% of our students would encourage other online courses to utilize scientific poster presentations. Holt et al. (2020) received similar positive feedback from students ($n = 66$) who participated in their virtual poster session for an upper-level ecology course. They identified several key benefits of an online poster session including enhanced instructor-student engagement, flexibility of the remote venue, and the ability to interact with peers in an otherwise isolated COVID world (Holt et al., 2020). Students who completed the poster assignments for our class were successfully able to:

1. Explain facts, principles, theories and methods of natural sciences.
2. Find, critically evaluate and responsibly use information from natural sciences.
3. Evaluate the social and ethical implications of natural science discoveries.
4. Explain the changing nature of scientific knowledge and methods.
5. Demonstrate how peer-review is an integral part of the scientific process to maintain high standards of quality and provides credibility to research.
6. Become better writers and speakers by focusing their attention on particular details and considering the input of an actual audience.

In conclusion, an online poster symposium can be used as a unique educational experience and assessment tool for an online, asynchronous courses. Here we described a study that takes place from 2017 to 2022 (pre- and post-COVID) and involves 5,625 students over 8 semesters. We demonstrate how online poster presentations and peer review can be used in an asynchronously taught online Natural Science, General Education course. The methods, tools and resources provided here (**Table 3** and **Supplementary Material**) can be adapted to fit other online courses that are being taught asynchronously or synchronously. Furthermore, we have demonstrated that by using a Learning Management System like Canvas, instructors can effectively manage the organization, student feedback and grading of poster assignments, even in large-enrollment online courses. Students found the poster assignments and the online poster event to be engaging, collaborative and offer interactive peer-to-peer experiences. Based on instructor and student feedback, we recommend the implementation of an online poster symposium to be used as a rewarding learning experience for students enrolled in DE courses that are being taught asynchronously or synchronously.

DATA AVAILABILITY STATEMENT

The original contributions presented in this study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

BL, EW, and KS: conceptualization, methodology, resources, review and editing, and project administration. BL: writing original draft and funding acquisition. All authors have read and agreed to the published version of the manuscript.

FUNDING

This work was supported by the U.S. National Science Foundation under (grant EAR-2038207).

ACKNOWLEDGMENTS

We would like to thank the students who were enrolled in ENR2100 and acknowledge their efforts to create high-quality scientific posters and professional poster presentations. We would also like to thank the U.S. National Science Foundation for funding this work under grant EAR-2038207 and the editor and three reviewers for their important insight and thorough evaluation.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feduc.2022.906995/full#supplementary-material

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frontiers | Frontiers in Education
CURRICULUM, INSTRUCTION, AND PEDAGOGY
published: 14 June 2022
doi: 10.3389/feduc.2022.890379

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Sharing Experiences in Designing Professional Learning to Support Hydrology and Water Resources Instructors to Create High-Quality Curricular Materials

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OPEN ACCESS

Edited by:
Bridget Mulvey,
Kent State University, United States

Reviewed by:
Christa Kelleher,
Lafayette College, United States
Anne Jefferson,
Kent State University, United States

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Specialty section:
This article was submitted to STEM Education, a section of the journal Frontiers in Education

Received: *05 March 2022*
Accepted: *26 May 2022*
Published: *14 June 2022*

Citation:
Gallagher MA, Habib EH, Williams D, Lane B, Byrd JL and Tarboton D (2022) Sharing Experiences in Designing Professional Learning to Support Hydrology and Water Resources Instructors to Create High-Quality Curricular Materials. Front. Educ. 7:890379. doi: 10.3389/feduc.2022.890379

The creation of high-quality curricular materials requires knowledge of curriculum design and a considerable time commitment. Instructors often have limited time to dedicate to the creation of curricular materials. Additionally, the knowledge and skills needed to develop high-quality materials are often not taught to instructors. Furthermore, similar learning material is often prepared by multiple instructors working at separate institutions, leading to unnecessary duplication of effort and inefficiency that can impact quality. To address these problems, we established the HydroLearn platform and associated professional learning experiences for hydrology and water resources instructors. HydroLearn is an online platform for developing and sharing high-quality curricular materials, or learning modules, focused on hydrology and water resources. The HydroLearn team has worked with three cohorts of instructors from around the world who were dedicated to creating high-quality curricular materials to support both their students and the broader community. In order to overcome some of the aforementioned barriers, we tested and revised several different models of professional learning with these cohorts. These models ranged from (a) instructors working individually with periodic guidance from the HydroLearn team, to (b) small groups of instructors collaborating on topics of shared interests guided through an intensive HydroLearn training workshop. We found the following factors to contribute to the success of instructors in creating modules: (1) instructor pairs co-creating modules enhanced the usability and transferability of modules between universities and courses, (2) dedicating an intensive block of time (∼63 h over 9 days) to both learning about and implementing curriculum design principles, (3) implementing structures for continuous feedback throughout that time, (4) designing modules for use in one's own course, and (5) instituting a peer-review process to refine modules. A comprehensive set of learning modules were produced covering a wide range of topics that target undergraduate and early graduate students, such as: floodplain analysis, hydrologic droughts, remote sensing applications in hydrology, urbanization and stormwater runoff, evapotranspiration, snow and climate, groundwater flow, saltwater intrusion in coastal regions, and stream solute tracers. We share specifics regarding how we structured the professional learning models, as well as lessons learned and challenges faced.

Keywords: engineering education, professional learning, curriculum development, backward design learning approach, learning objectives, online learning

INTRODUCTION

Creating high-quality curricular materials can be challenging for instructors, given that the creation of these materials requires both knowledge of curriculum design, as well as a considerable time commitment (Borrego et al., 2010; Bourrie et al., 2016; Habib and Deshotel, 2018). Many university-level instructors completed doctoral coursework that did not cover the knowledge and skills needed to develop high-quality curricular materials (DeChenne et al., 2012). Moreover, instructors often have multiple commitments, including teaching, conducting research, and service to the university and field. This leaves limited time for the creation of curricular materials. Additionally, when instructors do invest time in creating curricular materials, they often do this work alone and for their own courses. While developing curricular materials is an important part of the teaching process in higher education, multiple instructors around the world creating similar curricular materials is inefficient and duplicative, and may impact quality. In addition to the issues around the creation of high-quality curricular materials (Ruddell and Wagener, 2015), the recent COVID-19 pandemic generated a need for high-quality curricular materials (Loheide, 2020) that can be accessed online and are openly available. This rapid transition to online instruction was challenging for many faculty. For instance, Johnson et al. (2020) found that 97% of higher education administrators reported that at least some of their faculty had no online teaching experience and 61% of administrators reported that the greatest need was increased access to online digital materials. Many instructors were not just looking for materials online (e.g., repositories of slides), but rather modules that students could engage in.

We have sought to address these problems within the field of hydrology and water resources by establishing the HydroLearn platform.[1] HydroLearn allows instructors to find, adapt, and use high-quality online modules. Although the HydroLearn platform was designed prior to the COVID-19 pandemic, it was positioned to support instructors in the rapid transition to online instruction and serves as a useful resource of online modules to support hydrology and water resources content. To support instructors in creating high-quality curricular materials, the HydroLearn team designed online professional learning experiences, both synchronous and asynchronous, to support instructors in learning about research-based practices in curriculum design. We refer to instructors who participated in these learning experiences as fellows. The purpose of this article is to describe two approaches to professional learning experiences the HydroLearn team created to support fellows' use of research-based practices to design online modules. We first describe the research upon which our model for curriculum design and professional learning is based, then the two approaches of the professional learning experiences that we designed, and lastly we share lessons learned.

PEDAGOGICAL FRAMEWORKS

High-quality curricular materials are defined as those that have evidence of student learning, follow research-based methods of curriculum design, and are accessible to students with a variety of learning needs. The modules that were the outcomes of these professional learning experiences have evidence of student learning (Byrd et al., under review; Roundy et al., under review), were designed using the research-based methods described below, and as part of the review process, were required to incorporate features to make them more accessible (e.g., including captions on all videos, making sure figure captions were readable by screen readers, etc.). Thus, we consider the HydroLearn modules to be high-quality curricular materials. To support fellows in the creation of HydroLearn modules, we brought together two pedagogical frameworks: one from research in curriculum design (i.e., Backward Design) and one from research in professional learning (i.e., workshops). We describe the literature related to each of these in turn below.

Curriculum Design

The framework for curriculum design that we used is Backward Design (Wiggins and McTighe, 2005):

> *"One starts with the end—the desired results (goals or standards)—and then derives the curriculum from the evidence of learning (performances) called for by the standard and the teaching needed to equip students to perform."*

Backward design is an iterative process of curriculum design in which instructors first define their learning objectives, then create assessments that align with those learning objectives, and lastly design the content to be taught which will set students up to be successful with the assessments (see **Figure 1**). At each step, curriculum designers are constantly considering the constructive alignment of their materials, including carefully examining that the stated learning objectives match the assessed learning objectives and that the content taught will allow students to learn the content and skills needed to be successful in the assessments.

Learning objectives specify "not only what is to be learned, the topic, but how it is to be learned and to what standard"

[1] www.hydrolearn.org

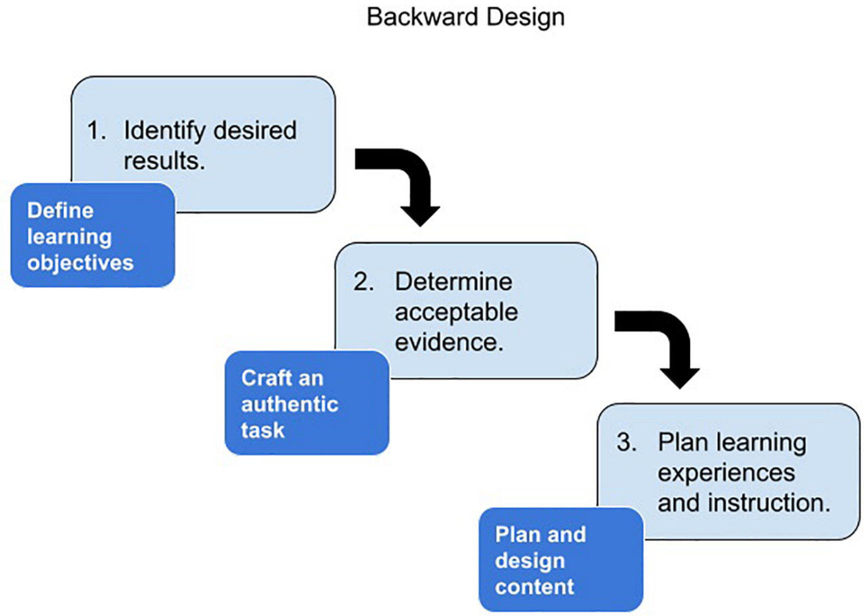

FIGURE 1 | Backward design model used to develop HydroLearn modules.

(Biggs and Tang, 2011, p. 97–98). Effective learning objectives are written with specific principles in mind, including that the learning objectives be written with measurable verbs (i.e., verbs that can be observed, such as identify instead of verbs that cannot be observed, such as learn or understand) and that instructors take into account the level of cognitive demand required of the learning objectives included within their modules, specifically using Bloom's Levels of Cognitive Demand (Krathwohl, 2002) to classify each learning objective. Hollowell et al. (2017) found that online courses that included clear learning objectives and constructive alignment, among other characteristics, were correlated with higher student learning, as measured by course grades.

Within the framework of Backward Design, once the learning objectives have been written, instructors should design assessments that align with those objectives. Authentic, high cognitive demand tasks can be used as assessments and are helpful in measuring learning objectives at the higher levels of Bloom's Taxonomy. High cognitive demand tasks include: (a) "guidance for working with [the] practices [of a discipline] but require students to access their own content knowledge;" (b) multiple possible "correct" answers where correctness is based on accurately applying content and justifying decisions; and (c) "engaging in practices to make sense of content and recognize how a scientific body of knowledge is developed" (Tekkumru-Kisa et al., 2015, p. 663). Authentic tasks are tasks that have real world relevance and may be representative of the task a learner of the subject may need to undertake with the knowledge learned. They are a subset of high cognitive demand tasks, and allow competing solutions and a variety of outcomes (Herrington et al., 2003). In engineering, activities that include the use of online computational and analysis tools, such as Jupyter Notebooks and Google Colab, offer opportunities for students to use real world open and accessible data to solve authentic, high cognitive demand engineering tasks.

Following Backward Design, once the learning objectives and assessment are crafted and aligned, instructors must then design the content to be taught (i.e., the content that will get students from their knowledge and skills at the beginning of the course to the knowledge and skills needed to complete the authentic task). The design of online materials allows for the inclusion of video, text, images, and animations to support students' comprehension of the content (Kumar et al., 2019). Additionally, when content is presented in online modules, students have the opportunity to revisit content as needed, which is typically not possible when content is delivered in-person (Mok, 2014).

Backward Design affords a specific organizational structure that allows instructors new to curriculum design to begin to create high-quality curricular materials. However, the format of the professional learning experience in which instructors learn about curriculum design can also impact their success in curriculum writing. Therefore, we purposefully provided training on Backward Design within a workshop model to support fellows' professional learning.

Professional Learning

Research on the professional learning of instructors highlights the need for those experiences to focus on the specific content instructors will be teaching and how students learn that content, to align with instructors' experience in the classroom, to use curriculum materials and assessments, and to be spread over time (Garet et al., 2001; American Educational Research Association [AERA], 2005; Desimone, 2011). Moreover, Walpole and McKenna (2015) described the importance of working with instructors in teams, given that they are influenced by their colleagues. Workshops are one way to create collegial environments that support participants in learning from one another (Loucks-Horsley et al., 2010). Researchers agree that lecturing is often not a useful pedagogical approach for professional learning experiences (Loucks-Horsley et al., 2010). Mundry et al. (2000, p. 6–8) suggest several features of effective workshops, including making sure participants are aware of the goals and that the goals align with those of the participants, integrating a variety of activities, and creating space for participants to create products that are useful for their goals. We considered these features in designing the HydroLearn professional learning experiences to support fellows in learning about curriculum design.

LEARNING ENVIRONMENT

The design of the professional learning experiences offered through the HydroLearn program went through two different approaches and engaged three cohorts of fellows over a period of 3 years. In education literature, the term "learner" often refers to K-20 students, but in this paper, the fellows were the learners, as they were the participants in our professional learning experiences. Given that time is a major constraint in the development of high-quality curricular materials, we asked participating fellows to dedicate time to this work and we compensated them for that time.

Structure of Workshops

Recruitment for the workshops varied by cohort. For Cohort 1, we used a targeted approach and invited specific individuals to apply for the fellowship. For Cohorts 2 and 3, we expanded our methods to include social media outreach, requests for applications *via* partnership channels, and direct email invitations. Some applicants to Cohorts 2 and 3 learned of the opportunity through word-of-mouth from friends and colleagues.

Cohort 1: The first approach, which we used with Cohort 1, was based on inviting individual instructors to develop teaching modules and deploy them on the HydroLearn platform. Each participating fellow worked individually to develop a module on a topic of interest that they planned to use in their respective courses. The guidance took place *via* bi-weekly virtual meetings and iterative review rounds of the modules throughout the academic year. The meetings were attended by the cohort participants (see **Table 1** for details); however, the development of the modules and the review process were primarily done on an individual basis, on their own time, for each participant. Interaction amongst the different participants was minimal and was limited to the time when they co-participated in the periodical meetings.

At the conclusion of Cohort 1, we hosted a virtual meeting with the participants to solicit their feedback about how to improve our model for professional learning. We also met with our project external evaluator to review our progress with Cohort 1 and gather his feedback regarding modifications we could make to Cohort 2. Based on this feedback, we revised our approach to foster more collaboration between the fellows and facilitate a process for improvement through interactions between the fellows (see **Figure 2**). This revised approach adopted a workshop structure to facilitate an intensive, collaborative experience. Also, recognizing the value of and limitations on fellows' time, we strove to have most work completed during the summer workshop (although in many cases there was considerable post workshop work). We called these workshops hackathons in reference to their intensive, collaborative, and online nature. We had initially planned to host the Cohort 2 hackathon in-person, however, just as we were preparing to announce the workshop, the COVID-19 pandemic took hold and many states went on lockdown. We pivoted to an online hackathon for Cohort 2, which we found to be quite effective, and so repeated this format the following summer with Cohort 3.

Cohorts 2 and 3: Following a hackathon approach, the fellows in Cohorts 2 and 3 came together, virtually, from across the world (**Table 1**). We placed the fellows in groups of 2–3 to collaboratively develop modules. The groups worked collaboratively to design and build a module of joint interest both synchronously and asynchronously. The worktime was setup following an iterative design approach with multiple sharing points and checking-in with other participants and the HydroLearn guides during the assigned hackathon time. In a few instances (in Cohort 2), some groups decided to create individual modules but still interact in their groups for feedback.

Differences in the nature and the timing of the cohorts resulted in a larger number of participants in Cohorts 2 and 3 compared to Cohort 1. For example, the pre-defined timeframe of Cohorts 2 and 3, compared to a rather loose participation time in Cohort 1, probably encouraged more instructors to commit and participate as fellows. Also, the recruitment announcement for Cohort 2 was sent out at the onset of the first COVID-19 wave, at which time faculty had already switched to remote instruction and the concept of co-developing sharable curricular material was most appealing. The success of Cohort 2 probably propagated into the community and colleagues encouraged each other to participate in Cohort 3, during which COVID-19 conditions were still highly present.

TABLE 1 | HydroLearn fellows by cohort.

	Cohort 1	Cohort 2	Cohort 3
Fellows by type of module			
Fellows who completed an individual module	6	4	0
Fellows who collaborated on a module	0	26	22
Fellows by location of university			
Number of US universities represented by the fellows	6	29	17
Number of international universities represented by the fellows	0	1	5
Fellows by gender			
Male	4	20	16
Female	2	10	6

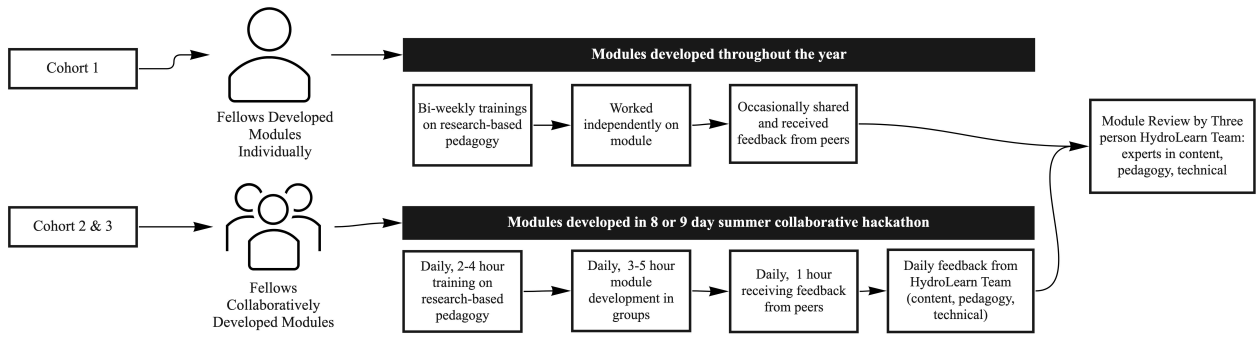

FIGURE 2 | Two approaches to professional learning used to develop HydroLearn modules.

The hackathons lasted 9 and 8 days for Cohorts 2 and 3, respectively. During each day fellows spent 2–4 h receiving training on the development of teaching content using research-based pedagogical approaches (described below), 3–5 h working in their groups, and 1 h receiving feedback from peers. The workshop leaders included a team of three hydrology and water resources professors who acted as "content guides," two education professors who acted as "education guides," and four graduate student researchers with expertise in the functionality of the HydroLearn platform who acted as "technical guides." Each group of fellows was assigned one content, one education, and one technical guide who provided them with feedback throughout the hackathon and beyond.

The workshop was conducted with the overall goal of developing high-quality modules that could be used as-is or adapted by other instructors (across the world) in their courses. Therefore, and based on the HydroLearn team's prior research in developing effective and adoptable learning modules (e.g., Habib and Deshotel, 2018; Habib et al., 2019) and other existing studies (e.g., Henderson et al., 2015; Shekhar and Borrego, 2016), the workshop participants were advised to consider the following aspects when developing their modules:

- Develop a module that follows evidence-based active learning pedagogical practices and that you, as the instructor, could use in your courses.
- While the primary and immediate users of the modules will be the ones who developed them, please develop the modules for potential use by other instructors.
- As you are working, think to yourself, "Is this something a colleague could use without my assistance?"
- Use open-source textbooks, readings, and software rather than copyrighted or subscription-based when possible.

The workshop interwove guidance and instruction on developing learning objectives, authentic tasks, rubrics, and content following evidence-based pedagogical practices, described in detail in the next section. We also incorporated time and support for hands-on content development using the HydroLearn platform allowing collaboration, discussion, and feedback around the effectiveness of the content being developed for achieving learning objectives.

Elements of Curriculum Design

One key aspect of the HydroLearn hackathon was the engagement of the fellows in intensive experiences to learn and apply processes of high-quality curriculum design. Before the start of the hackathons, fellows were asked to engage in a module on HydroLearn which was developed to be a primer in curriculum design (Gallagher et al., 2019). The concepts of Backward Design and authentic tasks were first introduced in this module and then reinforced during the live hackathons. Fellows were introduced to the backward design process articulated by Wiggins and McTighe (2005).

This process of beginning with the end in mind (i.e., identifying desired results) provided opportunities for fellows to clearly define the most essential learning objectives for their module by revisiting course outcomes, program goals, and professional standards. Next, fellows determined acceptable evidence that demonstrated that students met the desired learning objectives. Finally, fellows developed the instruction and hands-on learning experiences needed to move students toward demonstration of key learning performances. To operationalize the backward design process, fellows were introduced to the concept of constructive alignment (Biggs and Tang, 2011; Biggs, 2014). **Figure 3** shows the key components fellows were asked to consider during module design: learning objectives, assessment task, and instruction. Throughout the module design process, fellows were asked to evaluate their module design for constructive alignment between these key components.

Learning Objectives

In order to scaffold fellows in developing high-quality learning objectives, they were asked to use Bloom's Taxonomy as a means to ensure (a) each learning objective was properly structured [i.e., (CONDITION), the student will be able to (ACTION) (TASK) (DEGREE)] and (b) that at least some of the learning objectives were at the upper end of Bloom's Taxonomy (i.e., analyze, evaluate, create). Below are two example learning objectives from the Introduction to Floodplain Analysis module:

- Delineate watersheds and measure their associated properties/characteristics (Understand, Apply)
- Formulate a floodplain analysis that considers alternative design criteria (Create)

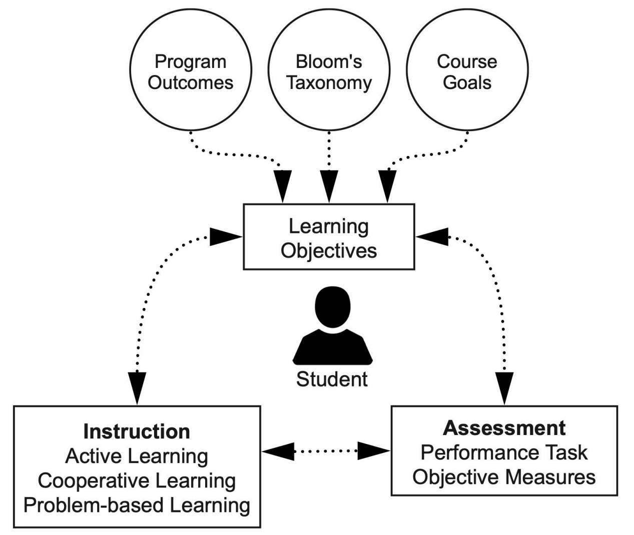

FIGURE 3 | Components of constructive alignment used to develop HydroLearn modules.

- Compare design alternatives under a changing climate (Evaluate)

In developing these learning objectives, fellows drew from their own domain and teaching experience, degree program outcomes, and professional standards. They then used their learning objectives to drive the design of their authentic assessment tasks.

Assessment Tasks

In HydroLearn, culminating assessments are performance tasks that demonstrate students have met the learning objectives. When scaffolding fellows in designing performance tasks, we considered the research on the cognitive demand of tasks (Stein and Lane, 1996; Boston and Smith, 2009; Tekkumru-Kisa et al., 2015) and modified a framework for evaluating cognitive demand developed by Tekkumru-Kisa and colleagues to include two categories: low and high cognitive demand (**Table 2**). Low cognitive demand tasks are aligned with Bloom's Taxonomy levels: remember, understand, and apply. High cognitive demand tasks are aligned with analyze, evaluate, and create. The juxtaposition of low and high cognitive demand tasks provided valuable insights to fellows for the design of their own module learning tasks.

To further deepen fellows' understanding of the characteristics of a high cognitive demand performance task, they were introduced to the qualities of authentic tasks. Authentic, high cognitive demand tasks included in HydroLearn are expected to mimic the types of problems that engineers may be asked to solve. For instance, the HydroLearn module entitled Introduction to Floodplain Analysis (Polebitski and Smith, 2020) engages students in authentic high-cognitive demand tasks. This module guides students through the analysis of a flood prone area on the Pecatonica River near Darlington, Wisconsin. In this real-world context, students:

- delineate the Pecatonica Basin using StreamStats and data from National Water Information System,
- apply principles of frequency analysis to determine peak discharge for the Pecatonica River,
- create, execute, and analyze a HEC-RAS model, and
- create a design and recommendation for the property of interest.

This engaging module provides an authentic context and tasks for students.

Instruction

Once fellows had well-articulated learning objectives at low and high levels of Bloom's Taxonomy that were clearly aligned to authentic learning tasks, they turned their attention to consider the content and learning experiences students would need to be successful on those tasks. For example, in the Introduction to Floodplain Analysis (Polebitski and Smith, 2020) module, the instructional materials to prepare students for the task of delineating a watershed include:

- videos defining watershed delineation, and watershed classification (HUC system), soil characteristics (e.g., texture, compaction, depth), geomorphology, land use and land cover;

TABLE 2 | Characteristics of low and high cognitive demand tasks adapted from Tekkumru-Kisa et al. (2015).

Low cognitive demand tasks	High cognitive demand tasks
Characteristics of low cognitive demand tasks	***Characteristics of high cognitive demand tasks***
• Reproducing definitions/explanations of practices • Reproducing definitions, formulas, or principles about particular content • Following a script (list of instructions/procedures) to work on practices or about content • Being guided for understanding practices or particular content • Having one correct answer • Solving an equation when all values are given	• "Guidance for working with practices but students must access their own content knowledge" (Tekkumru-Kisa et al., 2015, p. 663) • "Engaging in practices to make sense of content and recognize how scientific body of knowledge is developed" (Tekkumru-Kisa et al., 2015, p. 663) • Multiple possible "correct" answers where correctness is based on accurately applying content and justifying decisions • Authentic tasks in which students analyze or evaluate real data to make a decision or create a solution to a real world problem
Examples of low cognitive demand tasks	***Examples of high cognitive demand tasks***
(1) The _______ quantifies the probability that a range up to and including x will include the random variable X. (a) PDF (b) CDF (c) DDF (d) IDF	Imagine you are a scientist or engineer at the consulting firm tasked with designing the detention basin for Beau Bassin. Your client requested that you design the reservoir to achieve a 70% reduction in the peak of the incoming hydrograph (i.e., the outflow peak is no more than 30% of the inflow peak). Using the HEC-HMS model, design a reservoir that meets the desired goal of your client. Document your results using graphics and tables and write a discussion.

- video, text, and images on using StreamStats to delineate watersheds, retrieve basin properties, and use exploration tools (e.g., measure, elevation profile); and
- video, text, and images on using the National Water Information System.

The content knowledge and "how to" videos prepare students for the culminating task of delineating the Pecatonica Basin.

Review Process

Completed learning modules were then shared with a three-person review team consisting of a content guide, an education guide and a technical guide. This team used a detailed review form designed to evaluate the occurrence and quality of (1) relevant content, (2) authentic tasks, (3) clear learning objectives, (4) engaging and accessible delivery, and (5) clear and engaging learning activities with constructive alignment (see **Supplementary Material** for full HydroLearn Module Review Form). The review form included specific targeted questions such as "Do the learning objectives in this module represent different levels of Bloom's Taxonomy?" and "Is sufficient text/video presented to clearly explain key ideas?" as well as space for open-ended feedback/comments related to each module section. Reviews by each of the guides were returned to the module author(s), who subsequently submitted a revised module including responses to reviewer comments for final approval by the project team. This review process provided an opportunity to evaluate key pillars of HydroLearn modules presented in the hackathon and promote consistency among the modules.

RESULTS TO DATE

Given that our focus is on the professional learning experiences of hydrology and water resource engineering instructors, our results focus on the products and experiences of the HydroLearn fellows. The outcomes of HydroLearn's workshop/hackathon approach include 34 modules (completed to date) completed by the fellows that span a broad range of crucial topics in the field of hydrology and water resources. The subjects of the modules include, but are not limited to, Fluid Mechanics, Open Channel Flow, Physical Hydrology, Groundwater, Irrigation, Hydraulics, and Water Resources Management (see **Supplementary Material** for a list of each module and its learning objectives). Each module is designed around an authentic, high-cognitive demand task that emulates the work of professionals in the field. Of these 34 modules, 30 were implemented during the COVID-19 pandemic in the fellows' own classes. Additionally, 4 fellows chose to also implement modules written by other fellows in their courses. In addition to creating modules, several fellows have written about the unique contributions made by their modules, particularly highlighting the affordances of authentic tasks in an online format, which allows the integration of sophisticated software used by engineers in the field (Maggioni et al., 2020; Lane et al., 2021; Roundy et al., under review).

Over the course of the 2 years in which we implemented the HydroLearn professional learning experiences for Cohorts 1–3, we learned many lessons. Here we present aspects of the learning experiences that worked and challenges we faced in the hope that we can inform future efforts which also seek to design professional learning experiences to support instructors in designing high-quality sharable curricula.

What Worked

As previously mentioned, we made major revisions to our professional learning approach between Cohorts 1 and 2. We found that the quality of the modules submitted by fellows for review, was higher for those in Cohorts 2 and 3, as compared to Cohort 1. We assess this quality based on the amount of feedback and revisions we needed to ask fellows for before accepting their modules. There are several possible reasons for the higher quality of the first submitted modules by the cohorts which participated in the hackathon style workshop, including the intensive nature of the workshop, the commitment fellows made to attend all sessions, and the collaborative nature of the workshops.

We found the intensive workshop structure of the hackathons to be much more fruitful for the fellows than the periodical meetings that fellows in Cohort 1 experienced. We posit that combining training on evidence-based pedagogical practices and hands-on student activities during the hackathon enabled fellows to learn and then enact their learning immediately. The hackathon event also imposed an organized structure and a schedule over a specified time frame that led to fellows finishing the modules successfully. For instance, 17% of Cohort 1 fellows finished within 6 months of the end of the meetings, whereas 67% of Cohort 2 and 40% of Cohort 3 finished within 6 months. Unlike the approach used with Cohort 1, as part of their acceptance into the hackathons, fellows in Cohorts 2 and 3 were asked to commit to attend the designated days and times of their workshops. This dedicated time for both learning about and creating the modules seems to have supported fellows in the timely completion of their modules. In addition to the change to the structure of the meetings for Cohorts 2 and 3, another shift we made was to ask fellows to create modules collaboratively (i.e., two or three fellows working together to create one module), whereas each of the Cohort 1 fellows created their own modules. We found that the collaborative approach was highly effective and had a positive impact on the quality of the final products, possibly because it imposed peer evaluation and discussion and validation of the pedagogical structure of the ideas. Moreover, the pairings promoted sharing of content and cross checking that strengthened the modules that were developed. This process also made the modules more transferable/modular since they had to meet the needs of two distinct fellows and their associated courses and students. Although the module designs and some content were developed in pairs, some of the paired teams in Cohort 2 produced separate modules, which were also of high quality. Ultimately, we found that each fellow had to have ownership of the module they were using in their class and adapt it to their specific needs.

An unexpected positive outcome from Cohorts 2 and 3 was the sharing of modules within and between cohorts. We speculate that there is more within cohort sharing amongst our latest cohorts due to the structure of the workshop. We had daily check-ins and activities across small working groups, and modules of similar topics (e.g., climate change and drought) were grouped together for these discussions. For Cohort 3, a few fellows decided to expand upon the modules created by previous fellows which may also account for the sharing of modules between cohorts. In our most recent and extensive study (see Byrd et al., under review), the majority of the modules were implemented by the fellows who developed them. The exceptions to this were instances where fellows were sharing modules, as described above, and the use of three modules developed by the HydroLearn team that were used by a professor who was not a developer. Unfortunately, we cannot track how many faculty members who did not participate in the fellowship have adopted HydroLearn modules.

Although we had initially wanted to host an in-person hackathon for Cohort 2, the pivot to an online format had unanticipated positive impacts. First, this format forced us to find a structure for the workshop that kept fellows engaged for 7 h per day, which lead to the structure of: training, work time, feedback which we found to be successful. The pivot to an online format, rather than having an in-person weeklong workshop, likely also allowed primary caregivers to attend the workshop. Although the commitment was 7 h per day, there were many breaks throughout the day when fellows would stop to check on their children. In spite of these affordances, it may be that instructors who lost childcare due to the pandemic may have chosen not to apply to the fellowship program. However, the percent of the fellows who identified as female was higher in 2020, as compared to 2021, suggesting that perhaps childcare was not more of an obstacle in 2020 than in 2021. Most importantly, though, was that the move to an online format broadened participation. In Cohorts 2 and 3 we had fellows from Sweden, New Zealand, Ethiopia, and Turkey, among others. Without the impetus of the COVID-19 pandemic, we would likely have kept an in-person format and missed the opportunity to connect with this broader community.

Surprisingly, we did not see an immediate spike in new users when the pandemic hit. However, it does seem that HydroLearn has more than doubled in popularity since that time. Examining the Google Analytics for our homepage, we had nearly 20,000 page views between March 1 and May 31, 2020. Comparatively, the page views from the last 3 months (January 1 to March 31, 2022) were roughly 47,000. We cannot say definitively that this increase is due to the pandemic alone; However, we suspect that it likely played a role in this gain.

Lastly, the peer-review process, and the reviews provided by the guides, was key to strengthening the modules and make them a useful teaching tool. Although the review process was time-consuming, the reviews written through three different lenses (i.e., content, education, and technical guides) provided fellows with rigorous feedback and opportunities to revise.

Challenges Faced

Overall, we felt that the HydroLearn professional learning experiences, and in particular the hackathon workshops, were effective in supporting fellows in developing high-quality modules related to water resources and hydrology for undergraduate courses. Indeed, there is evidence that these modules have supported student learning gains (Byrd et al., under review; Roundy et al., under review). However, we also faced some challenges throughout this process related to time, over-committing, and collaboration. The most notable challenge was the considerable time commitment on the part of the fellows as well as the HydroLearn guides. Developing rich content, with active-learning components and real-world applications, is time-consuming and requires commitment from instructors. Designing and running the workshops, following up with fellows after the workshops, and engaging in peer reviews took considerable time for the HydroLearn guides. Additionally, although the fellows produced 34 modules across the 3 cohorts, 5 modules are still in progress, and 2 modules have been abandoned. For some fellows, the time commitment proved too great, especially as weighed against other demands on their time.

Relatedly, some fellows over-committed in the early design stages of their modules. Defining a reasonable scope for a module or designing it to be modular enough that some portion could be completed well in a reasonable amount of time was a challenge - both for the fellows and for the guides. Fellows were often excited about the modules and potential of HydroLearn and thus laid out a plan for a module that was larger than they had the capacity to finish in a reasonable amount of time. Most of the fellows who encountered this challenge ended up creating (and completing) smaller modules with the intent to build on additional sections in the future. We also feel that more guidance and more work upfront supporting fellows to plan a reasonable scope for their modules might have helped more fellows to complete their modules within 6 months. For Cohorts 1 and 2, no specific instructions were given to the fellows on the expected length or scope of the modules, other than an overall guidance on the intended audience and purpose of the modules. Building on the experience of the first hackathon, and given the intense nature of the online hackathon format, the HydroLearn team revised their expectations for the second hackathon (Cohort 3) and communicated to the fellows upfront that the scope of a certain module should be such that it can be covered within 2–3 weeks of class time. While we do not have direct evidence on whether this helped the fellows complete the modules more successfully, we believe that it resulted in a more positive participation experience by the fellows and led to better quality of the modules overall.

Lastly, collaboration between fellows was successful in most cases, but some challenges emerged. At times these challenges were related to time zone differences, which made communication challenging. In other instances, some fellows changed positions after the hackathon and were no longer teaching and thus were unable to support their groups in finishing their module. Some of the groups assigned by the guides did not work out because the fellows had need of different content for the courses they were teaching. If we had been able to host the hackathons in person, rather than virtually, perhaps some of these collaboration issues could have been avoided, as fellows would have been in the same location to build rapport and also to avoid time zone challenges. However, an in-person workshop might have been a barrier to participation for some of our international fellows. In spite of the challenges we faced, the workshop approach seemed to work well, as evidenced by the number of completed modules as well as the learning reported by students (Byrd et al., under review).

DISCUSSION

In order to support student learning, instructors need high-quality curricular materials. However, limited time to develop such materials and little training in the research behind curriculum design means that instructors may need additional support to create these materials. Additionally, the rapid shift to online teaching required by the COVID-19 pandemic forced many instructors to search for online curricular materials. HydroLearn was well-positioned to support faculty with a library of online modules. Additionally, the second cohort of fellows was recruited just at the start of the COVID-19 pandemic and lockdowns, which enabled us to provide fellows with learning experiences around developing online instructional materials in time for their fall 2020 courses. The HydroLearn professional experience model, in particular the HydroLearn hackathons, was successful in supporting fellows to develop high-quality curricular materials. Through the HydroLearn hackathons, we created dedicated time and space for fellows to learn about and enact principles of curriculum design, while supported by guides in engineering, education, and the technical platform. We encourage others interested in creating professional learning experiences for instructors to consider research in this field that supports the use of a workshop model and collaborative teams (Mundry et al., 2000; Loucks-Horsley et al., 2010; Walpole and McKenna, 2015). We also found the peer review process following the hackathons to be key to ensuring the modules deployed on the platform were of high-quality. The barriers to designing high-quality curricular materials (e.g., time, training, funding) need to be surmounted. We encourage others to adopt and adapt our hackathon approach to support instructors and improve the design of online curriculum materials. We offer our openly available HydroLearn module on curriculum design (Gallagher et al., 2019) as a starting point. We are also happy to collaborate with others to share additional details regarding our workshop design, slides, templates, and review documents, among others.

Although the hackathon approach was successful in supporting faculty to develop high-quality learning modules, its long-term sustainability would require resources for supporting key components such as training of participants and external review of the modules developed, both of which were critical in developing high-quality modules. Next steps for this project include working with the hydrology and water resources engineering community to scale up this model of professional learning experiences for instructors, and extending this model to include doctoral students in the field. We hope that by working in collaboration with the broader community we are able to establish a sustainable model for professional learning experiences and for the continued development of modules to meet the ever-changing needs of the field.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

MG and EH conceptualized and outlined the manuscript. MG, EH, DW, BL, and JB wrote sections of the manuscript. MG, EH, BL, and DT contributed to manuscript revision. JB aided with formatting. All authors contributed to the article and approved the submitted version.

FUNDING

The HydroLearn project was supported by the National Science Foundation (NSF) under collaborative awards DUE IUSE 1726965 and 1725989. Previous NSF awards, including I-Corps 1644493, TUES 1122898, and CCLI 0737073 provided support for the earlier research on HydroLearn.

ACKNOWLEDGMENTS

We acknowledge and appreciate the efforts of all the HydroLearn fellows who participated in the hackathon and authored modules.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feduc.2022.890379/full#supplementary-material

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frontiers | Frontiers in Water

METHODS
published: 22 June 2022
doi: 10.3389/frwa.2022.875732

Best Management Practices for Teaching Hydrologic Coding in Physical, Hybrid, and Virtual Classrooms

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OPEN ACCESS

Edited by:
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Specialty section:
This article was submitted to Water and Hydrocomplexity, a section of the journal Frontiers in Water

Received: *14 February 2022*
Accepted: *23 May 2022*
Published: *22 June 2022*

Citation:
Kelleher CA, Gannon JP, Jones CN and Aksoy Ş (2022) Best Management Practices for Teaching Hydrologic Coding in Physical, Hybrid, and Virtual Classrooms. Front. Water 4:875732. doi: 10.3389/frwa.2022.875732

As the field of hydrologic sciences continues to advance, there is an increasing need to develop a workforce with tools to curate, manage, and analyze large datasets. As such, undergraduate and graduate curricula are beginning to regularly incorporate scientific programing in the classroom. However, there are several key challenges to successfully incorporating scientific programming into a hydrology course or curriculum, such as meeting disciplinary outcomes alongside teaching students to code, equity issues with access to computing power, and effective classroom management. While these challenges were exacerbated by the global pandemic, shifting to online and hybrid learning formats provided an opportunity to explore and re-evaluate the way we facilitated our hydrology courses and integrated coding exercises and learning. In this article, we reflect on these experiences in three very different hydrology courses (e.g., courses housed in geoscience/engineering, environmental science, and biology programs) with an eye toward identifying successes and opportunities for improvement. We explore this by presenting ten best management practices (BMPs), representing a series of recommendations we have for teaching a virtual, hybrid, or in-person hydrology course that incorporates coding. While all recommendations provided can be applied to many programming languages, the focus of the paper (given the expertise of the authors) is on R. Our BMPs focus on technological facilitation, managing the virtual classroom, and instructional resources, with lessons learned that are applicable to in-person instruction. We also summarize the ways that the authors of this article integrate coding into our coursework to serve as a framework for prepping new courses or those revising existing hydrologic coursework. Above all, we hope these series of recommendations will evolve as hydrology courses continue to emphasize computational skills alongside disciplinary learning.

Keywords: coding education, hydrology, hydrogeology, computational thinking, STEM education and learning

INTRODUCTION

The field of hydrologic science—as well as science, technology, engineering, and mathematics (STEM) fields—is built on numerical inquiry. As hydrologists, we use data to interrogate research questions, to support decision-making, to benchmark variations and change, and to deliver new design solutions. As computing capabilities have continued to advance, and the volume and variety of the data we work with has continued to expand, many professional hydrologists and hydrogeologists are turning to scientific programming languages, including R, Python, and MATLAB, to complete daily tasks.

Scientific programming and closely associated skills are prized within the STEM workforce. A recent US federal report emphasizes that developing a national STEM workforce strategy goes hand-in-hand with promoting an understanding of the basics of computing and data science through research-based pedagogical practices (National Academies of Sciences, 2016). Indeed, work by Carnevale et al. (2011) identified the importance of knowledge of computers and electronics, an overarching knowledge domain that includes computer applications and coding, as 1 of 10 core knowledge domains most closely associated with STEM occupations. By their estimates, computer and electronics knowledge is not only crucial to a very high percentage of STEM occupations, but also represents a transferable skill beyond STEM occupations (Carnevale et al., 2011). Recent annual surveys indicate that more than 50% of superiors working closely with college graduates ranked skill sets associated with "complex problem solving", "critical thinking", the "ability to analyze and interpret data", and the "ability to work with numbers and statistics" as "very important" for new graduates (Finley, 2021).

Within the educational literature, the process of learning to write code most commonly aligns with developing abilities in computational thinking (Wing, 2006). Computational thinking is often described as the process of defining a problem and associated solutions such that either a human or machine (or both) can execute the proposed solutions (Wing, 2006). While no commonly accepted definition for computational thinking exists, the definitions used across the literature emphasize abstraction and automation (Lyon and Magana, 2020). Computational thinking and, more broadly, computational knowledge, are often developed within computer science (CS) courses as well as in courses that teach programming in disciplines beyond computer sciences, with the educational literature drawing distinction between the two. Around the world, countries are implementing the inclusion of computational thinking, digital literacy, and computer programming across the curriculum, and at the K12 and undergraduate level (National Academies of Sciences, 2016; The Royal Society, 2017; Valente and de Almeida, 2020; Nesen et al., 2021). Though the educational literature on computational thinking within programming courses (i.e., those outside of computer science departments) as well as the existence of publicly accessible coding exercises across STEM fields is expanding (Jacobs et al., 2016; Yan, 2017; Lin et al., 2019), understanding of best practices is still nascent, particularly at the disciplinary level. Overall, there is limited research on teaching and learning to code; and there is a general lack of educational materials to support teaching scientific coding methods (Medeiros et al., 2019). For this reason, core practices and publicly available repositories of teaching resources are still lacking.

The onset and continued evolution of the COVID19 pandemic has fundamentally changed the way we deliver content to students, and how we, the authors of this article, specifically taught scientific programming. In particular, the pandemic brought into sharp focus how we not only teach about computing technology, but how we most effectively use computing technology to accomplish this. Likewise, it forced us to consider what elements of our delivery were most effective in a virtual or hybrid classroom. Considering our approaches to teaching coding, it became even more important to minimize troubleshooting problems beyond just those with code (software versions, wrong directories, and more). Finally, it gave us the opportunity to reflect on and revise our courses and associated expectations from the lens of equity and inclusion within the classroom. This article represents ten best management practices (BMP), a double entendre given that BMPs are also used as conservation practices in hydrologic science, that we have arrived at for delivering a coding course at the undergraduate level. These BMPs represent what we view as core practices, in that they are constantly evolving through collaboration and feedback from learners and practitioners. Our hope is that while these recommendations were formulated in the context of virtual and hybrid teaching, they will improve student learning outcomes upon returning to in-person instruction.

WHAT DO WE MEAN BY "CODING"?

In this article, we are focused on approaches that we use to teach others (particularly undergraduate and graduate students) how to write code. Throughout the manuscript we primarily use the term "coding" instead of "programming". As highlighted by Corradini et al. (2018) the term "coding" may be preferred to "programming" given the many publicized initiatives that include "coding" in the title, broad media use of the term, and that, to put it simply, the term "coding" may sound more interesting or exciting than "programming". By "coding", we are referring to the process of students building skills in writing one or more lines of code to perform analysis, including computations, generating visualizations, or writing programs or functions (e.g., multiple lines of code that build to achieve some output; Van Merrienboer and Krammer, 1987). In non-CS disciplines, this often requires combining learning discipline specific knowledge alongside the commands and syntax of a given programming language (Van Merrienboer and Krammer, 1987). The authors primarily use the R coding language. Thus, most of the examples are given in R, but we note that the principles introduced in this text can be translated to any other programming language such as MATLAB or Python.

COURSES

Our reflections in this article are shaped by our experiences in developing and teaching three different courses that incorporate coding as part of course learning objectives and content. We briefly outline these three courses below.

Course 1—Physical Hydrology

A mixed undergraduate-graduate course aimed at introducing students to physical hydrology concepts. The course size was 18 students, with backgrounds split between the Earth Sciences and Civil Engineering and met twice a week for 75 min. The course was taught at Syracuse University (Syracuse, NY, USA). During the pandemic, the course was taught in the spring 2021 semester, though was offered in prior semesters as well. The course operated in hybrid mode for lectures (1 day a week) and in an online environment for all but the last few weeks for coding examples (1 day a week). Students were introduced to R coding to quantify hydrological processes, perform hydrologic analyses and hydrological modeling, and to compare watershed responses in variable environments.

Course 2—Hydroinformatics

A mixed undergraduate-graduate course taught at Virginia Tech (Blacksburg, VA, USA) aimed at introducing students to common introductory to moderately complex hydrologic analysis using coding. During the pandemic, the course was taught in 2021 during the spring semester, though was taught prior to this offering. The course was 14 students, with backgrounds in undergraduate data science and hydrology courses, as well as graduate students with a variety of backgrounds. This course was taught synchronously online twice a week for 75 min. Students were introduced to R over the first 2 weeks of the course, and then each week the class introduced hydrologic analyses and the coding concepts necessary to complete them. Topics include basic statistics, flood and low flow statistics, modeling, and basic geospatial operations like delineating watersheds and stream networks.

Course 3—Ecohydrology

A mixed undergraduate-graduate course aimed at introducing students to the water cycle and ecosystems taught at University of Alabama (Tuscaloosa, AL, USA). Course enrollment included 20 students with backgrounds in environmental science and biology and was taught in fall 2021. Weekly meetings included a 1-h synchronous virtual lecture where students were introduced to a broader topic, 1-h journal article discussion (graduate students only), and 6-h lab. The longer lab period allowed the class to be broken up into smaller groups. The first half of the course focused on components of the water balance (i.e., watershed storage, precipitation, streamflow, and evapotranspiration), and the second half of the course focused on how water interacts with ecosystems (i.e., wetland soils, plant-water interactions, catchment biogeochemistry, and flow-ecology relationships). Labs included a range of activities that included both empirical data collection and data analysis using R.

DISCUSSION

Below we summarize 10 considerations for incorporating coding into hydrology courses. We developed many of these practices through our experiences with pandemic teaching but emphasize that nearly all recommendations are applicable to a virtual, physical, or hybrid classroom environment. For any instructors who are currently teaching coding or considering adapting their disciplinary courses (in hydrology or otherwise) to include coding components, we underscore (as those beyond a novice stage can forget) that learning to write scientific coding is effectively learning a new language and can therefore be daunting at any point in the process (Medeiros et al., 2019). Colloquially, we've collectively encountered many students who have told us they're "just not good at coding". Our answer to these students is to emphasize that coding is just another skill that can be learned through practice, like teaching. In our classrooms, we all sought to foster a growth mindset throughout our courses (McGlynn, 2020), with many of the BMPs below reinforcing this overarching and ever-important tone.

BMP 1: Motivate the Importance and Benefits of Learning to Code Early in the Semester

In our colloquial experience, we have found that starting a course focused on coding off on the right foot requires demonstrating to students (i) why they should care about learning to code and (ii) how this skill will serve them now and into the future. One of the best ways we've found to motivate and excite students about the value of learning to code is to not simply *tell* students that coding is important, but to *show* that coding can save time and effort. In most cases, students have encountered spreadsheet programs (e.g., Microsoft Excel, Google Sheets) and used these programs for data manipulation and visualization. For this reason, we have found that it is impactful to spend class time benchmarking coding exercises against manual approaches combined with spreadsheet programs.

In a hydrology course, one way to show what can be gained by coding with students is by asking them to manually download publicly available streamflow data and transfer it into a spreadsheet program (**Figure 1**). The process to manually download streamflow data from the National Water Information System (NWIS) website can take some time, and even more time at the first instance of students encountering the NWIS dashboard (**Figure 1**). When juxtaposed with the fraction of a second and few lines of code in R (using the dataRetrieval package; (De Cicco et al., 2021), the gains from coding are clear (**Figure 1**). An alternative, complementary approach is to engage students in making a plot in Excel from basic data (such as streamflow or any other dataset that relates to course content). In this process, the students are asked to write a set of instructions for how to make an Excel plot, such that the process can be duplicated by another student, and to indicate or sum the number of "clicks" needed to do so. Again, comparing this process to

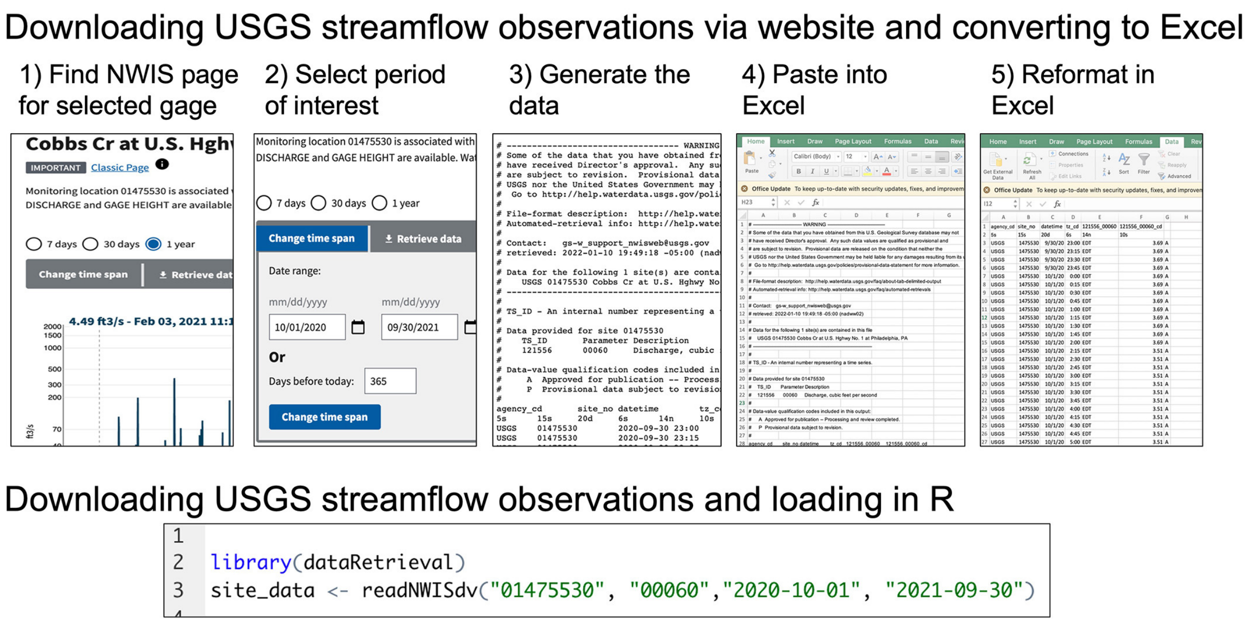

FIGURE 1 | Comparing the steps involved to generate streamflow observations for plotting in Excel (top) vs. two lines of code in R (bottom).

writing a few lines of code to produce a high-quality figure in R, MATLAB, or Python can emphasize the value of learning to code.

Another educational approach that we have used to show students the value of coding is to convey this to them in many formats. Outside of the classroom, one of the first places that educators can make this case to their students is within their syllabi. Within syllabi, it is always worthwhile to address the importance of course content and how it matters to students, both now and in the future; pointing to surveys of the workforce and job growth estimates in certain occupations can all be used to emphasize the value of learning to code in a hydrology course. Graduate student and undergraduate students engaged in research will have the additional benefit of coding serving their future research project needs. These same motivators can also be communicated in the first lecture of the semester.

The educational literature strongly supports motivating the importance of learning to code early in the semester (Carter, 2006; Jacobs et al., 2016; Yan, 2017). In a literature review focused on teaching surrounding introductory coding, Medeiros et al. (2019) found that student motivation was one of the biggest difficulties faced by students while learning to code. Likewise, instilling (and maintaining) student motivation is also a challenge for instructors. More broadly, self-determination theory suggests that intrinsic motivation plays a role in promoting learning in educational settings (National Research Council, 2000; National Academies of Sciences, 2018; Ryan and Deci, 2020). For example, if an instructor provides opportunities for students to take ownership of their work, it could lead to autonomous forms of motivation and enhance learning and engagement. Engaging students in metacognitive talk about what they want to achieve by the end of the course could also promote autonomy. Supporting learning through authentic context, for instance, by providing relevant examples to their daily lives, could motivate students as well. Drawing on students' lived experiences and prior understanding helps facilitate engagement and active learning.

BMP 2: Start Slow, and Remember Not Everyone Is Beginning With the Same Knowledge and Technological Ability

When reflecting collectively on our experiences incorporating coding into our classrooms, it was relatively easy for us to identify common pitfalls we all encountered. To this end, **Figure 2** highlights these common pitfalls that we recommend considering in the context of this best management practice. Why did we encounter these pitfalls? Simply put: it's easy to forget what we didn't know when we ourselves first learned to code. Often referred to as the "curse of knowledge," it is easy for instructors to skip introductory or fundamental concepts that are needed for a given task or skill (Kirschner and Hendrick, 2020). Moreover, students arrive in our classes from a variety of backgrounds (i.e., confirmation of understanding from one student is not necessarily representative of the entire classroom). Addressing students' prior understanding is central to learning and engagement (National Research Council, 2000). Therefore, when designing activities, it is important to remember students are still developing their conceptual models of both hydrological processes and requisite coding skills.

To both support student learning and to encourage instructors to "start slow", we suggest instructors practice "reverse engineering" activities, outlining the steps that it took them to achieve a given end point, and scaffolding these steps into a

How to unzip a folder

Why? Recent Microsoft updates allow students to view files before unzipping, leading to confusion when they can't access the data

Differences between file types

Why? Not all students are aware of the differences between txt, csv, and xlsx files. As this will impact how they import data, it's worth discussing the differences (and what type you prefer they use in class, if they're going to be using their own data at some point)

Types of data structures

Why? All programming languages use different data structures (e.g., vector, matrix, data frame, tibble in R). Be sure to introduce how to identify the type of data structure, why different data structures exist, and how students use this throughout the course.

Using an IDE

Why? Integrated development environments (IDEs) enable writing and executing testing code in a software (e.g., RStudio for R). Many if not all of your students will never have opened the software you are using. Spend time orienting them to the different components of the IDE/

R as a calculator

Why? It introduces students to the idea of a command line and how to interact with the IDE.

File settings

Why? Depending on the programming language and IDE students are using, there are likely settings within the software that will make it easier for them to access files. This may also require you to explain the idea of a path and how to navigate file directories. Likewise, there may be other initial settings to implement that will make it easier when it comes to scripting and saving files

Software versioning

Why? Your life as an instructor will be much easier if you ensure everyone is using the same version of the software and libraries. We recommend introducing versioning to your class, to not only identify those who may be using a different version of the software, but to explain that not everyone will have the same functionality if they are using different versions. This is a big one for minimizing errors.

How to load libraries/packages

Why? Many, though not all, programming languages use libraries or packages to facilitate functionality. Students need to be introduced to what a library or package is, and how they can load and access it within their IDE

Why and how to comment

Why? Introducing students to commenting on their code will help you as an instructor (to identify their thought process) and will also aid in the learning process (students have to articulate the purpose of each line or a few lines of code, and what these lines achieve

FIGURE 2 | Common oversights when first teaching students to code.

given activity for students. Moreover, we encourage instructors to then have students reverse-engineer their process for each coding exercise, articulating what each step or line of code achieves, and how they know this. Such approaches make student thinking an explicit component of class exercises, and encourage students to deconstruct their approaches, which can enhance their learning (Kirschner and Hendrick, 2020). Furthermore, as discussed previously, consider downloading streamflow data from the USGS National Water Information System (NWIS; https://waterdata.usgs.gov/nwis). This is a fairly common task for hydrology students; and within the R environment, streamflow data can be downloaded with one line of code using the dataRetrieval package (De Cicco et al., 2021). On the surface, it seems like this should be a simple exercise – the instructor should be able to provide an example line of code and move on to more advanced analysis. However, students must understand several concepts before being able to execute this one line of code. These concepts include: (i) What is an integrated development environment (e.g., RStudio), (ii) How do we operate command line software, (iii) What are libraries and how do we use them, (iv) What are data types and data structures, (v) How do we create variables and store/manipulate different data structures, and (vi) What is a function and what is the syntax required to use it. Notably, this list only considers scripting concerns; thus, providing information on streamflow measurements and data may be just as (if not more) important depending on the lessons learning objectives.

To reverse engineer activities, take a step back and consider all the steps necessary to complete the activity. As illustrated by the example of downloading streamflow data, even a simple 2-line task requires a basic understanding of operating within a coding environment. If you have not introduced students to these concepts, it will be necessary to do so. As you are reverse engineering your activity, it may be worthwhile to iteratively revisit and adjust learning objectives to balance hydrologic knowledge with coding skills.

BMP 3: Center Equity and Inclusion From the Beginning

From our perspective, equity and inclusion are the top concerns when teaching coding. If students feel they do not belong or do not have access to your material, programs, or other aspects of the class, the other components of your teaching will be ineffective. Through our experience in the classroom, we have identified three common barriers to running an equitable and inclusive classroom, especially in the context of virtual teaching, and offer specific solutions to each below. These issues are access to high-speed internet, access to a fully functioning computer, and student confidence issues stemming from feelings of imposter syndrome, stereotype threat, or a lack of self-efficacy. We want to note that all authors have experienced all of these challenges in every hybrid or online coding class they have taught. As these challenges are widespread, building your class to anticipate their existence can save instructors a lot of time while improving the experience for all students.

Internet Access and Quality

It is common for students to have slow or faltering internet connections for a variety of reasons. These include but are not limited to unstable housing, poor quality rural internet, power outages, or simply an overloaded connection with too many users. These issues cannot be fixed, but we can adjust the structure of our classes, so they do not leave these students behind. First, it is imperative to record lecture sessions in an online environment. This benefits students whose internet fails during class, but also, if you make these recordings available to everyone, students who just want to re-engage with lectures to help learn the material. Second, flexible deadlines and/or no penalties for late work can drastically reduce stress for students trying to find a stable internet connection in time to complete work. If instructors are flexible and compassionate, these strategies and lower stake assignments can help students perform better in the course. This also saves instructor time, as it reduces email volume and adjustment of scores/deadlines in your learning management system (LMS).

Functioning Computers

Another common issue, especially when trying to install and run software on student computers, is that student computers are not all of the same quality nor can they achieve the same level of functioning. Even at universities that require students to have a computer with minimum capabilities, by students' third or fourth year, those computers are often in disrepair, and may run slowly and be poorly functioning. Furthermore, students may have netbooks or chromebooks, meaning that such computers are incapable of running the software needed for coding. However, these issues can largely be addressed by offering ways for students to run required software in an internet browser window through cloud-based applications or virtual machines. RStudio can be run in a browser window using services such as binder (https://mybinder.org) and rstudio.cloud (https://rstudio.cloud). Additionally, the computing center at your institution may be able to help you set up a system to run RStudio on a virtual machine or server application. Moreover, many schools are beginning to offer virtual lab computers, where students can run a remote desktop in their browser window. In cases where a student's computer is completely non-functional, being prepared with a laptop that can be loaned out is the best course of action, but this is another benefit of having lectures recorded, as students can work through classroom activities outside of class time on a lab computer.

Imposter Syndrome, Stereotype Threat, and Self-efficacy

Imposter syndrome and stereotype threat are anecdotally the biggest hurdles to students learning to code in our classrooms. In this context, when we use the term "imposter syndrome" we mean students feeling like they don't belong or are destined to do poorly in the class, often manifesting as students sharing with instructors that they "can't code" or "are bad at coding" often when they have not had any coding instruction. Stereotype threat, on the other hand, is the anxiety students feel when they fear they are conforming to a societal stereotype about their social group (e.g., race or gender) and their performance on the subject at hand, and has been shown to negatively affect academic performance (Steele et al., 2002).

It is best to address imposter syndrome and stereotype threat directly. For instance, you can communicate to your students that you designed the class and activities to teach everyone from the beginning, using methods that research has shown enhance learning for everyone. Another approach is to encourage students to focus more on learning goals than performance goals. In the classroom, comparing coding to other skills can contextualize the learning process. For instance, remind students that they wouldn't expect to be able to just jump on a skateboard and effortlessly cruise around, so they shouldn't expect to immediately grasp coding concepts and practices. In both cases the key to improvement is practice.

An additional strategy is to communicate to students that those who put in effort and practice are the ones who learn the material best, not those who are "naturally" good at it. One impactful way to do this is to have students from the previous semester write about their experience in the class: their initial impressions of the course, their approach to the course, and their recommendations to students in the future. Sharing several of these, especially from students who found the material challenging early-on but then did well, can be a powerful tool for pushing back against student fears. Finally, we recommend engaging in the literature on ways to combat stereotype threat and other issues of inclusion in your classroom, as there are many other strategies than the few mentioned here (Killpack and Melón, 2016).

Self-efficacy, introduced by Bandura (1977), describes student beliefs about their own ability to succeed at a given exercise. Beyond coding education, science education research consistently emphasizes the importance of self-efficacy in student persistence and success in science (Pajares, 1996; McBride et al., 2020). Furthermore, higher self-efficacy is often, though not always (McBride et al., 2020), correlated with higher academic performance (Meral et al., 2012; Honicke and Broadbent, 2016; Loo and Choy, 2017) and even greater learning satisfaction in computer-based learning environments (Artino, 2008). As educators, we can support student self-efficacy through learning strategies and effective pedagogy.

Very broadly, one way any instructor can support self-efficacy in their classroom is to use active learning techniques, such as many discussed throughout all BMPs. Ballen et al. (2017) found that using active learning approaches improved academic performance for underrepresented minority students and increased all students' perceptions of their science self-efficacy. One approach we commonly employ in our classrooms to support self-efficacy is collaborative learning. Numerous studies in a variety of disciplines have shown that collaborative, peer-to-peer interactions can enhance self-efficacy (Samiullah, 1995; Fencl and Scheel, 2005; Sidelinger and Booth-Butterfield, 2010; Sollitto et al., 2013; Lewis et al., 2021; Stoeckel and Roehrig, 2021), especially in the context of learning to code

(McDowell et al., 2003; Hanks et al., 2011; Salleh et al., 2011; Dirzyte et al., 2021). While peer-to-peer learning can be challenging to accomplish virtually, the use of breakout rooms can be one way to facilitate these types of interactions. In our virtual, hybrid, and in-person classrooms, we have used peer-to-peer interactions (often groups of two or three) during in-class activities, to compare answers for short quizzes (see Section Low Stakes and No Stakes Assessments), and as a part of two-stage exams (see Section Two-Stage Exams) all in support of self-efficacy and learning. Another approach shown to increase self-efficacy is to have students map out their approach to a given problem or activity, and then track their progression and plans for next steps as they proceed (Schunk and Pajares, 2002). In the context of coding education, work by Govender et al. (2014) employed this approach by introducing students to a framework for problem solving that they can use when working through a coding exercise. In such a framework, students are taught to approach each problem holistically, with coding being one piece of the framework to arrive at a solution or end point (Govender et al., 2014). Finally, McBride et al. (2020) showed that accessible, inclusive, and student-centered practices increased students of color and international students' self-efficacy. Though we touch on effective teaching practices later in this article, it is equally important to mention this topic at this point in the text, given such practices are deeply connected with equity and inclusion.

BMP 4: Do Live Coding

All three authors have anecdotally found live coding to be an effective method of teaching students to write code. This anecdotal observation is bolstered by the coding educational literature, which indicates live coding is commonly seen as a "best practice" across different disciplines (Brown and Wilson, 2018; Selvaraj et al., 2021) as it directly supports active learning (Shannon and Summet, 2015) and exposes students to the process that the instructor uses to write code, allowing them to see many components of coding, including debugging and commenting, in action (Rubin, 2013; Raj et al., 2018, 2020). We describe live coding as the practice of an instructor typing out their code out as they explain what the code is doing and how the statements are constructed, with students following along on their own computers, though other definitions exist (Selvaraj et al., 2021). This challenging method of instruction has several advantages, but also comes with pitfalls. Other potential methods to teach coding include a flipped classroom approach and the use of slides or board notes typical of other topics of instruction. In the flipped classroom example, students complete interactive tutorials or watch lecture videos outside of class and work on activities during class time. We found this an especially helpful method, paired with live coding, when introducing introductory topics, as it offers students more guided practice using general introductory tutorials (see more of these in Section BMP 6: Know What Resources Are Available to You). However, we found that as we progressed to more discipline-specific topics, live coding was more advantageous, as it emphasizes in-the-moment problem solving and troubleshooting (Raj et al., 2018, 2020), as well as a view for students into how instructors write and construct code (Selvaraj et al., 2021). In this section, we outline some of the advantages and strategies for avoiding potential pitfalls, which we have learned through time and practice.

In our experience, the two primary advantages of live coding are that (1) students get immediate feedback when their code does not run due to syntax errors and (2) live coding facilitates weaving additional active learning and experimentation into live coding lessons. More generally, live coding, if done well, can serve as a form of scaffolding, an educational term that describes the support provided to learners by (in this case) instructors and more advanced peers to navigate different tasks (Harland, 2003; Anghileri, 2006; Sharma and Hannafin, 2007). In a live coding exercise, a student who types something incorrectly or has a common syntax error will either get an unexpected result or get an error indicating their code cannot be run. Given an appropriate amount of time and support to fix these errors, they can become valuable learning experiences for the student. In the absence of live coding, the identification of syntax problems and other misunderstandings might not occur until the student is working by themselves on a homework assignment. Additionally, when running a live coding session, it is often easy to let students explore and experiment to broaden their understanding. As instructors we can ask them to tweak the code and observe and explain the results. What happens if you flip the x and y axes in a plot? Can they change a parameter value in a function, and what is the result? These can be simple to execute and powerful for enhancing student learning.

Live coding is a challenging method of instruction and not without risk. In our experience the two most common pitfalls are "losing" students (where students fall behind, can't see your code, or get lost), and accidentally discouraging students from thinking they can learn the material. There are a variety of ways you can prevent both outcomes. To facilitate the ease of reviewing some of our favorite preventative measures, we have included them in a bulleted list below. Furthermore, **Figure 3** addresses one of the more pernicious problems with synchronous online live coding: how do you share your screen so students can follow along on a single, small computer display.

Given not everyone uses live coding in their courses, we compiled an additional list of tips and tricks to keep in mind when teaching in this fashion:

- **Pace:** Go slow! Be sure you give students time to catch up.
- **Explain:** Especially early on, explain every single thing you do. This includes how to run lines of code, saving scripts, etc.
- **Illuminate:** Don't correct errors you make without explaining them. New coders struggle troubleshooting and this is a great learning opportunity.
- **Encourage:** Normalize getting errors. It can even be good to intentionally make some common errors and then talk about them. Emphasize that getting and solving errors is part of the process!
- **Pause:** If students are following along on their own computers, pause frequently and ask students if they've had any "fun" errors. Thank them for sharing them and explain how you make corrections or find solutions when you have similar errors.

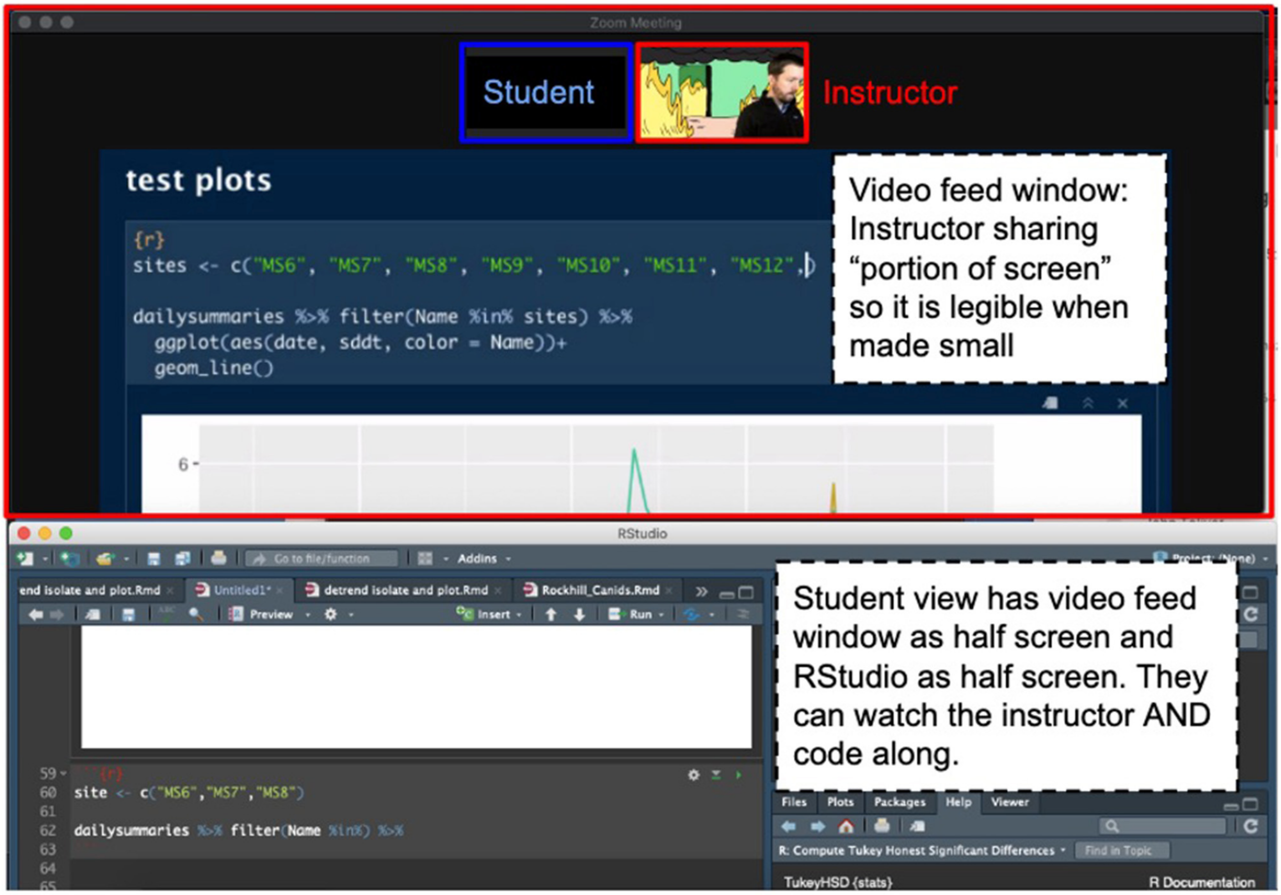

FIGURE 3 | In a virtual environment, encourage students to be mindful of how they set up their screen. In this figure, we show one setup that has worked well for the authors. The setup above shows an example of a student's single screen. In it, the student has their zoom window sized to fit the top half of the screen and RStudio sized to the bottom half. With this setup, the student can watch and code at the same time. It is critical for this to work that the instructor only shares part of their screen, allowing them to show just their code, making it legible even when a small window on an already small screen. We recommend sharing an image such as this at the start of the semester, especially for students participating in a virtual or hybrid learning environment.

- **Reflect:** Be careful with your language. Avoid saying things like "we simply do this", "we just do this", "this is easy" or "this is straightforward". Students hear this and if they are struggling, they may think they are not able to understand "easy" material and therefore get discouraged.
- **Avoid:** Don't make fun of spreadsheet programs (e.g., Excel). Students may have had trouble with them in the past. Many students will view learning to code as much harder than learning Excel and may therefore start to think they cannot be successful at learning to code.
- **Share:** When you have students complete a "challenge" or activity on their own, ask them to explain what they did to a partner before going over it in class. Then ask for a volunteer to explain their solution to the class. Explaining your code to someone else is a powerful learning tool.

BMP 5: Teach Students How to Help Themselves and Learn From Their Errors

One of the components of teaching coding that the authors of this piece are always seeking to improve is how to assist students in learning how to help themselves when their code doesn't work (e.g., receiving errors) or perform as expected. We have all had the experience when teaching a course—often on the first day of demoing coding and asking students to follow along—that a student says "my code isn't working". Likewise, we have had the same experience via email as students work through their first coding assignment. These four words are bound to be repeated to you, as they were to us, again and again.

In this context, there are several approaches that we use to teach students how to help themselves and learn from their errors. Above all, it is important to create a classroom environment where students feel comfortable asking for assistance and trust their instructors (Wang et al., 2021), and where encountering errors is normalized (see Section BMP 4: Do Live Coding). As instructors, we have shared with our students our own struggles learning to code, and how we have overcome these challenges; we always seek to be honest in how we represent our own experiences, to remind students that learning to code (and learning in general) is a process.

In the classroom, one of the best things we've found that we can do as instructors is to create a classroom environment where students feel comfortable asking questions and identifying that they are unsure of next steps (Sidelinger and Booth-Butterfield, 2010). One important consideration in this process is to normalize encountering errors (when you are teaching and hopefully live coding, see BMP 4). As experienced by the authors, you probably won't have to try hard to encounter errors that become teachable moments! In these moments, students have a chance to watch how you approach the debugging process, often via an internet search, another advantage of live coding, as described in Section BMP 4: Do Live Coding (Raj et al., 2018; Selvaraj et al., 2021). As an instructor, "getting stuck" is something to be upfront about ("it is going to happen to everyone!") and to discuss regularly as a class. One way to communicate this to students is to emphasize to them that learning to code is like learning to speak a different language. However, the goal is not memorization. Therefore, the overall objective of many discipline-specific courses that incorporate coding is not to teach students to code, but instead to teach them to problem solve in a coding environment. As educators who use coding in our research, one point we often explain to our students is that we, the instructors, rarely sit down and code from memory; instead, we discuss how we approach coding for our own projects—using example code (either ours or example code we find via internet search), and debugging (the process of finding and correcting errors in our code) via internet search.

One approach that many of us tried when first teaching coding was to attempt to solve each students' errors during in-class exercises. This amounted to a lot of stress on our parts—either moving from breakout room to breakout room or running around the classroom. Above all, we have learned to resist the urge to take the students' computer (or virtually, take over their computer via remote access) and fix the error. Instead, we encourage the student (or team) to explain what they are trying to do, and ask them questions to help they realize what they've done wrong.

For in-class exercises when only a few students have errors, one approach we have used in a virtual environment is to ask individual students to share their screens, and work as a class to spot the errors. This supports peer-to-peer interactions and reminds students that their peers can help them find their errors (instead of having them always come to the instructor). However, depending on the size of a given class and the length of the class period, this approach, and addressing all students who encounter errors, is often ineffective. An alternative, with benefits for all students, is to facilitate peer teaching, where students work in small groups of two or three and code and troubleshoot together (virtually, this can be accomplished via breakout rooms). This approach is known as pair programming and is widely lauded in the educational programming literature (McDowell et al., 2003; Hanks et al., 2011; Salleh et al., 2011). In pair programming, (often) two students work together to write code at a single workstation. Pair programming is a useful approach for both in-class activities as well as out-of-class assignments. The educational literature has shown numerous positive outcomes associated with this approach.

For in-class exercises, another effective practice is to have a signal that students can use to let you, the instructor, know when they are stuck. When in person, the Data Carpentries instructor training recommends the use of green and red stickies: a green sticker at the top of a computer monitor indicates no issues, while a red sticker indicates a problem has been encountered (The Carpentries, 2022). In the virtual classroom, the chat feature and emojis can be used in a similar way. Students may try to use the chat feature to message only the instructor; instead, encourage them to message everyone, and again, normalize everyone solving each other's errors and helping each other to learn together.

Outside the classroom, we have found it effective to dedicate portions of in-class time to discuss and develop with each class a procedure for how each student should go about getting help if they are stuck. This discussion serves two purposes: it indicates to students how they can best share information via email with their instructors if they are seeking help outside of office hours, and it can address how students can use educational resources to fix their own coding errors. As an instructor, it's worth considering how you prefer to assist students—is having them email their code preferred? Can you spot issues from code copy and pasted into an email? Be prescriptive about how students should go about asking questions, what expectations you have of approaches they should try before they reach out to you, and how they should explain their issue and their approach when they ask for help. It's also worth considering what level of help you're willing to give—a hint, or more.

As part of classroom instruction, the instructor should introduce students to the concept of debugging. The literature on "debugging"—a word that broadly describes identifying and fixing errors in code—is rich (McCauley et al., 2008). As emphasized by the literature, debugging must be taught—it is not a skill students will learn through the process of writing code alone (Kessler and Anderson, 1986; Carver and Risinger, 1987; Chmiel and Loui, 2004; McCauley et al., 2008). In addition to providing examples during class, instructors should introduce (and continue to remind students of) resources such as StackOverflow and DaniWeb, where students may be able to find discussions of those who have encountered (and solved) similar errors or to post their own questions. In this vein, we also recommend an assignment where students post their code and an error they are having to a website, to engage students in the process of intelligently framing a coding question for an online forum. It's worth pointing out to students that learning to code is equally important as learning how to problem solve their coding errors.

BMP 6: Know What Resources Are Available to You

When each of us sought to either build our courses or to add coding into our existing courses, one of the first things we did was to begin looking for existing resources on educational websites and as shared by colleagues on social media platforms. For this reason, we remind all readers who are approaching teaching a coding course (or incorporating coding into an existing course) that there are always resources available to support your needs.

TABLE 1 | Freely available resources that can be used to incorporate coding into hydrology courses.

Resource category	Title	Website
Introductory Resources	Swirl	https://swirlstats.com
	Basic Basics	https://rladiessydney.org/courses/ryouwithme/01-basicbasics-0/
	R for Data Science	https://r4ds.had.co.nz/
	CyberHelp at SESYNC	https://cyberhelp.sesync.org/lesson/
	Fundamentals of Data Visualization	https://clauswilke.com/dataviz/
	R for Cats	https://rforcats.net/
R and Hydrology	HydroInformatics	https://vt-hydroinformatics.github.io/
	Geocomputation with R	https://geocompr.robinlovelace.net/
	R for Water Resources Data Science	https://www.r4wrds.com/intro/index.html
	Hydrological Data and Modeling Resources in R	https://cran.r-project.org/web/views/Hydrology.html
Course Materials and Repositories	HydroShare	https://www.hydroshare.org/
	Earth Data Science by EarthLab	https://www.earthdatascience.org/
	Science Education Research Center (SERC)	https://serc.carleton.edu/index.html
	Data Carpentries Semester Course in Biology	https://datacarpentry.org/semester-biology/

Resources are all based around R.

We advocate perusing such available resources before developing your own assignments. In **Table 1**, we highlight several resources related to hydrologic sciences and popular coding languages; this is far from an exhaustive list but represents the tools we are aware of and have often used in the classroom. We recommend investigating materials that introduce the R basics (or the basics of any given language) and that are interactive (e.g., swirl), as they are great for initial homework assignments or supplementing instruction. Depending on the discipline you are teaching in, hydrology or otherwise, there are likely to be other repositories for course assignments and modules (**Table 1**). There are also many educators who host such material on their personal websites, though these materials may be harder to find. Finally, we encourage anyone pursuing this route to also network amongst your colleagues, as many are more than willing to share their course materials, and to eventually be willing to share your own materials.

Though resources can limit the time you spend preparing educational materials, the process of learning to effectively *teach* coding will take time. In addition to these resources, the authors also wish to highlight and recommend training offered through Data Carpentries (see: https://carpentries.github.io/instructor-training/). This type of training is not focused on how to teach any specific computing language but can be thought of as a training in how to effectively teach coding.

BMP 7: Align Hydrologic Content With Coding Principles

This is the part of teaching we as instructors all struggled with the most, as educators teaching course content infused with coding. When students start such a course, they often haven't used R before, and, for many, are taking their first course in hydrology, but are expected to possess working knowledge of both by the end of the semester. If planned well, instructors can introduce the skills needed to perform the analyses they are teaching. As instructors, we are still perfecting our approaches to this, and have found that reflecting and taking good notes after each lesson has helped us iterate our approaches and our courses (especially in terms of where students either immediately grasped a concept, or a place where they collectively struggled). Based on our own experiences, **Table 2** shows examples from our courses that align hydrologic course material and R coding.

BMP 8: Assess Student Learning Often and With Low Stakes Interactions

In our coding courses, and in agreement with the educational literature, we have found providing low stakes assessments (anecdotally) appears to improve the classroom experience for students as well as overall learning outcomes. Low stakes assessments are those that provide students with an opportunity to test their knowledge and receive feedback but via an assignment or quiz that constitutes only a small percentage of each student's overall grade. We all have used low stakes assessments that encourage students to actively engage with the material by providing opportunities for repetition needed to build skill competencies in a structured environment. Moreover, such assessments provide instructors with real-time feedback on the status of student learning (i.e., formative assessments). Below are several assessments that we found useful in our courses that draw from the educational literature.

TABLE 2 | Matching hydrologic concepts with coding concepts in a hydrology course.

Hydrologic concepts	Coding concepts	Useful R libraries
Differences in hydrographs across climate regions	Commands and options for creating a figure	*ggplot2*
Flow duration curves	Creating vectors; Basic data wrangling (e.g., sorting)	*dplyr*
Computing runoff ratios	Basic data wrangling (e.g., aggregating and grouping)	*dplyr*
Stage-discharge relationships	Generating statistical models	*stats*
Linear reservoir modeling	*for* loops, *if/then/else* statements	-
Estimating potential vs. actual evapotranspiration	writing functions	-
Watershed delineation	Geospatial analysis	*Whitebox, tmap*
Extracting watershed precipitation	Geospatial analysis	*prism*
Hydrologic model calibration and optimization	Developing workflows	*TUWmodel, rtop*

Low Stakes and No Stakes Assessments

In our coding courses, we have found short quizzes at the beginning and end of class (∼5 questions over 5 min) to be an effective low stakes assessment (Narloch et al., 2006; Lyle and Crawford, 2011). These assessments can be a mix of hydrologic and coding-based questions, and we suggest the quizzes be very similar in format (if not identical) from week to week. This provides students opportunity for additional repetition and to show improvement. Optional questions could include writing a short snippet of code, answering multiple choice questions, or drawing a conceptual model describing hydrologic process.

Retrieval Practice

In conjunction with pre- or post-class quizzes discussed above, we suggest incorporating retrieval practice throughout class. For example, one approach used by one of the authors is to provide a code chunk to the class and instruct students to look for errors, or to engage students in writing pseudo-code (i.e., provide a written summary of what the code does; also described in the computer science literature as verbal algorithm specification) as part of their assignments. Importantly, these activities can be done as a class, in small groups, or individually—providing flexibility under circumstances when the classroom may transition between virtual, in-person, or hybrid modes.

Two-Stage Exams

As introduced by Zipp (2007), two-stage exams emphasize cooperative learning for testing, turning exams into not only an assessment, but an opportunity for learning. In coding courses, we recommend the use of two-stage exams. In this approach, students complete their exam, and the exam is returned to them by the next time the class meets. During that next class meeting, students are given time in class to work in teams to correct everything that is wrong. This allows students who understood the material to learn it better by teaching it to others and allows those students who didn't perform as well to re-engage with the material and learn from their peers. There are many examples in the educational literature documenting the successes of two-stage exams and providing recommendations for how to incorporate this practice into various types of classrooms (Knierim et al., 2015; Bruno et al., 2017).

BMP 9: Learn Evidence-Based Effective Teaching Best Practices

While none of us consider ourselves experts when it comes to evidence-based teaching practices, we have all found immense value in engaging with this literature to improve our awareness of these techniques and to test these techniques in our classrooms. There are numerous well researched and well-developed strategies for effective teaching. Though the literature on the topic continues to expand our understanding of how individuals learn, there are also many commonly accepted best practices. From our experience, one of the best ways to learn about these best practices, both what they are and how they work, is to read books that summarize them. Diving into the literature can be overwhelming and difficult to translate into classroom actions. Instead, we recommend instructors find a book. *Small Teaching* (Lang), *Teaching at Its Best* (Nilson), *The Chicago Guide to College Science Teaching* (McGlynn), and many others offer neatly summarized best practices, examples, and explanations based on the literature. Likewise, instructors should familiarize themselves with Universal Design for Learning (UDL). UDL features an evolving set of guidelines that are aimed at helping instructors meet student needs (Courey et al., 2013; CAST, 2018). Many of the recommendations contained in this article are inspired by UDL principles in the context of coding education. UDL is ever-evolving, thus revisiting UDL resources year after year is likely to be a good use of time.

Another resource available to build awareness of effective teaching best practices are teaching workshops offered by college and university teaching centers or professional organizations. In addition to being engaging ways to learn more about teaching and get new ideas for your classroom, they can be a great way to meet others at your institution or in professional organizations who share your interest in the subject. From our experiences, we found that engaging with multiple books and workshops was the best way to identify best practices for our classrooms. Additionally, it helps to update or annotate your course notes, class schedule, or other material immediately after you engage with these new materials, lest they be lost to the thousand other demands on your time.

Though we include a discussion of student self-efficacy earlier in this piece, we note in this section that educator self-efficacy is equally important to supporting student self-efficacy. Thus, an awareness of and practice with evidence-based teaching strategies will not only improve an educators' experience in the classroom, but will also support their students' self-efficacy, motivation, and learning (Woolfolk Hoy, 2004). In this frame, we encourage educators teaching coding to experiment with educational activities in the classroom: try a new approach, or strategy, and reflect on what went well (or what didn't go well). While not every strategy that we have used in classrooms has always worked, or achieved the intended outcome, such experiments are useful information for improving approaches through time.

BMP 10: Grow Your Knowledge Every Year

Best practices for teaching are ever evolving. In this vein, we have all found it incredibly useful to engage in training on teaching each year, whether that is reading a book, attending a seminar, or reading a few articles in the peer-reviewed literature. We feel it helps keep us current and gives us new ideas to bring into the classroom, which improves our teaching and helps keep teaching interesting and exciting for us. As core practices in science education are constantly evolving, this also helps us to keep practicing and learning new skills.

CONCLUSIONS

Teaching is challenging. However, it is not a magical mystery show. Just as we don't expect our students to be automatically good at coding, we cannot expect to be automatically good at teaching. Teaching is a skill that can be improved through practice and training. As we highlight in this article, there are many resources available to aid instructors on our journey, including the recommendations presented here. These recommendations are aimed to help any instructor consider how to approach teaching students to code, whether under virtual environments or otherwise. We caution that this is not an exhaustive list and represents a set of core practices that we expect to evolve over time, both within our classrooms and within the hydrology community.

Providing instruction during the pandemic has been (and continues to be) challenging for so many reasons. However, this experience was crucial for us to identify how we could improve our teaching around coding, given all the changes and circumstances that virtual teaching and learning presented. Above all, we believe this experience, as reflected by these recommendations, will lead to more effective and inclusive teaching in the future.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

CK, JG, and CJ contributed to the conception of the manuscript. All authors contributed to various sections of the manuscript, read, and approved the submitted version.

FUNDING

Funding was provided by Lafayette College and a Syracuse University CUSE Grant to CK.

ACKNOWLEDGMENTS

The authors wish to thank the students in their courses who made this article possible and who helped form our experiences teaching coding in the classroom. We also appreciate the thoughtful feedback we received from the three reviewers listed on this article.

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frontiers | Frontiers in Education

ORIGINAL RESEARCH
published: 23 June 2022
doi: 10.3389/feduc.2022.907801

Prioritizing Engagement of a Diverse Student Cohort in Online Hydrology Learning at the University of Western Australia

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Like most water education institutions worldwide, hydrology instructors at the University of Western Australia (UWA) had to rapidly adapt traditional teaching strategies to manage the COVID-19 pandemic. With diverse student cohorts, including a large fraction of international students prevented from reaching Australia by travel restrictions, key requirements from this transition were to create supportive, inclusive online educational settings, and to maximize student engagement in their courses. Here, we draw on experiences in four hydrology courses to illustrate how we used a holistic approach spanning course structure, content delivery, active learning experiences and authentic assessment to protect these key pedagogical requirements during the transition to online learning. Some aspects of this approach—for example, creating an online "virtual watershed" in lieu of field trips—required sophisticated technology to support online innovation. Other aspects, however, relied primarily on existing features in learning management systems such as Blackboard and on re-organization of course structure and communication approaches to support online learning, with minimal need for new technology or software. The outcomes in these courses as measured by student engagement, enrolment and self-reported satisfaction were positive, with student evaluations remaining similar to those of pre-pandemic levels. Previous interest in running flipped classrooms and familiarity with technology among instructors and students were helpful in enabling the transition. While content-delivery may remain in an online mode for hydrology classes at UWA long term, opportunities to re-introduce field work, laboratories and other face-to-face active learning activities are eagerly awaited by instructors and students alike.

Keywords: hydrology, education, online, holistic, engagement (involvement), international student, sense of place, communication

Edited by:
Bridget Mulvey, Kent State University, United States

Reviewed by:
Alfonso Garcia De La Vega, Autonomous University of Madrid, Spain
Murugesu Sivapalan, University of Illinois at Urbana-Champaign, United States

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Specialty section:
This article was submitted to STEM Education, a section of the journal Frontiers in Education

Received: *30 March 2022*
Accepted: *18 May 2022*
Published: *23 June 2022*

Citation:
Thompson SE, Bourke SA, Callow JN and Hipsey MR (2022) Prioritizing Engagement of a Diverse Student Cohort in Online Hydrology Learning at the University of Western Australia. Front. Educ. 7:907801. doi: 10.3389/feduc.2022.907801

1. INTRODUCTION

The University of Australia (UWA) is located in Perth, a geographically isolated city of approximately 2 million people on the Indian Ocean Rim (Kennewell and Shaw, 2008). Hydrology and water management have featured in UWA's education program since the university was founded in 1911 (UWA, 2021). Today hydrology remains foundational to programs in civil and environmental engineering, environmental science, geography, earth science and hydrogeology. Whilst the employment drivers for graduates have changed over the decades, hydrology has remained critically important to Western Australia and Perth for a variety of reasons, including the water resource supply and management consequences of sustained climatic drying (since approximately 1970, McFarlane et al., 2012; McFarlane, 2016); the water resource management needs of the mining industry—which underpins much of Australia's economic prosperity, is substantially headquartered in Perth and which employs many UWA graduates; issues of secondary salinization which have shaped land use policy (Elshafei et al., 2015; Callow et al., 2020); and in the context of conserving the exceptional biodiversity hotspot of South-West Western Australia (Hopper and Gioia, 2004).

In common with higher education institutions worldwide, UWA has had to rapidly respond to the lack of mobility of students and staff brought about by the COVID-19 pandemic (Marinoni and van't Land, 2020). Hydrology teaching at UWA has largely been based on traditional face-to-face lecture and workshop learning environments, supplemented by laboratories, computer laboratories and field trips. Although some courses had begun to offer aspects of the hydrology curriculum online prior to 2020, in most cases the COVID-19 pandemic required rapid innovation in hydrology teaching. While transitioning teaching presented challenges to instructors, it was also timely and aligned with trends affecting higher education and working practices in Australia and worldwide. These trends include the rapid digitization of work (Arntz et al., 2020) and the need to limit long distance travel due to the unfolding climate crisis (Wright, 2021). Together these challenges motivate us to seek new and effective approaches related to both content and delivery, for example, encouraging students to explore data-driven aspects of hydrologic science (e.g., Carey and Gougis, 2017), without losing the opportunity to learn field skills and all the experiences and complexities therein.

Here we draw on the experiences from four hydrology courses taught within separate Masters degree programs (**Table 1**) to illustrate how we used a holistic approach to transition our teaching online. Firstly, we present some context about UWA, including major trends in teaching modality and student demographics prior to 2020. Next we highlight shared elements of a pedagogical framework prioritized by all hydrology instructors at UWA during the transition to online teaching. Differences in pedagogy and learning aims between courses and disciplines are also noted. We follow the elements of this framework to demonstrate how specific teaching strategies that supported our pedagogical aims were realized as a variety of online innovations. We support this presentation with an online repository of teaching material examples (available from: https://doi.org/10.26182/q642-qp74).

TABLE 1 | Post-graduate level hydrology courses at UWA discussed in this paper.

Course title	Masters degree(s)	Focus
Water in a Changing Climate (GEOS4499)	Hydrogeology and Environmental Science	Water balance concepts, non-stationarity, and adapting to climate change
Hydrogeological Systems (GEOS4401)	Hydrogeology, Geoscience, Environmental Science, Professional Engineering	Water storage and flow in groundwater systems
Catchment and River Processes (ENVT4406)	Environmental Science and Hydrogeology	Hillslope and catchment hydrology and geomorphology
Engineering Hydrology (ENVE4402)	Professional Engineering	Mechanistic flow equations and design

2. INSTITUTIONAL CONTEXT

UWA is a public Australian University: it is self-governing but operates within legislative requirements established by the Australian Federal (national) Government. Australian educational policy is set at state and national levels. Changing national policy over the past 20 years has achieved a number of broad outcomes, including (Norton et al., 2016):

- Increases in the total number and the proportion of the university-aged population engaged in higher education;
- Increases in the proportion of students engaged in remote or multi-modal (face to face and online) learning;
- Increases in the number and proportion of students who are "international" (non-Australian or New Zealand residents).

In addition to changes in national policy, these outcomes also reflect changing technology, demographics of students, job-market expectations, international competition for full-fee paying students and Australia's relatively attractive profile as an education provider to these students, along with normalization of online teaching (Bradmore and Smyrnios, 2009; Norton et al., 2016). Although UWA's student demographics largely followed the national trends (see **Table 2**), prior to 2020 UWA was an outlier in terms of provision of external (off-campus) or multi-modal enrolments. UWA has encouraged instructors to create external access to learning materials *via* universal use of online Learning Management Systems (LMS, such as Blackboard) and policies requiring lecture capture and web-hosting since 2010, with broadened requirements for flexible teaching and learning in 2018 (University of Western Australia Senate, 2018). Yet as of 2018, only 3% of domestic students at UWA were enrolled in

TABLE 2 | Context of student numbers, demographics and learning mode, nationally and at UWA.

	Australia		UWA	
	2003	2019	2003	2019
Student numbers ('000s students)	362	645	5.6	8.3
Proportion enrolled external/multimodal	19%	40%	0%	3%
Proportion international students	28%	37%	21%	25%

Data sources for 2003 sourced from Department of Education Skills and Employment (2005) and for 2019 from Department of Education Skills and Employment (2020).

external or multi-modal courses (Department of Education Skills and Employment, 2020) (**Table 2**).

Prior to 2012, teaching in hydrology occurred at the undergraduate level, with a single course teaching into Environmental Engineering, Geography and Environmental Science majors, with also an advanced Engineering Hydrology unit. In 2012 UWA restructured degree programs following the "Bologna Model" (Zahavi and Friedman, 2019). Degrees were modernized to include second cycle Masters degree offerings with a range of water-related specializations. Hydrology-related teaching emerged as a core component of new Masters programs in Hydrogeology, Environmental Engineering, and Environmental Science. The contemporary student cohort in each of these programs originates from varied backgrounds with different levels of prior learning, and often pursuing distinct employment opportunities after graduation. Accordingly, a range of water-related courses are now offered, each with a unique focus in their learning objectives (see **Table 1**). In general, these Masters programs also attract a larger proportion of international students compared to the university wide data shown in **Table 2**.

3. COVID-19 EXPERIENCE IN WESTERN AUSTRALIA

Western Australia's COVID-19 experience has been unusual. Until March 2022, Western Australia successfully pursued an "elimination" or "zero-COVID" strategy by severely restricting travel to the state. Western Australian travel bans were internal (applying within the state and to other states in Australia) and operated within a larger set of Australia-wide restrictions on international travel. Travel that was allowed required a 2-week mandatory quarantine period before visitors could enter the Western Australian community. The COVID-19 pandemic emerged during the long Australian university summer holiday period. Many international students were thus unable to return to (or begin study at) UWA due to the travel restrictions. Many international students present in Australian depend on local employment to support their income as they study. These students were not made eligible for financial support associated with COVID-19 restrictions, and were openly advised by national leadership to "return home" as the pandemic took hold. Many students did so. Consequently, supporting the education of a substantial international student cohort based outside of the country has been a persistent requirement of pandemic online teaching.

In spite of the local elimination strategy, public health restrictions have impacted teaching at UWA. Instruction moved completely online for 4 months from March to July 2020. Several short "lockdowns" in February, April, May, and June 2021 also required temporary periods of online instruction. Online instruction at UWA has now been normalized by the need to cater for off-shore international student participation, to rapidly shift between modes of instruction in the case of lockdowns, and to offer domestic students an opportunity to select learning modes based on preference, convenience, or public health grounds.

The use of online instruction to rapidly provide flexible content delivery, engagement and assessment at UWA thus parallels experiences in other global educational environments. Specific local issues arise around the demography of the classes and the need to prevent pre-existing differences between local and international students—differences of culture, experience, language and familiarity with the hydrology and environment in Western Australia—from being further exacerbated by distance, time-zone and technology.

4. PEDAGOGICAL APPROACHES

4.1. Teaching Philosophy

The instructors and courses we discuss are connected thematically by water, and pedagogically by our commitment to creating a learning culture of engagement, support, inclusion, and inspiration (Ramsden, 2008). This commitment represents our common response to the challenges created by the pandemic and online learning in our classes and underpins our shared pedagogy. Across our classes, we also share a common constructivist outlook (Fosnot, 2013). We are all committed to authentic learning and assessment experiences in our classes (Cowan, 2004; Stefani, 2008), and to personalized learning that recognizes the individuation of each student (Itow, 2020). We all seek to be integrative—in the sense that the courses we teach are related to other educational experiences within our students' degree programs. These features have long been highlighted as important components of online education (e.g., Miranda et al., 2008; Lalonde, 2011; Itow, 2020).

Differences in disciplinary perspectives and pedagogies nevertheless emerge across the hydrology courses. For example geography courses emphasize experiential learning cycles (e.g., concrete experience → reflective observation → abstract conceptualization → active experimentation, Kolb, 1976; Healey and Jenkins, 2000). Conversely, engineering courses reflect the engineering competencies defined by Engineers Australia (which provides accreditation to professional engineering degrees in Australia, Engineers Australia, 2011) and emphasize connections between hydrological content knowledge and the engineering design process (Dowling et al., 2020). **Table 3** outlines shared pedagogical goals across our hydrology teaching, the strategies we used to achieve these goals and the specific innovations we used to implement these strategies online.

4.2. Course Organization

As summarized in **Table 3**, we targeted four pedagogical goals as we developed online courses: to maximize student engagement, which included making the course material accessible to employed students; to ensure that theory was connected to application within the course structure, and scaffolding learning so that depth and sophistication of the course content increased across the semester. These goals were largely achieved by designing the courses around small modules—an approach sometimes popularized as "chunked learning" (Martin et al., 2019). We adopted this strategy in all four

TABLE 3 | A shared pedagogical framework for the four classes discussed in this paper.

Topic	Pedagogical goals	Strategy	Online innovation
Course Organization	Maximize student engagement	Modular structure	Online content presented in short modules
	Connect theory & application	Learning goals, content & assessment linked	Module order enforced
	Increase depth of learning across course		
	Accessible to multimodal students		Allow asynchronous / self paced learning
Content Delivery	Maximize student engagement	Mix passive/active learning	Short high quality pre-recorded short lectures
	Maximize peer-peer / student-led learning	Consider attention span	Active learning pauses in lecture
	Facilitates experiential learning	Flip classroom	Live workshops
Relation- ships	Supportive instructor-student relationship	Minimize barriers to learning	Avoid "hybrid" workshops
	Positive peer-peer relationships	Small group instruction	Chat rooms
	Inclusive & equitable environment	Multimodal communication	Chat streams, emails, wikis & workshops
	Develop individuals	Student-student introductions	Introductions wiki
Active Learning	Experiential learning	Engagement with natural environment	Virtual catchments
	Student engagement		Virtual site visits
			Online workbooks replace lab manuals
Assessment	Authentic assessment	Consistency with workplace requirements	Guided design reports
	Growth mindset	Opportunities for improvement	Two-attempt assessments
	Assess across communication modes	Multiple assessment formats	Podcasts, blogs, vlogs

For each topic area—spanning course organization through to assessment, pedagogical goals were linked to teaching strategies, with particular online implementation actions.

courses, combining online, self-paced and asynchronous learning activities with scheduled online active learning sessions. This structure responded to both the need for flexibility in accessing learning content across the different student settings in the classes, and to the need to offer diverse learning experiences in online settings (Farmer and Ramsdale, 2016). For example, the *Water in a Changing Climate* course was split into 8 learning modules, each with explicit learning objectives. Several short pre-recorded videos supported content delivery. External resources were linked to the module to offer context and consolidation. The module concluded with a formative test for students against the learning objectives. The progression of module topics represents a logical development of ideas and complexity, scaffolding learning across the course. In *Water in a Changing Climate*, the first 4 weeks built understanding of hydrologic processes, data types and data sources. The second half of the course developed analytical and prediction skills with real-world applications.

Within each course, we staged the student progress across the modules to assist in conceptual development. This staging attempted to account for the diversity of graduate entry and exit points across the set of courses, and non-uniform student prior learning in areas of earth science and mathematics. Where students entered courses without a quantitative background, we provided optional "refresher" modules addressing concepts such as probability distributions. Exposure to mathematical concepts was heavily contextualized. For example, statistical distributions and non-stationarity were taught in the context of changing rainfall patterns using real data, and differential equations introduced through concepts of intuitive water balance exercises and explaining system non-linearities.

The logical structure of the material was supported by using existing tools in Blackboard allowing for scheduled or adaptive release of material to students. For example, in *Engineering Hydrology*, students needed to successfully complete a 5 question quiz about the previous module content before the next learning module's material could be accessed—thus tying together formative assessment and self-assessment with the course structure, and guiding students through a logical conceptual progression that deepened as the course progressed. This structure is illustrated in **Figure 1**.

4.3. Content Delivery

In designing online content delivery, we aimed to support high student engagement, create opportunities for peer-peer or student-led learning, and to facilitate experiential rather than abstracted or passive learning (see **Table 3**). The major strategy we used to achieve this goal was to flip our classrooms (Bishop and Verleger, 2013). Some of the courses operated as flipped classrooms prior to the pandemic, while others were conventionally structured. With online learning, we all found a flipped classroom model was essential. In line with a modular course structure, we also adopted a modular approach to sharing lecture material, usually delivered as high quality, short (5–20 min) pre-recorded lectures which were supplied to students online through the Echo360 platform.

Videos for content delivery were recorded in a variety of platforms (*via* MS Teams, in a purpose-built recording studios at UWA, *via* Powerpoint or Echo360). Use of the recording studio allowed for improved audiovisual quality and the use of professional editing software. Some fieldtrip content was filmed once inter-regional travel was possible, using DSLR (with a tripod and wireless radio microphones to ensure adequate sound quality) and drone footage, which we then edited into vignettes using Adobe Premiere Pro. Students were able to access

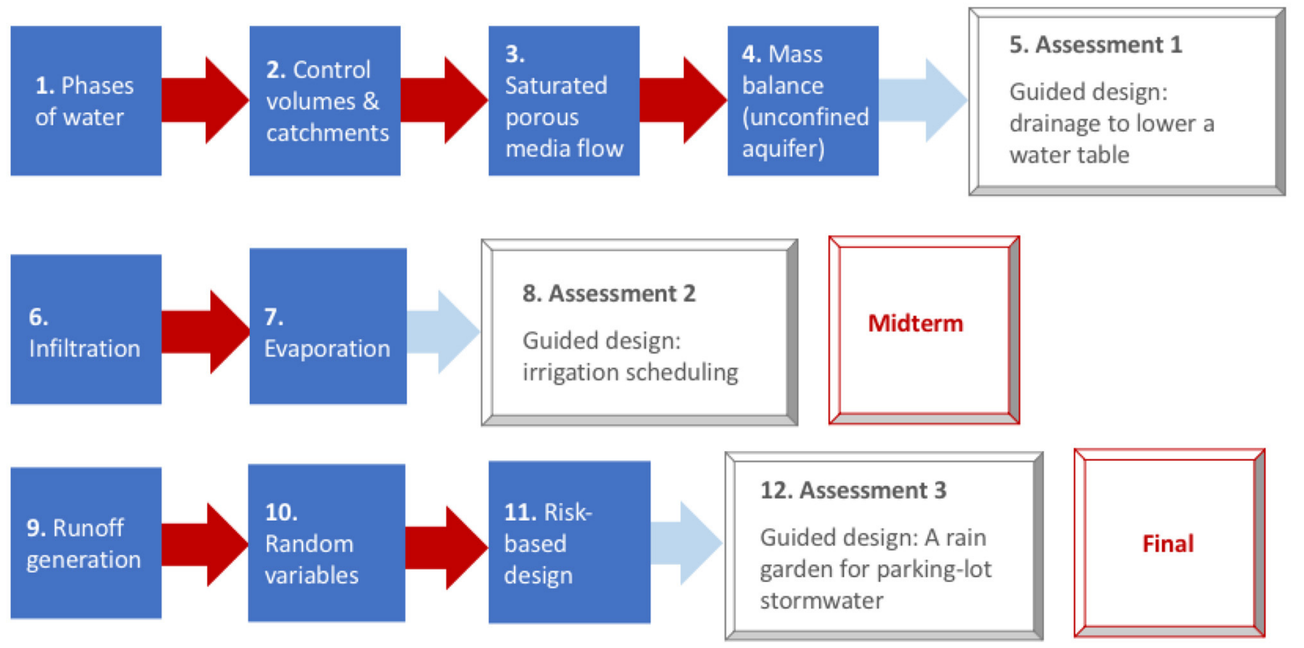

FIGURE 1 | Modular course structure in *Engineering Hydrology*. Numbers indicate the week in the semester (12 teaching weeks). Red arrows indicate points where access to subsequent course content required passing an ungraded quiz on previous content. Access to materials relating to project-based assessments (blue arrows) was unrestricted. Each course module builds in the previous, culminating in a guided-design assessment. Examination-based additional assessments complement and contrast with the "project-based" assessments.

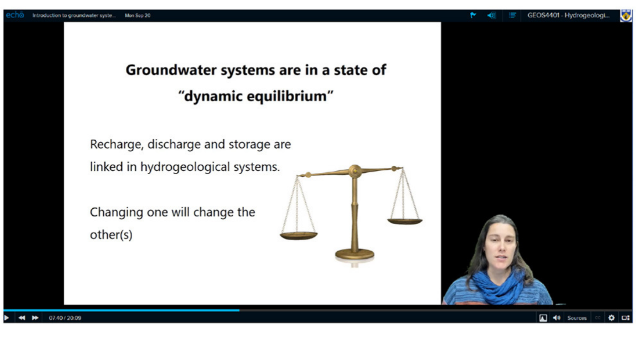

FIGURE 2 | Screen-shot of video recording captured in one of UWA's purpose-built recording studios and deployed to students through the Lecture Capture system, featuring author SB.

the videos within Blackboard or through a Lecture Capture software interface linked to Blackboard. Slides were simplified to maximize student focus on the lecturer's narration (e.g., see **Figure 2**).

Our use of short modularized lecture material was a response to literature showing that long lecture formats reduce student engagement in online education (Farmer and Ramsdale, 2016), and that attention spans often decline within 15 min of a lecture commencing (Middendorf and Kalish, 1996). The lecture videos were generally watched outside of scheduled classes, in line with a flipped classroom model. If lecture recordings were watched during timetabled online workshops, then breaks between lecture modules were used to introduce active learning elements (known to improve student perceptions of teaching, and learning outcomes, Jones, 2003). For example, students completed guided-note-taking worksheets, or quizzes on the video material. Within each learning module the lecture content was supported by clearly defined learning objectives and key terms, location-specific applications of theory, external links to contextual information and a formative quiz to facilitate students testing their achievement of the learning objectives. An example of a weekly learning module's content is provided in **Figure 3**.

One challenge posed by a diverse student cohort is to move beyond idealized ("textbook") depictions of hillslope hydrology and aquifer processes, with particular reference to the specifics of "place" around UWA. Students often struggle to link concepts about processes to the biophysical expression of real landscapes—particularly Western Australian landscapes which often defy unstated assumptions about geomorphic or hydrologic processes as depicted in international texts. Inclusion of WA-specific content has thus become particularly important as a response to COVID-19 border closures, and online content delivery emphasized place- and problem-specific conceptualizations. For example, the challenge of rising saline watertables in the inland region of Western Australia (brought about by land clearing), and the declining fresh watertables in the sandy coastal plain (brought about by extraction and declining recharge) are commonly conflated and confused by students. To provide necessary scaffolding to student learning, we firstly conceptualized sites

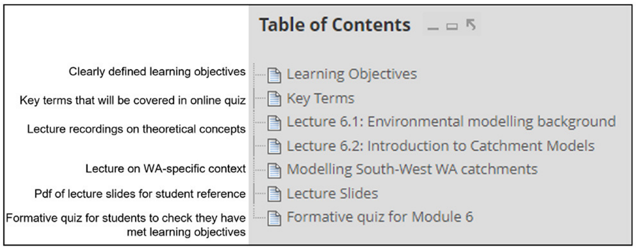

FIGURE 3 | Annotated Table of Contents from LMS showing modular delivery of learning content on the topic of Modeling Hydrologic Systems within the *Water in a Changing Climate* course.

and landscapes, then encouraged students to interrogate the dominant hydrological processes and their interactions, ultimately emboldening students to move from "questioning their learning" to "learning to question" (Abrandt Dahlgren and Öberg, 2001).

4.4. Student Engagement and Relationships

A major concern we held when moving classes online was how to build rapport with our students and facilitate the formation of positive peer-peer relationships in the classes. To achieve this we strove to create opportunities for interpersonal communication and engagement within our classes, to use multiple media to enable such communication to occur, and to set clear expectations for our class. We used multiple communication channels in our courses, which meant moving away from traditional (oral, email) communication media to more instant and responsive options. *Hydrogeology*, for example, moved communication with the lecturer primarily to a chat function in MS Teams. The use of a phone-based app allowed the lecturer to be more responsive to students in real time than was possible *via* email. We were aware that a consistent communication style might be particularly valuable for students using English as a Second or subsequent Language (ESL). Some courses achieved this consistency through the use of common templates for syllabi (course outlines), which were rolled out, for example, across Environmental Science and Geography classes. *Engineering Hydrology* used a consistent weekly email format which identified what material students needed to access online that week, what quizzes to complete, which assessments were in progress and their due dates, and any other relevant material to help students stay on track in the absence of face to face classes.

Functionality within online teaching and meeting tools provided further opportunity for student engagement and rapport building. An Introductions Wiki allowed students (and teaching staff) to share personal stories prior to the commencement of the course. The use of "break-out rooms" within Teams was one successful strategy to encourage development of peer-peer collegial learning communities, in which smaller groups worked to solve problems together, similar to a table of 2-6 students in a traditional classroom environment. Real-time engagement during workshops was fostered through collaboration on virtual whiteboards using the Limnnu software. In *Engineering Hydrology* where enrolment was split nearly 50-50 between domestic and international students, two workshops were offered, one for each cohort. This allowed students to speak with peers in their shared languages, and for instructors to provide additional assistance with language and interpretation in the "international" workshop, where language skills were a significant pedagogical issue.

4.5. Active Learning and Skill Development

Active learning experiences form a key attribute of our pedagogical approach (see **Table 3**). Field and laboratory experiences, which provide a foundation for conceptual learning (Dummer et al., 2008; Dunphy and Spellman, 2009), were particularly impacted by the pandemic. These hands-on experiences would conventionally provide an opportunity to learn through the "ODES" framework, presented in **Table 4**, which links to the cycles of learning through Observation; Description; Explanation; and Synthesis. ODES deliberately embraces Bloom's taxonomy (Bloom, 1956), by escalating from observation, through description, to explanation and concluding in synthesis. To retain this style of learning opportunity online we provided learners with measured data (substituting for real world observations) and used these data to guide students through the ODES framework.

The instructors of *Catchment and River Processes* constructed virtual field sites using digital imaging technologies. These allowed students to perform field-like digital fluvial geomorphology investigations. Virtual fieldtrip data was collected using a DJI Mavic 2 Pro drone, (operated under UWA CASA ReOC licence CASA.ReOC.0628), flown at 75 m AGL and processed using Agisoft Metashape Professional with workflows from Callow (Callow et al., 2018) and May (May et al., 2021). Students visualized the datasets in QGIS, ArcGIS Pro and the free Agisoft Viewer software. Students were provided with a high resolution (5cm) orthphotomosaic (**Figure 4A**), a Digital Terrain Model (DTM) or bare-earth Digital Elevation Model (**Figure 4B**), and a Digital Surface Model (DSM). From these datasets, students could extract elevation cross sections, view and map river hydraulic and geomorphic courses, and compute a Canopy Height Model (CHM, calculated as CHM = DSM-DTM, **Figure 4C**) from which ecotones could be inferred. Additionally, full 3-D models of the virtual catchment allowed students to 3-D manipulate and orientate the scene, and to also explore profiles (**Figure 4D**). Learners then used these data in-lieu of field surveys to construct conceptual models of the system, processes and outline management issues. All datasets described above and used in **Figure 4**, are available from https://doi.org/10.26182/q642-qp74).

Prior to the remote teaching requirement the *Water in a Changing Climate* course engaged students in hands-on laboratory activities. These illuminated concepts relating to Darcy's Law, runoff thresholds and aquifer transport pathways within "desktop catchments"—desktop-scale physical models of a sandy hillslope or aquifer cross-section. We replaced

TABLE 4 | The ODES framework (from a field handbook as given to students for a field exercise).

Attribute	Instruction and learning activity characteristics
Observe	Collect data, and look!...what IS there, what does it look like, what is NOT there (what should be there but is missing). LOOK AGAIN!!
Describe	Describe what you see, what is it made of, what could have created it [natural or anthropogenic (created by humans)], has it changed or been stable. Describe this to a partner and work together. Break apart the system into its individual components. Start to write some notes or record a sketch of what is here and what you see.
Explain	Now present your ideas to your peers and add details, and also justify the "why" of your observations to someone else, test your descriptions on a peer or your group. Explain the "what" and "how" you have just seen and described—what is it, what created it, what processes are changing or modifying it, how is it changing or resisting being changed. You will likely need to repeat the first three steps multiple times to refine your explanation (observe, describe, explain). Add annotations and further notes to explain more detail about the features you see.
Synthesize	Pull together your observations of the individual components, description and explanation. Put this information back together into a summary of (1) what is there, (2) how it works, and (3) what it means or why it is important. Write some summarizing notes—start to record why these features are important, are they changing or resisting change, have they been manipulated by humans.

Note that the instructions descriptions are modified for various field and laboratory exercises.

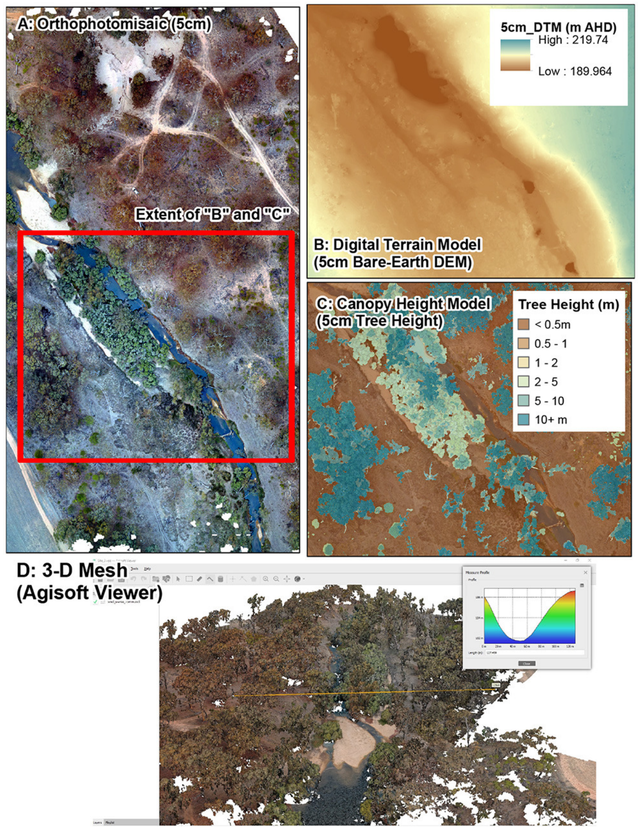

FIGURE 4 | Example of digital field sites constructed from drone photogrammetry to create various types of digital field data in-lieu of field data collection, including: **(A)** A 5 cm high-resolution digital orthophotomosaic of the field site; **(B)** A Digital Terrain Model (DTM) or bare-earth Digital Elevation Model (DEM) of elevation; **(C)** Canopy Height Model of tree height; **(D)** 3-D scene as viewed in Agisoft Viewer.

these laboratory sessions with an online workbook of activities created in R Bookdown. Students were able to complete many components of these exercises independently, supported by video vignettes. Student-generated data were compiled in online worksheets, which formed focal points for discussion in timetabled workshops. Whilst the activity workbook could not fully reproduce hands-on experimental learning, time-lapse videos of the hands-on experiments were included as vignettes, and supplemented with the online digital tools or models as appropriate. For example, students used the ParFlow SandTank model (https://sandtank.hydroframe.org) to attempt to replicate experimentally generated aquifer flow states (**Figure 5**). Guided data analysis was challenging in an online environment when students were constrained to one screen on which to consider demonstrations, read notes and undertake analysis. Providing dedicated time in workshops in which students could immediately rewatch demonstrations was helpful in reducing these hardware-related blocks to learning. After each "chunk" of material in the workshop the recordings were stopped and a note made in the chat about the topic of that recording so that students could easily find specific learning content later, and students could re-watch the demonstration during the workshop while they attempted the activity themselves.

4.6. Assessment

All courses aimed to create authentic and fair assessment experiences (see **Table 3**). These were designed to explicitly test the course learning objectives while offering students an opportunity to produce assessed materials that were consistent with workplace expectations. Thus, the courses considered content knowledge while also assessing communication skills, critical thinking, and competency across different communication styles. For example *Catchment and River Processes* replaced an in-class oral presentation with a 3-min podcast on a geomorphic or hydrological topic of their choice. Not only were students enthusiastic about the novelty and pleasure of this experience, but the set of class podcasts was then made available as a resource for other students—a distinct outcome from the transient nature of an in-class oral. The assessment thus also helped support deeper learning among a student cohort which was familiar with the broad themes of the course but had limited specific topical knowledge.

Transparency in assessment was facilitated by publishing marking rubrics for each assessment, and using the markup tools (e.g., quicknotes) in Turnitin to provide individual feedback on written reports. Overall comments on student performance in particular assessment items were provided using Teams or LMS announcements. This scaffolded approach to feedback allowed efficient individualized feedback delivery, which we have found to be particularly important when teaching to cohorts of mixed backgrounds (e.g., domestic vs. international students; with or without cognate background).

Online assessment opportunities were also able to support pedagogical goals such as promoting a growth mindset. For example, administering an examination online with Blackboard's inbuilt multiple-choice examination tools speeds grading enormously. With the flexibility to test and assess multiple times, *Engineering Hydrology* adopted a 2-stage midterm examination approach. Students were able to take the 15 question exam twice in 4 days, and receive a weighted (75–25%) average of their scores. Almost all students were able to improve their performance between the two attempts, some dramatically so—suggestive of the students learning from their initial struggles.

5. DISCUSSION

5.1. Feedback and Student Experience

Moving hydrology education at UWA online enabled us to maintain continuity of instruction during a period of profound disruption to the University and its students. While the rapid transition required significant time investment from instructors and is yet to represent a mature and fully developed approach to course delivery, it also led to distinct benefits and improvements to student learning outcomes.

Student feedback about all four courses has been generally positive. Instructors were nominated for excellence in teaching awards, and, although course evaluations were suspended in 2020, student evaluations of online teaching in 2021 were also generally positive. Students have expressed appreciation for the care in course organization and content delivery. International students in particular highlighted the significant benefits of pre-recorded lectures. The capacity to pause, re-watch and if necessary slow down the playback rate of lecture material was consistently highlighted as a positive that particularly benefits students whose first language is not English. Once the initial recording of lecture modules was complete, having pre-recorded material lowers the workload for course preparation, so that time could be invested in improving and updating select material and offering active support to students. As instructors we have had to be more deliberate in designing our courses, more selective about the quantity and purpose of the material we include, and to provide greater effort in communicating weekly work plans and expectations to students. It is likely that these efforts addressed areas that may have previously been weak or unstated in our teaching.

5.2. Enabling Factors

As instructors, our experience in moving classes online was smoothed by two things: Firstly we were all independently committed to active learning and flipped classrooms. Our pedagogies retained elements of classical behaviorist university instruction (e.g., lectures), but also contained constructivist and social-constructivist approaches (Ertmer and Newby, 1993), with student-centered, peer-driven, active learning in all courses. Our classes were all therefore either flipped or in a transition toward being flipped—a situation which set us up well to adapt to online instruction in a flipped mode. Secondly, our expertise and available technologies were well-suited to solving many of our online teaching challenges. As instructors, we were all technologically literate, able to code and to program, and willing to use available educational technologies. Our students had a similar profile. From discussions across the whole of UWA, we understand that this distinguishes our experience from that of colleagues in less technologically-oriented fields, where neither instructors nor students were as well-prepared or as well able to endure the transition online.

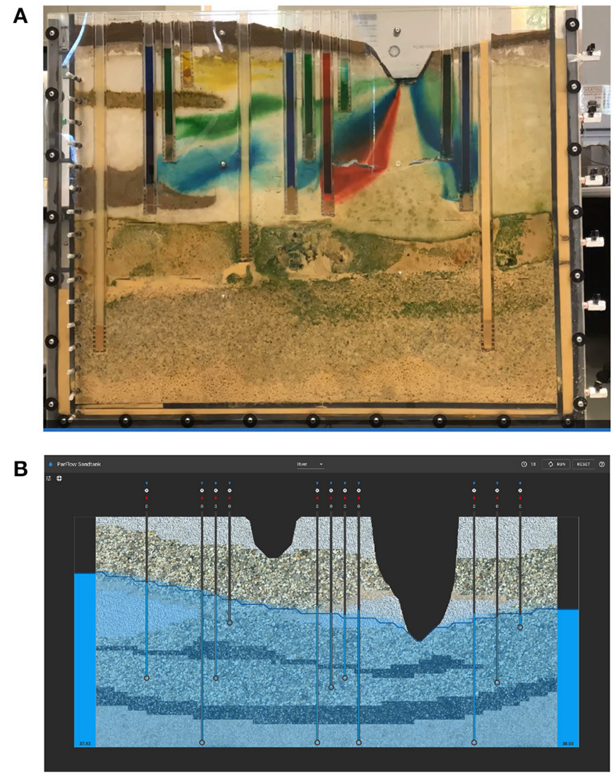

FIGURE 5 | Example of transitioning a hands-on physical aquifer model **(A)** to a digital analog based on the ParFlow SandTank **(B)**.

As such, we were largely able to create online learning experiences that delivered on our strategies and pedagogical aims. Technological challenges were present, perhaps most notably for international students operating behind firewall-protected ISPs. These students, while able to use a UWA VPN, sometimes struggled with access to 3rd party sites and software. Building collegiality and encouraging interaction in online settings has sometimes proven difficult, yet is key to ensuring good learning outcomes. Allocating time and creating activities in breakout room sessions has been effective in some cases to ensure that students understand the expectation to use their videos and actively participate, rather than sitting muted in the background. Encouraging use of the chat function has also, in some cases, helped shy students, those lacking in confidence in their English skills, or those with weak internet connections, maintain positive communication with peers and instructors.

5.3. Moving to a Post-COVID Teaching Model

The nature of the work students do in online learning can offer strong parallels with the expectations of the workplace. Many of our students will or already do work in the resources or development sector, or as government or regulatory officials, industry proponents or environmental consultants. These sectors are also pressured—acutely by COVID-19, and in the longer term by cost, carbon-footprint and safety requirements—to adopt virtual and remote technologies for site assessment and collaboration (McNab and Garcia-Vasquez, 2011). Including desktop-analysis of 3-D reconstructed, digital field sites in the course was embraced by students as teaching key, workplace relevant skills. Similarly, familiarity with online and virtual communication, engagement, team building and project delivery, all of which were modeled in the online classes, increasingly represent necessary workplace skills (Balliester and Elsheikhi, 2018; Cook, 2020).

Some learning experiences are and will likely remain challenging to fully replicate online. Observational field skills are difficult to teach without being present in the field. Rapport building and teamwork among students are easier to achieve online if supplemented by some level of face-to-face interaction, and can be very hard to achieve in online-only settings where technology, internet quality and language barriers all "distance" people from one another (Meluso et al., 2020). Sharing a sense of place and building intuition about the physical environment in a novel location is also difficult without the opportunity for immersive experiences in that environment. Feedback from students highlights that opportunities for in-person learning are highly valued, perhaps more so now than before the pandemic.

For this reason, we expect that online teaching will likely remain in our courses, but that in many cases we will attempt to enact a blended learning model with some level of face to face learning retained. Face to face learning experiences would focus on teaching field skills, fostering environmental literacy and a sense of place, and on relationship-oriented active learning experiences where peer-to-peer instruction and student-led experiences are prioritized.

6. CONCLUSION

With online teaching of hydrology likely to find ongoing applications at UWA and worldwide, our collective experiences during the first years of the COVID-19 pandemic highlight some valuable lessons for others teaching hydrological subjects online. Our five key take-home messages are summarized in **Figure 6** and described below.

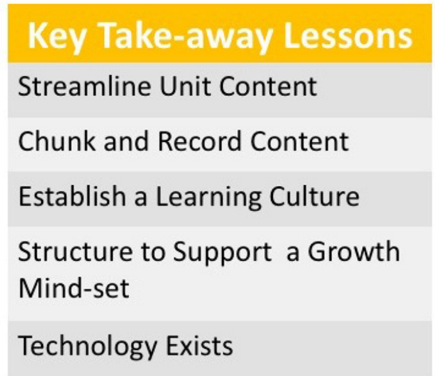

FIGURE 6 | Five core messages for others considering taking hydrology content online, based on the UWA experience.

- **Streamline unit content:** Streamlining involves reducing content to that the core messages and tasks are the clear focus of the course. Making explicit connections between learning objectives, content, active learning activities and assessment helps communicate the logic of the course design to students. This communication is important, as opportunities to clarify course objectives and purpose are limited in the absence of face to face communication.
- **Chunk and record content, for student-paced learning:** Small units of content maximize flexibility for students to access course material at times compatible with diverse schedules and timezones. Opportunities to re-watch content enables students to revisit areas of confusion. This has been particularly valuable for students speaking English as a second or subsequent language.
- **Establish a learning culture:** Online modalities can promote passive learning styles. Student participation needs to be actively encouraged through use of multiple fora, active online activities, and, where possible, retention of some face-to-face engagement that focuses on building trust and rapport.
- **Structure opportunities for growth mind-set into course design:** By structuring the course around repeated activities/assessments with some commonalities, the course structure can promote continuous improvement and consolidation. Streamlining course content (as per point 1) can clarify which activities are likely to offer most value in line with course objectives.
- **The technology exists:** Existing tools enabled successful delivery of learning materials online. Digital analogues have limitations, but also benefits. For example, synthetic catchments or systems may span a greater range of conditions than students can physically visit in the field or simulate in the lab.

With the experience of moving our courses online now complete, and with streamlined courses with pre-recorded content and thoughtful design now in place, the hydrology instructors at UWA are well-equipped for ongoing multi-modal instruction. We fully expect that sharing our experiences and learning from those of other instructors innovating in digital water teaching, in conjunction with new innovations in technology for online learning, will produce ongoing improvements in our courses, their delivery and online student learning outcomes.

DATA AVAILABILITY STATEMENT

Data cited in this manuscript are available from: https://doi.org/10.26182/q642-qp74. Other queries may be directed to the authors.

AUTHOR CONTRIBUTIONS

ST and SB conceived the paper and contributed material relating to the *Engineering Hydrology*, *Water in a Changing Climate*, and *Hydrogeological Systems* courses. MH and JC contributed material relating to the *Water in a Changing Climate* and *Catchment and River Processes* courses. All authors contributed to writing and editing the text.

ACKNOWLEDGMENTS

Prof. Matthew Tonts was acknowledged as the co-developer of the ODES framework (**Table 4**) with JC, as part of the course GEOG2202 Reading Landscapes course. We also sincerely thank the UWA Educational Enhancement Unit members Miela Kolomaznik and Lee-Von Kim who contributed to the design of many innovations described here.

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CURRICULUM, INSTRUCTION, AND PEDAGOGY
published: 28 June 2022
doi: 10.3389/feduc.2022.905777

Using Wikipedia Assignments to Teach Critical Thinking and Scientific Writing in STEM Courses

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Specialty section:
This article was submitted to STEM Education, a section of the journal Frontiers in Education

Received: *27 March 2022*
Accepted: *30 May 2022*
Published: *28 June 2022*

Citation:
Gareis JAL, Larson EI, Ardón M, Berges JA, Brandt JE, Busch KM, Chraibi VLS, Gallagher EN, Hondula KL, Kincaid DW, Levine TD, Little CJ, Nodine ER, Rock AM, Shogren AJ and Vanni MJ (2022) Using Wikipedia Assignments to Teach Critical Thinking and Scientific Writing in STEM Courses. Front. Educ. 7:905777. doi: 10.3389/feduc.2022.905777

While many instructors have reservations against Wikipedia use in academic settings, editing Wikipedia teaches students valuable writing, editing, and critical thinking skills. Wikipedia assignments align with the community of inquiry framework, which focuses on the elements needed for a successful online learning experience. We report on a faculty mentoring network, created by WikiProject Limnology and Oceanography, which helped 14 instructors with little to no prior experience implement a Wikipedia assignment in their classes. We found that Wikipedia assignments increase students' motivation to produce high quality work and enhance their awareness of reliable scientific sources. Wikipedia assignments can be comparable to other writing assignments in length and complexity, but have a far wider audience than a traditional research paper. Participants in our mentoring network reported challenges with implementing this new type of assignment, and here, we share resources and solutions to those reported barriers.

Keywords: community of inquiry, limnology, oceanography, faculty mentoring network, science communication, digital skills, online education, information literacy

INTRODUCTION

While academia and Wikipedia have historically had an uneasy relationship, Wikipedia assignments offer an opportunity to bridge the gap between scholarly information and the public (Jemielniak and Aibar, 2016; Konieczny, 2021). Students can play a critical role in this process by adding missing information to articles and thereby improving a freely-accessible resource. In particular, students can directly improve the quantity and quality of information about water-related and other science, technology, engineering, and math (STEM) topics on Wikipedia (Kincaid et al., 2020, Stachelek et al., 2020). Wikipedia assignments also offer opportunities for instructors to foster collaboration between students and subject-matter experts (Radtke and Munsell, 2010) and to have class discussions about the reliability and quality of various online sources of information. Finally, editing Wikipedia helps students experience a direct transfer of information from academic, often paywalled, sources to a more public distribution of information (Callis et al., 2009). These assignments provide a unique philosophical perspective on the scope and nature of peer-review, both within the scientific community and more broadly, and can work well in a variety of instruction modalities. When writing assignments are completed in isolation with no audience beyond the instructor or fellow students in the course, students may not feel a strong incentive to produce quality written work. At the same time, education research supports the idea that writing is both a critical skill and a way to construct knowledge and deepen understanding about scientific topics (NGSS Lead States, 2013). Structuring writing assignments so that students know their work will reach a broader audience could incentivize students to focus on clarity and comprehensiveness (Apollonio et al., 2018).

Editing or creating new Wikipedia articles is an innovative way to teach critical thinking and scientific writing in online, in-person, or hybrid (including elements of both online and in-person) course formats. Assignments where students either edit existing articles or create new articles on Wikipedia teach students to write clearly and effectively for a broad audience (Vetter et al., 2019). These assignments also motivate students to engage in a writing assignment with immediate and measurable societal impact. Moreover, the quality of the resulting Wikipedia articles helps instructors assess student learning about a particular course topic. Wikipedia assignments can be structured so that collaboration and interaction with colleagues are intended learning outcomes (Koziura et al., 2020). For example, students can jointly edit and improve an article, peer review each other's articles, and/or incorporate expert reviewer feedback as part of the Wikipedia assignment structure (Shane-Simpson and Brooks, 2016). A focus on group learning aligns with many institutional priorities for novel and active learning and peer engagement. Moreover, Wikipedia assignments provide an alternative to academic service-learning projects, with a more global focus on the intended audience, as well as a mechanism for community engagement on a virtual platform (Vetter et al., 2019). These assignments also provide students with opportunities to work with experts beyond their academic institution, a powerful motivator to complete quality work and an opportunity to gain varied insights on a topic.

In addition to meeting specific or requisite learning objectives, Wikipedia assignments provide a creative approach for accomplishing more co-curricular goals of ethical literacy. While digital literacy, information equity, and ethics might not necessarily be core competencies or explicit course objectives, they are nonetheless important topics for students to learn in an increasingly digital world (Coffin Murray and Pérez, 2014). Importantly, Wikipedia assignments help break the "ritualization" of student literature search practices (Bhatt and Mackenzie, 2019), as students are confronted with an assignment that breaks the mold of the typical term paper. Wikipedia assignments also help students become more savvy consumers of online information, an increasingly critical skill (Brossard, 2013). Additionally, Wikipedia editing assignments align with the principles of open pedagogy (Koziura et al., 2020), where students not only produce open information, but also have to consider open access principles and the accessibility of science communication.

In this article, we describe outcomes and resources generated from a multi-institution faculty mentoring network led by members of WikiProject Limnology and Oceanography[1] during the 2020–2021 academic year, during which most of the mentored instructors were teaching courses with either hybrid or online delivery. The intent of the faculty mentoring network was to provide resources and support to faculty implementing a Wikipedia assignment for the first or second time in their science courses related to aquatic systems. This support included reviews of student Wikipedia drafts by subject area experts that were recruited for this purpose by members of WikiProject Limnology and Oceanography. We report some of the successes and challenges that faculty experienced in carrying out Wikipedia assignments and suggest resources and strategies to support instructors who are interested in doing a Wikipedia assignment in their STEM course.

WIKIPEDIA ASSIGNMENT ALIGNMENT WITH THE COMMUNITY OF INQUIRY FRAMEWORK

A Wikipedia assignment maps onto the Community of Inquiry framework developed for online learning and therefore aligns with constructivist theories of learning (Garrison and Arbaugh, 2007). Briefly, the Community of Inquiry framework posits that three overlapping elements are needed for a successful online educational experience: social presence, cognitive presence, and teaching presence (Garrison et al., 2001). Different portions of Wikipedia editing or writing assignments map on to each of these three elements (**Figure 1**). First, social presence is the ability of learners to project their whole and authentic selves in an online learning environment. In a Wikipedia assignment, this element is achieved through students' ability to work informally in a virtual draft environment, called the "sandbox" (**Supplementary Material:**) (WP L&O The Sandbox[2]), on the Wikipedia site. In this space, students can select topics of interest and interact with peers through offering feedback or working collaboratively on a single topic. Second, cognitive presence is the way that learners construct understanding through continued cycles of reflection and communication. Wikipedia assignments can be structured to go through iterative phases of feedback as student work develops and are scaffolded to facilitate this construction of knowledge. Finally, teaching presence is defined as the ways that courses are designed and instruction is delivered to facilitate student understanding. As mentioned previously, Wikipedia assignments can be tailored with different levels of student–teacher interaction individually or in groups. The free platform, WikiEdu,[3] also delivers asynchronous online modules on how to edit Wikipedia and provides instructor support for Wikipedia assignments.

[1] https://en.wikipedia.org/wiki/Wikipedia:WikiProject_Limnology_and_Oceanography
[2] https://en.wikipedia.org/wiki/Wikipedia:About_the_sandbox
[3] https://wikiedu.org/

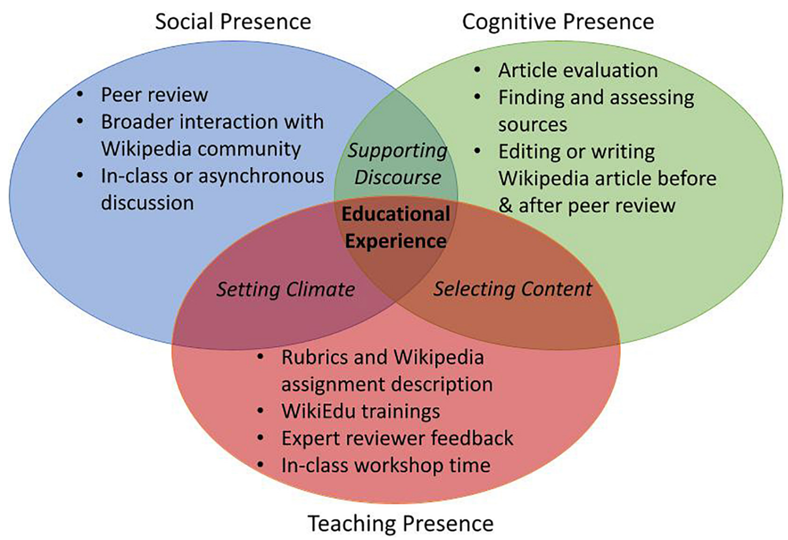

FIGURE 1 | Conceptual model of the Community of Inquiry framework (Garrison and Arbaugh, 2007), adapted to include parts of a Wikipedia assignment that apply to the various elements of the framework. Areas of overlap indicate interdependent goals that combine to create a meaningful educational experience.

In addition to mapping onto an established pedagogical framework for online learning, Wikipedia assignments help meet specific learning objectives in STEM courses, such as critical thinking and evaluation. For example, Wikipedia has standards about what types of sources can be referenced.[4] Learning about appropriate referencing can be both a lesson objective and an aspect of assessment on the finished project by including training about this topic. Additionally, Wikipedia assignments require reconciling potentially conflicting sources of published information and deciding how to present them. For example, several students in a course taught by one of the authors identified substantial discrepancies among sources of lake depth data. Ultimately, the search for a scientific "truth" led students to further question: *How can we rationalize this? What "facts" should be given on the page when there is conflicting information? How do we report conflicting information while staying within the Wikipedia guidelines for unbiased reporting?* Recognizing that conflicting evidence may exist in the scientific literature and critically evaluating which sources are reliable to provide encyclopedic information are possible learning outcomes that Wikipedia assignments can help to both teach and assess.

In addition to facilitating critical thinking, Wikipedia assignments can help students gain understanding of and confidence in the iterative scientific writing process (Rayner et al., 2014). As students move through drafts to the final stages of a Wikipedia assignment, they transition from first learning through writing to then writing to communicate. Removal of scientific "jargon," linking to existing pages, and simplifying text can help the students better understand complex information. By emphasizing quality over quantity of content added, instructors work with students to identify the essential information to focus on what readers *need to* know, rather than what readers *could* know. Wikipedia pages (like all encyclopedia entries) should be thought of as points of entry to concepts, so it is important to make sure the essential information is prioritized. This style of writing is more technical and concise, and also less narrative, than students might experience when writing in their other courses. Many undergraduate students will never publish a research paper or manuscript, but they will likely need to create some form of written content for a general audience in the course of their careers. Learning to write for different audiences, such as subject-matter experts and the public, is crucial, and is accomplished with Wikipedia-based assignments. Finally, Wikipedia assignments can include valuable training on editing writing when students must modify text in response to feedback from a variety of readers. Learning to understand what is meant from feedback and how to respond to and give respectful and constructive critical feedback is a valuable scientific skill that forms the basis of peer review.

THE ADAPTABILITY OF WIKIPEDIA ASSIGNMENTS TO VARIED LEARNING ENVIRONMENTS AND LEARNING OBJECTIVES

A key strength of a Wikipedia assignment is its flexibility, which can be adapted for use in a wide range of learning environments and to address a variety of learning objectives. This adaptability was exemplified by the 15 courses that were supported through our 2020–2021 faculty mentoring network, which were diverse in subject, class demographics, and delivery method.

The 15 supported courses were offered at 14 institutions across North America, ranging from small liberal arts colleges to large, research-intensive, doctorate-granting institutions. Three of the 13 American institutions are identified as minority serving institutions by the Rutgers Graduate School of Education, 2020. While all 15 courses addressed topics related to the environmental sciences and ecology, they ranged from broad

[4] https://en.wikipedia.org/wiki/Wikipedia:List_of_guidelines

survey courses in limnology, aquatic ecology, and the aquatic environment, to more specialized courses such as stream ecology and ecotoxicology. Most courses focused entirely on aquatic sciences and emphasized inland waters, while others (e.g., Climate Change, Ecotoxicology) spanned several ecosystem types. The majority of the courses were primarily scientifically focused, although two included aspects of environmental management and one was a science course designed for non-science majors. While all courses were geared to upper-year undergraduate or graduate students, several included a mix of students at both academic stages. Class sizes ranged from seven to 30 students, with an average size of 18 students per class, and students worked individually, in pairs, or in small groups of up to four students to complete their Wikipedia assignments. Due to the on-going COVID-19 pandemic, most courses were offered virtually, while some were offered only in-person and others followed a hybrid model that included elements of both virtual and in-person instruction. In all cases, the instructors who participated in our faculty mentoring network were able to tailor their Wikipedia assignment to their learning environment, for example, by curating a list of topical Wikipedia articles for their students, focusing on ecosystems near their institution, or adjusting the amount of student interaction that was required during the assignment.

The 14 instructors that participated in our faculty mentoring network in 2020–2021 were also diverse with respect to their career stage and prior teaching experience. Participants included senior-level tenured faculty, as well as faculty within the first five years of their appointments. Most participating instructors had not previously used Wikipedia-based activities in their courses, but prior teaching experience ranged widely; while some instructors had taught at the post-secondary level for many years, at least one instructor was teaching a post-secondary course as the senior instructor for the first time.

Wikipedia assignments can also be easily tailored to address a wide range of learning objectives, and can be adapted to the learning level of the students by adding (or removing) elements or complexity (see **Table 1** for examples). For instance, an assignment can be made more advanced by increasing the amount of text that is required, or can be made less advanced by instead focusing on adding media or missing citations to an existing article. In all courses supported through our network, students either edited an existing Wikipedia article or wrote a new article to meet the learning objectives specific to their course. Although the learning objectives varied widely among the supported courses, we identified a number from the course syllabi that were shared by multiple courses:

1. *Developing scientific and technical writing skills*. Effectively writing scientific and technical documents, such as journal articles, protocols, and reports, requires a specific writing style characterized by clarity, brevity, and neutrality. This writing style is also used by the community of Wikipedians (i.e., volunteer editors of Wikipedia articles) who follow the Wikipedia Manual of Style[5]. By writing and editing Wikipedia articles, students were therefore able to practice and develop their scientific and technical writing skills.
2. *Communicating scientific knowledge to the public*. Wikipedia is the most common source of introductory information on a topic, and has the potential to share scientific knowledge more equitably than traditional methods of dissemination, such as journal articles or reports. Therefore, Wikipedia can be a tool to improve public knowledge on a range of scientific topics (Brossard, 2013; Kincaid et al., 2020). Articles are held to a high standard of public accessibility and readability by the community of Wikipedians. Course assignments supported the development of plain-language communication skills as students interpreted complex scientific concepts for the public, and explained them in accessible language that met the standards of Wikipedia.
3. *Thinking critically*. Successful completion of Wikipedia editing or writing assignments requires students to critically review and evaluate information from multiple sources, and to resolve any inconsistencies. This can require an evaluation of diverse sources of information and decision-making regarding what information to include. This provided the opportunity for students to critically review, assess, and evaluate existing and new information in their assigned Wikipedia articles.
4. *Researching and resourcing information*. Students were tasked with identifying appropriate references and information to back up their Wikipedia contribution. They also reviewed any existing article text, assessed the suitability of its references, and removed or replaced any inappropriate or out-of-date references. Although the citation styles used by Wikipedia tend to be more journalistic in form, as opposed to the formal citation styles used in academic writing, the importance of locating and citing appropriate sources to back up statements of fact remains the same as in an academic paper. Wikipedia assignments also provided an opportunity for students to evaluate information equity and access to scientific information; for example, the value to the public of open source information versus information stored behind paywalls.
5. *Developing digital skills*. It is critical that students learn how to find, evaluate, and communicate information online. Wikipedia editing and writing assignments allowed students to develop these skills while also navigating online training modules, resources, and comment pages that were facilitated by the WikiEdu support team.
6. *Developing an awareness of diversity and representation in science*. Minoritized individuals are under-represented both in terms of the numbers of editors actively contributing to Wikipedia (Koerner, 2019), and the number of articles about them (Wagner et al., 2016; Gupta and Trehan, 2021). In articles on STEM topics, minoritized individuals are even less equitably represented (Salam, 2019). Several courses explicitly focused on increasing the awareness and representation of minoritized scientists during their Wikipedia editing assignment by writing

[5]https://en.wikipedia.org/wiki/Wikipedia:Manual_of_Style

biographies of notable scientists from under-represented groups, while others focused on including references that were written by members of under-represented groups. For example, students updated Wikipedia pages about lakes to include Indigenous place names that had been given to those lakes prior to colonization(e.g., Green Lake in Wisconsin, United States[6]), and added sections that discussed the broader significance of waterbodies (e.g., the cultural history of the Chilcotin River in western Canada[7]).

FINDINGS: INSTRUCTOR-REPORTED SUCCESSES, CHALLENGES, AND RESOURCES

While there are compelling reasons to include Wikipedia assignments in STEM courses, we recognize that instructors may face challenges with incorporating novel assignments into existing or planned courses. We note some common instructor challenges and offer resources to help overcome those challenges, based on our experience both as instructors of courses that have used Wikipedia assignments and as members of WikiProject Limnology and Oceanography (**Table 2** and **Supplementary Material**). In particular, we share resources we have developed to introduce instructors to Wikipedia assignments, including two handouts on how to manage Wikipedia assignments (**Supplementary Material:** WP L&O Managing Assignments, **Supplementary Material:** WP L&O Resources for Wiki Assignments), a handout about selecting articles to edit (**Supplementary Material:** WP L&O Selecting Articles), and a handout on maintaining student engagement (**Supplementary Material:** WP L&O Student Engagement). We also include handouts that address specific technical questions about using Wikipedia in the classroom, such as how to draft articles in the sandbox (**Supplementary Material:** WP L&O The Sandbox), how to add images to Wikipedia (**Supplementary Material:** WP L&O Adding Images), what a sample schedule for a Wikipedia assignment might look like (**Supplementary Material:** Wikipedia Term Assignment Schedule), a guide for expert reviewers of student work on Wikipedia (**Supplementary Material:** WP L&O Reviewer Guide), and an example of a

[6]https://en.wikipedia.org/w/index.php?title=Green_Lake_(Wisconsin&oldid=%20992398001#History

[7]https://en.wikipedia.org/w/index.php?title=Chilcotin_River&oldid=1017983811#Cultural_Significance

TABLE 1 | Learning objectives shared by multiple courses participating in the faculty mentoring network, and elements of a Wikipedia assignment that can be used to support those learning objectives.

Learning Objectives	Supporting Elements of a Wikipedia Assignment
Developing scientific and technical writing skills	- Revise an existing Wikipedia article to better meet Wikipedia's core content policies (https://en.wikipedia.org/wiki/Wikipedia:Core_content_policies) - Add a section to an existing Wikipedia article - Develop a new Wikipedia article - Incorporate feedback from peer reviews into a drafted Wikipedia article following the iterative model of scientific writing
Communicating scientific knowledge to the public	- Select and add data, images, or other supporting information to a Wikipedia article - Discuss open access information and information accessibility with peers - Increase information equity by prioritizing open access information and resources when adding to Wikipedia - Translate complex information into plain-language text that is intended for the public
Thinking critically	- Evaluate a Wikipedia article for its content, accuracy, and completeness - Evaluate a Wikipedia article for the suitability of its supporting information and citations - Read source material, evaluate, and synthesize when writing or adding to a Wikipedia article - Review work by peers and provide constructive feedback and suggestions for improvement
Researching and resourcing information	- Cross-link to other Wikipedia articles where appropriate - Add supporting information and citations to existing Wikipedia articles - Increase information equity by prioritizing open access information and resources when adding to Wikipedia - Conduct research on a topic, synthesize information, and craft original text for a Wikipedia article
Developing digital skills	- Learn how to access the scientific literature and use library resources - Navigate the WikiEdu dashboard and training modules - Interact with WikiEdu support staff, instructors, and peers via the online message board system - Create and add content using the online Wikipedia "what you see is what you get" content editor
Developing an awareness of diversity and representation in science	- Discuss how the representation of minoritized individuals and groups affects who gets heard, what viewpoints are prioritized, and what ways of knowing are elevated/ignored - Assess the supporting information and citations used in a Wikipedia article, and add resources by minoritized individuals and groups - Add text to an existing Wikipedia article to make it more inclusive or representative - Write an article, or add to an article, about a scientist who is a member of a minoritized group

The supporting elements for each objective are arranged from the shortest-duration activities to the longest, and can be selected or adjusted as needed to meet the specific learning objectives of a course or the learning level of the students.

TABLE 2 | Challenges reported by instructors, with resources to overcome those challenges and specific citations or links to access those resources.

Assignment Phase	Instructor Challenge	Resources and Solutions	Citations/Links
Early	Lack of familiarity with editing Wikipedia	WikiProject Limnology & Oceanography instructional video WikiEdu platform with educational modules and technical support	• https://www.youtube.com/watch?v=_Nin4RENHU4 (Alternate Wikipedia Link: https://en.wikipedia.org/wiki/File:Motivational_V3-FINAL.webm) • https://wikiedu.org/ • Instructor Training: https://dashboard.wikiedu.org/training/instructors • **Supplementary Material:** WP L&O Managing Assignments • **Supplementary Material:** WP L&O Resources for Wiki Assignments
Early	Finding appropriate articles to edit	WikiProjects Wikipedia Article Finder	• Relevant WikiProjects: ∘ https://en.wikipedia.org/wiki/Wikipedia:WikiProject_Limnology_and_Oceanography ∘ https://en.wikipedia.org/wiki/Wikipedia:WikiProject_Lakes ∘ https://en.wikipedia.org/wiki/Wikipedia:WikiProject_Women_scientists ∘ https://en.wikipedia.org/wiki/Wikipedia:WikiProject_Rivers ∘ https://en.wikipedia.org/wiki/Wikipedia:WikiProject_Fishes ∘ https://en.wikipedia.org/wiki/Wikipedia:WikiProject_Algae ∘ https://en.wikipedia.org/wiki/Wikipedia:WikiProject_Ecology • https://dashboard.wikiedu.org/article_finder • **Supplementary Material:** WP L&O Selecting Articles
During	Initiating and maintaining student engagement	WikiProject Limnology & Oceanography motivational video Breaking overall assignment into sub-projects	• https://www.youtube.com/watch?v=6ny9Z7CDWq8 (Alternate Wikipedia Link: https://en.wikipedia.org/wiki/File:Motivational_V3-FINAL.webm) • Paper suggesting best practices: Vetter et al., 2019 • **Supplementary Material:** WP L&O Student Engagement
During	Uneven computing skills and access to internet	If possible, carving out in lab/class "workshop" time for students to work on project Breaking Wikipedia assignment into a group project	• Printable handouts with Wikipedia editing instructions: https://wikiedu.org/for-instructors/#instructors • Case studies on how instructors have adapted and modified Wikipedia assignments to meet their students' needs: https://commons.wikimedia.org/wiki/File:Case_Studies,_How_instructors_are_teaching_with_Wikipedia_(Wiki_Education_Foundation).pdf
During	Wikipedia culture: jargon, edits to student work, negative interactions with other Wikipedia editors	Dedicated discussion or FAQ time on Wikipedia culture and policies, particularly harassment policies WikiPage Templates indicating that editors are students Wiki Education Expert support Drafting in the sandbox	• https://en.wikipedia.org/wiki/Wikipedia:Harassment • https://en.wikipedia.org/wiki/Template:Dashboard.wikiedu.org_assignment • https://en.wikipedia.org/wiki/Wikipedia:Five_pillars • https://en.wikipedia.org/wiki/Wikipedia:Policies_and_guidelines • https://en.wikipedia.org/wiki/Wikipedia:Editing_policy • **Supplementary Material:** WP L&O The Sandbox • **Supplementary Material:** WP L&O Adding Images • Article about women's experiences with Wikipedia editing: Menking et al., 2019
During	Timing/pacing of assignment	WikiEdu recommended timelines Example assignment schedule	• https://wikiedu.org/ • **Supplementary Material:** Wikipedia Term Assignment Schedule
End	Varying quality of peer reviews & peer review participation	Make peer review part of the final grade Include a rubric for expectations for peer review assignment	• Modifiable, generic peer review rubric: https://serc.carleton.edu/details/files/96845.html • **Supplementary Material:** WP L&O reviewer guide
End	Assessing student work	Existing rubrics Coordinating expert peer review Identifying student changes using article history or WikiEdu tools	• https://qubeshub.org/community/groups/coursesource/publications?id=2615&tab_active=about&v=1 • https://commons.wikimedia.org/wiki/File:Wiki_Education_Classroom_Program_example_grading_rubric.pdf • https://upload.wikimedia.org/wikipedia/commons/9/92/Instructor_Basics_How_to_Use_Wikipedia_as_a_Teaching_Tool.pdf • **Supplementary Material:** Wikipedia Evaluation and Editing
End	Deciding whether to publish revisions to Wikipedia	Allow time in course sequencing for students to receive reviews and feedback from larger Wikipedia community Do not make grading contingent on edits being accepted	• https://en.wikipedia.org/wiki/Help:Editing • Article about best practices: Shane-Simpson and Brooks, 2016

Challenges are grouped by assignment phase; early (before the course begins or in the beginning stages of the assignment), during (when the students are actively working on the assignment), and end (at the end of the course or assignment as the instructor is assessing the assignment).

Wikipedia assignment description and rubric (**Supplementary Material:** Wikipedia Evaluation and Editing). We also share data from courses taught in Fall 2020 and Spring 2021 to provide quantitative context about Wikipedia assignments (**Figure 2**).

While we focus on universal challenges that instructors could encounter when using a Wikipedia assignment, we want to also highlight that Wikipedia assignments can take many forms. As a minimal example, an instructor could assign students a Wikipedia article related to course content to read and evaluate and then discuss strengths and weaknesses of the article during a class period or via an asynchronous discussion board. A more involved assignment could include a subsequent step where students do research about the article topic and suggest edits or improvements to the article. A third assignment level could require students to edit an existing Wikipedia article, with varying levels of editing required, based on instructor discretion. These edits could range from adding a handful of references or sentences or adding informative images, to adding new sections or paragraphs, creating new diagrams or other imagery, and including multiple references to substantially improve an existing article. Finally, the most time-consuming option is to have students create a new Wikipedia article on a topic not currently covered by Wikipedia, which is most likely appropriate for advanced undergraduate or graduate students. Depending on the instructor's preference, students can keep their edits in their "sandbox," a space on Wikipedia for drafting edits that is still public-facing, or students can be asked to publish their edits to the Wikipedia article so that they are live. Additionally, students can either work alone or in pairs or groups to complete the assignment. The WikiEdu platform allows for a range of possibilities for designing a Wikipedia assignment (see **Figure 2** for examples). As an example, assignments can range in effort from a group assignment where students work together to make small changes to an article (**Figure 2A**) to an individual assignment where students work alone to make substantial additions to an article (**Figure 2B**). Based on our teaching experiences, editing an existing Wikipedia article or creating a new article are both equivalent to assigning a term paper, in terms of the effort required by students to complete the assignment. Wikipedia assignments can therefore be adapted to meet the learning objectives of a course and the needs of the instructor(s) and students.

Notably, Wikipedia assignments combine the skill-building of a writing assignment with the societal impact of a science communication or outreach assignment. For the courses taught by instructors in our faculty mentoring network, students added an average of 670 words to a Wikipedia article, with a maximum course average of 1,590 words added per student (**Figure 3**). Students added an average of seven references to the articles they edited, with a maximum of 20 references added (**Figure 3**). While it is tempting to compare these values to similar word or citation counts for a more standard written assignment, it is important to note that due to the concise nature of encyclopedic writing, quality of edits should be prioritized over quantity. While the number of words or citations might be comparable to a typical written assignment, Wikipedia assignments can have outsized effects on how student work is seen and valued. For example, in the courses taught by instructors in our faculty mentoring network, the average article edited by students received nearly 8500 views in the 2 months following the course (roughly 140 views per day). Article views ranged from 67 to nearly 78,000 per student article, encompassing a far broader impact than a typical paper that is seen only by the instructor and perhaps fellow students in the course. Writing for an audience beyond the members of a course can provide an incentive for students to produce high-quality work.

In addition to these quantitative measures of Wikipedia assignment impact, instructors reported qualitative measures of student engagement and learning outcomes. For example, one instructor said that students "had more positive feedback on this assignment and were more motivated than on assignments where only the professor would have seen their final product." Another instructor reported that, based on a question asked in their course evaluations, students agreed that the Wikipedia assignment improved their ability to communicate scientific topics to the public. Instructors reported that students were attracted to the idea of the Wikipedia assignment having a broader impact, saying "it was surprisingly clear to them how valuable this effort was in a larger societal context. In particular, they really caught on to the idea that we have unique access to scientific information both in terms of the library and our understanding of it and that we have an obligation to share that understanding." Students also noted that while they may never author a scientific publication, they have now made a societal contribution by improving a Wikipedia article. In their course evaluation, a student concurred, saying "I think this project was an amazing opportunity to practice those research skills but gave us students way more of a reward than just a research paper to turn in. We actually created a whole Wikipedia page; I mean it still seems unreal!" Instructors also reported that the Wikipedia assignment fostered discussions about information equity, with one student sharing in their course evaluation, "The Wikipedia project gave me a better understanding of the work that goes behind sharing information with the public and how much time that takes. I had not really appreciated the position I was in as a student, having access to articles and information that the public does not have." Finally, the Wikipedia assignment led to nuanced discussions and understanding of what constitutes a reliable source, with one student sharing in their course evaluations: "I always thought that Wikipedia was this lawless website who let anyone join and edit pages but after all the modules I had to complete I quickly understood that Wikipedia was not as horrific as my teachers had described growing up." Overall, based on student and instructor feedback, Wikipedia assignments help students gain a more nuanced understanding about the responsibility of authorship and the reliability of sources, particularly Wikipedia.

LESSONS LEARNED FROM THE 2020-2021 FACULTY MENTORING NETWORK

The instructors who participated in our 2020-2021 faculty mentoring network reported a number of lessons learned that can

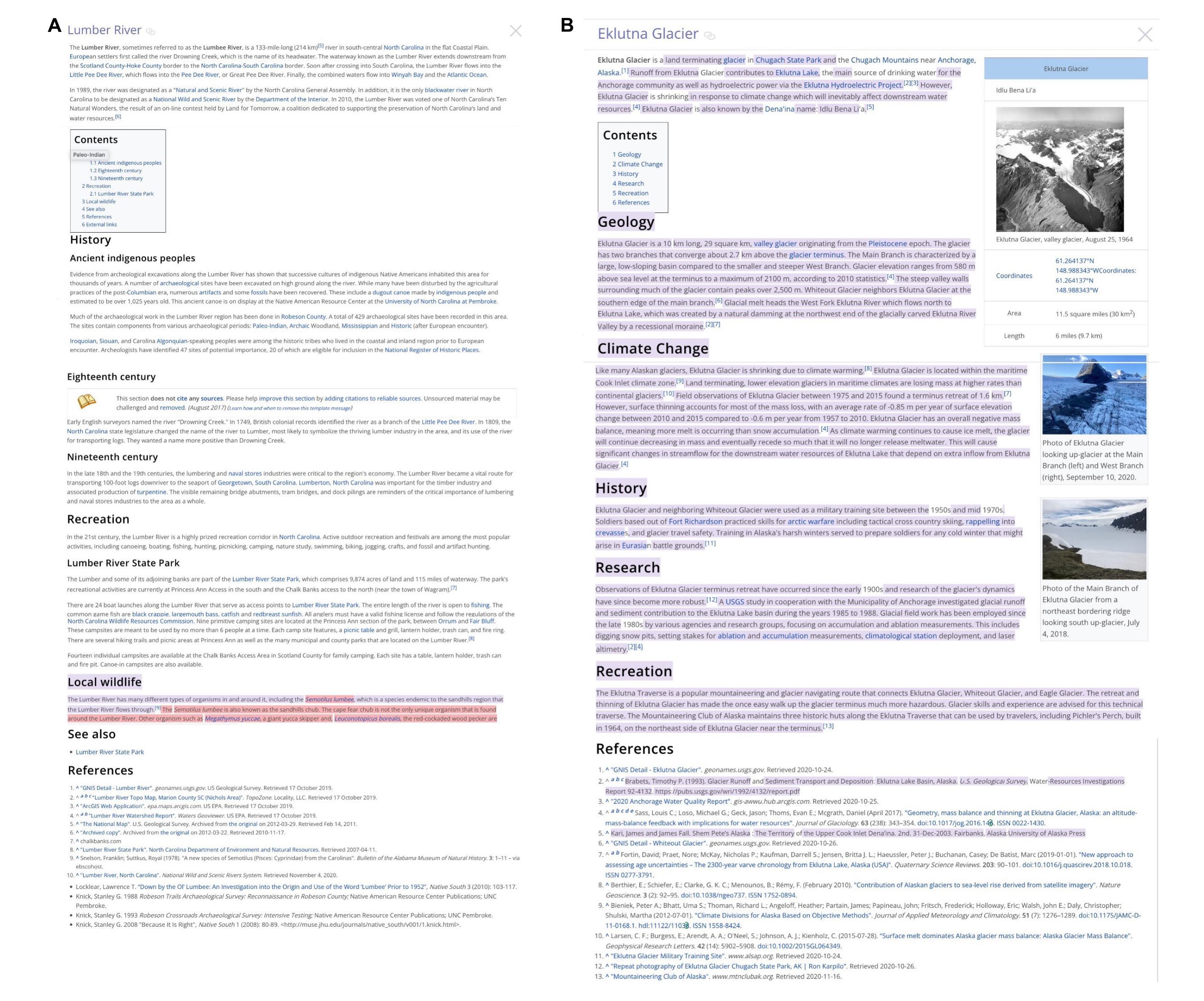

FIGURE 2 | Examples of student edits to Wikipedia in two of the courses taught by members of the Wikipedia Limnology & Oceanography faculty mentoring network that highlight the range of possible student edits and Wikipedia assignment complexity. Shaded text highlights student additions to each article, with different color shading indicating different student editors. The article on the Lumber River **(A)** was edited by two students, who jointly added 217 words and 2 references to the article, while the article on the Eklutna Glacier **(B)** was edited by one student, who added 2183 words and 19 references to the article.

be applied in future Wikipedia assignments to improve instructor and student experiences, not only in post-secondary courses in the aquatic sciences but in STEM courses more broadly. Herein we outline some of those key lessons that were shared by course instructors who participated in the faculty mentoring network, from both their and their students' perspectives.

Several instructors noted that, for both instructors and students with no prior experience editing Wikipedia, the assignment involved a steep learning curve. Within the first few weeks of the assignment, students were required to set up a Wikipedia account, complete a number of training modules through the WikiEdu dashboard, and begin the process of selecting an article or topic to work on. As a result, some instructors and students reported that the assignment felt intimidating at first, and noted that it was easy for students who felt this way to fall behind in the WikiEdu training modules, causing further feelings of intimidation. Instructors emphasized that extra effort was required in the first few weeks of the assignment to ensure that students completed the training modules, and that assigning marks to the completion of training modules was a good incentive. Those instructors who had previously used Wikipedia and the WikiEdu dashboard in their courses also recognized that their confidence in teaching with Wikipedia increased in subsequent semesters, making it easier to run the assignment and manage student progress.

Students in the 15 courses that were supported by the faculty mentoring network created 22 new Wikipedia articles and edited 173 existing articles, with each student adding an average of

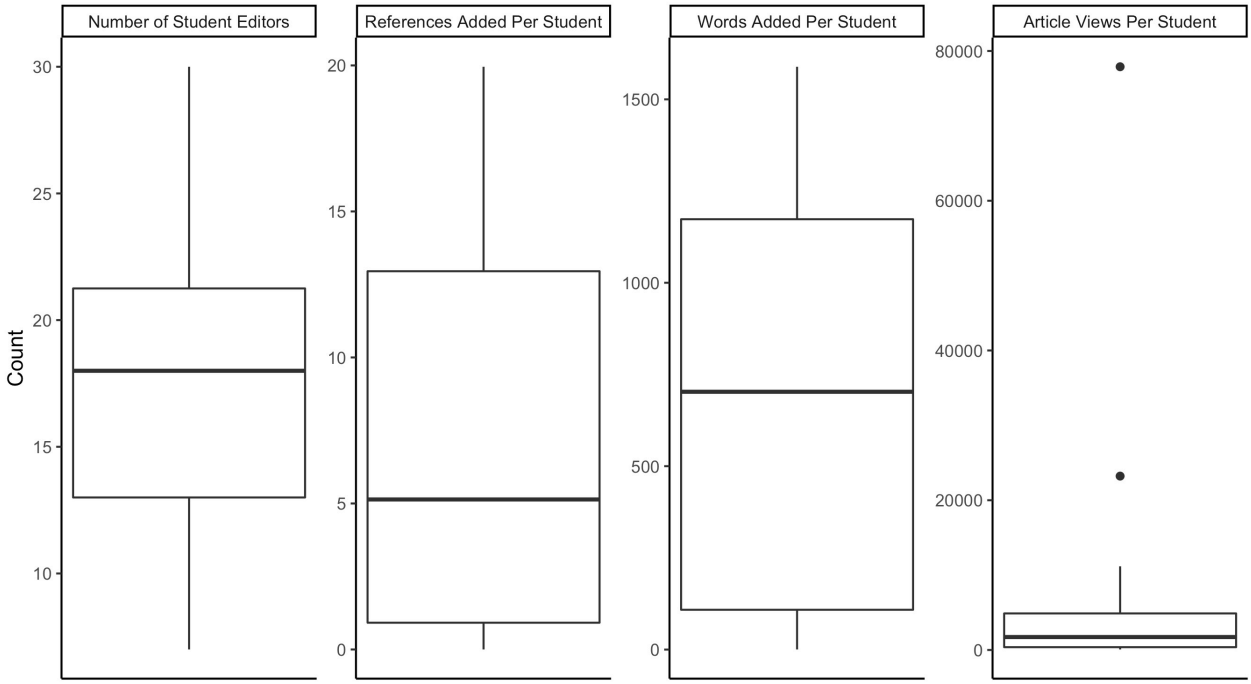

FIGURE 3 | Boxplot summaries of Wikipedia articles edited by students in courses taught by instructors in our faculty mentoring network during Fall 2020 and Spring 2021. Article views are tabulated for the two months following the end of the course.

nearly 700 words (**Figure 3**). This represents a large amount of work that must be reviewed by the course instructor, with students in each class sometimes working on a wide range of articles and topics. Since the end goal for the assignment is often for the student's work to be publicly posted on Wikipedia, there is a large burden on the instructor to catch any errors and provide informed, high-quality feedback on a diverse set of articles. One way to offset this workload is to pair students with expert reviewers (graduate students, technicians, faculty members, or research scientists) who can provide feedback on articles in their area of expertise, although sufficient time must be allocated in the assignment schedule for the feedback to be incorporated into the article.

The instructors who participated in our faculty mentoring network all noted that a supportive community was critical to the success of their Wikipedia assignments. Instructors were able to find community support during the 2020–2021 academic year through their participation in the WikiEdu platform, our faculty mentoring network, and an expert review process that was facilitated by the WikiProject Limnology & Oceanography team. Participation in the WikiEdu platform included access to a WikiEdu staff member who could provide technical support for the Wikipedia website and training modules, while participation in the faculty mentoring network included access to resources (e.g., those included as **Supplementary Material**) and a team of colleagues who could provide support for subject-specific and classroom-specific questions. The expert review process facilitated a review of student Wikipedia articles by STEM practitioners and provided access to a broader community for both instructors and students. While instructors received help with reviewing and providing feedback on their students' Wikipedia articles, which could span a wide range of topics, students received feedback from someone with expertise on their particular article topic which increased their confidence in the final version of their work. Participating in and interacting with a supportive community therefore improved the overall experience of both the instructors who implemented Wikipedia assignments in their courses and their students, based on feedback we received from instructors.

Instructors also realized that it was important to create a schedule for the Wikipedia assignment that allowed enough time for the students to complete all components. Many instructors noted that Wikipedia assignments worked better as a semester-long exercise, which allowed enough time for students to complete the training modules, written assignment, and peer review, along with other course work and deliverables such as exams and lab assignments. One key issue is that, if Wikipedia assignments run the length of the semester, other course work can be crowded out of the schedule. Instructors recommended that, in order to prevent this and to give students the best chance at success at both the Wikipedia assignment and the course overall, good planning and scheduling is critical.

Generally, students viewed Wikipedia editing and article writing assignments more positively than other aspects of their courses. Students seemed to be motivated by the fact that their work would be publicly-available beyond the end of the course, and viewed this as a positive aspect of the assignment relative to a traditional course assignment that would only be viewed by the instructor. Students also seemed to appreciate the opportunity to research and write about scientific topics that were important to them on a personal level. This was demonstrated in several courses where students were tasked with writing about regional waterbodies that did not have a Wikipedia entry, or that had an inadequate or incomplete entry. In some cases, students communicated with citizen groups that were associated with these waterbodies, or reached out to individuals with longstanding ties to the region, leading to discoveries and the sharing of informal but nevertheless valuable information. Although this information did not necessarily meet the standards for inclusion in a Wikipedia article, students found these interactions to be interesting and rewarding, and the interaction itself provided an alternate way for students to engage with the subject matter. The impacts of a Wikipedia assignment can therefore go beyond the assignment and generate a broader interest in science communication and public engagement for the student.

Instructors reported that their students gained a deeper appreciation of diversity and equity in science through their Wikipedia assignments. Students were given the opportunity, many for the first time, to think critically about whose voices are heard and shared when communicating science. It was noted by several students that Indigenous voices and experiences were excluded from articles about North American waterbodies, while other students endeavored to add the Indigenous names for local waterbodies to the corresponding Wikipedia pages. Students democratized access to science information by prioritizing open access resources rather than resources located behind a paywall, enabling more members of the public to access primary sources of information. Students also served as translators and interpreters of scientific information for the public. In most cases, this involved taking complex scientific concepts and applying their specialized skills and knowledge to communicate these concepts in plain-language. In two separate classes, students served as actual translators as they translated information about waterbodies in China into English, thereby making the information accessible to a broader audience. While this examination of diversity and equity in science communications was a generally positive aspect of the Wikipedia assignments, at least one student avoided adding content to Wikipedia that would have amplified the experiences of an under-represented group due to the potential removal or negative review of their work by other Wikipedians. It is important to note that editors who attempt to reduce bias and increase representation in Wikipedia articles can sometimes receive negative or hostile feedback from other Wikipedians (Menking et al., 2019; Kincaid et al., 2020). **Table 2** provides resources to mitigate negative interactions between student editors and Wikipedians.

Overall, many students reported to their instructors that their opinion of Wikipedia changed over the course of the semester. After completing the WikiEdu training modules, critically reading Wikipedia articles, assessing shortfalls, conducting research and gathering resources, and then crafting their own text or other content, students reported both more favorable and more skeptical views of Wikipedia as an information resource. Many students were surprised to learn that the community of Wikipedians adheres to a code of conduct and other guidelines when editing or adding to articles, and that posted information is constantly checked and corrected by the community. Other students were more critical of what they found on Wikipedia following the assignment, since they themselves had been able to login and edit articles. Overall, student-reported outcomes at the end of the semester suggest that students had developed a more nuanced opinion of Wikipedia, and were more aware of both its utility as a resource and the need to investigate primary sources for credibility and accuracy.

STUDY LIMITATIONS

In spite of the overall success of this initiative, two methodological constraints of this study of our faculty mentoring network must be considered: (1) the complex effects of COVID-19 on university courses and (2) the inherent limitations of a case study approach.

First, the 2020–2021 faculty mentoring network took place during the first full academic year of the COVID-19 pandemic. After having to pivot to online teaching on very short notice during March 2020, many of the instructors who took part in our faculty mentoring network were delivering their courses entirely online for the first time during the 2020–2021 academic year. At the same time, those instructors who taught in person during the 2020–2021 academic year, or who delivered a hybrid course with elements of both online and in-person instruction, were searching for assignments and learning activities that could be easily moved online if local circumstances surrounding the pandemic changed. Like many STEM instructors, those who participated in our faculty mentoring network were also searching for activities that could meaningfully replace labs, field trips, and other in-person activities that were no longer possible for health and safety reasons. Because of these extenuating circumstances, instructors were perhaps more willing to modify their course syllabi and try an entirely new teaching activity (and one with a fairly challenging learning curve) than during a "normal" academic year.

Second, this was not a formal research study, but rather a case study approach wherein instructor experiences were queried both while they were using Wikipedia in their courses and after their courses had ended. Instructors in both semesters shared their experiences during network team meetings, asked questions or looked for team feedback via email and a Slack channel, and accessed a set of resources that were curated by the WikiProject Limnology and Oceanography team. After each semester had ended, all instructors were asked to complete an exit survey and to share course materials (e.g., syllabi, rubrics, and assignment descriptions) that they had used in their courses. Therefore, the experiences of the 14 instructors who used Wikipedia assignments in their post-secondary aquatic science courses are fairly well-captured in this paper. On the other hand, student experiences are not adequately represented because we did not have *a priori* ethics approval in place to survey students or request their feedback. Although some instructors have passed along anonymous comments provided by their students during course evaluations, this has been anecdotal and informal. The reliance on instructor-reported student outcomes can be addressed during any future studies by obtaining ethics approval in advance in order to measure student success and satisfaction with Wikipedia assignments.

CONCLUSION

Overall, our 2020–2021 faculty mentoring network was a success, with all instructors reporting positive experiences during their participation in the network and using Wikipedia assignments in their aquatic science courses. Many of the instructors who participated have continued to use Wikipedia editing or article writing assignments in subsequent courses, having found the assignment to be an effective way for their students to achieve meaningful learning outcomes. We encourage instructors to consider implementing a Wikipedia assignment in their post-secondary STEM courses to support the development of critical thinking, ethical literacy, science communication, and scientific writing skills.

DATA AVAILABILITY STATEMENT

The original contributions presented in this study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

EL and JG co-led the drafting and editing of the manuscript and are joint first authors. All other authors contributed ideas and substantial revisions to manuscript drafts. MA, JAB, JEB, VC, JG, EL, TL, CL, EN, AR, AS, and MV participated in the faculty mentoring network, and KB and EG participated as course instructors, with all providing reflections on instructor challenges and successes with Wikipedia assignments. JB, KH, DK, EL, and AS helped found WikiProject Limnology & Oceanography and helped support the faculty mentoring network activities. All authors contributed to the article and approved the submitted version.

FUNDING

The 2020–2021 Faculty Mentoring Network was funded by the Wikimedia Foundation Project Grant titled "WikiProject Limnology and Oceanography - Recruiting Aquatic Editors" (https://meta.wikimedia.org/wiki/Grants:Project/WikiProject_Limnology_and_Oceanography/recruiting_aquatic_editors).
The Wikimedia Foundation Project Grant was also used to fund the creation of informational videos. Funding for EcoDAS XIII and for open access publication fees were provided by Ecological Dissertations in the Aquatic Sciences (Eco-DAS) funding provided by the NSF Biological Oceanography Program (Awards OCE-1356192 and OCE-1925796) and the Association for the Sciences of Limnology and Oceanography (ASLO). MA acknowledges funding from NSF DEB-1713502. DK acknowledges funding from NSF EAR-2012123 and NSF EAR-2033995. AS acknowledges funding from NSF DBI-1906381. The National Ecological Observatory Network (NEON) is a program sponsored by the National Science Foundation and operated under cooperative agreement by Battelle Memorial Institute. This material is based in part upon work supported by the National Science Foundation through the NEON program.

ACKNOWLEDGMENTS

We thank Jacob Zwart for his vision and leadership in founding and supporting the work of WikiProject Limnology & Oceanography and for his feedback on this manuscript. We also thank the two reviewers for their helpful suggestions and comments.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feduc.2022.905777/full#supplementary-material

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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frontiers | Frontiers in Water

ORIGINAL RESEARCH
published: 29 June 2022
doi: 10.3389/frwa.2022.901393

Advancing Hydroinformatics and Water Data Science Instruction: Community Perspectives and Online Learning Resources

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OPEN ACCESS

Edited by:
Bridget Mulvey,
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Reviewed by:
Chris Lowry,
University at Buffalo, United States
Mohamed Abdelmoghny Hamouda,
United Arab Emirates University,
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Specialty section:
This article was submitted to
Water and Hydrocomplexity,
a section of the journal
Frontiers in Water

Received: 21 March 2022
Accepted: 26 May 2022
Published: 29 June 2022

Citation:
Jones AS, Horsburgh JS, Bastidas Pacheco CJ, Flint CG and Lane BA (2022) Advancing Hydroinformatics and Water Data Science Instruction: Community Perspectives and Online Learning Resources. Front. Water 4:901393. doi: 10.3389/frwa.2022.901393

Hydroinformatics and water data science topics are increasingly common in university graduate settings through dedicated courses and programs as well as incorporation into traditional water science courses. The technical tools and techniques emphasized by hydroinformatics and water data science involve distinctive instructional styles, which may be facilitated by online formats and materials. In the broader hydrologic sciences, there has been a simultaneous push for instructors to develop, share, and reuse content and instructional modules, particularly as the COVID-19 pandemic necessitated a wide scale pivot to online instruction. The experiences of hydroinformatics and water data science instructors in the effectiveness of content formats, instructional tools and techniques, and key topics can inform educational practice not only for those subjects, but for water science generally. This paper reports the results of surveys and interviews with hydroinformatics and water data science instructors. We address the effectiveness of instructional tools, impacts of the pandemic on education, important hydroinformatics topics, and challenges and gaps in hydroinformatics education. Guided by lessons learned from the surveys and interviews and a review of existing online learning platforms, we developed four educational modules designed to address shared topics of interest and to demonstrate the effectiveness of available tools to help overcome identified challenges. The modules are community resources that can be incorporated into courses and modified to address specific class and institutional needs or different geographic locations. Our experience with module implementation can inform development of online educational resources, which will advance and enhance instruction for hydroinformatics and broader hydrologic sciences for which students increasingly need informatics experience and technical skills.

Keywords: hydroinformatics, water data science, collaborative instruction, graduate education, online education, community resources, educational module

INTRODUCTION

In an increasingly data intensive world, researchers and practitioners in water sciences need to apply data-driven analyses to address emerging problems, to explore theories and models, and to leverage growing datasets and computational resources. Within hydrology and related fields in environmental and geosciences, observational data are increasing in scope, frequency, and duration, and computational technologies are essential to solving complex problems (Chen and Han, 2016). Without training, students are unprepared to work or conduct research centered around large and complex data, questions, and tools (Merwade and Ruddell, 2012). To meet this need, hydroinformatics and water data science have been growing as specific topics of instruction, both in university programs and in community education settings (e.g., Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI) Virtual University and University of Washington WaterHackWeek) (Popescu et al., 2012; Burian et al., 2013; Wagener et al., 2021). In parallel, incorporation of technical tools in traditional water science courses is growing, though uptake has been uneven and lags behind what many see as needed (Habib et al., 2019; Lane et al., 2021). Hydroinformatics and water data science both combine computational tools and water-related data to achieve actionable knowledge. Although the fields are overlapping, there are subtle differences, and both terms are used throughout this paper.

Within the geosciences, there is increased focus on reusability and reproducibility of research data, code, and results, as well as educational materials (Ceola et al., 2015). Several online spaces have emerged as hubs for storing and sharing lectures, code, examples, and scripts developed by instructors in hydrology, water resources, and other geosciences (Habib et al., 2012, 2019; Lane et al., 2021). The widespread shift to online education resulting from the COVID-19 pandemic illustrated the value of online instructional materials and rapidly accelerated development and transition to online formats (Beason-Abmayr et al., 2021; Rapanta et al., 2021). Community educational resources, online platforms, and increased accessibility of digital tools offer an opportunity to more fully incorporate informatics tools and techniques for data-driven hydrologic applications into water science education.

This paper reports on the current state of hydroinformatics and water data science education in the United States based on available literature and qualitative interviews and surveys with instructors of relevant courses. Another objective of this work was development of online educational modules and evaluation of the implementation platform to share insights with other instructors. Study participants offered information about key topics and technologies, formats and methods of delivery, challenges and gaps, and impacts of COVID-19 on instruction. In addition to the results of the survey, we performed a functional review of online educational platforms based on participants' criteria. Their perspectives and our evaluation were used to inform the development of online learning modules that address some of the identified challenges and gaps while demonstrating existing tools. The modules are community resources that can be incorporated into any related course, workshop, or educational program. They are a step toward sharing educational resources for reuse not only by instructors that specialize in hydroinformatics, but to incorporate informatics skills and topics more broadly in water science courses. The lessons learned from platform feature evaluation and module implementation are valuable for instructors sharing content and for further platform development.

In the Background section, we present a literature review of hydroinformatics and water data science education, including best practices for sharing educational content and outstanding gaps. The Methods section outlines the procedures and literature-informed questions of the surveys/interviews and the methodology for development of educational modules. In the Results and Discussion, we present survey results and the key points that drove the design and implementation of learning modules. The Results and Discussion also covers a review of existing online platforms and module implementation successes and challenges. Finally, the Conclusion offers an outlook for the future of hydroinformatics and water data science instruction.

BACKGROUND

Hydroinformatics and Water Data Science

In an early conceptualization, hydroinformatics was described as encompassing computational tools to transform water related data and information into useful and actionable knowledge (VanZuylen et al., 1994). Although hydroinformatics may be technical in nature, water issues are inherently social, and consideration of human factors for the presentation and dissemination of results and information is a key component (Vojinovic and Abbott, 2017; Makropoulos, 2019; Celicourt et al., 2021). More recently, the definition of hydroinformatics is broadening to encapsulate water science, data science, and computer science (Burian et al., 2013; Chen and Han, 2016; Vojinovic and Abbott, 2017; Makropoulos, 2019). The objective of data science is application of analytical methods and computational power with domain understanding to transform data to decisional knowledge (Gibert et al., 2018; McGovern and Allen, 2021). When applied to the water domain, this definition is very close to that of hydroinformatics, and for most practical purposes, it is difficult to draw boundaries between hydroinformatics and water data science.

Based on the increasing volume, variety, and availability of data sources and the advancement of software and hardware tools, there is opportunity and need for the application of data science to water, environmental, and geoscience domains (Burian et al., 2013; Gibert et al., 2018). Hydrologic science is shifting from collecting data to support existing conceptual models toward analyses based on models derived from observational data (Chen and Han, 2016). In this paper, we report on how current instructors of hydroinformatics and water data science define their fields and the topics and technologies that are growing in importance in these fields.

Hydroinformatics and Water Data Science Education

Without training in data intensive approaches with modern technological tools, students will be unprepared to solve emerging water problems (Merwade and Ruddell, 2012; Lane et al., 2021). Technology integration and data and model-driven curriculum are key components for advancing hydrology education (Ruddell and Wagener, 2015). Many have recommended educational pedagogies for hydrology that are "student-centered" or "problem-based," which describe applications that deepen learning by connecting to real-world contexts (Wagener and McIntyre, 2007; Ruddell and Wagener, 2015; Habib et al., 2019; Maggioni et al., 2020). Students need to learn using real-world datasets, actual tools, and open-ended problems, also referred to as "ill-defined," "authentic," or "experiential" (Ngambeki et al., 2012; Burian et al., 2013; Maggioni et al., 2020; Lane et al., 2021).

Hydroinformatics was initially taught in the mid-1990s to enable engineers to apply information technology to complex water problems (Abbott et al., 1994). Specific programs have since developed including courses for professionals (Popescu et al., 2012) and graduate students (Burian et al., 2013) and complete doctoral programs (Wagener et al., 2021). However, hydroinformatics courses remain limited, and to gain informatics skills, students often rely on technology incorporated into traditional hydrology courses, pursue self-learning (e.g., online courses, tutorials, etc.), or enroll in computer centric courses that do not address the focused set of topics with domain-specific applications covered by hydroinformatics.

Training in data science is typically separate from domain sciences; however, data science curricula cannot adequately address domain knowledge, so students are expected to rely on their own "substantive expertise" (Grus, 2015). Voices in industry and academia are calling for well-rounded and technology-literate water scientists (Chen and Han, 2016; McGovern and Allen, 2021), which may be achieved by packaging informatics and/or data science topics with real-world water science applications (Gibert et al., 2018; Wagener et al., 2021). In this paper, we use information gathered from instructors to understand how courses are being taught, what techniques are successful, and what would be useful going forward.

Sharing Educational Content

As technology and applications advance, books and even online content may become outdated quickly, and hydroinformatics and water data science instructors are challenged to keep up (Wagener et al., 2007; Makropoulos, 2019; Maggioni et al., 2020). Given shifts toward big data, open data sources, reproducible research, and data-driven analysis, many have called for advancement in content for teaching water science and methods for delivery of that content (Seibert et al., 2013; Habib et al., 2019). The COVID-19 pandemic caused many courses to be moved to virtual platforms, prompting evaluations of instructional formats and a call for additional online educational material (Maggioni et al., 2020).

Community platforms and resources can advance water science instruction by facilitating data-driven learning and offering common principles and approaches for teaching (Merwade and Ruddell, 2012; Popescu et al., 2012; Wagener et al., 2012; Makropoulos, 2019). Although water science modules have been shared and published online (e.g., Habib et al., 2012; Wagener et al., 2012; Merck et al., 2021; Gannon and McGuire, 2022), without integration within a common platform, modules are difficult to identify, access, and implement. In 2012, Merwade and Ruddell noted that an appropriate system was not yet in place, and there remains no single clearinghouse of educational resources in the field. More recently, Maggioni et al. (2020) and Lane et al. (2021) developed and published course content *via* HydroLearn (https://www.hydrolearn.org/). Lane et al. (2021) made the case that online educational materials should be supported by active learning, basic templates, adaptation, multiple content types, and pedagogical tools, which are emphasized in the HydroLearn platform. To these functional capabilities, we add that systems need to offer persistence as we were unable to access many of the online resources that were reported in the literature. They were either missing completely, lacking crucial metadata, or using outdated software or systems.

Our review of the literature identified key components, guidelines, and best practices for sharing educational content along with gaps and opportunities to improve. In this paper, we also consider key components to successful online modules as identified by hydroinformatics and water data science instructors, which we used as criteria to select an online educational platform. Based on these findings, we describe the development and implementation in an online system for four modules focused on hydroinformatics and water data science, which are available for instructors adapt into courses and may serve as examples to the community.

METHODS

Survey and Interview Methodology

We developed survey and interview questions that focused on the instructors' courses and their perspectives on the future of the field (**Table 1**). Participant responses were analyzed to identify common themes surrounding key research questions: (1) What is the current state of instruction in hydroinformatics and water data science, including the effectiveness of tools being used for in-person and online instruction?; (2) How has the COVID-19 global pandemic affected instruction?; (3) Which topics comprise hydroinformatics education and what topics are growing in importance?; (4) What are the major challenges in hydroinformatics instruction?; and (5) How can shared instructional resources be beneficial for instructors and students? Although this analysis was primarily qualitative, where commonalities emerged, we were able to tally responses and present quantitative results.

Potential participants were initially identified *via* investigator connections, review of relevant literature, and information on institutional and personal websites discovered by Internet searches. Target participants were selected based on their experience teaching hydroinformatics, water data science, or

TABLE 1 | Survey/interview questions.

Survey/interview questions
The term "hydroinformatics" is used throughout. If your course or program uses a different title or term (e.g., "water data science"), consider that term instead.
Course details
What is the name of the hydroinformatics-related course/program at your institution?
Is this course/program taught at a graduate level?
Are any hydroinformatics topics taught at an undergraduate level?
How is "hydroinformatics" defined in the context of the course/program offered at your institution?
What are the objectives for the hydroinformatics related course/courses/or programs offered at your institution?
Course expectations
What prerequisite informatics skills are expected of students?
Do most students exhibit the prerequisite informatics skills at the start of the course?
What informatics skills (and level of skill) are students expected to attain in this course?
What benefits have students derived from taking the course? This could be quantitative or anecdotal.
Formats
What are the sources of the teaching materials used for the course/program?
What is the course/program format? (e.g., in-person, online, etc.) Please clarify if this changed due to COVID.
What platforms or instructional tools are being used in course delivery? (e.g., Canvas, HydroLearn, MyGeoHub, HydroShare, etc.) Please clarify if this changed due to COVID.
Did the COVID pandemic impact instruction related to hydroinformatics courses at your institution? If so, how?
What platforms or instructional tools have proven effective for in person versus online instruction (if your course has been offered online)?
If your courses have been offered online (due to COVID or other reasons), what were the biggest challenges in delivering online instruction?
Topics and technologies
What topics are emphasized in the hydroinformatics courses at your institution? (e.g., machine learning, databases and data models, numerical modeling)
What informatics technologies are emphasized? (e.g., Python, R, MySQL, ArcGIS)
What (if any) geospatial data and techniques are covered in the hydroinformatics course(s) at your institution?
How have the topics and technologies changed over the time that the course(s) have been taught?
What topics and technologies are growing in importance in hydroinformatics?
What are the gaps in existing hydroinformatics instruction/education?
Shared resources
What **types** of shared community resources for instruction would be useful? (e.g., online modules that could be incorporated into courses)
In developing shared resources, what **topics** would be helpful in addressing gaps and challenges?
What **formats** would be conducive to shared resources?
What informatics **technologies** would be useful for shared resources?
What is your level of interest in sharing and exchanging teaching resources and materials with the community? (Very Interested, Interested, Moderately Interested, Slightly Interested, Not Interested)
What would motivate hydroinformatics instructors to participate in sharing/exchanging teaching resources?
In your view, what resources would a useful shared educational module consist of?
Wrap up
Do you know of any other instructors who would be a good fit for this survey/interview? Please provide a name, institution, and email address (if known).

related subject matter at an institution of higher education. We used email to invite contacts to participate, and participants elected to respond to questions either *via* online survey or recorded interview. During each interview or survey, participants were asked to identify any additional instructors who might be a good fit for the project.

While the questions for surveys and interviews were the same, both approaches were used so that participants could choose their preferred mechanism to respond. We acknowledge that the different modes for data collection may have influenced the length or character of the responses, but we made this decision to maximize the potential for participation. We observed that content specificity did not differ greatly between surveys and interviews. The survey was composed using Qualtrics software and administered with links personalized for each participant. Interviews were conducted over Zoom, recorded, and subsequently transcribed. Each interview lasted approximately 45–60 min. Notes were taken during all interviews in case of issues with audio. A total of 18 instructors participated in interviews ($n = 7$) or responded *via* survey ($n = 11$). Herein, we refer to interview and survey participants as "participants" and do not differentiate between the mode in which they participated. Procedures were approved by the Utah State University Institutional Review Board for Human Subjects

Research with participation limited to instructors within the United States.

Review of Educational Platforms and Modules

From participants and our own review, we identified several existing online platforms for sharing educational content. Using the survey and interview responses, we extracted characteristics that participants considered important in an online platform for depositing materials and used these to assess available options. We identified specific instances of educational materials from the hydroinformatics community that are available online for each of the considered platforms.

Module Development

We evaluated educational platforms based on the criteria identified in interview and survey results to determine the repository and format to use for depositing the educational modules developed as part of this work. At a minimum, we required that modules be implemented in an open access format. Our selection of a particular platform does not signify that it should be preferred for all instructors, courses, or learning situations, and we anticipate that instructors will adapt content to their preferred interface.

We used the suggestions from participants to inform the topics for the educational modules developed as part of this work. Given the breadth of suggested topics, our team could not develop modules to comprehensively cover all areas. This points to the need for community resources to take advantage of the varied teaching and research expertise of instructors. Rather than serve as a complete and unified set of educational content, the modules we developed act as a demonstration and a launching point for sharing content.

Our conceptual model of a learning module independent of any specific technological implementation consists of the following elements: (1) learning objectives, (2) narrative, (3) example code, and (4) technical assignment. The learning objectives guide the content that is presented through the other elements and may be contained separate from or as part of the narrative. The narrative covers the core of the concepts and topics and is communicated through various formats–e.g., slides, documents, and/or video. Example code may take the form of scripts, formatted markdown or text, or an interactive code notebook. Technical assignments consist of authentic, open-ended tasks based on real-world data that require students to implement code and write a descriptive summary. Authentic tasks are high cognitive-demand activities designed to reflect how knowledge is used in real life and to simulate the type of problems that a professional might tackle. Authentic tasks have no single answer and thus avoid concerns with publicly available solutions and achieve higher level learning objectives. Each assignment includes a grading rubric to ensure that expectations and evaluation criteria are clearly defined and activities are aligned with learning objectives, outcomes and assessment, referred to as constructive alignment (Biggs, 2014).

RESULTS AND DISCUSSION

Survey and Interview Results

Each instructor's definition of the terms "hydroinformatics" or "water data science" was unique, but all centered on common themes of using computers and informatics tools to solve water problems, including data collection, storage, sharing, interpretation, analysis, synthesis, and modeling. One participant simply defined hydroinformatics as "*data and water.*" The following quote summarizes the motivation for teaching these subjects:

> *"We have... talented, quantitatively savvy people... engineers and geologists and hydrologists and scientists that live and breathe data analysis and are limited by the tools they use. And we also have increasing data volume and aging infrastructure, emerging pollutants, drought, climate change. There [are] so many challenges our field faces. So, the goal is to give people modern tools to deal with modern water data challenges."*

The interviews and surveys generated a rich body of results, which we distilled in view of our core research questions. The current state of instruction in hydroinformatics and water data science is addressed in the subsection Courses, Platforms, and Modes of Delivery including impacts related to the COVID-19 pandemic. The subsection Challenges and Benefits of Online Delivery focuses on the effectiveness of tools for online instruction. What comprises hydroinformatics education is covered in the subsection Content, Technolocy, and Topics. There is a subsection Challenges and Future Directions of hydroinformatics. The Shared Resources subsection addresses interest, considerations, and potential benefits of shared institutional resources. In the following results, the number of participants (out of 18 total) that correspond to each response is reported parenthetically.

Courses, Platforms, and Modes of Delivery

The courses taught by participants include hydroinformatics and related courses with emphases on data science, research computing, and data and analysis tools (see **Table 2**). Most of the courses taught by participants are directed to university graduate students (14), though a few are undergraduate Introduction to Data Science classes (2), several courses are a mix of undergraduate and graduate students (4), and a few are designed for professionals (2). Most of the graduate classes permit some undergraduate enrollment, and several instructors noted that students at their institutions are exposed to some hydroinformatics topics in lower-level hydrology or geographic information system (GIS) classes.

Most of the courses are conducted in-person, although some had an online component even prior to COVID-19. In total, 12 out of 18 participants teach courses in person. Of these, most moved to an online format because of the COVID-19 pandemic. A few instructors (4) did not teach during this period due to buyout, sabbatical, or changing institutions. Multiple instructors (3) developed courses during the pandemic that would normally be held in-person. Of the courses offered fully online (6), one is a course for professionals, one was offered through an online

TABLE 2 | Courses taught by study participants.

Course titles	Count	Audience
Hydroinformatics	5	Graduate (4), undergraduate and graduate (1)
Informatics for sustainable systems	1	Graduate
Physical hydrology (with a hydroinformatics unit)	1	Undergraduate and graduate
Intro to environmental data science	1	Graduate
Water resource data science applications	1	Graduate
Earth data science	1	Graduate
Ecological and environmental data and tools	1	Graduate
Introduction to data science	2	Undergraduate and professional
R for water resources data science	1	Professional
R for water resources research	1	Undergraduate and graduate
Python for environmental research	1	Graduate
Research computing in earth and environmental sciences	1	Graduate
Modeling earth and environmental systems	1	Graduate
Computational watershed hydrology	1	Undergraduate and graduate
Data Analysis for water quality management	1	Graduate
Sensing and data	1	Graduate

community college, one was designed for a virtual university, and the remaining 3 are taught through universities.

Of those participants who moved from in-person to online because of COVID-19, most did not significantly change course structure but continued to use a format consisting of lectures with slides and coding demonstrations. Some instructors held synchronous classes over Zoom while others recorded lectures for asynchronous viewing. Generally maintaining course content with some changes to modalities was a commonly reported adaptation to the global pandemic (Beason-Abmayr et al., 2021; Smith and Praphamontripong, 2021). Additional modifications to address challenges of online learning are described in Section Challenges and Benefits of Online Delivery. Although hydrology and hydroinformatics have been identified as well-suited for online instruction (Merwade and Ruddell, 2012; Popescu et al., 2012; Wagener et al., 2012), even technologically savvy instructors with informatics-focused curriculum were generally returning to in-person formats even before the COVID-19 pandemic was over. The return to in-person instruction may be related to institutional expectations and instructors' preferences rather than ineffectiveness of tools and technologies (Rapanta et al., 2021). However, several instructors perceived benefits to online aspects and reported adjusting their teaching formats accordingly. A handful plan to shift modalities to alternate in-person and online classes or to a flipped format where lectures are recorded and viewed asynchronously while in-person class periods are work sessions. One participant was pleased with outcomes from online instruction and planned to continue with a purely online format. This is consistent with literature from other fields reporting that a flipped teaching format eased the transition between in-person and online education (Beason-Abmayr et al., 2021). Furthermore, the forced transition to online instruction can facilitate a deliberate integration of online and in-person instruction that is beneficial to active learning (Rapanta et al., 2021).

Instructors reported implementing a wide range and multiple layers of educational platforms to support instruction and handle course materials. Out of 18 participants, most (16) used a learning management system (e.g., Canvas, Blackboard, Brightspace, Sakai) for grading and assignment submission. For messaging with students, some used Canvas (or similar), though several instructors reported success in transitioning all course communication to Slack (2). For some, the learning management system was used to share files, while others stored and shared code and datasets with repositories in GitHub (6) and HydroShare (4), and a few reported using email or Google Drive. All these platforms were generally reported to be effective for both in person and online instruction, and several instructors planned to continue using Slack when returning to in-person instruction.

Most of the participants reported conducting live coding during lectures, whether synchronous or asynchronous, online or in-person. Some instructors switch between traditional teaching material (e.g., slides, videos) and live coding while others exclusively use coding interfaces for instruction. Many instructors (6) reported teaching with code notebooks (e.g., Jupyter) that can be launched from a web browser and include text and images as scaffolding to explain and support the code. Some instructors reported advantages to using GitHub and Jupyter notebooks:

> *"Jupyter notebooks enable us and our students to have a conversation with a problem and link to resources, like audio, video, images, visualizations and implement water resources projects step by step."*

"Jupyter notebooks work great for teaching either online or in person... They are especially nice for students working through in-class exercises. We...share screens while the instructor or students work through problems."

"...copying [the assignment] to my private [GitHub repository] for grading and...deleting ...the code that the students need to fill out but leaving the results...then committing those to the public repo [is]...a great tool...because [they] know what the answer should look like. ... there's...self-training and...self-evaluation...by...working on their code until they get it to look like what it should."

Challenges and Benefits of Online Delivery

The most reported challenges for online delivery were interpersonal and not unique to hydroinformatics or water data science. Instructors were concerned about meaningful engagement with students, lack of feedback and participation during lectures, and students struggling without the camaraderie and accountability of an in-person instructor and classmates. The paucity of in-person interaction and decreased student engagement have been reported as common concerns with the abrupt shift to online learning (Daniels et al., 2021; Godber and Atkins, 2021).

"...a lot of tactile things...are lost in a virtual format, and that can be very frustrating for students and instructors and really slow the course down."

"You ask a question, and there's no feedback. You don't see anybody's faces. You don't hear any response. ...you have to force those interactions and knowledge checks through some other mechanism."

Instructors also reported difficulties with determining the best formats and technologies for rapidly pivoting to online instruction and the time-consuming nature of creating high quality online content. Reduced interaction and the time required for instructors to develop content are established drawbacks to online learning (Habib et al., 2019; Wagener et al., 2021), especially with the rapid shift that occurred in 2020 (Godber and Atkins, 2021; Rapanta et al., 2021).

A concern expressed by multiple instructors (6) specific to computer-based classes was the difficulty of troubleshooting and reviewing code and errors without being able to crowd around the screen, consistent with challenges reported by Gannon and McGuire (2022). Another issue for several instructors was getting hardware and sensors into the hands of students.

"...during the hands-on lab, I stop by each student and see if they're following and if they can finish that specific section of the code.... But in Zoom, it's relatively harder to see all the screens and then go back to each one...a classroom environment is often very engaging and more hands on for students. They can easily talk to the person next to them and get some help."

"Live coding is challenging because students don't often have multiple screens, so typing code while watching the lecture requires some careful window manipulation."

To address these challenges, instructors adjusted to hold more office hours and help sessions and increase communication opportunities, which was also important for Smith and Praphamontripong (2021) in transitioning a coding class online.

"I polled students [to ask] what's going on? What are the pain points? ... they really enjoyed being able to watch stuff on their own time. So instead of doing a live lecture, I ended up doing recordings and then during the lecture times I [held] office hours. In fact, I started doing...office hours at...9pm, 10pm. It was crazy how busy they were."

"We do a lot of office hours due to COVID so that we can connect, look at their screen... What's the problem with their code? I increased [office hours], but also, I schedule meetings with students if they have a [specific] problem...it's not really that engaging as in person, but still, we try to support the missing pieces...through some online meetings."

Participants reported that communicating expectations for online classes and deliberately facilitating interaction helped ensure student engagement.

"We make it a point to tell students that being in an online class is no different than being face-to-face in terms of being engaged or not....This helps the students get to know each other and learn how to navigate online meetings, which is a great professional skill to develop. We are also more intentional in encouraging community in the online class; I have an "ice breaker" question related to data science each day, and many students submit their answers in the chat window."

Despite the challenges of online delivery, instructors deemed several aspects of online instruction as beneficial. Zoom was an effective technology for interactive remote instruction, and several participants preferred live coding via Zoom rather than in the classroom because students could more easily follow along and screenshare their own work. For some participants, Zoom breakout rooms facilitated group work. Others reported benefits of live coding with screen sharing as well as online breakout rooms (Beason-Abmayr et al., 2021; Smith and Praphamontripong, 2021).

"If anything, the class may have gone more smoothly this way because everyone was sitting at a computer all the time so we could more easily screen share and debug and demonstrate across the instructor and student machines."

"There are some elements of being online that work really well for this class. ...The course is ...flipped, so each professor prepares...videos for the students to watch in advance, and they also prepare a set of in-class exercises. During class, we split the students into breakout groups of 4-5 students each, and they work on the exercises. The professors and TA circulate through the rooms answering questions. At the end of the class period, we

reconvene to discuss interesting problems or issues that arose while the students worked."

Even with a return to in-person instruction, some are retaining approaches that were successful during the online period. These adjustments include non-traditional modalities for synchronous/asynchronous lecture and work sessions and increasing the use of tools and platforms such as Zoom, Slack, and Jupyter notebooks. This reflects the recommendations made by Rapanta et al. (2021) to retain effective aspects of online learning when blending with in-person modalities so that digital technologies support rather than hinder active learning.

Content, Technology, and Topics

All participants reported creating custom materials for their course and/or adapting content from other sources. A majority (13) created most of the instructional materials for their course. Only a handful (4) used any textbook: one hydroinformatics text, one modeling text, one statistics text, and one converted an existing coding book to water resources examples. A reported challenge is the rapidly evolving nature of the field in which the technology and applications change faster than published textbooks can account for. Several instructors (4) borrowed, exchanged, or modified material from each other.

"I have created all of my own course materials. I do not use a text. Most materials were drawn directly from my own research and project experience or that of my close colleagues."

"We have built up the course material from scratch... we were not aware of a... textbook that would teach the students at the level that we wanted and with the types of R programming that we wanted while illustrating with the water-related data that we wanted."

Regarding technologies emphasized, almost all instructors teach coding in Python (10) or R (6). In addition, instructors cover structured query language (SQL) (4), ArcGIS (3), Arduino (3), and web technologies (i.e., PHP, JavaScript, HTML, CSS) (3). For several cases, the course evolved from using Matlab to R to Python so that students have experience in a non-proprietary coding language that they can use in subsequent settings regardless of affiliation.

"I had a student who was just an outstanding computationalist. ...got a great job... came back and she said... I really loved your class and I wish I still had... the ability to do those kinds of analyses, but our company won't pay for the MATLAB license... it was just heartbreaking because... think about what your company is missing out on you not being able to do that... I [determined] to... move this to Python or something that they're going to continue to have access to, regardless of where they work in the future."

Although hydroinformatics is centered on tools, rather than emphasizing specific technologies, participants emphasized teaching students how to learn new informatics tools, a finding that echoes the emphasis of Burian et al. (2013). Several instructors noted that hydroinformatics technologies continue to advance, which makes it hard to settle on a set of tools to use in teaching a course and highlights the need to teach students how to recognize which tools to use in different scenarios.

"Students might never use those specific tools again, but have skills to learn new tools."

"I do not expect that students leaving my class will be experts in any of these skills. However, they should have explored each of them and developed a level of proficiency that they know which of them will be the most useful in their research and future careers and which may be the most important for them to invest further time and effort into becoming more proficient."

"I think we have reached a point where there are relatively good cyberinfrastructure components out there in the hydroinformatics domain and now one of the bigger problems is composability - e.g., how can students and researchers learn all of the available tools and then decide which tools to put together in composing a research, data analysis, data science, modeling, etc. workflow."

Other instructors emphasize data and project management skills, which are agnostic to specific technologies or tools.

"My expectations for the informatics skills... are... more about... habits of mind and computational practices around... reproducibility and... sustainable code... making sure that their code is under version control, making sure that they're using things like Jupyter notebooks to provide... traceable and reproducible demonstrations of their workflows, more so than any kind of specific technique that they're using."

An important skill repeated by participants was appropriate troubleshooting, including understanding documentation and finding help through forums and other resources.

"We... encourage students to use the internet to help them work through problems and troubleshoot coding errors (e.g., Google, StackOverflow)."

Each instructor and each course have specific emphases. While there is variety in what is taught, the overlap of common subjects illustrates key topics and themes that currently comprise hydroinformatics instruction (**Figure 1**). Most instructors (13) focus on scripting and coding basics (in Python, R, or Matlab) with emphases on data formatting, manipulation, and wrangling (12) and data visualization and plotting (11). Data science (10), basic statistics (7), and machine learning topics (7) were commonly mentioned. About half of participants covered geospatial topics such as mapping (7) and spatial analysis (10), which some instructors view as essential while others exclude these topics as they are covered by other courses. Several participants (6) include instruction on workflows, reproducibility, and best practices for coding. Other topics mentioned by multiple instructors included databases, data models, and SQL; dataloggers and sensors; modeling; the data life cycle and metadata; Git; and web services and web mapping tools.

Because of the open-ended nature of the questions, these numbers should be interpreted generally –e.g., more instructors

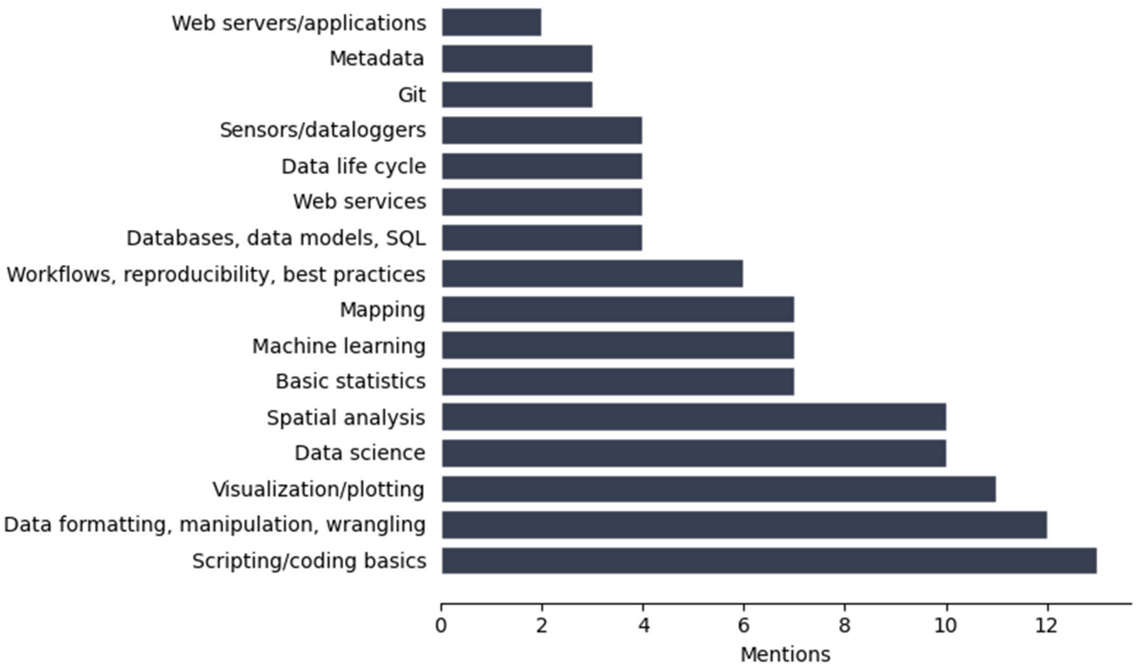

FIGURE 1 | Count of mentions related to subjects taught by participants.

may include content on metadata but did not explicitly mention it. Similarly, "modeling" is a broad term with various meanings and implementations. Despite these limitations, we can identify a few important takeaways. First, hydroinformatics is broadening its focus from modeling with custom tools and graphical user interfaces (GUIs) (as described in many of the papers we reviewed) to more strongly emphasize data management, visualization, and analysis using open-source scripting tools. These capabilities provide a broader path for addressing water-related challenges and questions.

> *"[The] basics of how to organize, use, and process data has not changed, but the technology to do that keeps changing. For example, we no longer use interface or GUI… The term workflow was not used earlier but is now used frequently. There is more use of internet-based tools and publicly available/open-source tools."*

> *"Things are becoming more standard; the tools keep getting better. We are now able to use mostly open-source mainstream languages and tools for our specialized environmental informatics work; 20 years ago we needed to build and use clunky, custom-purpose tools. This is much better now. It also means, however, that there is less need for 'hydroinformatics' specific tools and methods."*

Second, a primary objective for many of the instructors was to ensure that students are comfortable working in one scripting language and understanding the basic concepts of functions, conditional statements, iteration, logical operation, data management, querying, and visualization. Any modeling being taught is within the context of open-source scripting environments. We observed that data science, statistics, and machine learning topics are generally being taught in the water data science courses while databases, sensors, and spatial analyses are being taught in strictly hydroinformatics classes. However, the crossover between these topics is growing, and the boundaries between hydroinformatics and water data science are fuzzy.

Third, several instructors emphasize communicating scientific data and results, and others focus on enabling students to translate the skills gained in the course to resume entries or digital code portfolio.

> *"I'm big on science communication…that was the first time that they had ever really had someone be pedantic enough to talk about presentation of data, quality of graphs, quality of the writing."*

> *"I try to work with them to put it on their resume in a way they can explain it. …they're getting some really cool jobs…they wouldn't have gotten, as a result…So it basically opens up career trajectories that are not just typical civil and environmental consulting."*

> *"At the end of the class I'm hoping that they have…a GitHub repository that has…Jupyter notebooks that are their problem sets that they feel comfortable sharing on their LinkedIn profile or their CV that [is] a small e-portfolio of a demonstration of things [they] can do computationally."*

Challenges and Future Directions

There was little consensus in identified challenges and future directions (**Figure 2**), which reflects our finding that instructors are developing their own content based on their own definition of the field, drawing from their own research and experience.

Many participants identified machine learning, deep learning, and/or artificial intelligence as increasingly relevant, reflecting the growing use of these techniques in water science (Shen, 2018; McGovern and Allen, 2021; Nearing et al., 2021). Beyond covering those topics broadly, some instructors offered specific ideas, including better understanding why some techniques do or do not work for some datasets, addressing correlation in data, and using data-driven modeling with physics-informed machine learning. Sensors and hardware-related subjects were identified as important by many participants, including managing high frequency data, low power and ubiquitous sensing, and smart sensors with controls and feedback for real-time decision making. Participants also mentioned electronics, drones, and satellite data. Data management aspects included data quality, reproducible analyses, big data, database schemas and SQL, and collaborative version control (e.g., GitHub).

> *"So there's always going to be an importance in a baseline proficiency in working with tabular and spatial data within water resources data science. . . . as data volumes increase, then you need. . . database skills, so creating schemas, interacting with databases, whether that's Postgres on a cloud or [SQLite] on your local computer. . . . something [that will] hold really big volumes of data, and then interact with it in a structured query language."*

One participant noted that web applications are overtaking desktop applications, further evidenced by several participants identifying cloud computing and technologies as an area of growing importance. For geospatial topics, emerging applications include open technology and platforms (e.g., Google Earth Engine) and open remote sensing products. Although visualization is covered in most of the courses, several participants noted that creative, interactive visualization tools and dashboards are increasingly important.

The range of responses regarding topics of growing importance demonstrate that these subjects are broad and varied, and that the tools, technologies, and topics continue to evolve, compelling instructors and courses to be agile. The challenge of defining and teaching a moving target was reiterated by several participants. Despite the long list of possible topics to cover in a course, one participant suggested that simplifying to cover fewer tools and models is preferable. Given the inflexibility of most engineering and science degree curricula and class structures, it is unlikely, outside of specifically focused degree programs, that additional hydroinformatics and water data science classes will proliferate in most university settings. However, it is feasible, and arguably preferable, that hydroinformatics and data science topics be better incorporated into other existing courses.

> *"Students have told me previous versions of this course was foundational for their PhD/MS and that it was 'the most useful course I have ever taken'. They appreciated. . . the hidden curriculum (stats/R/programming) was brought to the forefront in my classes."*

> *"Students get very little, if any, exposure to hydroinformatics with their undergraduate degrees. I am in a Civil and Environmental Engineering department, and our undergraduate curriculum is so tight that students have very few options for tailoring their undergraduate degrees. Thus, many. . . show up in graduate school lacking the preparation for making advances in hydroinformatics."*

A major gap reported by participants is students' lack of baseline programming experience. Most of the courses expect some level of domain knowledge but do not require programming skill. However, getting students up to speed consumes precious time, and instructors would prefer programming/scripting at earlier levels (i.e., undergraduate). Participants reported difficulty in approaching advanced topics when students are learning to program for the first time, similar to Lane et al. (2021). Although computational skills are critical to water science and hydrology fields (Merwade and Ruddell, 2012), students are often expected to figure them out without explicit instruction (i.e., the "hidden curriculum").

> *"Mainly I think hydroinformatics concepts could be introduced earlier or at all in undergraduate education. These things are so critical to the field that I think a solely analog hydrology course is a disservice to students."*

> *"If students don't come prepared with coding competency and conceptual fluency in computer science, they struggle to learn the applications to environmental fields."*

Shared Resources

Participants unanimously indicated moderate to high interest in sharing and exchanging teaching materials, and several reported already depositing educational content online. However, the materials are spread out in various formats over multiple platforms, and we were unable to locate some of the resources reported to be available. There is no single centralized platform, and implementations range from files uploaded to a personal website to a fully interactive online course. Reported interest and rate of uptake is uneven. One participant prepared and posted course content in a public repository with no knowledge of reuse while another shared content in an interactive website and received feedback from multiple external users. Even so, the level of reuse is modest relative to what some participants consider necessary for high impact.

> *"You have to make it easy and provide a venue where a significant number of students or other faculty will pick up on content."*

Despite universal interest in sharing materials, some participants expressed hesitancy to rely on others' content, to personalize and adapt it to fit their class, and to invest the time to gain the expertise to present others' materials.

> *"I don't know that. . . I would have grabbed someone else's material and. . . taught. . . a course. There's a lot of value I found as an instructor in having to prepare all the material from scratch myself as a way of making sure I actually know what I'm talking about. . . . it is very nice to have other resources [as a] stencil of what a class might look like, and what good topics would be. . . I would probably*

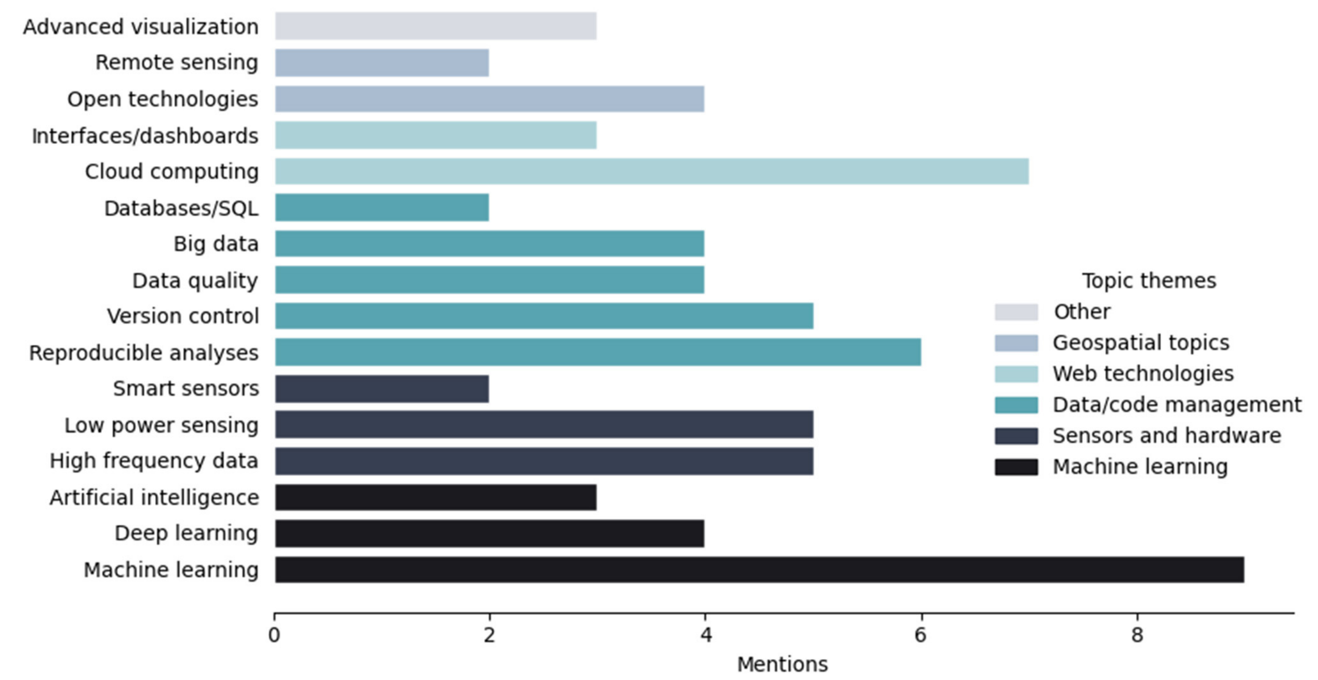

FIGURE 2 | Count of mentions related to subjects of growing importance sorted by thematic topics.

> *still have to spend the time to develop... a copy of that myself so that I actually knew what I was doing."*

A barrier to exchanging materials is the difficulty of knowing what modules or case studies exist, so an ideal system would facilitate discovery. Other desirable qualities of a platform, as identified by participants, include complete descriptions/metadata, a navigable interface, straightforward functionality for adding content, and separate teacher/student access.

> *"Some website where it is easy to search and find modules. It should be easy to navigate and easy to add new contributions. It would be cool if you could see how other faculty members have put together modules to create their own course."*

For shared resources, instructors are interested in portable programming examples, particularly: (1) Jupyter notebooks consisting of code and supporting theory and instructions in markdown, and (2) GitHub repositories that can be cloned and adapted. Other suggestions included slide decks, videos, handouts, example assignments, HydroShare resources, and ArcGIS online content. Participants wanted modular, self-contained exercises that can be modified and swapped into classes.

> *"Self-contained coding exercises that maybe on the first iteration can address a single problem, but then the instructor themselves can develop the sequence of problems that are the deeper dives after that. Something that can be easily plug and played into an existing curriculum or into an existing lecture, and then... would encourage ownership of the content."*

Similar to topics of increasing importance, topics of interest for shared resources varied (e.g., databases, interactive visualization, data-driven hydrologic models, cloud computing, etc.). Regardless of topic, domain specific datasets were consistently mentioned as a key need for shared resources.

> *"The biggest [need] is domain specific data that works for the kind of examples that we need to show... datasets that are large, complex, have hidden components in them that we're going to find, can be used to make a case for or against something... that can serve as good examples. And it's a slippery slope because either the dataset is too simple and it's silly. It's like 10 data points and we're drawing a line through it. Or it's... somebody's PhD dissertation and good luck getting that like into some sort of format where an undergrad can actually use it in the class."*

> *"Datasets that are ready to be used for illustration in class. These must have associated metadata that describes why the data was collected, what the researchers hoped to achieve with it, what each of the variables is, the sampling frequency, and what the data can be used to illustrate (i.e., clustering, visualization, regression, etc.)."*

Several participants recognized that licenses with clear conditions for reuse and citation would help instructors understand limitations and expectations for repurposing content.

> *"... one of the best ways to learn is to look through other people's well-documented code, so open-sourcing the code and data used*

for scientific research, and using FAIR data standards to improve documentation and usability, is very important."

"I think a GitHub with data with notebooks... that has a clear Creative Commons license for both the data and the notebook. And so I know I can use it, change it without getting a nasty gram... from someone's legal department seven years later."

Regarding barriers for exchanging resources, the most common response was that credit could motivate instructors to publish instructional material. This may take the form of counting toward tenure and promotion decisions, citations to document the contribution, or monetary payment – e.g., a grant related to platform or repository development.

"Support from universities for "teaching" efforts beyond the... classroom, and consideration of these efforts and outcomes (e.g., pageviews/downloads) for hiring & tenure decisions."

"Money - there's a lot I think we'd all do for a small amount of money. If you pay professors for their time, they will engage."

Normalizing sharing teaching materials and developing a community around the exchange was another commonly repeated suggestion. Reciprocity was mentioned as crucial so that the exchange is mutually beneficial rather than a one-way offering.

"... if there are ways to, outside of the traditional incentive structure of writing research papers, to incentivize... technologically savvy researchers, postdocs, faculty to contribute lessons like this, then you'll see more participation... it has to be made important and valued by... the community somewhere."

"[I would] go through the trouble of sharing... my resources if I knew that others were sharing theirs and that there could be an exchange from which I could benefit. All of my course materials have been online and openly available for a long time. Others have asked if they could use them, and I have always said yes. I've never had anyone offer to let me use modules they have developed, so the 'exchange' part of this would be important for me."

Collaboration via feedback and edits on shared content was suggested, and multiple participants mentioned that workshops would be helpful to exchange ideas and build rapport.

"This course material is available to only 25 students per year. And seeing that it is used by many more... by different instructors and different institutes would be a nice... outcome of all these efforts. We really put a lot of effort for these materials to be created and used and refined throughout the years. ... potentially giving feedback to these material and... seeing some updated versions of it by other instructors...a community level refinement of the course materials, and creating new versions and better, maybe more up to date versions of these slides will be... useful."

"It would... motivate me if I knew that my contribution would be widely viewed and/or utilized. A workshop that drew educators/contributors together to share could be a helpful place to start."

Building Educational Modules for the Future

Using information gathered on online educational platforms and examples of hydroinformatics educational content from study participants and our own search, we reviewed existing online platforms considering participant-identified attributes and selected HydroLearn for module implementation, covered in Section Online Educational Platforms and Materials. Section Online Module Development describes the modules developed by this work and how they address identified gaps. Module implementation is related in Section Online Module Implementation, including the mapping of module components to HydroLearn concepts and the benefits and challenges of implementing modules in online platforms such as HydroLearn.

Online Educational Platforms and Materials

There was no consensus among instructors on the preferred approach for sharing hydroinformatics educational material (**Table 3**). Some of these platforms are growing in popularity in the hydrologic science community but have not gained traction with the hydroinformatics instructors that we surveyed. The options include systems specifically designed for sharing and publishing educational content (HydroLearn, MyGeoHub, eddie, ECSTATIC), more generic repositories for data or code (HydroShare, GitHub), and customizable interfaces (personal websites, Canvas, or online courses). We reviewed these options with respect to characteristics extracted from the literature and our survey results (**Table 4**). Desirable characteristics include flexibility for hosting various types of materials, compatibility with open data practices, formal pedagogical structure, structured metadata, review and curation of content, and separate faculty and student access (Merwade and Ruddell, 2012; Popescu et al., 2012; Wagener et al., 2012; Makropoulos, 2019; Lane et al., 2021).

The major tradeoffs between the identified platforms are the level of control for creators versus structure to support education-specific content. Whereas, personal websites and custom online courses allow for a great deal of specialization, regular updating, and customizable interfaces, they do not include the searchability, structured metadata, curation, and educational support offered by several of the education focused platforms. A particularly attractive feature for hydroinformatics and water data science instruction is the ability to launch and run code notebooks. Two of the platforms that we examined have Jupyter servers and can launch notebooks: MyGeoHub and HydroShare. Potential challenges with these platforms include scalability for use with classes of students, inclusion of data files that accompany code, and installing desired software packages. Although existing systems currently do not support all desired functionality, we anticipate those limitations will be overcome with future development.

In deciding which platform to use for the educational modules of this work, we considered the factors in **Table 4** with a focus on reuse and collaboration. We deposited materials in HydroLearn as it facilitates export and adaptation of courses and includes metadata, citation, curation, and pedagogical structure. HydroLearn is a repository for instructional material related

TABLE 3 | Educational platforms and instances of hydroinformatics or related implementations.

Platform	Description	Examples
HydroLearn https://www.hydrolearn.org/	Specifically designed for instructors to post and share educational modules for hydrology and water resources	Bandaragoda and Wen, 2020
MyGeoHub https://mygeohub.org/courses	Hosts groups, datasets, tools, and educational content for geoscience research and education	Hamilton, 2021
environmental data-driven inquiry and exploration (eddie) https://serc.carleton.edu/eddie/index.html	Repository for classroom modules and datasets for environmental subjects	No hydroinformatics or water data science modules. Stream Discharge Module: Bader et al. (2015)
Excellence in Systems Analysis Teaching and Innovative Communication (ECSTATIC) https://digitalcommons.usu.edu/ecstatic/	Repository for water resources systems analysis teaching and communication materials	Gorelick and Characklis, 2019
HydroShare https://www.hydroshare.org/	Repository for sharing water related data, models, and code. HydroShare is generally focused on data and code, but several instructors have also used it for educational materials.	Garousi-Nejad and Lane, 2021; Ward et al., 2021
GitHub https://github.com/	Repository for software and code with version control	Flores, 2021
Personal or institutional website	Users determine structure	Kerkez, 2019
Canvas (or similar)	Institutional learning management system	Horsburgh, 2019
Customized books/websites	Users determine structure. Some programming languages have packages to convert code to an online book or website.	Gannon, 2021; Peek and Pauloo, 2021

to hydrology and water resources. Developed on the edX learning management system, HydroLearn is designed to support collaboration around instructional content, reuse and adaptation of materials, and flexibility for implementation in organized courses or by self-paced learners. Although it is relatively new, several cases observed enhanced learning of concepts and technical skills by students using HydroLearn and its precursors (Habib et al., 2019; Lane et al., 2021; Merck et al., 2021). Although it does not natively support launching and running notebooks, Lane et al. (2021) demonstrated linking notebooks *via* HydroShare.

Online Module Development

Based on the survey results, online educational materials are being used and modules have potential to address challenges in hydroinformatics and water data science education. However, there is substantial variety in topics and methods of instruction. While a unified curriculum and approach to the subject matter may be appealing, it does not match the reality of a rapidly changing field with dynamic courses and instructors. Instead, we sought to develop and publish example educational modules that focus on addressing gaps identified by participants and to illustrate an approach for additional online content creation and sharing.

The online modules were designed to address key challenges/gaps in hydroinformatics and water data science education reported by instructors. These gaps relate to: (1) content, (2) platform, and (3) organization. Regarding content, there is a lack of data-driven and problem-based learning that uses datasets from the water domain. Instructors requested notebooks for online coding examples, and there is a need for baseline levels of instruction in coding and scripting. To address the content gap, online educational content should include interactive code with water-related data and problems. Currently, instructors use various platforms for hosting educational content, and participants repeated the need for a system to facilitate upload, discovery, and community involvement. The platform gap may be addressed by publishing and publicizing resources in a system that meets many of the criteria in **Table 4**. We add that active and ongoing support are essential to ensure that the resources are not siloed or lost. Finally, the organization gap can be addressed by ensuring that the content is designed and structured to be modular and adaptable to different instructors, courses, and modes of delivery.

For our online modules, we worked to follow these recommendations to address the needs of hydroinformatics and water data science education. The modules address four topics: (1) Programmatically accessing water data *via* web services, (2) The sensor data life cycle and sensor data quality control, (3) Relational databases and SQL querying, and (4) Machine learning for classification (**Table 5**). These topics were selected based on survey and interview results indicating the need for reproducible code and the growing importance of high frequency sensor data, data quality control, databases, big data, web technologies, and machine learning. In conceptualizing these modules, we drew from our own expertise and datasets generated or used as part of our research efforts. The datasets are available for reuse, or instructors could apply the examples to data from other locations.

Online Module Implementation

HydroLearn facilitates a "Backward Design" approach wherein desired outcomes are first defined, then authentic tasks are crafted to meet outcomes, then instructional content is designed to present necessary information

TABLE 4 | Characteristics of educational platforms related to instructor-defined criteria.

Platform	Discoverability	Metadata	Navigability	Content	Student/ Instructor Access	Licenses	Scalability	Reusability	Citation	Curation	Education support	Collaboration
HydroLearn	Searchable, indexed for Internet search	User-defined metadata	Hierarchical structure. Expandable navigation menu.	Text, videos, links to files and webpages	Supports separate access	Creative commons licenses	Not expected to be an issue	Expected	User-defined	Available but optional	Learning objectives, discussions, many problem types	Commenting and creating derivatives supported
MyGeoHub	Searchable, keywords, indexed for Internet search	Basic description	Courses with modules containing files	Any file type. Natively run Jupyter notebooks	Not explicit support, but could be achieved with groups	Creative commons licenses	Some issues reported for multiple users running notebooks	Unclear	Citation generated but not obvious on landing page	Approval required for uploading files	Quizzes, exams, homework, discussions	Participants may comment
eddie	Searchable, filterable, indexed for Internet search	Detailed outline	Outline with links to files	Any file type	Supports separate access	Unclear	Unclear	Expected	Unclear	Multistep review process	Structured around teaching objective	Unclear
ECSTATIC	Searchable, filterable by type	Abstract and keywords	All content in zip file	Any file type	No	Present on landing page	No issues	Expected	Included	Very light review	None	None
HydroShare	Searchable, filterable, indexed for Internet search	Abstract and keywords		Any file type. Natively run Jupyter notebooks with data files.	Could be achieved using different privacy levels	Present on landing page	Could occur if there are many users on the Jupyter Hub server	Expected	Included	None	None	Commenting and groups
GitHub	Searchable, but difficult	Minimal metadata required	Creators can structure files as desired	Any file type. Code and markdown rendered.	Could be achieved using different privacy levels	Available but not required	No issues	Expected	Can be generated	None	None	Facilitated by forking another repository
Canvas (or similar)	Only if user knows what to look for	Creators can include as much as desired	Predetermined structure with some customization	Any file type	Separate access for creator but not for resuse	Possibly	No issues	Unclear	Possibly	None	Quizzes, exams, homework, discussions	Potential for collaboration
Customized books or websites	Only if user knows what to look for	Creators can include as much as desired	Creators can structure files as desired	Any file type	Separate access for creator but not for reuse	Possibly	No issues	Unclear	Possibly	None	None	None

TABLE 5 | Educational modules developed and deployed as part of this work with descriptions of essential components and datasets.

Module	Programmatic data access	Sensor data quality control	Databases and SQL	Machine learning classification
Topics	• Open web technology • High frequency data • Visualization • Big data	• High frequency data • Data quality • Big data • Machine learning	• Databases and SQL • High frequency data • Big data	• Machine learning • Smart sensors • High frequency data
Narrative	• The United States Geological Survey (USGS) National Water Information System (NWIS) • Web services for accessing data	• Data life cycle for *in situ* aquatic sensor data • Sensors, hardware, and infrastructure • Sensor data quality assurance and quality control	• Data models and database implementation • SQL queries (e.g., selecting, joining, and aggregating data) • Observations Data Model (ODM, Horsburgh et al., 2008)	• Common machine learning approaches, concepts, and algorithms • Python package scikit-learn Problem of labeling residential water end use event data
Code examples	• Use the Python dataretrieval package • Import and plot data *via* USGS NWIS web service endpoints • Examine local hydrology using flow statistics	• Import and plot a time series • Use the Python pyhydroqc package • Perform rules-based and model-based anomaly detection	• Use SQL to select data, sort results, perform joins between tables, aggregate and group data	• Explore data features • Apply basic machine learning model • Compare multiple algorithms • Hyperparameter tuning and optimization
Assignment	Retrieve data, calculate statistics, and generate plots to explain the impact and severity of drought conditions	Apply package algorithms and determine performance metrics to consider using the software in an observatory quality control workflow	Construct SQL queries to compare data to state water quality criteria and identify potential water temperature impairment	Apply machine learning models to develop guidance for using smart meters to collect residential water use data
Dataset	Water data collected by national agency available *via* web. Similar data/methods may be available for data from other agencies.	Flat files containing high frequency Logan River aquatic data with raw data and technician labels. Posted on HydroShare.	SQLite ODM database with high frequency water temperature data for several sites in the Logan River. Posted on HydroShare.	Flat file of labeled residential water use event data. Posted on HydroShare.

Modules are accessed at Jones et al. (2022a).

(Maggioni et al., 2020). Although in our case, development did not proceed in this order, the essential elements in our module design methodology correspond to backward design concepts and specific HydroLearn components: (1) learning objectives map to desired outcomes, (2) narrative maps to instructional content, (3) example code maps to both instructional content and authentic tasks (i.e., learning activities in HydroLearn), and (4) technical assignment maps to authentic tasks (learning activities). Implementation of each of the components in HydroLearn is reported in the following subsections.

Structure and Organization

Each HydroLearn course contains "modules" or "sections", which is the level to which we matched our modules. Although our modules stand alone, we included them under a single course umbrella (Hydroinformatics–USU 6110) to fit the HydroLearn schema. Modules consist of "subsections" comprised of "units." The subsections are only titles, whereas content is contained as components (e.g., text, discussions, problems, HTML code, videos) within units. In HydroLearn, users have control over using either many components within fewer units, which makes interaction with content more vertical (i.e., scrolling on a single page), or using many units, which makes interaction with content more horizontal (i.e., navigating from unit to unit). While this provides flexibility in presenting content, we found that navigation between subsections and the different levels of each module was not always clear.

Figure 3 illustrates the organization of a module implemented in HydroLearn. While this is an intuitive structure, it imposes hierarchical levels that may be overly strict for some users. For example, we found "subsection" to be an unnecessary level for some modules and would have preferred to directly use "units" under the module level–or to have had control over the hierarchical levels. Granularity and organization are persistent questions for many repositories, regardless of content type (Horsburgh et al., 2016), and developers of many data repositories determined to leave organization and structure up to the user (e.g., FigShare, HydroShare, Zenodo). Although there are benefits to imposed structure, there is no single prescriptive pattern, and users may prefer different organizational levels. We identified degree of control as the main distinction between platforms, and giving users more control over organization and structure may improve the appeal and uptake of HydroLearn

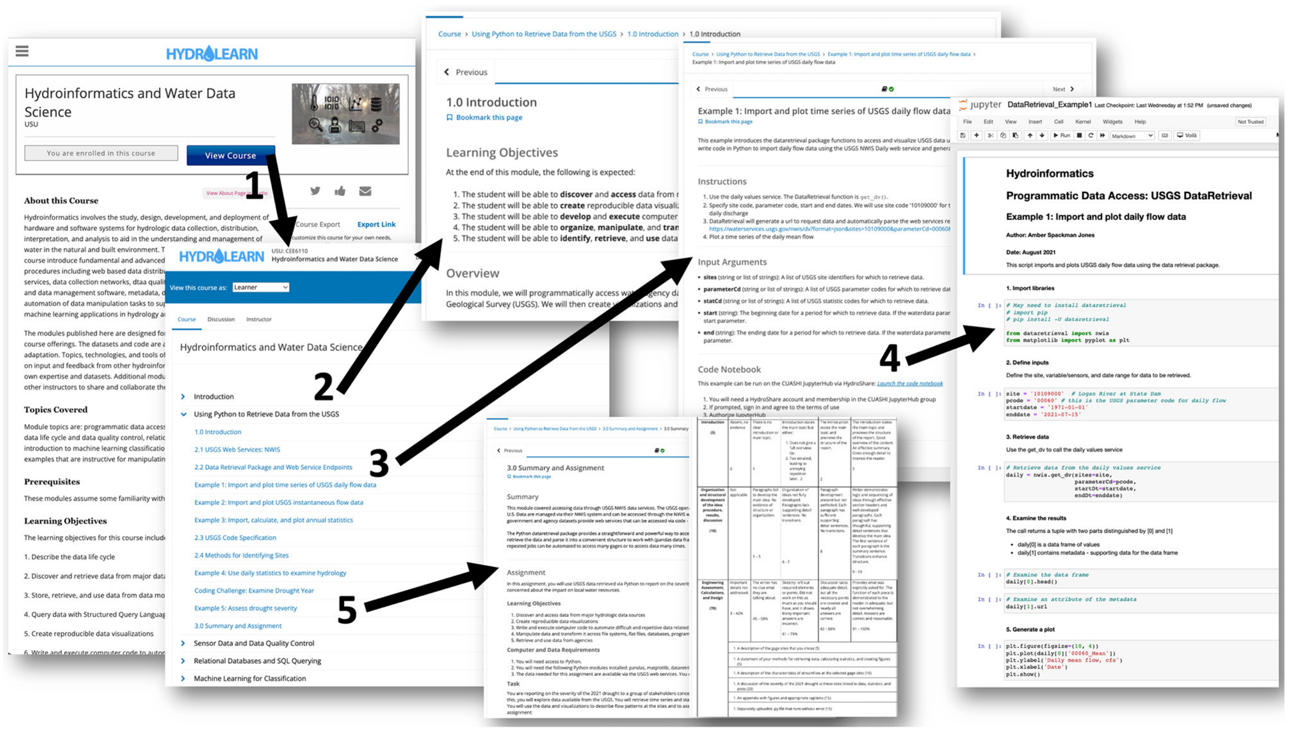

FIGURE 3 | Module implementation in HydroLearn. The numbered steps indicate the order of workflow and the location of essential module elements: (1) the course landing page contains metadata and links to a course outline, (2) learning objectives in the module introduction, (3) the narrative consists of text, links, images, tables, and code snippets, (4) code examples are interactive notebooks in the CUAHSI JupyterHub linked from HydroLearn, and (5) the technical assignment and associated rubric are a separate module component.

(and similar platforms). Despite these limitations, we were able to fit our module content to the HydroLearn structure.

Learning Objectives

Learning objectives are the desired outcomes of instruction and are ideally action-oriented, specific, and measurable. As a major part of its pedagogical emphasis (Lane et al., 2021), HydroLearn facilitates the creation of learning objectives, which can be entered manually or developed using a wizard according to an established structure (Maggioni et al., 2020). Although our learning objectives were defined prior to using HydroLearn, the wizard helped improve their specificity and robustness. HydroLearn functionality can directly connect module learning objectives to other module components (e.g., rubrics).

Narrative

For each module, the narrative was created in slides with text and images, then content was transferred to HydroLearn. Because study participants reported commonly using slides for lectures, the modules include linked slide deck files. Overall, we were successful in translating our content to HydroLearn components. Despite it being somewhat tedious to adapt text to HTML and to import and export images from slides to HydroLearn, we found it straightforward to edit content, to duplicate and modify components, to reorder units, and to publish changes. Building the course from the foundation of a HydroLearn template offered helpful organization and instructions.

Example Code

Each module contains 3–6 example scripts, each of which illustrates a task or piece of functionality (**Table 5**). There may be redundancy as examples build on each other, and instructors may choose to use fewer examples than provided. Code examples are shared in Jupyter notebooks as part of HydroShare resources that can be opened and run *via* the CUAHSI JupyterHub Server. We opted to use the CUAHSI JupyterHub because: (1) common Python packages are pre-installed, and additional packages can be installed by request, both of which are dependencies in our examples, and (2) data files can be called by code, which is essential for our modules. If data files are necessary to examples, they accompany the code notebooks in the HydroShare resources.

HydroShare resources containing notebooks and data can be linked and opened in a separate browser window or embedded as iFrames in HydroLearn units (Lane et al., 2021). We used links that directly launch the CUAHSI JupyterHub (**Figure 3**). From the link in HydroLearn, a user is prompted to sign into HydroShare and choose a coding environment and then is taken to their server directory where the notebooks are ready to be launched. This simplifies deployment of example code as learners do not have to install software or match a particular coding environment to view, execute, or manipulate code.

Technical Assignment

The technical assignments were conceptualized to meet recommendations in educational literature for open-ended, ill-defined, problem-based learning. For each assignment, students are expected to synthesize the narrative and code examples and apply the data and analysis tools to real-world applications. Each assignment requires coding and a written summary report to communicate and defend the results and conclusions. Within each module in HydroLearn, the assignment is a unit with components that specify the assigned tasks and expected deliverable. Assignments are accompanied by a customized rubric that sets expectations for students and facilitates objective grading for instructors. We adapted rubrics developed by a team of hydroinformatics instructors to each assignment (Burian et al., 2013). In another approach to assessment, HydroLearn offers rubric templates that connect the degree of student performance related to each learning objective (Lane et al., 2021).

Platform Challenges and Opportunities

Our experience with HydroLearn shows that it contains functionality that addresses each of the needs for online sharing and content organization that we identified in surveys and interviews with study participants. We also experienced challenges that present opportunities for continued advancement of educational platforms. We acknowledge that others who use HydroLearn may have varied experiences, and while it is beyond the scope of this effort, there is opportunity to gain further insight by soliciting feedback from users of HydroLearn and/or other platforms. In this section, we describe our experience using HydroLearn with respect to identified criteria, and each of the following paragraphs corresponds to a category in **Table 4**. While these outcomes may be specific to HydroLearn, we anticipate that other platforms face similar challenges and may require further development to support online educational resources.

Discoverability refers to locating content using keyword searches from Internet browsers and search functionality within a platform. After creating a course on HydroLearn, it appeared in the results of basic Internet searches. Within HydroLearn, we were able to search for the course and within the course. The platform could enhance discoverability by including keywords as part of the metadata for each course or module and filtering courses on keywords.

Metadata are displayed on the course landing page. The course template suggests metadata elements, which we used (e.g., target audience, tools needed, suggested citation), but elements are optional. HydroLearn could better standardize metadata by requiring certain elements and by automatically generating elements where possible. Creating metadata requires editing HTML code, and HydroLearn could improve usability through webforms or markdown.

Navigability of HydroLearn courses is dictated by the hierarchical structure described in the Structure and Organization Section. Even with a logical organization for content, moving between sections and knowing how to proceed through the module sequentially can be challenging for beginners. This may be improved by adding text to the icons in the navigation bar and by displaying a course outline and navigation in a persistent sidebar.

In **Table 4**, content refers to the types of files that are supported by the platform. We were able to use HydroLearn to share text, images, interactive websites, and to link files for download. Videos, equations, code snippets, and other HTML components are also supported. Supporting either a JupyterHub for launching notebooks or more directly integrating with the CUAHSI JupyterHub would strengthen the platform's ability to support code files.

Separate access for students and instructors is supported by HydroLearn. Course creators can elect to restrict access of certain content to course staff. Other instructors can access restricted content by exporting the course or by contacting course creators, though that may be unreliable. Although we used open-ended assignments, some require specific coding tasks. In these cases, we created scripts or notebooks as a solution key to the assignment, and we were able to use this functionality to restrict access without separating the solution from course materials.

Licenses can be specified by creators at the course level. HydroLearn supports Creative Commons licenses (e.g., Attribution, Noncommercial, No Derivatives, Share Alike), and related icons and messaging are displayed on course subsection pages. Licensing could be made clearer if displayed prominently on the course landing page.

Scalability refers to the ability for multiple users (e.g., classes of students) to use the materials or program. We have not yet tested HydroLearn in the context of multiple simultaneous users, but we are not aware of any limitations. It is built on an established online learning platform (edX), which offers robustness. There may be scaling issues with many users running notebooks on the CUAHSI JupyterHub, for which Lane et al. (2021) observed student frustration related to losing server connection and authentication.

Reusability of educational materials is an intent of HydroLearn, and modules are expected to be designed with consideration for uptake by other instructors. While the modules described here have not yet been reused, we found it straightforward to export and customize a HydroLearn course, and Lane et al. (2021) report that adaptation of a HydroLearn course by instructors at other institutions was straightforward. Reusability is facilitated by licenses and citations, and the course metadata template includes "Adapted From" to acknowledge source material. HydroLearn courses have been used for both online and in-person instruction and can be designed to be student-paced or with an imposed schedule making them compatible to the mix of modalities reported by study participants.

Citations are a recommended (but optional) metadata element for HydroLearn courses. Creators can structure the citation as desired, and it is displayed on the course landing page. There is opportunity for the platform to standardize by automatically generating a citation for each course or module, as is done for data and code resources in HydroShare (Horsburgh et al., 2016).

Curation of courses is not required in HydroLearn, and instructors may deposit and share content without review. However, most of the modules currently available on HydroLearn were developed through intensive summer hackathons including substantive instruction on pedagogical best practices and feedback from the HydroLearn team (Maggioni et al., 2020; Gallagher et al. *in prep*). As a result, much of the educational content shared on HydroLearn meets their criteria for high quality modules. However, there is no long-term system in place for module review and curation by the project team. As our modules were developed outside of the formal hackathons, we requested the feedback of a HydroLearn team member who was able to review and offer helpful suggestions. The approach of offering but not requiring curation balances increased overhead with fostering high quality content. Also, compensating fellows increases their motivation to deposit high quality material, as noted by study participants.

Educational support refers to assistance with teaching pedagogy and tasks, and is provided by HydroLearn through multiple features. HydroLearn emphasizes learning objectives throughout course development and includes functionality for various problem types to assess student learning (e.g., multiple choice questions, open responses, advanced mathematical expressions). Following templates and recommendations, capitalizing on features, and taking advantage of review by HydroLearn staff offers an approach that will result in a robust pedagogy. Although we did not tap into all these capabilities in developing modules, this is major benefit of HydroLearn.

Collaboration is facilitated in HydroLearn through the inclusion of multiple instructors who share editing abilities and co-authorship on a course. HydroLearn also has the ability give feedback through comments. It was uncomplicated to add instructors to our course and for all authors to edit materials; however, we did not experiment with feedback.

Outlook for the Future of Hydroinformatics and Water Data Science Instruction

In light of the transition to online courses precipitated by the COVID-19 pandemic as well as the growing prevalence of material online, instructors may need to consider how to best bring value to their course offerings. As expressed by one interview participant:

> *"…the incentive, the value proposition of the classroom is fundamentally altered after COVID. …No matter how good somebody is at explaining something, there's always somebody better on the internet. …what really is the role of the instructor…and modern classroom? … Obviously in person, it's made easier by the fact that [students are] there. But then the question is, is it you or is it the fact that they can be around each other?…online [content] is growing and dismissing it [is naïve]."*

Several participants indicated that the merit of an organized course for students is interaction with an instructor curating content and facilitating learning. Despite the possibility of learning from purely online materials, a knowledgeable and engaged instructor still has much to offer. This echoes Rapanta et al. (2021) in identifying a teacher's role to organize and curate the learning process and recommending that instructors increase technology expertise to adapt to changing educational environments.

> *"…engagement, pre and post class discussions, office hours, a tailored curriculum to the class. …my class changes every semester based on…what I'm perceiving in lecture and what I'm hearing in office hours."*

> *"We're in an era where it's not necessarily the content that's most valuable to the students, it's me facilitating their use of the content. And so, I think that the content should be shared as broadly as possible."*

Access to educational material that is current, flexible, and reusable can help instructors adapt to the rapidly evolving field. The modules presented in this work are a first step and an invitation to the community to continue development and sharing of content online. In this way, instructors can address the gaps we identified related to content, platform, and organization of community materials. As instructors consult the list of topics of growing importance in the field and consider which of their materials and datasets may be most useful as community resources, we envision that they will deposit modules that include relevant water-related datasets and accessible code examples with ideas for problem-based learning.

This work illustrated that materials deposited in HydroLearn are modular and adaptable, and as HydroLearn advances and usage increases, it may address the platform gap related to limited community and siloed resources. This vision depends not only on sharing content, but also on uptake by other instructors implementing, reviewing, and engaging with shared material. As articulated by study participants, reciprocity, credit, and feedback will all motivate sharing and reuse of content, which will help advance instruction in hydroinformatics and water data science. Further implementation of online educational modules may help corroborate our experience in meeting identified criteria and may point to additional challenges or gaps.

CONCLUSION

We interviewed and surveyed instructors that teach hydroinformatics and water data science at collegiate and professional levels to assess the current state of practice regarding topics, teaching tools, shifts to online instruction related to COVID-19, and the potential for shared online resources. Results indicated a mix of online and in-person modalities. Although nearly all courses moved online because of COVID-19, there was a strong preference for in-person learning, and most were returning to in-person teaching. However, instructors are retaining some virtual aspects that facilitated instruction, particularly related to live coding. Student feedback and interaction were lacking in purely online modalities, leading to the conclusion that even successful online resources and tools require deliberate interpersonal components.

Instructors generally customized teaching materials to meet the demands of a rapidly developing field. Results show variety in topics currently taught and topics of growing importance, with consensus around emphasizing reproducible code development in open-source languages and competence regarding learning and selecting informatics tools. Live coding for online and in-person settings was facilitated by the growing use of online code notebooks. A key finding was a common need for technical skill development earlier in students' college experience.

We found high interest in shared online educational content, although a lack of recognition, reciprocity, community, and credit were deterrents to sharing. Although participants currently use multiple layers of miscellaneous educational platforms, there was an expressed need for common community resources. Participants reported gaps and challenges to hydroinformatics instruction related to content (water-related datasets, online notebooks, and data-driven problems), platform (community-based, facilitates discovery), and organization (modular, adaptable).

The educational modules we developed attempt to address these challenges, center around subjects of growing importance in the field, and were developed and deposited in HydroLearn, a platform for water-related educational modules. We found that HydroLearn was successful in meeting participants' criteria for a community content platform. HydroLearn has robust functionality for educational tools and pedagogy, and its scaffolding supports content sharing (i.e., metadata, citation, discoverability, collaboration, reusability). The major drawbacks were related to an imposed hierarchical structure, and improvements could be made regarding minimum metadata requirements. These modules are a step toward developing a rich set of online resources and an active community of instructors to meet the advancements in hydroinformatics and water data science.

In conclusion, shared online resources hold promise for overcoming challenges in hydroinformatics and water data science education. As instructors are already accustomed to tailoring content for their courses, adapting online modules with a water emphasis is accessible. Current and flexible resources would help instructors keep pace with the rapid development of technology and topics in the field and maintain the value of their course and teaching for students.

DATA AVAILABILITY STATEMENT

The materials generated by and reported by this work are publicly available. The survey responses and interview transcripts are available via HydroShare (Jones et al., 2022c). The educational modules are published via HydroLearn (Jones et al., 2022a) along with code and associated datasets in HydroShare (Jones et al., 2022b).

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Utah State University Institutional Review Board. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

AJ, JH, and BL conceptualized the presentation of survey and interview results with associated educational modules. AJ formulated the survey and interview design with support from JH and CF. AJ facilitated all surveys and interviews and analyzed the responses. AJ, JH, and CB created the educational modules and published them with support from BL. AJ wrote the manuscript with consultation and contributions from JH, CF, BL, and CB. All authors contributed to the article and approved the submitted version.

FUNDING

This research was primarily funded by the United States National Science Foundation Under Grant Number 1931297. Additional support for the educational/training modules was provided by the FAIR Cyber Training Fellowship program at Purdue University corresponding to National Science Foundation Grant Number 1829764. HydroLearn is supported by National Science Foundation Grant Number 1726965. Additional funding support was provided by the Utah Water Research Laboratory at Utah State University.

ACKNOWLEDGMENTS

We gratefully acknowledge the input and expertise of the instructors who were participants in the surveys and interviews reported in this paper and the support we received from the HydroLearn team in setting up and sharing our educational modules.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers | Frontiers in Water

TYPE Original Research
PUBLISHED 19 July 2022
DOI 10.3389/frwa.2022.912776

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SPECIALTY SECTION
This article was submitted to
Water and Hydrocomplexity,
a section of the journal
Frontiers in Water

RECEIVED 04 April 2022
ACCEPTED 28 June 2022
PUBLISHED 19 July 2022

CITATION
Roundy JK, Gallagher MA and Byrd JL
(2022) An innovative active learning
module on snow and climate
modeling. *Front. Water* 4:912776.
doi: 10.3389/frwa.2022.912776

An innovative active learning module on snow and climate modeling

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The interaction between climate and the hydrologic cycle is complex due to intricate feedback mechanisms that can have multiple impacts on key hydrologic variables. Under a changing climate, it is becoming increasingly important for undergraduate engineering students to have a better understanding of climate and the hydrologic cycle to ensure future engineering systems are more climate resilient. One way of teaching undergraduate students about these key interactions between climate and the hydrologic cycle is through numerical models that mimic these relationships. However, this is difficult to do in an undergraduate engineering course because these models are complex, and it is not feasible to devote class time and resources to teaching students the knowledge base required to run and analyze these numerical models. In addition, the recent COVID-19 pandemic required a rapid change to flexible teaching methods that can be implemented in online, hybrid, or in-person courses. To overcome these limitations, a backward design and constructive alignment approach was used to develop an active learning module in the HydroLearn framework that allows students to explore the connection between snow processes and streamflow and how this will change under different climate scenarios using numerical models and analysis. This learning module provides learning activities and tools that help the student develop a basic knowledge of snow formation and terminology, snow measurements, numerical models of snow processes, and changes in snow and streamflow under future climate. This module is particularly innovative in that it uses Google Colabs and an interactive user interface to facilitate the students' active learning in an environment that is accessible for all students and is sustainable for continued use and adaptation. This paper describes the approach, best practices and lessons learned in developing and implementing this active learning module in a remote and in-person course. In addition, it presents the results from motivation and student self-assessment surveys and discusses opportunities for improvement and further implementation that have implications for the future of hydrologic education.

KEYWORDS

snow, climate, modeling, Hydrolearn, active learning

Introduction

In a warming world, the frequency and patterns of precipitation have the potential to change due to changes in global circulation that may cause some areas of the world to see increases in drought and other areas to see increases in floods. In a warming climate, changes in atmospheric circulations patterns will lead to poleward displacement of storms that can produce subtropical dry zones (Marvel and Bonfils, 2013) and an enhancement of the rainfall response to El-Nino Southern Oscillation (ENSO) which amplifies rainfall extremes (Bonfils et al., 2015). The interaction between climate and the hydrologic cycle are complex due to intricate feedback mechanisms that can have varied impacts on key hydrologic variables in space and time. One area of the hydrologic cycle that is particularly sensitive to climate variability is seasonal snow pack. There has been extensive research showing changes to seasonal snow pack characteristics under a warming world. This includes less winter precipitation falling as snow, migration of snow pack to northern latitudes, changes in the timing and magnitude of spring peak runoff, and the intensification and increase in length of snow droughts (Barnett et al., 2005; Demaria et al., 2016; Huning and AghaKouchak, 2020). These feedbacks between climate and the hydrologic cycle will cause strain on existing water resources and water infrastructure and will be a generational challenge for future engineers. Therefore, it is becoming increasingly important for undergraduate engineering students to have a better understanding of climate and the hydrologic cycle to ensure future engineering systems are more climate resilient.

One way of teaching undergraduate students about these key interactions between climate and the hydrologic cycle is through measurements of key hydrologic variables and through numerical models that mimic these relationships through mathematical equations. Models allow students to test simple hypotheses and modify the assumed relationship between variables to determine the outcome. This exploration of the hydrologic cycle takes on real world meaning when the numerical models are validated and analyzed with key hydrologic variables such as streamflow, precipitation, and snow in order to assess and evaluate the extent to which the model mimics reality. This provides students with an intuitive way to learn how different processes interact within the hydrologic cycle and gives students an opportunity to actively explore parts of the hydraulic cycle and its interaction with climate. Yet, teaching students how to explore models and evaluate their ability to answer specific questions using real world data is not easily achieved (Lane et al., 2021).

Research has shown that active learning increases student performance on examination and concept inventories over traditional lecturing in Science, Technology, Engineering and Mathematics (STEM) fields (Freeman et al., 2014). Merck et al. (2021) showed that an active learning module allowed students to take part in the modeling process while helping students understand the mathematical models and develop their skill set. Specifically, within the hydrologic sciences, there has been a lot of work in creating online active learning modules to foster deeper conceptual knowledge of the students through a learning platform called HydroLearn (www.hydrolearn.org; Gallagher et al., 2021).

HydroLearn is a web-based platform that was developed with the primary purpose of supporting hydrology and water resources instructors in finding, adapting, and creating learning modules that integrate authentic problems, instructional content, real data, and modeling resources to create an active learning environment for students. More than just a repository for instructional materials, the modules housed within HydroLearn go through a rigorous development and review process based on research in curriculum design (Gallagher et al., Accepted). Modules include Development of Design Storms, Quantifying Runoff Generation, Developing Storm Inflow and Outflow Hydrographs, Culvert Design Using HEC-RAS, Physical Hydrology, and Detention Basin Design (Gallagher et al., 2021; Lane et al., 2021; Merck et al., 2021). All modules on the HydroLearn platform are freely available to students and instructors.

Even though online active learning modules have been shown to be an effective way to teach students new skills and deeper understanding of the subject, it is also important to recognize that technology and decisions relative to model selection can still be a barrier to student learning (Merck et al., 2021). Difficulties arise because models are complex and require a large amount of input data and a prior familiarity with running numerical models and using computer programming. Even after running the model, there is still a significant level of expertise needed to process and analyze the model results. While developing these technical computational skills can be an important part of students' education, it is not feasible to devote class time and resources to teaching students the knowledge base required to run and analyze numerical models in a course that is not focused on numerical analysis. As such, using coding-based solutions can sometimes lead to too much focus on the tools and syntax of implementing the module activity that limit the student's ability to explore the fundamental process (Lane et al., 2021). To help address this, we developed an active learning module using Jupyter Notebooks that allows students to explore the connection between numerical snow models and climate. The motivation for using Jupyter Notebooks is to strike a balance between a "black box" standalone applications and open access code development (Peñuela et al., 2021). The advantage of using a "black box" application is that students do not get lost in the coding and therefore are able to focus on utilizing the tools to solve the authentic problem. However, the downside is that the underlying codes and assumptions are not readily available and cannot be changed. In using widgets within Jupyter

Notebooks, the module provides the students with a simple and intuitive way of analyzing the data without the requirement of needing to understand and manipulate computer code. At the same time, the computer code is readily available and can be manipulated or changed by the instructor or advance student to further develop and explore the data and the model. In this way, Jupyter Notebooks provide a flexible framework that is effective for both the instructor and the students. The purpose of this paper is to share how this active learning module was designed, as well as lessons learned from implementing it in an undergraduate class in order to add to the knowledge base in the field regarding the design of active learning modules. This work was also highly motivated by the COVID-19 pandemic and the sudden need for flexible teaching methods that utilize best practices and can be implemented for both in-person, hybrid and online courses. The remainder of this paper discusses the development of the Snow and Climate Module (Section Module development), the effectiveness of the module (Section Module effectiveness) and lessons learned from its implementation (Section Lessons learned).

Module development

The Snow and Climate Module (SCM) includes five sections. Each of the sections of the module are discussed following the same design structure of the module which includes an Overview (2.1), Snow Basics (2.2), Snow Measurements (2.3), Snow Modeling (2.4), and Snow and Climate (2.5). While this paper discusses the development of the module, the reader is strongly encouraged to explore the module itself at https://edx.hydrolearn.org/courses/course-v1:KU+CE552+Fall2021/about. Most of the module content can be explored without registering for an account, however, the "Check Your Understanding" activities can only be viewed by registered users.

Overview

The first section of the SCM discusses and presents the learning outcomes and objectives. The SCM was developed using a backwards design approach (Wiggins and McTighe, 2005), which means it starts with the learning outcomes and then the content is developed based on helping the student to achieve the learning outcomes. The SCM as a whole has four learning outcomes which are given below.

Given examples of various aspects of snow physics and snow dynamics, students will display a technical vocabulary of snow science and snow measurements.

Given snow measurements, the student will be able to analyze the difference in snow measurements and monthly and annual relationships between snow depth, Snow Water Equivalence (SWE), and streamflow at two locations in the US.

Given simulated snow estimates, the student will be able to contrast modeled and observed snow relationships while considering uncertainty.

Given simulated snow estimates based on projected climate, the student will be able to analyze the temporal change in snow due to climate projections and develop recommendations that consider uncertainties in the snow model and changes in climate.

While these outcomes are listed in the order they are presented in the module, it is important to note that in the backwards design approach, outcome 4 was the primary outcome identified and then outcomes 3, 2 and 1 were developed to support the achievement of outcome 4. This approach provides an intuitive progression of knowledge through the module that culminates with achieving the main learning objective.

While the structure of the module is driven by the learning outcomes, this module was also designed to be an active learning module. To help facilitate active learning within the module, the module learning outcome is presented to the students in the form of a problem and is the first thing presented in the module. The motivating problem for the module is given below.

"You work for a consulting company and one of your clients is expanding their snow centered business across the US and is interested in knowing how climate change will impact snow and streamflow in the intermountain west and the northeastern United States. They have hired you to project likely changes in future snow depth, snow duration and streamflow under climate change. The client would like your analysis presented in a report that analyzes the change in snow and streamflow for two 30-year periods (1991–2020 and 2021–2050) and includes a description of snow measurements, snow models, and climate projections used in the analysis and their associated uncertainties."

In summary, after the first section the students have been given a problem that will help facilitate active learning and are given a road map of how they will learn the necessary knowledge and skills to complete the project and achieve the learning outcome.

Snow basics

This section of the module provides the foundational knowledge that is imperative for students to be able to begin to understand the snow-climate relationship. This section of the module introduces a wide range of snow-related science and terminology, including snowflake formation, types of snow, and snow meteorology. There are three main learning objectives associated with this section.

- The student will be able describe the characteristics and properties of snowflake formation.

- The student will be able to describe some of the meteorological processes that create snow, including, orographic effect, weather bombs, atmospheric rivers, and lake effect snow.
- The student will be able to identify key terminology related to snow types and climate from definitions from the National Snow and Ice Data Center.

The content in this section is presented using a variety of text, videos and activities to help the students check their level of understanding of the content. These activities are a nice way to keep the student engaged and actively learning in an online format. These activities include, true or false questions, multiple choice questions, and drag and drop matching. An example of one of these learning activities is shown in Figure 1, which shows the drag and drop activity associated with section Snow modeling in the module designed to facilitate student learning of snow terminology. All of these activities provide feedback to the students and the students are allowed to redo the activities as much as they like.

Snow measurements

The snow measurements section of the module introduces the students to the various methods and agencies involved in snow measurement and provides an active learning opportunity for the student to analyze snow measurements at two locations in the U.S. This section has four learning objectives that are given below.

- The student will develop a technical vocabulary to describe snow states and measurement.
- The student will be able to describe how to dig and make measurements in a snow pit.
- The student will be able to describe how regular measurements of snow are made including SNOTEL and Snow Course monitoring network and where to access the data.

The student will be able to analyze snow measurements to assess the difference in snow measurements and monthly and annual relationships between snow depth, SWE, and streamflow at two locations in the US.

Like the previous section of the learning is done through a series of videos, text and learning activities that help the students understand the vocabulary and process of making snow measurements, but it also provides an opportunity for the students to analyze real snow measurements from two locations in the U.S. This is accomplished by using Google Colabs and programming a front-end user interface in python using the ipywidgets library which creates interactive HTML widgets within a Jupityer notebook. The way this technical activity is incorporated into this learning activity is one of the unique and innovative aspects of this module. A Jupyter Notebook is a combination of text and code within a single file. Google Colab provides the server on which the interface is run and is free and accessible for anyone with a google account. This setup provides a nice way to have all students running in a consistent computing environment that is easily accessed through a web browser. The notebook framework also provides a means to include formatted text alongside the computer code to provide a clear and easy to follow directions for the learning activity.

The Jupyter Notebooks used in SCM are designed to be used by anyone and require no prior knowledge of Python programming. This is achieved by making the Notebooks self-contained and self-initiating through detailed instructions, figures and code that automates setup and configuration of the user interface. This translates to the user only seeing a couple lines of code, while the backend of the learning activity is written in the Python programming language and consists of thousands of lines of code that set up the user interface and allows the students to explore the data and generate figures that can be used to complete the activity. Specifically, the first code block downloads the data and the user interface code and sets up the directory structure. This code can be run by simply pushing the run button in the top-left corner of the code block. Once the data is downloaded the student can move to the next section and run another code block that only has two lines of code, which generates the user interface. Figure 2 shows the first section of the snow measurements activity which includes a brief introduction that is followed by a description of setup and a small three-line code block that downloads the backend code and data and sets up the environment and directory structure. The code block can be run by clicking on the play button. The snow measurement activity includes four different interfaces that allows the students to explore snow depth, SWE and streamflow at the two measurement locations. These activities include (1) analyzing the daily timeseries of snow depth and SWE values, (2) analyzing the monthly timeseries of snow depth, SWE and streamflow, (3) analyzing the monthly relationship between snow depth, SWE and streamflow using scatter plots and (4) analyzing the annual relationship between snow depth, SWE and streamflow through scatter plots. In each of these activities the student has the option to save the figure as a PNG file for use in their report. This learning activity provides a simple and effective way for a student to explore snow measurement data without needing a technical background in data analysis.

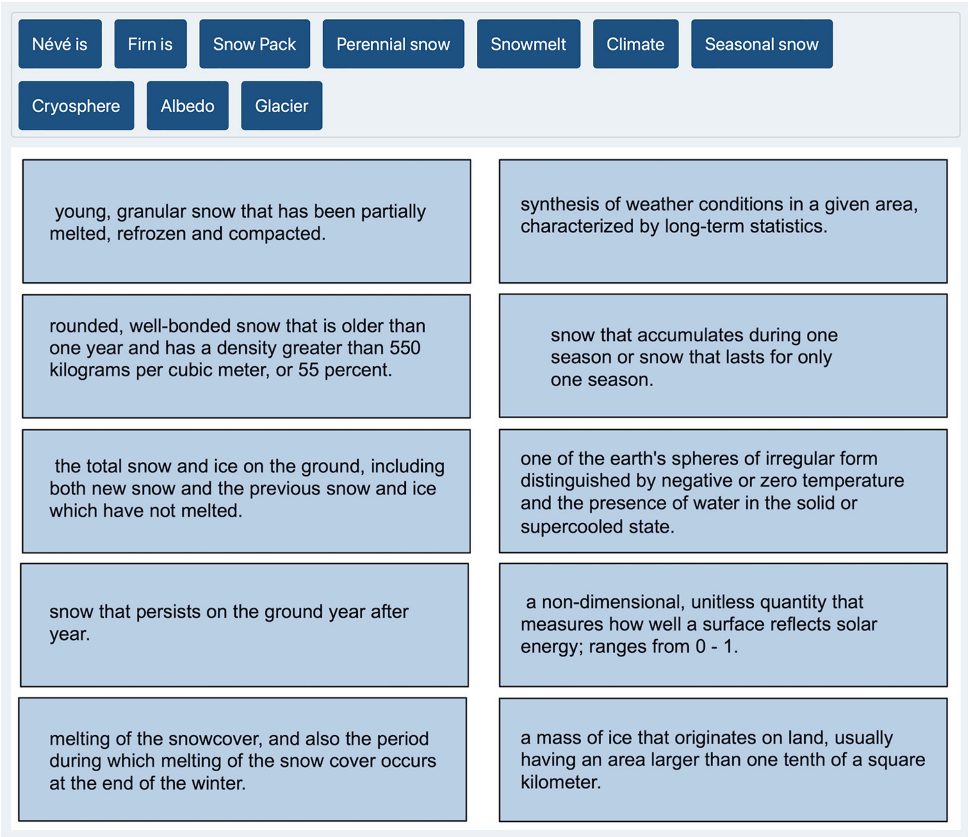

FIGURE 1
An example of a drag and drop learning activity in Section Snow Modeling in the module focused on facilitating learning and retention of key snow terminology.

Snow modeling

The Snow Modeling section introduces the students to modeling snow accumulation, snow melt, streamflow, the importance of parameter estimation and the uncertainty associated with inputs, parameters, and model structure. There are six learning objectives in this section and include:

- The student will be able to describe the need for snow modeling.
- The student will be able to analyze model uncertainty.
- The student will be able to analyze model performance.
- The student will be able to list the key components of snow models.
- The student will be able to demonstrate the relationship of snow properties and streamflow in models.
- The student will be able to contrast modeled and observed snow relationships while considering uncertainty.

Just like previous sections, the content includes text, figures and videos that help the students learn about snow modeling. In the first section, students learn about numerical modeling, uncertainty and the importance of model validation and ways of assessing models through statistical summary measures such as the Nash Sutcliffe Efficiency (NSE) and the Kling-Gupta Efficiency (KGE; Gupta et al., 2009). This section ends with a series of True and False questions and a drag and drop activity to check the student's level of understanding. The next section introduces the snow model structure and includes a section on snow accumulation and snowmelt. Only one model for snow accumulation is presented but three different models are presented for snow melt. This includes the Temperature Index Model, Hybrid Model, and Energy Balance Model. Each of these three snowmelt models have varying levels of complexity and together provide a way for students to explore the impact of different model structures on the model outputs. The next section discusses model inputs or driving variables needed to run the snow models and different sources of these inputs. The different inputs provide another way for the

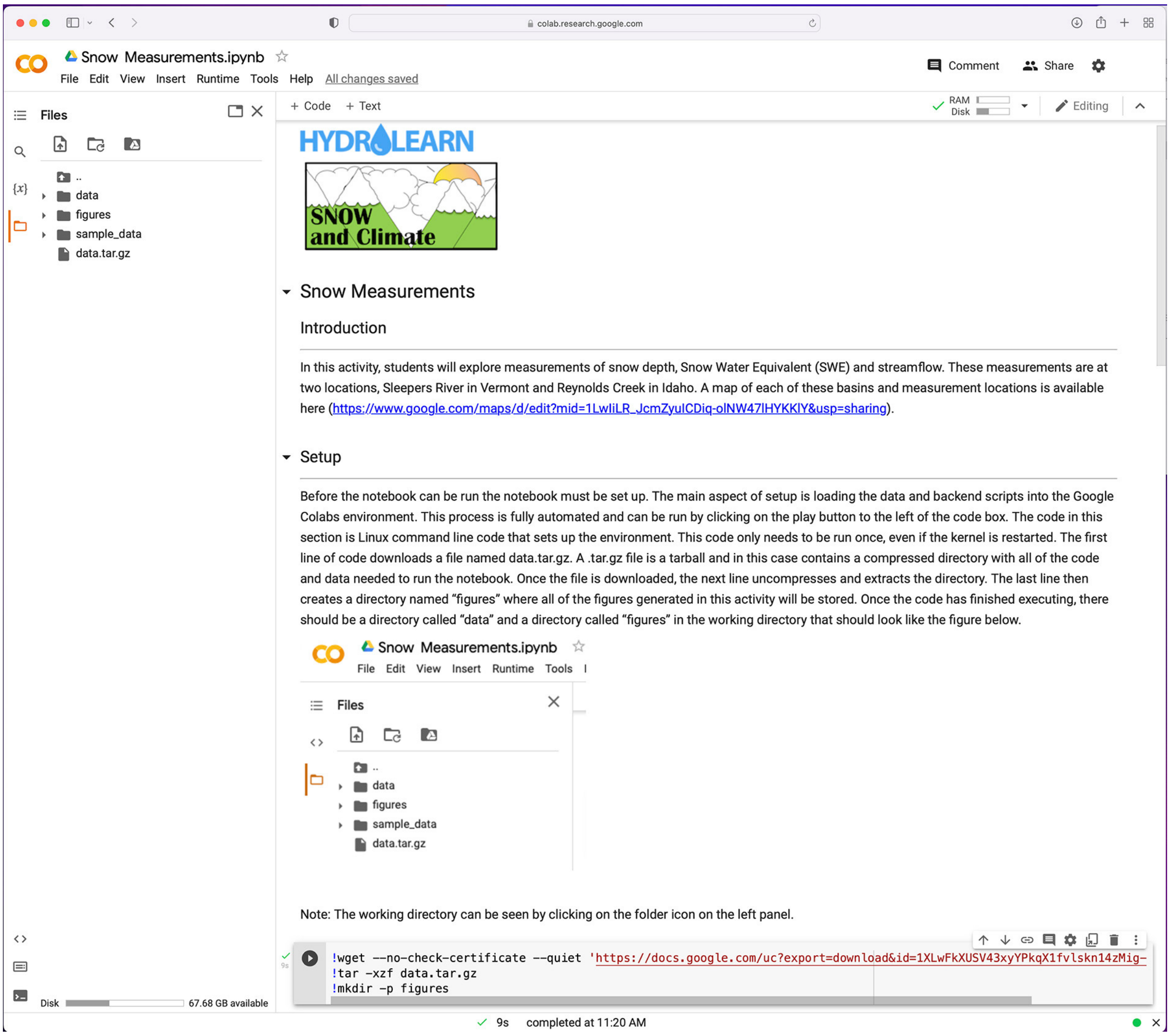

FIGURE 2
The first section of the learning activity for the snow measurement active learning module. This section includes a brief introduction, a description of how the notebook is set up and a small code block that downloads the backend code and data and sets up the environment and directory structure so that the activity can be easily run through an internet browser.

students to actively understand the uncertainty and sensitivity of having different model inputs on the model outputs. The next section then focuses on identifying the key parameters in the snow accumulation and snowmelt models and discusses the importance of parameter estimation. This is then followed by three questions where students can apply what they have learned by using the three snowmelt model equations to estimate the snowmelt for a particular day. The snow modeling section then ends with a learning activity where the students get to run and analyze the snow models at the two study sites. The first part of this section provides some background information about the hydrologic model used with the snow model for this activity and includes a brief discussion of other processes such as infiltration, evaporation, and streamflow routing that are included in the hydrologic model. The learning activity is structured the same as the previous activity in that it is a self-contained Jupyter Notebook that seamlessly downloads the model and data and sets up the environment, directory structure, and each of the four individual learning components. The first learning component of the activity allows the students to explore the uncertainty in the model structure, inputs, and parameters by changing the snowmelt model, the input data and key parameters and see how these changes impact the snow depth, SWE, and streamflow from the model through an interactive user interface. The next part of the learning activity allows students to run different models and compare the models with observations to facilitate

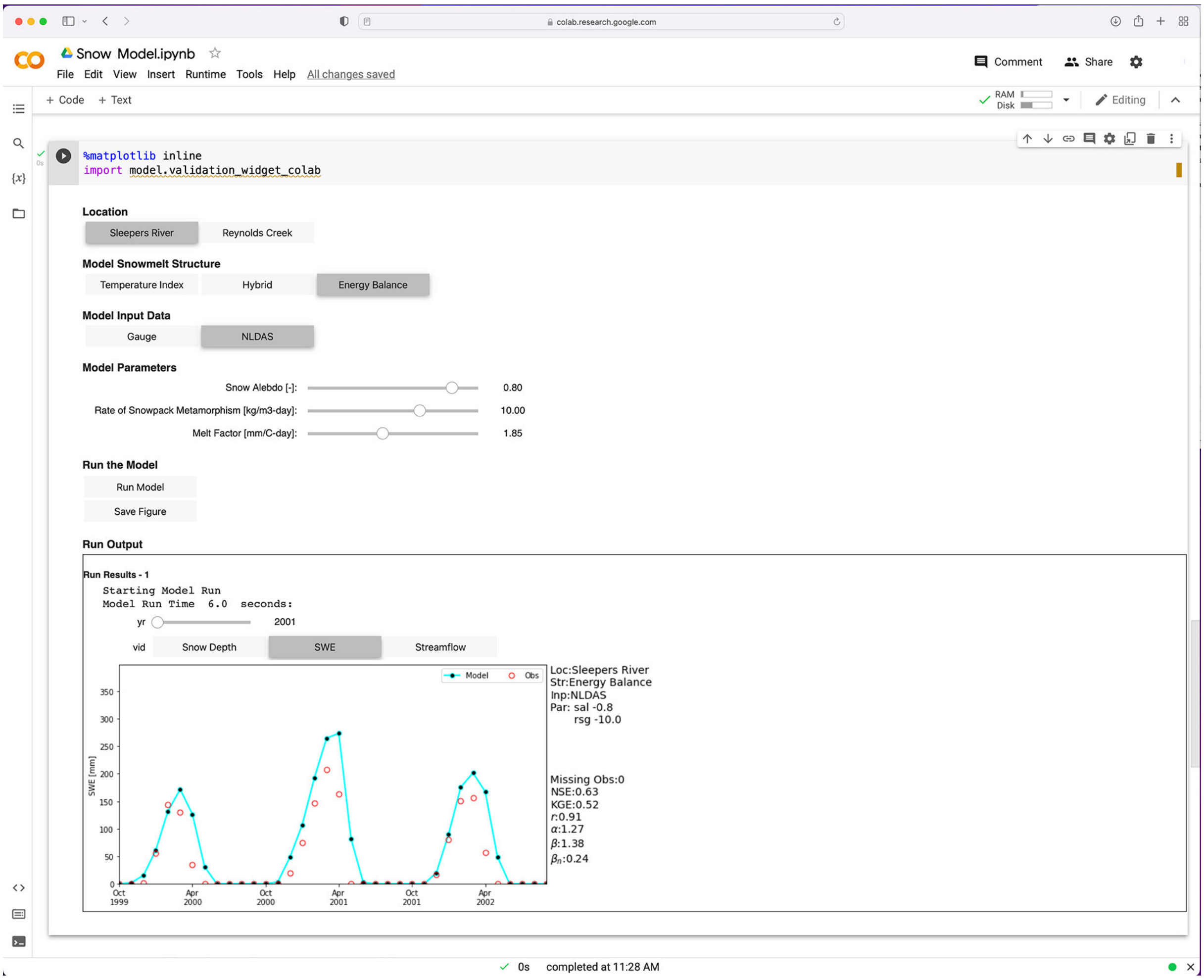

FIGURE 3
An example of a learning activity in the SCM that allows students to run different models and compare the model with observations in order to facilitate selecting a model that they will use for the final report.

selecting a model that they think is best. An example of this is shown in Figure 3. Once the students have selected and run their model of choice, they can then do a detailed comparison between their model and the observed snow depth, SWE and streamflow using monthly and annual statistics in the last two sections. Just like the previous activity, students can download images they create to include in their report.

Snow and climate

The Snow and Climate section introduces the students to climate modeling, the concept of downscaling climate models, using statistical tests to quantify statistically significant differences between two periods and analyzing temporal changes in snow due to climate. The five learning objectives for this section of the module are given below.

- Develop a technical vocabulary to describe climate models.
- Describe the downscaled climate model outputs used in the snow model.
- Utilize a difference in the means test to assess the statistical significance of model data over two different climate periods.
- An analysis of the temporal change of snow due to climate projections.
- Recommendations that are backed by both observations and models and that considers uncertainties in the snow model and changes in climate.

The same format of including text, figures, and videos is used in the final section of the module. The first part of this section uses several videos and figures to introduce the students to climate models and some of the key terminology. It also explicitly introduces the five climate models that will be used in the final learning activity. Next the module teaches the students about downscaling outputs from climate models and why it is important. The next section introduces using a difference in the means test to assess if there is a statistically significant difference in snow or climate variables between two periods. This is then followed by a series of questions to help students check their understanding. Like other learning activities throughout the module, students can complete these questions as many times as they need to ensure that they understand the key concepts. Lastly, the final learning activity is introduced using text and demonstration video. As with the other major learning activities, this last activity uses a self-contained Jupyter notebook to download the code and data needed to set up and configure the different components of the learning activity. This final learning activity includes three sections. The first section allows the student to explore the climate input data (Precipitation, Temperature, Humidity, Wind, Pressure, Shortwave Radiation, and Longwave Radiation) to the snow model by analyzing a timeseries from 1991 to 2050. In addition to downloading the figure, the students also have the option of downloading the data to a csv file so that they can perform statistical tests to determine which input variables show a significant change between the average value over the base period (1991–2020) and future climate (2021–2050). In the next section of the learning activity, the students can run the snow model from 1991 to 2050 using the climate forcing they explored and using the model structure and parameters that they identified in the snow modeling section. Once the students have run their snow model, they can download and analyze the changes in annual statistics of snow depth, SWE and streamflow using a difference in the means tests as well as using the figures generated in the final section of the learning activity. An example of this user interface is shown in Figure 4 which allows the students to explore the data and utilize the knowledge they gained in the module to complete the main objective in the form of a report that includes figures and analysis from all of the learning activities.

Module effectiveness

Data collection

To determine the effectiveness of the module, we collected and analyzed data regarding students' self-assessed learning gains and their motivation for learning before implementing the module (pre) and immediately after (post). We then analyzed these data to see if there were statistically significant changes from pre to post. Additionally, students were given the choice of completing the module independently or in groups and so we also chose to analyze the data to see if there were statistically significant differences from pre to post for students who completed individually as compared to those who completed in groups.

Course description

The SCM was implemented in a senior design course at a mid-western university during the COVID-19 pandemic in 2020 and 2021. The senior design course requires students to have taken a course in both Fluid Mechanics and Hydrology. In 2020 there were 47 students enrolled in the course and in 2021 there were 53. Both courses took place during the COVID-19 pandemic and due to involving regulations in the classroom the learning environment was different for each year. In 2020, the module was implemented during the last 2 weeks of the course which were after the Thanksgiving break and University regulations required that all content be online to reduce transmission from students traveling for the holiday. Therefore, the students in 2020 worked on the module individually and it was implemented as a fully online course even though the course was hybrid before the break. In contrast, in 2021, the course was back to normal in-person delivery with the only regulations being that masks were required in the classroom. For consistency, the SCM was implemented during the last 2 weeks of the semester which again occurred after Thanksgiving break. However, in 2021 students were given an option to complete the module individually or in a group. Students who completed the module individually did it at their own pace and were not required to attend class during the module portion of the class. In this sense the individual students completed the module similar to what would be expected in an online course. The students who chose to work in groups were required to attend class and work with their groups on the learning activities. The group size ranged from 2 to 3 students. The group work format is consistent with the learning style of the course. Even though students were allowed to self-select between working individually or with a group, it was a fairly even separation with 31 students choosing to work individually and 22 students selecting to work in groups.

All students in the class, both semesters, were invited to participate in the study and 33 consented to participate and had complete data. Of the participants, 61% ($n = 20$) identified as male and 85% ($n = 28$) identified as White.

Student-assessment of their learning gains

The Student Assessment of their Learning Gains (SALG) survey was created in 1997 and has continually been upgraded to promote greater clarity, consistency of language, ease of student comprehension, and to make the instrument adaptable enough to suit different disciplines and learning objectives (Seymour et al., 2000). We modified the SALG survey used in this study to align with the learning objectives of the SCM. Students participated in the SALG survey at two-time points, as they

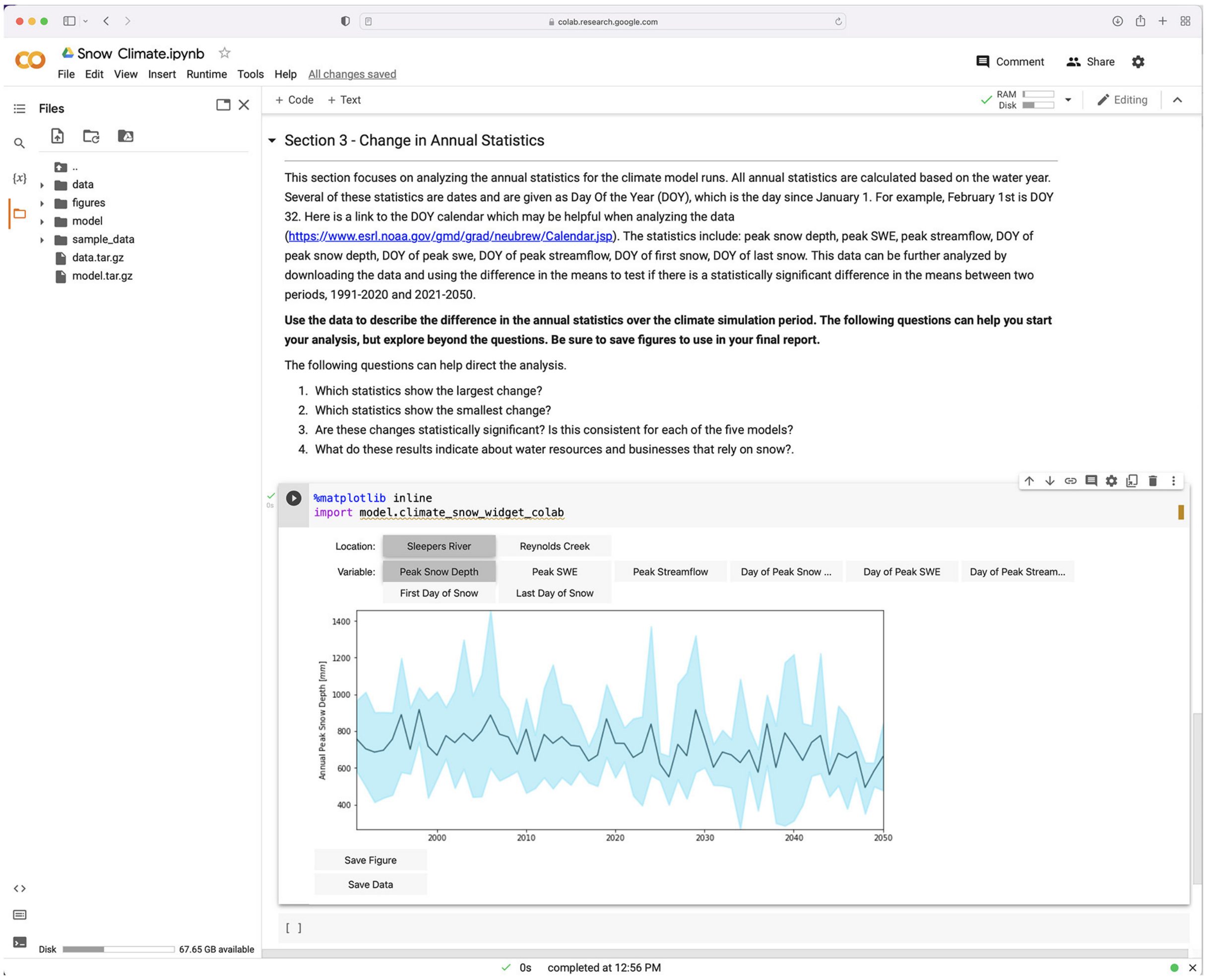

FIGURE 4
An example of the learning activity where students get to explore the change in the snow model outputs due to projected climate from 1991 to 2050. This final activity provides an opportunity for the students to apply the knowledge they gained throughout the entire learning module and complete the main objective.

were introduced to the module (pre) and after completing their final assignment (post). The survey consists of two parts that ask students to report their understanding of concepts and their proficiency in using technical skills pertaining to the module. The concepts items begin with, "Presently I understand the following concepts that will be explored in this module…" followed by items representing key concepts from the module. For example, in the Snow and Climate module, one concept item is "Snow terminology." The skills portion follows the concepts portion of the survey. The skills statement begins with, "Presently, I can…" followed by items representing the skills students learn using the module. An example of a skills item is, "Use Jupyter notebooks." Students rank each item on a 6-point Likert scale that ranges from 1-Not applicable to 6-A great deal. See Supplemental Materials for the full Likert scale and a list of the concepts and skills items for the Snow and Climate module.

Motivated strategies for learning questionnaire

Motivation is a key predictor of student learning (Caldwell and Obasi, 2010; Bong et al., 2012; Torenbeek et al., 2013). In particular, students can be extrinsically motivated by grades, rewards, or other external factors or they can be intrinsically motivated by their own interest in a subject or a personal desire to learn the content. Intrinsic motivation has been found to be a stronger predictor of student learning, as students are more able to use that internal motivation to persevere through challenges. The SCM was purposefully designed around an authentic problem to pique students' interest. Thus, we hypothesized that students would feel greater intrinsic value toward this problem as compared to traditional instruction. Additionally, students' motivation is also affected by their self-efficacy, their belief in their own ability to be successful (Schunk, 1989; Parker et al., 2014). The content in the SCM was carefully created to support students to be able to successfully complete the authentic problem by considering exactly what concepts and skills students would need exposure to before being asked to solve this problem. We hypothesized that these supports would enhance students' self-efficacy.

In addition to being purposefully designed to be motivating for students, the SCM also required students to engage in self-regulated learning. Self-regulated learning requires students to be proactive in determining what they know and do not know, and seeking out the support they need to master new content (Zimmerman, 1990). Students who are self-regulated use specific cognitive strategies, such as organizational strategies (Pintrich and de Groot, 1990). The SCM includes text, videos, and questions that support students' learning if those students are self-regulated and choose to take advantage of them. Therefore, students' success with the module depends on their ability to self-regulate and use cognitive strategies. We hypothesized that engaging with this module would support students' self-regulation skills and cognitive strategy use.

The Motivated Strategies for Learning Questionnaire (MSLQ) measures students' motivational beliefs and self-regulated learning strategies (Pintrich and de Groot, 1990). The survey consists of five factors, four of which we used in this study: self-efficacy, intrinsic value, cognitive strategy use, and self-regulation. The original MSLQ also contains a factor for measuring test anxiety; however, we chose to omit this scale because it does not apply to the SCM.

The two factors related to motivational beliefs are self-efficacy and intrinsic value. The self-efficacy scale has nine items that measure perceived confidence and ability in classwork performance (e.g., "My study skills are excellent compared with others in this class."). Intrinsic value, which includes nine items, refers to a student's intrinsic interest in and perception of the relevance of coursework, as well as a desire for challenge and goal mastery. An example item is, "Understanding this subject is important to me." Self-regulated Learning Strategies comprises two scales: cognitive strategy use and self-regulation. Elaboration strategies such as summarizing and paraphrasing, rehearsal strategies, and organization strategies are examples of cognitive strategy use. One example of the 13 items is, "When I study, I put important ideas into my own words." Finally, self-regulation relates to students' planning, scanning, cognitive monitoring, perseverance, and dedicated effort on difficult or tedious tasks and includes (nine items. An example of a self-regulation scale item is, "I ask myself questions to make sure I know the material I have been studying."

In total, students responded to 52 items that measure these four scales. We calculated each scale by taking the mean score of students' responses to items from each category. The order of survey items was randomized, and students ranked these items on a seven-point Likert scale (1 = not true of me at all to 7 = very true of me). The MSLQ used in this study is included in the Supplementary Materials Section.

Data analysis

We first conducted six paired samples t-tests to determine if there were statistically significant differences from pre to post on the two components of the SALG (i.e., the concepts and skills presented in the Snow and Climate module) and on the four factors of the MSLQ (i.e., self-efficacy, intrinsic value, cognitive strategy use, and self-regulation). We used paired samples t-tests to account for the dependence of observations (i.e., one student's scores from pre to post; Warner, 2012). To determine if there were statistically significant differences from pre to post based on whether the students chose to work independently or in groups, we first computed gain scores for each student and then examined two analyses of variance (ANOVAs), one each for gain scores on SALG concepts and SALG skills. We first examined the assumption of normality by examining histograms of all variables. All appeared normally distributed.

Results

Overall

On the SALG survey, we found statistically significant improvements for students in both concepts, $t_{(47)} = 15.05$, $p < 0.001$, with a large effect size Cohen's $d = 0.83$ (Cohen, 1988), and skills, $t_{(47)} = 9.94$, $p < 0.001$, with a large effect size Cohen's $d = 0.74$ (see Table 1). These findings suggest that not only did students improve in their self-reported learning of the concepts and skills in the module (which would be expected), but that the module had a very large effect on their learning, as indicated by the large effect sizes.

With regard to students' motivation for learning, we found no statistically significant changes from pre to post. There are several possible explanations for this lack of change. It could be that undergraduate students' self-efficacy, intrinsic value, cognitive strategy use, and self-regulation are fairly fixed, it could be that the module did not target these specific aspects of students' motivation, or it could be that because the timing of the post administration of the survey was on the final day of class and students were not feeling motivated.

Individual vs. group

When we tested whether there were statistically significant differences in the gain scores (computed by subtracting pre scores from post scores) between the two groups of students (i.e., those who chose to complete the module individually vs. those who chose to complete it in groups), we found no statistically significant differences for gain in concepts, $p = 0.39$ (see Table 2). However, we did find statistically significant differences for skills, $F_{(1,46)} = 4.27$, $p < 0.05$, partial eta$^2 = 0.09$ a medium effect size (Cohen, 1988). These findings suggest that students who chose to complete the SCM in groups self-reported a greater

TABLE 1 Means, standard deviations, and sample size on the SALG and MSLQ factors from the student assessment.

	SALG		MSLQ			
	Concepts	Skills	Self-efficacy	Intrinsic value	Cognitive strategy use	Self-regulation
Pre	2.98* (0.76) $n = 48$	3.75* (0.66) $n = 48$	5.03 (0.99) $n = 33$	5.30 (1.08) $n = 33$	4.66 (0.77) $n = 33$	4.58 (0.90) $n = 33$
Post	4.78* (0.69) $n = 48$	4.80* (0.63) $n = 48$	5.08 (1.18) $n = 33$	5.14 (1.06) $n = 33$	4.77 (0.82) $n = 33$	4.49 (0.91) $n = 33$

*p < 0.001.

TABLE 2 Means, standard deviations, and sample size on the SALG gain scores for individuals vs. groups.

	Concepts gain	Skills gain
Individual		
$n = 31$	1.73 (0.86)	0.89*(0.81)
Group		
$n = 17$	1.95 (0.79)	1.33*(0.44)

*$p < 0.05$.

gain in skills as compared to those who chose to complete the module individually.

Lessons learned

In implementing the SCM in the classroom for a senior design course in Civil and Environmental Engineering majors there were several lessons learned. First, the interactive and self-contained nature of the SCM received an overwhelming positive response from the students. This was qualitatively assessed by a discussion period on the last day of the class where the students took the post survey and after the survey there was a general discussion about the module. One of the specific comments from the students was that they appreciated the change of pace and the freedom to complete the assignment either individually or in a group. This flexibility allowed students to choose the learning method that worked best for them. From an instructor point of view, this flexibility in implementation was greatly appreciated especially during 2020 when the University required that the last 2 weeks of the course be fully online. With the sudden switch to online, it was relatively simple to adapt the SCM to an online format. The overall flexibility for the students and the instructor is one of the main advantages of developing course content using the Hydrolearn platform.

Overall, students appreciated the fact that they did not need to manipulate or write computer code in order to complete the activities, however, there were still some technical challenges. One of the quirks with using the embedded widgets within a Jupyter Notebook is that it can sometimes glitch and the widget can crash. When this occurs, the widget cannot be fixed by simply reloading the widget, but the Notebook environment needs to be restarted and then the widget can be reloaded. Restarting the Notebook does not erase the underlying data that was generated by the student, but it can disrupt the workflow and was only a mild inconvenience for most. However, for a few of the students who worked individually this glitch in the widget kept them from finishing the module, despite the fact that instructions for fixing the glitch were provided within each of the Jupyter Notebooks and discussed in class before the students started their individual work. This problem was only seen for students that worked individually, as those who worked in groups were more likely to ask group members or the professor about this issue when they ran into this while working with the module. When students were asked about trouble shooting this error, most had forgotten that it was discussed and did not bother to read the instructions in the Jupyter Notebook file. This indicates that more effort needs to go into clearly directing students on how to troubleshoot the activity when they run into an issue. One way this could be done is to include a section in the Notebook that is specifically labeled troubleshooting so that students know exactly where to look when encountering problems with the activity.

Another major finding from this study is that students reported large gains in their conceptual understanding and technical skills after participating in the SCM. Such large effect sizes (concepts, $d = 0.83$, skills, $d = 0.74$) far exceed the average effect size in education research ($d = 0.40$; Hattie, 2009) and suggest that this module may be particularly impactful on students' acquisition of these concepts and skills. These gains in concepts and skills mirror gains found for undergraduates completing other HydroLearn modules (Byrd et al., under review). Additionally, given that this module takes only 2 weeks to complete, these findings suggest considerable learning in a short time. We also found that the students who chose to complete the SCM in groups gained more in skills as compared to those who chose to complete the module individually. Because of the small sample size and research design, we cannot infer causality from these findings (i.e., we cannot infer that working in groups impacted students' learning of skills). It may be that students who were more likely to gain skills were also those more likely to self-select into groups. It may also be that the additional time in class working with their groups enabled these students to learn more skills. Nevertheless, these findings are interesting and warrant further investigation.

This module also demonstrates the effectiveness for creating active learning modules to teach key concepts of the hydrologic cycle and has the potential to be expanded to include further components of the hydrologic cycle and the impact of a changing climate on engineering design. One way this could occur is to expand the module to include other key components of the hydrologic cycle such as rainfall, soil moisture, evaporation, streamflow and groundwater. In fact, several HydroLearn modules on these subjects already exists and could easily be integrated together to create a semester long course specifically focused on the hydrologic cycle. Furthermore, there are also several ways that the existing SCM could be expanded to provide a more complete coverage of the many impacts of snow on engineering design and how it may evolve under climate change. One such addition would be considering the impact of changes to snowpack on the water supply by adding a reservoir component to the module so that students can assess water storage and the impact of climate change. The module could also be expanded to include further analysis on the impact of snow on scheduling and carrying out of engineering works. The SCM module could also be expanded to include a broader set of statistical tools such as trend analysis and time series decomposition in order to provide students with greater set of tools that would have broader impacts for engineering design.

Another lesson learned is that the development of this active learning module was a significant time investment. The majority of the time was spent developing the Jupyter Notebook widgets and the backend codes that integrated the snow models with the simple hydrologic model and the climate simulations. However, since these codes are freely available, they can be used as a basic framework for implementing new and extensions modules. Thus, making the development of another module similar to the SCS significantly less time consuming. Furthermore, the significant time investment required to create an active learning module in general, further emphasizes the importance and necessity for a curriculum sharing web-based platform like HydroLearn. While an individual may invest a large amount of time in creating a module, the overall benefit of those efforts will be justified if the module is utilized in many courses around the world. This sharing of content also provides a means of standardizing best practice and facilitating new ideas into the broader hydrologic curriculum. In this vein, the authors welcome suggestions, bug reports and additional expansion ideas as others implement the module into their own curriculum.

Overall, this work shows that complex and data intensive model applications can successfully be brought into undergraduate courses through Jupyter Notebooks and Google Colabs without requiring students to edit or write computer code or create complex computing environments to run models. This provides students with a unique learning opportunity to expand their knowledge of the hydrologic cycle and its interaction with climate. While this work used both *in-situ* measurements and climate model simulations to create the learning activities, the underlying hydrologic model is very basic and is only a simple teaching model based on roughly connecting key components of the hydrologic cycle. In the future, these applications should include models that have undergone years of model development and continue to evolve and improve through community development such as the Noah-MP (Niu et al., 2011) or the Community Land Model (CLM; Lawrence et al., 2019) land surface models. These models would provide students with a more complete set of modeling tools to explore the hydrologic cycle and would give students access to the state of the art in land surface modeling. While there are still several challenges to overcome to make this happen, including streamlining data requirements, reducing runtimes through more efficient computations, and setting up a more complex computing environments, this work illustrates the feasibility and a path forward for making this happen.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

JR developed the Snow and Climate module and was the primary author of the paper. MG analyzed the data and helped write the paper and JB helped collect and process the data and helped write the paper. All authors contributed to the article and approved the submitted version.

Acknowledgments

We would like to thank David Chandler, Emad Habib and David Tarboton for their guidance and feedback while developing the Snow and Climate Module. We would like to acknowledge the support of the National Science Foundation (NSF) under collaborative awards DUE-IUSE 1726965 and 1725989 Collaborative Research: Improving Student Learning in Hydrology and Water Resources Engineering by Enabling the Development, Sharing, and Interoperability of Active Learning Resources, which funded the Hydrolearn fellowship that allowed Dr. Roundy to create this module during the summer of 2020.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frwa.2022.912776/full#supplementary-material

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frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 05 August 2022
DOI 10.3389/fenvs.2022.876853

OPEN ACCESS

EDITED BY
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SPECIALTY SECTION
This article was submitted to Freshwater Science,
a section of the journal
Frontiers in Environmental Science

RECEIVED 15 February 2022
ACCEPTED 28 June 2022
PUBLISHED 05 August 2022

CITATION
Lowry CS, Dunkle KM, Kairies-Beatty CL, Arslan S, Stahl M, Bogie N and Cuthbert MO (2022), Groundwater origami: Folding paper models to visualize groundwater flow.
Front. Environ. Sci. 10:876853.
doi: 10.3389/fenvs.2022.876853

Groundwater origami: Folding paper models to visualize groundwater flow

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The training of geological scientists, more so than any other natural science, is dependent on how students learn to visualize and interpret complex three-dimensional problems at scales from micrometers to kilometers over time scales that span from seconds to centuries. Traditionally, our classrooms are at a disadvantage due to our standard two-dimensional use of whiteboards or slide decks. We are at an even bigger disadvantage when courses go to online education. While computer simulations and three-dimensional visualizations are used, they can lack the flexibility for students to perform free-form exploration. The novelty of this research is in the use of paper aquifer models and their implementation across seven academic institutions to provide three-dimensional physical examples for students to visualize subsurface geologic structure and quantify fluid flow through porous media. Students can cut, fold, and build three-dimensional hydrologic problems at home or in the classroom. Our methodology allows students to physically rotate their aquifer models to visualize cross-sectional areas, layer thicknesses, heterogeneity, and confining units. These foldable paper models provide a low barrier of entry for students to understand and quantify the relationships between water levels and geologic structure. Our experience using these models in both in-person and online classrooms highlights the advantages and disadvantages of these models. Results, although mostly anecdotal, suggest the paper models improve students' learning and enhance their engagement with the material. The formal evaluations of pre- and post-model implementation show that low-scoring students had the most significant gains after being introduced to the paper aquifer models. At the same time, there was no change in the number of students in the highest scoring group. Our experience in the classroom points to new opportunities to engage with remote learners and tools for supporting flipped classroom activities. Our vision for the paper aquifer models is to provide the hydrologic community with an additional tool to help bridge the virtual classroom gap, engage students, and help them develop mastery of three-dimensional problem-solving.

KEYWORDS

groundwater science, 3D visualization, instructional resources, online learning, origami

Introduction

Of all the natural sciences, the geological sciences arguably have the strongest association with multidimensional research problems (King, 2008). This can lead to difficulty in the training of future geoscientists as visualizing multidimensional problems forces students away from fact-based crystallized intelligence to more malleable learning using their fluid intelligence (Jaeger et al., 2017; Bresciani Ludvik, 2021). An example includes students learning to map dipping and striking geologic strata in order to build geologic maps, where they integrate fact-based identification of rock types and field observations to create complex three-dimensional representations of the subsurface (Ishikawa and Kastens, 2005; Clark et al., 2008; Kuiper, 2008; Chenrai, 2021). These are open-ended problems where students must integrate their knowledge across a range of information (Dickerson et al., 2005). Similar examples in the hydrologic sciences include interpreting geologic wellbore data to create aquifer maps or fence diagrams. In these problems, students integrate scientific knowledge from point locations to create three-dimensional models where flexibility in interpolation is led by expert knowledge and exact solutions are unknown. In such contexts, three-dimensional visualization is a core student skill and must be further developed in order to be successful professionals. Yet, as educators, we spend much of our time teaching in a two-dimensional world on whiteboards or using slide decks. We continue to evaluate students on their fact-based crystallized intelligence and do not open the opportunity for fluidity in student exploration of geologic problems. This gap increased as our classroom settings drastically changed in the face of online and hybrid instruction.

Difficulties in teaching three-dimensional thinking were exacerbated due to the COVID-19 pandemic as the majority of our educational system, for at least some period of time, was moved to online learning. This change forced a cohort of students to follow video lectures with limited hands-on or field opportunities. In addition, faculty were given limited time and resources to change the historical ways in which we teach (Garcia-Vela et al., 2020). The situation, although challenging, provided room for educational opportunities (Andrews et al., 2020) and the potential for a more inclusive community (Bursztyn et al., 2022). The abrupt shift to virtual learning set the stage for the advancement of new off-the-shelf teaching tools to reconnect students to hands-on opportunities to visualize and solve three-dimensional problems in the geosciences. Here we present the use of low-technology origami-inspired paper aquifer models and describe their use across seven academic institutions.

The motivation for these paper aquifer models is rooted in teaching the governing equations for groundwater flow. The application of three-dimensionality in groundwater science is directly connected to the formulation of Darcy's Law, accounting for the change in hydraulic head through space within a geologic unit and the cross-sectional area over which groundwater flows. While these concepts can be simple for students when dealing with visible sediment-filled columns, it becomes more difficult when translating to flow through hidden, subsurface, regional aquifer systems. These large regional aquifer systems represent a scale that can be difficult to visualize by the novice student and typically poorly illustrated in scientific reports, presentations, and on a classroom whiteboard. Our experience with students has shown across institutions that simple ideas like defining the cross-sectional area that groundwater flows through an aquifer can be extremely difficult to visualize by students. This cross-sectional area is often confused as being parallel to the hydraulic gradient, not perpendicular. This has led our group to think beyond two-dimensional illustrations and develop origami inspired three-dimensional paper aquifer models.

The origami inspired models were therefore developed to support the instructional need for students to visualize three-dimensional groundwater problems. The use of these models acts to slow students down in their attempt to search for an equation with the same number of variables given in a homework problem. The concept of students slowing down their minds to think and solve problems during COVID-19 pandemic instruction is a theme that may be a bright spot emerging in the literature (Phillips et al., 2021). Models are designed for students to make actual measurements using the model geometry and then apply these measurements to arrive at a solution. The value of these interactive teaching tools became increasingly apparent as many classrooms transitioned to online learning. Our group discovered that through these simple models, students are able to physically build models and explore concepts of three-dimensional groundwater flow in a much more open and tangible environment as compared to traditional assignments. Importantly, these paper models focus the students' attention on the physical conceptualization of the problem of interest—something that is easy for students to lose sight of when dealing with new concepts in solely text-based problems.

While computer generated three-dimensional visualizations are impressive, it is highly effective to supplement these visualizations with low-tech paper aquifer models. Additionally, in most computer models, two-dimensional projections of three-dimensional models are presented, which can be difficult to understand (Kuiper, 2008). On a practical level, these paper models take less time to prepare when compared to computer models and can provide flexibility in the types of problems that can be assigned to students. They can also easily be distributed to students as handouts or through email, removing technological barriers to access and use.

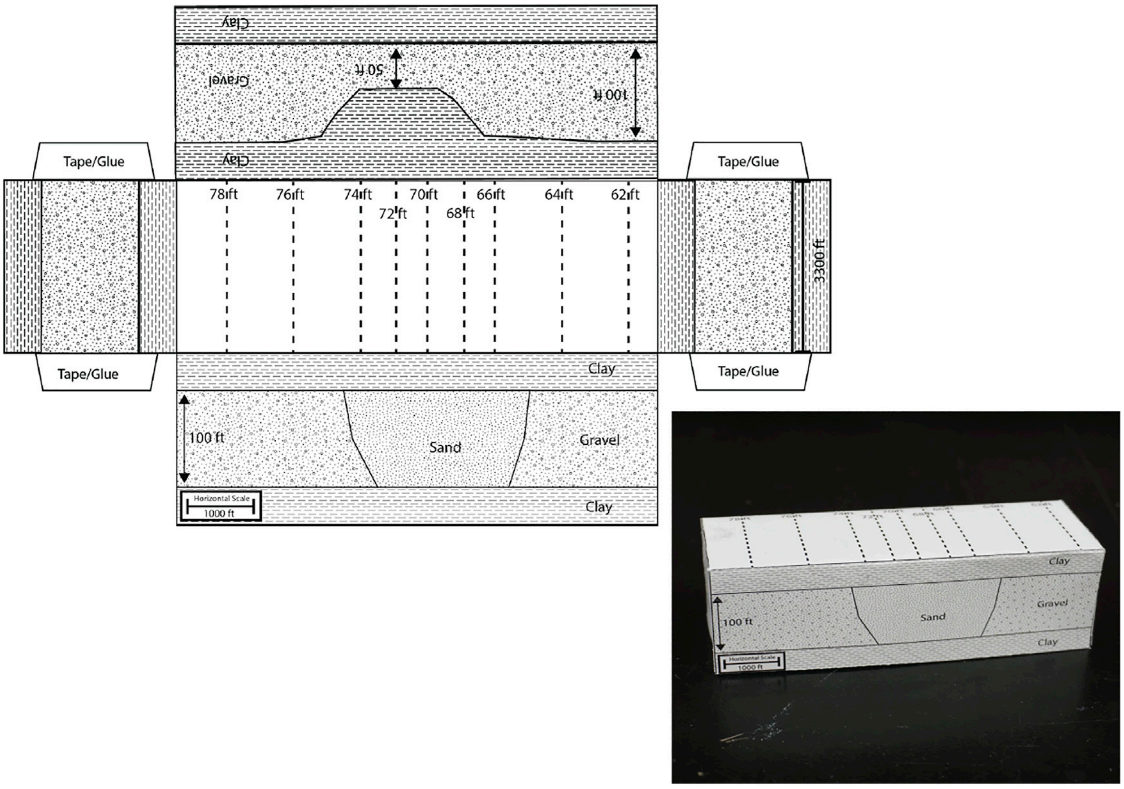

FIGURE 1
Example of a paper aquifer model used to illustrate the relationship between hydraulic conductivity, aquifer thickness, and hydraulic head in confined aquifers.

The motivation of this work is to present a new set of tools to help students visualize three-dimensional groundwater flow through a series of hands-on exercises, and to demonstrate and discuss their pedagogical effectiveness based on reflective practice in the classroom across multiple institutions and teaching settings. These models are simple to use and easy to adapt to a range of groundwater related assignments both in traditional and online classrooms. Our goal is to provide instructors with descriptions of where these models have been used and when these methods have been most useful. The contribution of this work can be applied to traditional and online classroom environments. We do this using an open science framework that allows users to take and adapt our models to a wide range of hydrologic problems.

Classroom methodology

The foldable aquifer models are based on rectangular cuboid paper models that are cut and glued together by the students (Figure 1). Each model has an associated problem set that can be used by the instructor, or instructors can choose to use the paper model by itself with their own specific set of questions. The current suite of models includes problems related to porosity/sediment packing, Darcy flux, radial flow, pumping tests, and image wells, with approximately 20 models in the initial offerings (Supplementary Table S1). Across most institutions, online students are expected to print out a given model and construct the model at home based on the provided instructions (Figure 1). In some cases, faculty were able to provide paper copies of the models to students in advance, and in one instance these were printed on card-stock and pre-cut. Unlike traditional hydrologic assignments, students must use these models to measure geologic thickness, hydraulic heads, and distance to boundary conditions, which are all drawn to scale. This reduces the ability of students to simply look at an assignment-provided set of variables and then find an equation where all variables are applied. Through building and then making measurements of a given model, students must use their full knowledge base to solve these assignments.

The barrier of entry for these models is designed to be low but can still create challenges for implementation. Students are given these models as single sheets of paper or are asked to print them out, then cut and glue/tape the models into their three-

TABLE 1 Institutional uses of origami aquifer models.

Institution/Classification[a]	Course title	Classroom implementation
Ankara University/Doctoral Universities	Hydrogeology	Homework assignments and in class examples
Austin Peay State University/Master's Colleges	Hydrogeology	Flipped classroom
Cardiff University, UK/Doctoral Universities	Water in the environment Water in the geological environment	Small groups (in person) tasked with finding the best solution to a relatively complex multi-part problem in competition with other groups
San José State University/Master's Colleges	Hydrogeology	In-class examples prior to hands-on or online labs
Union College/Baccalaureate Colleges	Groundwater hydrology	In class examples and group activities
University at Buffalo/Doctoral Universities	Hydrogeology	Homework assignments and flipped classroom
Winona State University/Master's Colleges	Applied hydrogeology	Homework assignments, flipped classroom group activities

[a]Carnegie classification of institutions of higher education.

dimensional form. Limited instructions are given as to the direction to fold the paper as the aquifer images are only printed on one side of the sheet. During the COVID-19 pandemic, limits to the adoption of these models occurred as some universities did not expect students to have access to printers at home (Becker, M. personal communication 9/28/2021). The literature shows that during the COVID-19 pandemic, the lack of printers in students' homes can be as high as 20% (Kanetaki et al., 2021). While this implementation is not perfect, most students had the resources and ability to construct these models with limited extra help from the faculty over various institutions (Table 1).

Across the institutions represented here, these aquifer models were applied to four general categories of course instruction: homework, flipped classroom, breakout rooms, and class projects (Table 1). Homework is defined here as a problem set designed to be completed outside the formal classroom environment. While flipped classrooms do not have a standard definition (Song et al., 2017), in this context, this type of classroom is defined by students learning terminology and baseline knowledge on their own at home through online lecture videos and readings outside of the scheduled course time, and then applying and developing that knowledge during course time through activities and discussions guided by the faculty in the classroom. Breakout rooms represent small group assignments embedded in traditional lecture format. Class projects are defined as comprehensive assignments designed to incorporate multiple modes of knowledge to solve a multi-step problem. Models were used in both in-person classrooms and remote learning from 2019 through 2022 and of varying course enrollments from eight students in-person to 101 students online. The majority of models were downloaded from the Foldable Aquifer Project web page (http://aquifer.geology.buffalo.edu) with the exception of those used at Cardiff University, which was specifically designed for an integrated class project. Not all faculty used the associated problem sets supplied with each aquifer model, some faculty chose to write their own problems based on a specific aquifer model.

The implementation across seven academic institutions represents a heterogeneous group of faculty implementing these paper models in the classroom. This project was not designed to be a pedagogical study. This implementation is a reaction to the need to engage students as many institutions went online due to the COVID-19 pandemic and, as such, describes our experience across a diverse range of institutions. This project should not be confused with the full-scale implementation of a curriculum and instruction educational research paper. In general, a qualitative assessment of the effectiveness of the aquifer models in the classroom is based on anecdotal feedback from students, except for the implementation of a formal evaluation of the flipped classroom implementation pre- and post-model use at Austin Peay State University. Anecdotal feedback comes from informal conversations with students, primarily during office hours, which is typically biased toward students struggling with particular concepts or problems. Feedback from students helped the instructors gauge the usefulness of these models and allow for modification of the implementation of these models in the classroom.

Results and discussion

The implementation of paper aquifer models across institutions represents a variety of applications; all focused on maintaining engagement. These simple models increase student participation in hands-on activities while retaining the universal desire during the COVID-19 pandemic to keep workloads affordable for teachers and students (Lepp et al., 2021).

Challenges across institutions have addressed formal classroom assessment techniques through the faculty transition to online education. This lack of classroom assessment was the norm during the pandemic, not the exception (Fisher and Tatomir, 2022). The results and discussion presented herein describe how these paper aquifer models were used and, when possible, document students' reactions and outcomes.

Homework

The original use of these models was as homework assignments, implemented by three of the seven institutions represented here, where students build and solve these problems on their own. Across the institutions, adoption of the models as homework assignments ranged from no use to using one model per homework assignment. As expected, participation among students was mixed, with some students folding every model while others did not fold the models but took measurements off the unfolded templates. In the case of students who did not cut out and fold the models, some students could still easily solve the problem. These students represent a group of students who already have the skills to interpret three-dimensional problems given a two-dimensional example. The rationale for not folding the models was to save time in completing the homework assignments, as described by one student during office hours. However, a group of students could not visualize the unfolded models in three dimensions and were unable to arrive at the correct solution early on in the course. In most cases, students learned from their early mistakes and took the time to fold the models.

In general, students enjoyed using the paper aquifer models used in homework assignments. All models were simple enough for students to construct independently without instructions. Those students who had the skills to visualize the problems without folding were not required to fold the model. Students who needed the models to visualize the problem fully did not complain about their use. An unforeseen advantage of using these models was the pride students took in building the models and then displaying them. This created a touch point where students were reminded of information presented in class long after a homework assignment was turned in.

Flipped classroom

The flipped classroom methodology was used in three of the institutions represented here. After watching the online videos and reading prior to class, students were then given the models and quantitative problems centered around the aquifer models to work with during class. These activities occurred several times throughout the semester at multiple institutions and students had positive responses to faculty members and teaching assistants actively interacting with students using the aquifer models in the flipped classroom format, including a willingness to be photographed with their models for social media. Written student feedback at the end of the course focused on the usefulness of the paper models; a representative example response stated "3D aquifer modeling proved its usefulness during the build-up toward our final project, which included an in-depth analysis of possible future locations for municipal wells in a fictional city. . ..models helped us visualize the aquifers' cross-section, thickness, and hydraulic gradient in a three-dimensional format, which was significant when studying the underground geology and analyzing the groundwater flow of the city..." At one institution, Austin Peay State University, formal evaluations of student learning pre- and post-use of the aquifer models in a flipped classroom format were evaluated. The instructor of the flipped hydrogeology course collected significant amounts of qualitative and quantitative data in order to determine the effectiveness of this flipped pedagogical change, with preliminary results indicating the flipped classroom increased students' persistence, learning, and attitudes toward the course (Dunkle and Yantz, 2021). The instructor has continued to collect these data, which allows for comparisons between the pre-paper model (Fall 2015; Spring 2017; and Fall 2018; $n = 35$) and post-paper model (Spring 2020 and Fall 2021; $n = 29$) iterations of the course. Students' learning was assessed through their scores on homework, quiz, and exam questions, while student persistence was defined as the motivation to complete all assignments. Results indicate that both learning and persistence increased with the use of the paper models for Darcy's Law and Storage concepts.

Signs of increased engagement in homework were observed as the percentage of students who attempted homework assignments increased. The largest gains in persistence occurred with a homework assignment addressing the concept of groundwater storage, with an increase from 80% of students' pre-paper models who attempted these groundwater storage problems to 93% post-paper models. Students' perceptions of their own learning for Darcy's Law were measured through Anonymous Learning Surveys, which showed minimal change from pre- to post-paper model implementation across all students (Supplementary Table S2). Results from the Likert scale questions for Darcy's Law (Supplementary Table S3) also indicated similarities in learning perception pre- and post-paper models, with minimal increases 1 week after the activity. Increased learning observations include gains in mean scores and a decrease in the number of students with low scores in homework, quiz, and exam questions (Supplementary Table S4). Most notably, the mean scores from three multiple choice final exam questions related to Darcy's Law and requiring calculations also increased from 60% (pre-paper models) to 76% (post-paper models). While there are limitations to this study given the small number of participants, the variety of data collected and overall results (Supplementary Material) indicate the use of these paper models may increase student's persistence and learning, especially in the longer term as indicated by larger gains in the final exam questions. Results of perceptions of learning indicate minimal differences, with the exception of an increase in topics related to Darcy's Law being least understood initially. This is likely due to an increased awareness of the topic due to the use of the paper models for calculating discharge and ultimately average linear groundwater velocity.

In-class example and lab prep

At San José State University, the foldable porosity model was used in an in-person setting to cover the general description of porosity as well as the associated problem set to derive porosity geometrically. While the use of the 3D model was not formally assessed, the scores for the subsequent lab assignment on porosity (the first lab of the semester) were higher in the Spring of 2020 (96 ± 9%, n = 9) when the model was not used than in the Fall of 2021 when the model was used (89 ± 7%, n = 8). While the grades did not show an improvement in the lab using the paper aquifer model, anecdotally, the model allowed students to visualize the concept of grain packing, review volume calculations, and also give them a hands-on 3D model to work with.

Zoom breakout rooms

One of the more challenging aspects of remote teaching is identifying ways to effectively engage students to actively participate in learning activities rather than simply turning off their cameras and tuning out. Additionally, for at least some students, the normal fear and anxiety of participating in a traditional classroom setting seemed to be amplified by the transition to virtual learning and the knowledge that if you contributed to a discussion or answered a question all eyes were looking directly at you.

At Winona State University, to promote an active learning environment where students felt comfortable participating, the paper models were used as part of Zoom breakout room exercises. After introducing a concept either with a short lecture over Zoom or following more of a flipped classroom approach, three to four students were sent to each of the breakout rooms (students picked up or were mailed hard copies of the foldable aquifers at the beginning of the semester) and asked to work on one or more of the problems that accompanied the model (students were told in advance which models needed to be cut out for class). After allowing the students an appropriate amount of time to begin to work on the problem, the instructor rotated through each of the breakout rooms to check on progress and answer any questions. In many cases when the instructor entered each room the students were chatting with each other and collaboratively working through the problem. Anecdotally, the models appeared to help students visualize important hydrogeological concepts. Perhaps more importantly, the models were a truly valuable mechanism by which students could connect with each other in the virtual environment.

Integrated class project

For use in two different MSc level classes (n = 24) at Cardiff University, a bespoke origami problem was designed to test students' ability to link a number of hydrogeological concepts together based on learning materials given in introductory lectures on various aspects of physical hydrogeology. The problem was based on the movement of a conservative contaminant within a layered aquifer system separated by a layered aquitard. This required them to first conceptualize, in 3-D, the overall qualitative nature of the likely flowpaths of a contaminant moving through the system both horizontally and vertically, based on supplied borehole data. They then broke the problem down into separate components for calculation by different individuals in their groups which included: a 3-point flow problem in different directions in each aquifer, effective hydraulic conductivity of the aquitard, and the direction and advective velocity through each layer. A final solution was required to be presented as to the likely location and timescale of the solute breakthrough at the edge of the model. Each group annotated their paper models and presented them at the front of the class for ranking as to the best solution, before a class discussion about the learning experience and clarification of any concepts which were not yet clear. The students clearly enjoyed the competitive and interactive nature of the exercise, seemed proud of their models, and showed a discernible development of their understanding throughout the class of the important concepts. Written student feedback at the end of the course described the use of the paper aquifer models as "...very helpful for visualizing the spread of contamination." General student evaluation comments described the use of these models as "fun," "interactive," and "engaging." In the subsequent mid-term anonymous module feedback this class activity was the one that the cohort singled out most often as positively facilitating their learning experience.

Conclusion

There are challenges associated with teaching the directly unobservable concepts of groundwater science due to the fact that groundwater is a hidden resource. This became even more difficult during a global pandemic where courses at many institutions were forced online. The role of visualization in learning basic hydrogeological concepts like Darcy's law is incontrovertible. Being novice learners of groundwater science, students need help while dealing with three-dimensional visualization of these concepts, no matter in which environment the courses are carried out.

According to the experiences gained by seven different faculty members in different institutions during Hydrogeology or related courses, the paper models presented in this study help with three-dimensional visualization and filled a much-needed deficiency in hands-on activities when courses went to online instruction. A combination of anecdotal and formal course evaluations showed that student learning is enhanced with the utilization of these models. The faculty noted the added value of students slowing down to take time to fold the paper aquifer models, slowing down to take more time to think about problems has been noted in the literature as a beneficial change during the COVID-19 pandemic. Results also show these models provided a second touch point as students took ownership in building these models resulting in the paper models sitting on desks and shelves. Across all seven institutions, there is clearly variability in participation rates. Based on interactions during office hours and informal discussions, many students who struggled with basic concepts seemed to appreciate the models. Some students who attended office hours did admit to not taking the time to fold the model. However, when these students were shown the folded models during office hours, all attendees appeared to recognize the value in visualizing the problems in 3D, and many went back and took the time to fold the paper model. As faculty, we are not naive enough to think that students do not take shortcuts, but it is nice to have evidence that struggling students went back and took the time to execute the problems as originally designed.

Across the institutions represented here, the overall perception was that the paper aquifer models were a constructive tool to increase student learning independent of the classroom format, assuming students took the time to participate. These results are primarily based on anecdotal evidence, with the exception of one institution that performed pre- and post-assessments. This generally low level of formal assessments by the faculty also follows literature trends during the COVID-19 pandemic, when faculty were just trying to survive. The formal evaluations of pre- and post-model implementation show that low-scoring students had the most significant gains after being introduced to the paper aquifer models. At the same time, there was no change in the number of students in the highest scoring group. These results need further investigation with large sample sizes but follow anecdotal evidence that students at the highest level did not need to fold the paper aquifers models to solve the assignments.

The open-ended nature of these paper models allows for highly flexible implementation, including customization. The paper models can easily be modified and designed to fit different classroom projects. They can be used as homework or implemented *via* flipped classrooms. In an online environment, the models were a valuable mechanism for students to connect within breakout rooms. They are small and easy to transport and add a novel and fun element to teaching. These models can even be employed in the field to aid students' understanding of the hidden groundwater resources if representative sites can be found. Most importantly, they are open to everyone.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

CL developed the paper aquifer models and framed the original manuscript. KD conducted the data collection and analysis of outcomes of the paper aquifer model use in the flipped classroom. All authors implemented the use of the paper aquifer models in the classroom. CK-B designed and implement the use of the paper aquifer models in zoom break out rooms. CL, SA, and CK-B implemented the use of the paper aquifer models in homework assignments. MS and NB implemented the use of the paper aquifer models using in class examples/demonstrations. MC designed and implemented the use of class specific paper aquifer models for use in an integrated class project. All authors participated in the writing and editing of the manuscript.

Acknowledgments

Mark Cuthbert gratefully acknowledges funding from the UK Natural Environment Research Council (NE/P017819/1).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.876853/full#supplementary-material

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frontiers | Frontiers in Water

TYPE Original Research
PUBLISHED 22 August 2022
DOI 10.3389/frwa.2022.909918

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OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Water and Hydrocomplexity, a section of the journal Frontiers in Water

RECEIVED 31 March 2022
ACCEPTED 26 July 2022
PUBLISHED 22 August 2022

CITATION
Gallagher LK, Farley AJ, Chennault C, Cerasoli S, Jourdain S, O'Leary P, Condon LE and Maxwell RM (2022) The ParFlow Sandtank: An interactive educational tool making invisible groundwater visible. *Front. Water* 4:909918. doi: 10.3389/frwa.2022.909918

The ParFlow Sandtank: An interactive educational tool making invisible groundwater visible

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Physical aquifer models are a highly effective teaching tool for hydrology education, however they come with inherent limitations that include the high cost to purchase, the static configuration of the model materials, the time required to visualize hydrogeological phenomena, and the effort to reset and clean them over time. To address these and other limitations, we have developed an interactive computer simulation of a physical aquifer model called the ParFlow Sandtank. In this gamified interface, users run the simulation using a familiar web-app like interface with sliders and buttons while learning real hydrologic concepts. Our user interface allows participants to dive into the world of hydrology, understanding assumptions about model parameters such as hydraulic conductivity, making decisions about inputs to groundwater aquifer systems such as pumping rates, visualizing outputs such as stream flow, transport, and saturation, and exploring various factors that impact real environmental systems such as climate change. The ParFlow Sandtank has already been used in a variety of educational settings with more than 9,000 users per year, and we feel this emerging educational tool can be used broadly in educational environments and can be scaled-up to provide greater accessibility for students and educators. Here we present the capabilities and workflow of the ParFlow Sandtank, two use cases, and additional tools and custom templates that have been developed to support and enhance the reach of the ParFlow Sandtank.

KEYWORDS

ParFlow, groundwater, online education, hydrology, subsurface

Introduction

Understanding the hydrologic cycle and how humans interface with and impact various components is paramount to our collective water future. Water is also a significant force in extreme weather and climate events, which continue to steadily climb in frequency and severity each year. The water challenges of the future are here and it is our responsibility to educate the next generation to make informed choices to respond and remain resilient to the changing climate.

In hydrology education, physical models are used extensively to teach a variety of concepts, from streamflow generation to climate change related phenomena. Schulz et al. (2018) developed an active participation experiment that gave students the opportunity to be conduits of water in a catchment, moving water through systematically using simple rules for flow routing, to generate a hydrograph. This activity used plastic balls to represent a unit of water, and students were arranged in different seating schemes to demonstrate how spatial differences in the catchment could impact the generated hydrograph. Although this group did not formally study the outcome, they determined that this activity positively impacted the learning experience of the students. Physical models are also particularly useful to visualize groundwater and subsurface processes since these pose challenges for visualization and are often ignored or underrepresented. Using a juice box to represent an individual pore of a confined aquifer, Singha (2008) developed a simple activity to demonstrate how pumping from a confined aquifer can potentially lead to subsidence. The concepts of aquifer contraction and water expansion were acknowledged to be difficult processes to understand, hence the motivation for Singha's model development. By working in groups to make observable connections between the effective stress, applied total stress, and fluid pressure, the researcher concluded that the juice box apparatus provided students with memorable ways to solidify these concepts in their minds. Finally, there are Darcy Tubes—plexiglass cylinders filled with porous material that can be used to demonstrate Darcy's Law. This demonstration tool has been used by many to teach foundational hydrology concepts (Werner and Roof, 1994; Nicholl and Scott, 2000; Neupauer and Dennis, 2010).

Our research team has relied heavily on physical aquifer models for education and outreach, which resemble an "ant farm,"—a rectangular box made of plexiglass filled with various geologic materials like gravel, clay, and sand. An example of this apparatus can be seen in Figure 1. Rodhe (2012) describes the use of this model type, to visualize and define a variety of features, including the water table, saturated and unsaturated zones, confined and unconfined aquifers, and flow lines and particle velocity. This tank model has been used extensively by Rodhe (2012), who concludes that these models are valuable tools for students and lecturers, and that the initial training on this teaching tool is a worthwhile investment. Singha and Loheide II (2010) took these sandtank models a step further by linking the physical model sandtanks with commensurate models in COMSOL Multiphysics. The authors' work was motivated by the fact that the geosciences have become

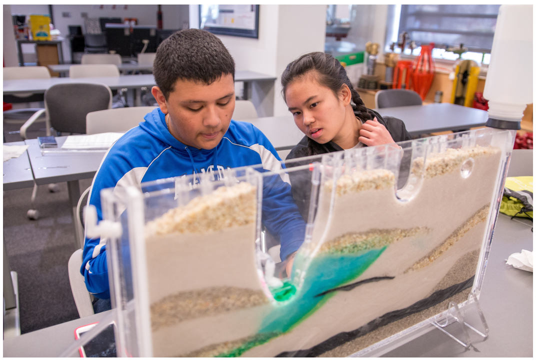

FIGURE 1
Students exploring groundwater scenarios using a physical aquifer model.

mathematically intensive, which results in challenges when developing pedagogical content to relate this demand to physically based processes they have learned about. The students participating in this coupled activity improved their understanding of the capabilities and limitations of numerical modeling.

Although these physical aquifer models are exciting and effective teaching tools for hydrology education, they have inherent limitations: (1) Users require access to the physical model; (2) models have a prohibitively high cost to purchase for many educators; (3) models often require trained personnel to deliver instructive lessons; (4) the required time to visualize hydrogeological phenomena and "reset" the system can be long; and (5) the static configuration of model materials does not allow for setup variety. To address these inherent limitations as well as the need for quick pivoting to online teaching during the 2020 COVID-19 lockdown, our team developed an interactive computer simulation of a physical aquifer model called the ParFlow Sandtank (PFST; Figure 2). Our development goal was to create an educational tool that could be used to achieve the same instructional goals as the physical model, while addressing the limitations described previously.

Although our development of the PFST began prior to the initial lockdown of 2020, we quickly saw that this tool could be highly useful under these rapidly changing circumstances that required educators to make extremely quick pivots to online teaching. In addition to the PFST model, we have developed a user manual, additional templates (described in Section Custom templates and additional functionality), and a machine learning teaching tool based on PFST, called Sandtank-ML (Gallagher et al., 2021).

In this paper, we provide an overview of the ParFlow Sandtank capabilities, workflow, and backend components, followed by a collection of sample learning objectives and two use cases.

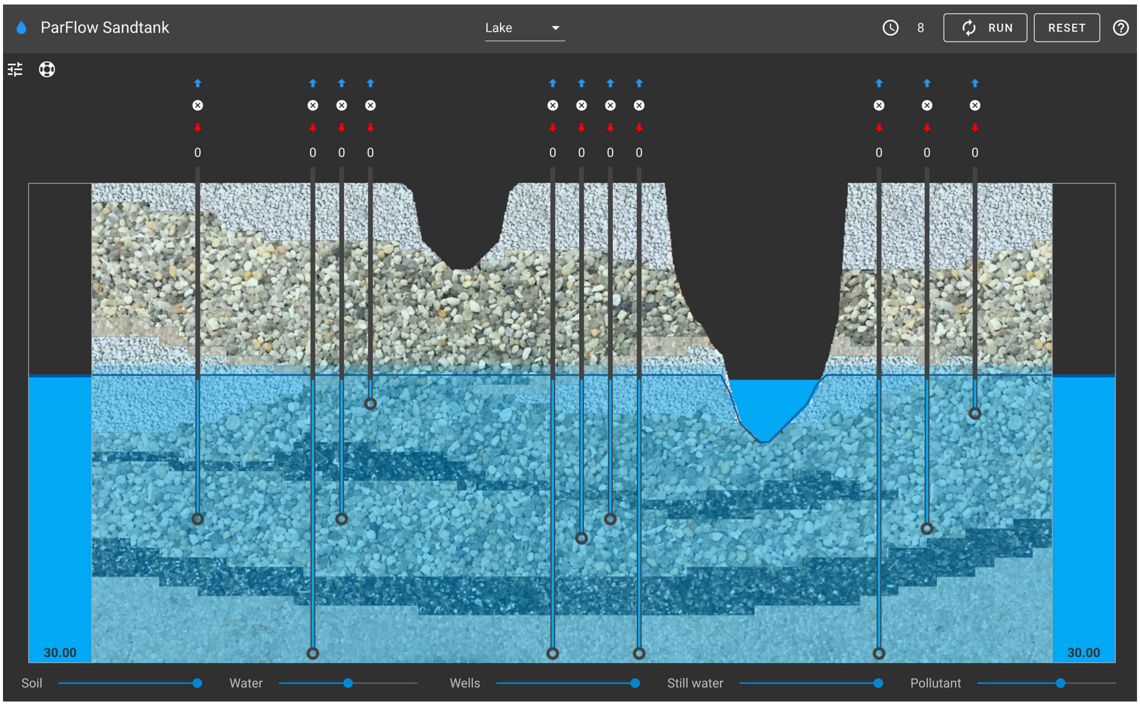

FIGURE 2
The ParFlow Sandtank model interface.

ParFlow Sandtank: Pieces, parts, and how-to

In previous sections, we highlighted the benefits and limitations of the physical model for delivering large-scale, complex hydrologic concepts to students. To create a competitive computational model replacement of the physical model, we must maintain the hands-on benefits of the physical model while addressing some of its limitations. Our computational model design focuses on integrated components to support dynamic domain configuration and client-server interactivity to achieve the primary hands-on requirement. The PFST components are described in each section below, they are a workflow that wraps all components in a gamelike interface, the ParFlow integrated hydrologic model used to simulate the physical sand tank model, and the EcoSLIM particle tracking code used to simulate dye injection *via* the well ports.

ParFlow Sandtank capabilities and application workflow

The ParFlow Sandtank has a game-like browser-based interface that builds upon open-source software components developed by Kitware (e.g., ParaView and SimPut), executing the integrated hydrology model ParFlow, using a framework built upon the widely used Python scripting language. Users run the simulation using a familiar web-app like interface with sliders and buttons, yet are learning hydrologic concepts. Our user interface allows participants to dive into the world of hydrology, making decisions about inputs to groundwater aquifer systems such as pumping rates and conductivity, visualizing outputs such as stream flow, transport, and saturation, and exploring various factors that impact real environmental systems. What makes this educational tool unique, is that the PFST is actually running ParFlow in the background, inputting user selections and generating real output. Additionally, our virtual slice of the subsurface, the PFST, overcomes many of the limitations of the physical model.

The default ParFlow Sandtank, along with highlighted features, is presented in Figure 3. First, we have the *water drop button*, which allows the user to toggle between light and dark backgrounds to aid in visualization. Feature 2 is the *Lake/River dropdown* menu, which provides the choice between setting feature 14 (lake/river feature) to behave as either a lake or a river, storing water or allowing water to flow freely from the feature. The *clock icon* is feature 3, which tracks the elapsed number of timesteps; each time the user clicks the *run button* (feature 4) eight timesteps will occur. Feature 5 is the *reset button*, which

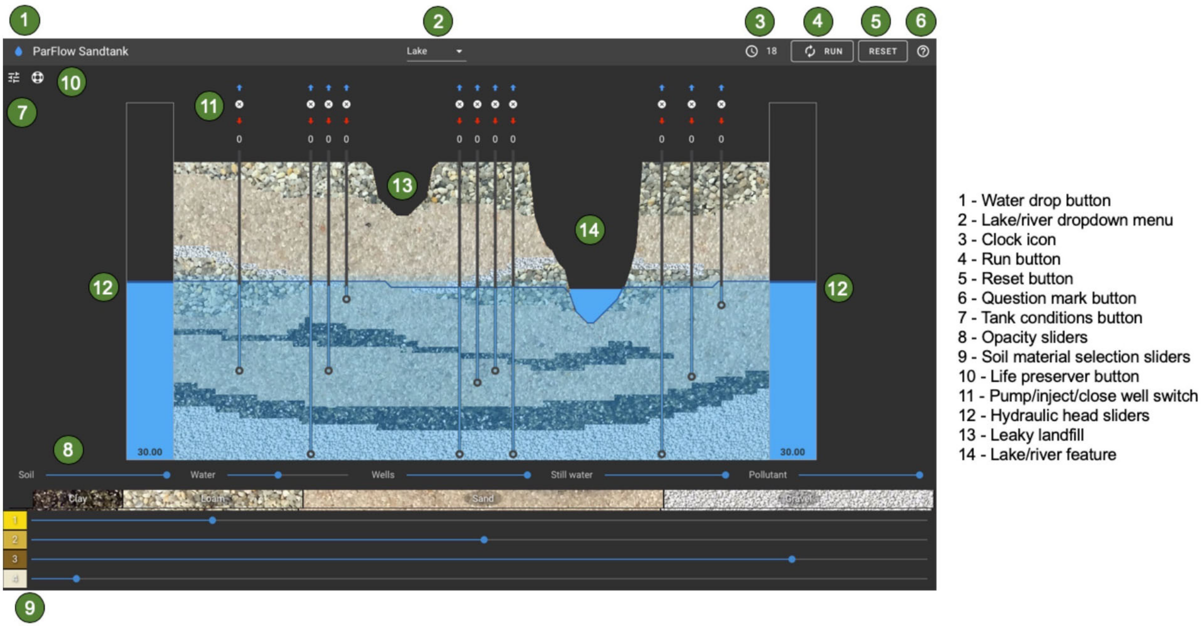

FIGURE 3
Feature identification for the ParFlow Sandtank (also found in user manual).

returns the *hydraulic head sliders* (feature 12) to the default setting of 30.00 (note that the geologic material settings will not be changed with the *reset button*; also the water table will not return to the default setting of 30.00 until the user also clicks on the *run button*). The *question mark button* (feature 6) has two functionalities: if the user clicks on this button, an informational box appears that provides general development information about PFST; If the user hovers their mouse over this icon, lake storage or river flow metrics are displayed depending on the toggle selection. Feature 7 is the *tank conditions button*, which displays features 8 and 9 to the user. The *opacity sliders* (feature 8) let the user change the opacity of the soil/geologic features, water, wells, still water, and pollutant. *Soil material selection sliders* (feature 9) provide the user with flexibility in the type and location of material in the model. Feature 10 is the *life preserver button*, which takes the user to the ParFlow Sandtank user manual on the hydroframe.org website. Feature 11 is the *well switch*, which lets the user pump water from each well, inject water/pollutant into each well, or turn the well off. The *hydraulic head sliders* are feature 12, located on the left and right side of the model. These sliders adjust how much and where water is added to the system. Next, is the *leaky landfill* feature (number 13), which can represent a landfill, wetland, or other feature with connection to the surface. The last feature is the lake/river feature (feature 14). Water interfaces with this feature based on the user inputs, as well as the specific feature toggle selection.

ParFlow

ParFlow is an integrated hydrology model that simulates (Kuffour et al., 2020) both variably saturated and subsurface flow (Jones and Woodward, 2001) and overland flow (Kollet and Maxwell, 2006). It has been applied to many domains worldwide and has a large active user and development community. ParFlow is open source, written primarily in C and is freely available on GitHub[1]. It has been developed to take advantage of parallel compute architectures (Ashby and Falgout, 1996) and runs on many architectures from laptop to supercomputer. Recently, ParFlow has been deployed in containerized environments, such as Docker and Singularity, to allow for easy deployment in virtual machine or cloud environments. For this application, ParFlow is built in a container and connected to other application components as detailed below.

EcoSLIM

EcoSLIM is a parallel, Lagrangian, particle tracking platform (Maxwell et al., 2019) that simulates advective and dispersive transport in variably saturated systems and has been extended to multi-GPU platforms (Yang et al., 2021). EcoSLIM is an

1 https://github.com/parflow/parflow

open-source platform that is actively under development and available on GitHub[2]. EcoSLIM uses the flux output from an integrated hydrology model (in this case ParFlow) to track parcels of water through a flow system. It has been used to determine source water attribution and for numerical (simulated) hydrograph separation (e.g., Bearup et al., 2016) or evapotranspiration. EcoSLIM outputs particle point information and volume averaged concentrations in the popular VTK file format[3]. In this application, EcoSLIM is used to track the water injected from wells, in the same way that injected food coloring dye is used in the physical aquifer model. EcoSLIM is also containerized and connected to the rest of the ParFlow Sandtank system as described below.

Custom templates and additional functionality

The ParFlow Sandtank allows users to develop customized templates in addition to the available default template. The default template is designed so that its layout and components are the same as the physical sand tank model, including features such as confining layers, both unconfined and confined aquifers, pumping and extracting wells, and other features discussed previously. By adjusting the input files or developing new ones, users can create custom templates and expand the utility of this educational resource. This process requires the same level of technical ability as is required to develop a ParFlow run.

Custom templates can be developed by altering features such as topography, subsurface configuration, well placements, initial head boundary conditions, and various visualization components. In the default sandtank model the topography includes a combined river/lake feature and a landfill/wetland feature. These features can be changed, and additional features can be added (e.g., a contoured domain surface). The default template subsurface includes four soil types and a subsurface configuration featuring a confining unit. The subsurface can also be customized by creating a new configuration. Eleven wells are featured in the default template with various locations and depths. Wells can be removed and added to a domain with the ability to specify their location and pumping depth. While the default template sets the left and right constant head boundaries equal at 30 m, these boundary conditions can be set individually and for any value. Finally, visualization components such as the background images of soil textures, the pollutant color, and the well injector arrows can also be customized.

The hillslope template which can be found on our project website[4] is an example of editing the default files to develop a new template. Detailed instructions of how to develop custom templates, as well as how to contribute templates can be found on our GitHub[5]. Additionally, hydroframe.org hosts custom templates called "Tucson TCE" and "Agrosystem," which each feature different capabilities. The "Tucson TCE" template represents a local aquifer in the Tucson area that has experienced historic TCE pollution and allows users to explore how the subsurface conditions of that aquifer impact pollutant dynamics in the subsurface. The "Agrosystem" template expands the reach of educational topics to include watering practices, crop choices, and other related agricultural decisions, as well as issues related to the changing climate. The "Agrosystem" template uses the same layout as the hillslope template (Figure 4), but builds upon the default sandtank capabilities. Users can adjust surface recharge to simulate different climate conditions, and select the irrigation and water use efficiencies to explore the impact of agricultural water use on the aquifer; it also generates additional output metrics of crop yield, revenue, and total storage of the system, in addition to the default river flow or lake storage metrics.

Design and backend functionality

Integrated components

The ParFlow Sandtank application consists of a client-side presentation layer that leverages server-side modeling, computational, and analysis services that encapsulates the advanced modeling and simulation workflow, including pre-processing, processing, and post-processing tasks. On the server-side, we have two types of services: one stateful and one stateless. A stateful service creates and uses a session to match the service process to a client. It stores state from client requests on the server itself and uses that state to process further client requests. A stateless service does not retain state but rather pulls necessary information from a database or file system to process client requests.

The stateful service provides the modeling and analysis services and leverages ParaViewWeb, which offers a full-featured infrastructure for controlling a stateful Python-based environment. From the ParaViewWeb based service, we can generate a ParFlow input deck from client-side modeling and access ParaView to utilize the visualization toolkit's (VTK) vtkPFBReader for reading ParFlow output for client-side analysis and visualization. In contrast, we use the ParFlow hydrologic model to simulate surface and subsurface flow on high-performance computers and EcoSlim to simulate the advective and diffusive movement of water particles for the stateless computational service that pulls the input deck from a co-located data store.

2 https://github.com/reedmaxwell/EcoSLIM

3 https://vtk.org

4 https://hydroframe.org/groundwater-education-tools

5 https://hydroframe.github.io/SandTank/docs/contributing.html

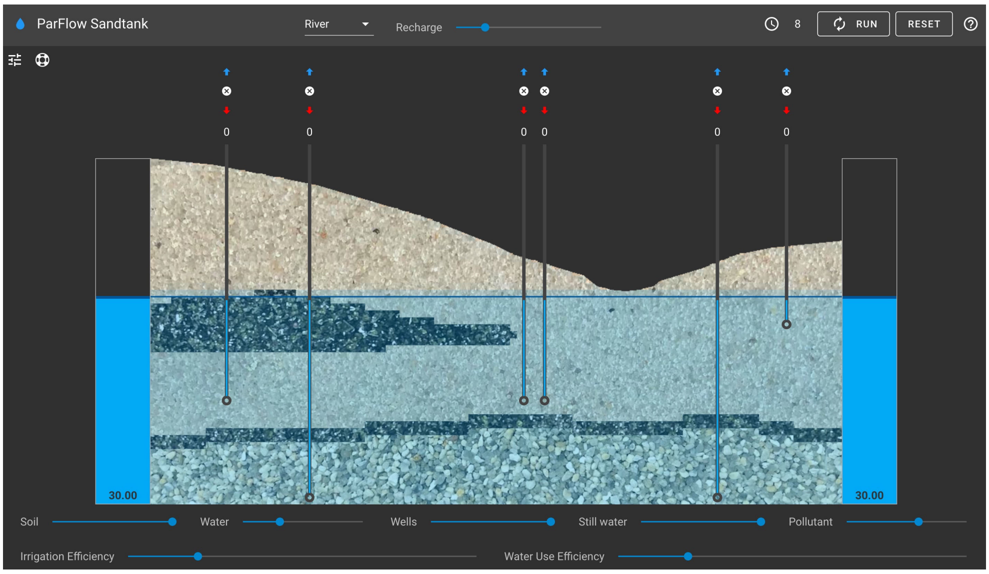

FIGURE 4
The ParFlow Sandtank Agrosystem custom template.

Client-server interactivity

Our JavaScript client-side presentation layer enables various end-user interactions with the computational model, including swapping out geologic material types, changing constant head boundary conditions, toggling between river flow and lake storage, and injecting, pumping, or closing a variety of wells. The run button requests the generation of the ParFlow and EcoSlim input decks from the stateful service, followed by a simulation request from the stateless service. Finally, the client can monitor and analyze the running ParFlow/EcoSlim simulation requesting data from the stateful service, which reads the current simulation output and forwards the relevant information back to the client. As depicted in Figure 5, the client-side web application goes through a middle layer launcher to start the interactive, stateful ParaViewWeb service when first visiting the web page or the stateless ParFlow/EcoSlim simulation service when pressing the run button. The remaining interactions utilize bi-directional communication directly between the client and stateful ParaViewWeb service using a WebSocket.

Deployment

The ParaFlow Sandtank application relies on complex software such as ParaView, ParFlow, Hypre, EcoSlim, and ParaViewWeb with a meticulous installation process that varies based on the operating system. To alleviate the requirement of the complex compilation of software for the deployment of ParFlow Sandtank, we leverage Docker. Docker allows us to create a reusable image where we pre-build all the pieces of ParFlow Sandtank to run on various systems. The docker image serves the web application and the infrastructure to run the complete advanced modeling and simulation workflow. This image provides a streamlined deployment and execution of the application. Using the simple command presented below will automatically download the docker image, hydroframe/sandtank, from DockerHub if it is not present on the target computer and run the application where the end-user can access it through HTTP on port 9000 using their browser.

$ docker run -p 9000:80 -it hydroframe/sandtank.

How can we use ParFlow Sandtank

The PFST has been used in a variety of educational settings since the abrupt shift to online teaching, from middle school to undergraduate level environments. This tool was used to introduce groundwater to middle school students to discuss the impact that agricultural practices have on groundwater quality and quantity. The educators we worked with for this event provided highly positive feedback about PFST, mentioning its game-like interface, which appealed to many of their students and allowed them to explore and visualize how groundwater behaves in the subsurface. Outreach events have also been a good setting for using the PFST. Our team has used PFST to teach remote lessons to high school age students, allowing them to work as small groups in breakout rooms to explore scenarios like groundwater-surface water connectivity, wetland dewatering, etc. Since the return to in-person teaching and outreach events, we have also had the opportunity to use the PFST at in-person events with high school students. We participated

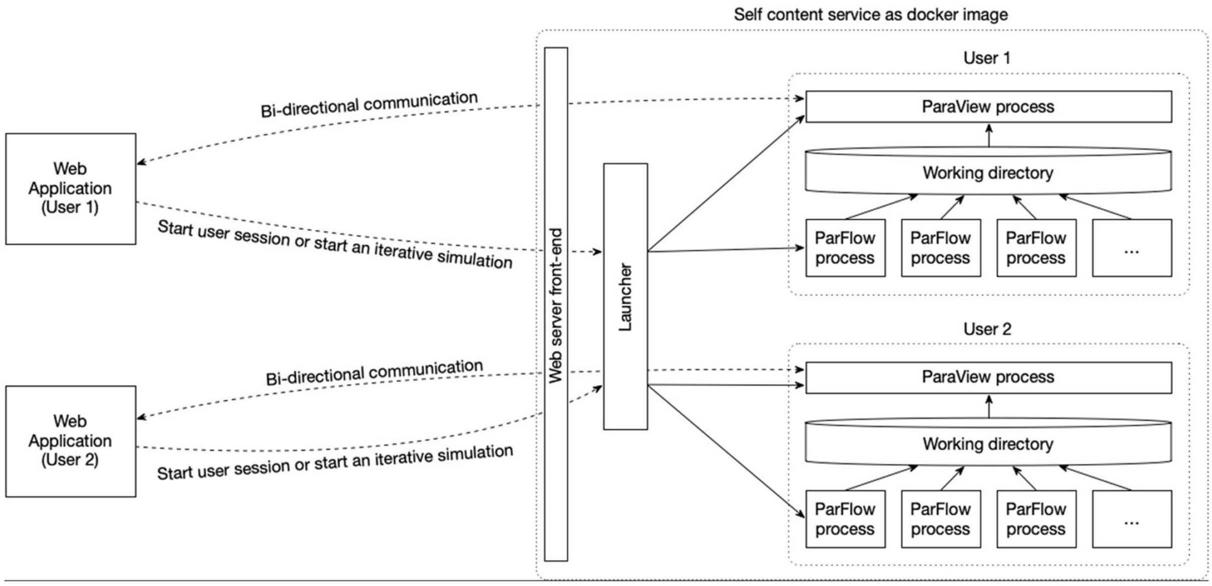

FIGURE 5
Communication pattern of the ParFlow Sandtank application.

in a week-long summer workshop, where students had the opportunity to explore the physical aquifer models first, learning about the water table, confined and unconfined aquifers, and concepts like saturation and recharge. After exploration with the physical models, students were introduced to the PFST and asked to walk through various scenarios to evaluate how water behaves in the environment. The participating students, in both remote and in-person settings, were highly engaged and many mentioned how much they liked learning about these concepts through this interface. The in-person students also found the introduction with the physical model helpful. Another educational setting example where PFST has been used is for undergraduate recruitment. This event was designed to highlight fields of study available to the undergraduate population at Princeton University. Students interacted with physical models and PFST; participating faculty and students responded with positive feedback, commending the highly interactive nature of the PFST tool and its ability to easily demonstrate concepts that are more challenging to visualize using the physical models.

Sample learning objectives

This is a list of example learning objectives and how to teach them using the ParFlow Sandtank. This list is not exhaustive, but provides an overview of the types of concepts that can be addressed using this tool. Additional examples can be found in user stories 1 and 2, which are based on real scenarios in which the ParFlow Sandtank has been used.

There are different geologic materials in the ParFlow Sandtank; these materials have different properties that impact how water is transmitted.

- Use the *soil material selection sliders* to vary the tank materials; users can choose clay, loam, sand, or gravel and compare how water is transmitted (pumping, pollutant movement, etc.).
- Hydraulic conductivity (K) is provided on a sliding scale for each material, so users can compare different materials or the same material with different K values.

Aquifers are areas under the ground that store and transmit water; there are two types of aquifers: (1) confined and (2) unconfined.

- Users can set up the PFST to have a confining layer of clay for material 4 (scroll below the PFST on screen to see the guide), creating a confined aquifer. Two wells in close proximity but in different aquifers can be pumped to visualize how the confined and unconfined conditions result in different dynamics.

The saturated zone is where all available spaces (pores, fractures, etc.) are filled with water; the unsaturated zone is where a mix of air and water fill the available spaces.

- Users can visualize the saturated and unsaturated zones by moving the "soil" *opacity slider* all the way to the left, completely removing the soil components from the system. This allows the user to see the saturated and unsaturated zones, with various shades of blue that represent decreasing levels of saturation that vary based on user input.

The water table is delineated as the upper surface of the saturated zone.

- The water table is represented by a blue line in the ParFlow Sandtank system. This line sits at the top of the saturated zone and can be visualized by users with or without geologic materials present. Users can adjust inputs, such as the *hydraulic head sliders*, pumping wells, or injecting pollutant into wells then see how the water table is impacted by each choice.

Surface water and groundwater are connected and interact with each other in many landscapes.

- This concept can be demonstrated by setting the *lake/river dropdown menu* to "lake" allowing water to collect in this surface feature. The user can then increase the *hydraulic head sliders* and visualize how the water enters the lake from below to fill the feature. The same concept can be demonstrated using the *leaky landfill* feature. Additionally, the concepts of recharge and discharge can be demonstrated using the *hydraulic head sliders* as well as the available surface features.

Groundwater can become polluted, which can impact drinking water supplies and surface water.

- When users inject water into any well in the system, pollutant will be viewable. This feature can be turned off by moving the "pollutant" *opacity slider* all the way to the left. Impacts of groundwater pollution can be demonstrated by injecting pollutant into a well, then observing:
    - Preferential transport based on geologic material type
    - Additional well pumping in vicinity and the impact on pollutant transport
    - Impact of continued pollutant injection vs. single injection.

User story 1: A basic hydrology lesson

Mx. Garcia is a middle school STEM teacher who has learned about the ParFlow Sandtank and wants to use the tool to teach their students some concepts in hydrology. First, Mx. Garcia uses the PFST to teach their students about saturation and the water table. In the PFST, the water table is delineated by a dark blue line sitting at the top of the water in the system. Mx. Garcia shows their students how to adjust the hydraulic head on each side of the tank, click on the *run* button, and watch in real time as the water table adjusts to the new inputs (Figures 6A,B). They teach their students that the water table is the upper surface of the saturated zone. Their students ask what the saturated zone is. In this case, Mx. Garcia would like to better visualize saturation in the PFST. To do this, they ask their students to remove the geologic materials from the system by moving the "soil" *opacity slider* all the way to the left, as displayed in Figure 6C. By removing the geologic material, this allows the students to see only the water in the system, displayed by cells as either saturated or unsaturated conditions. Mx. Garcia explains the difference between saturated and unsaturated conditions and uses the *hydraulic head sliders* to adjust water conditions in the system multiple times to show their students how saturation changes as the water input to the system changes. In this transitional zone, the blue line representing the water table can be visualized, sitting on the top of the saturated zone and the bottom of the unsaturated zone (note the water table line does not enter the river/lake feature, as the water in this feature is considered "still water" in the system and computed differently).

In another class session, Mx. Garcia would like to teach their students how and where water is stored underground. Our educator begins by discussing the different materials in the sandtank, highlighting the difference in the particles, spaces between particles, and how water is transmitted through each. They then use the PFST to show the difference between an unconfined and confined aquifer. As we can see in Figure 7A, Mx. Garcia has set up the PFST to have a confined aquifer, using a layer of clay as the confining layer. Above the confined aquifer is the unconfined aquifer, which is shallower and in contact with the surface. After explaining the differences between the aquifer types, Mx. Garcia uses the PFST to demonstrate that wells in different geologic units (i.e., unconfined and confined aquifers) respond differently to pumping, even when in close proximity to each other. For example, if their students pump 5 units of water from well G, Figures 7B,C shows the result: well G is completely emptied of water, the water level in well F drops significantly, but the water level in well H only drops a small amount. Even though well H is very close to well G, well H represents a different geologic unit and therefore is not as strongly impacted by pumping in well G (when compared to a well in the same geologic unit, like well F). Mx. Garcia instructs their students to continue exploring the various wells and how they are impacted by pumping water.

User story 2: Place based exploration

This user story is based on a classroom lesson developed by Dr. Alejandro Flores and used with his permission. Dr. Sandy Loam is a university professor teaching an undergraduate hydrology course and has built a lesson around the ParFlow

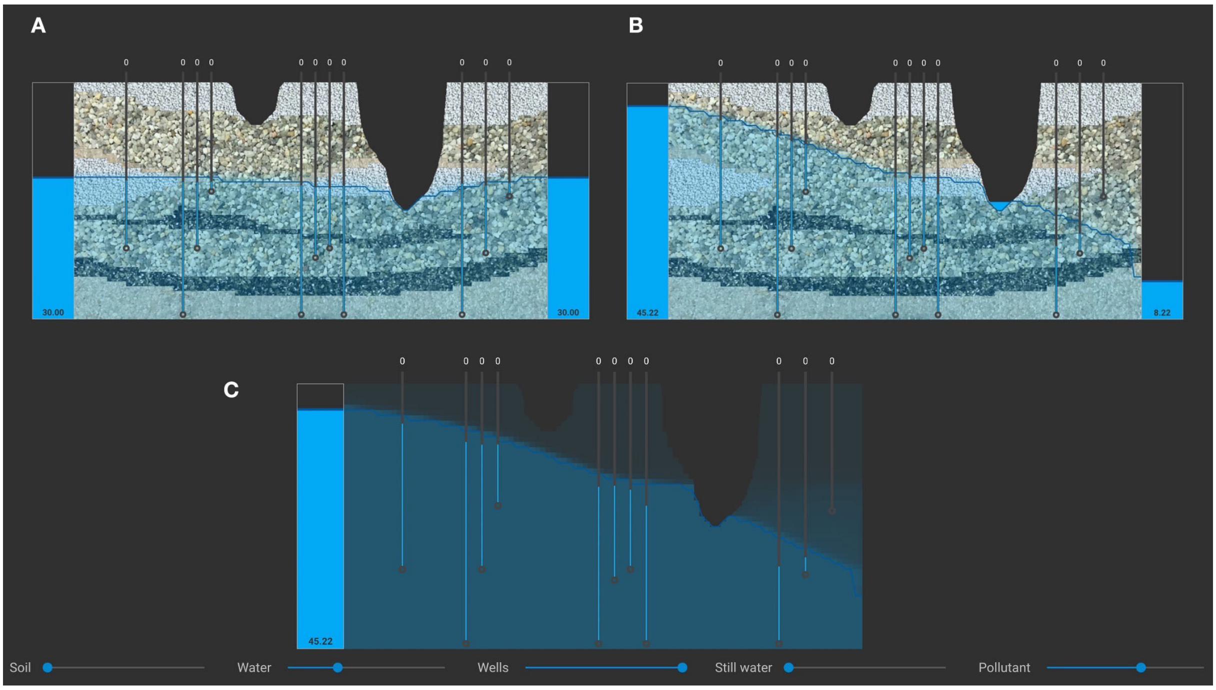

FIGURE 6
Mx. Garcia's demonstration of the water table responding to changing input. **(A)** Initial conditions. **(B)** Water table after user input adjustment and one timestep. **(C)** After removing the geologic materials the users can see saturation conditions in the PFST.

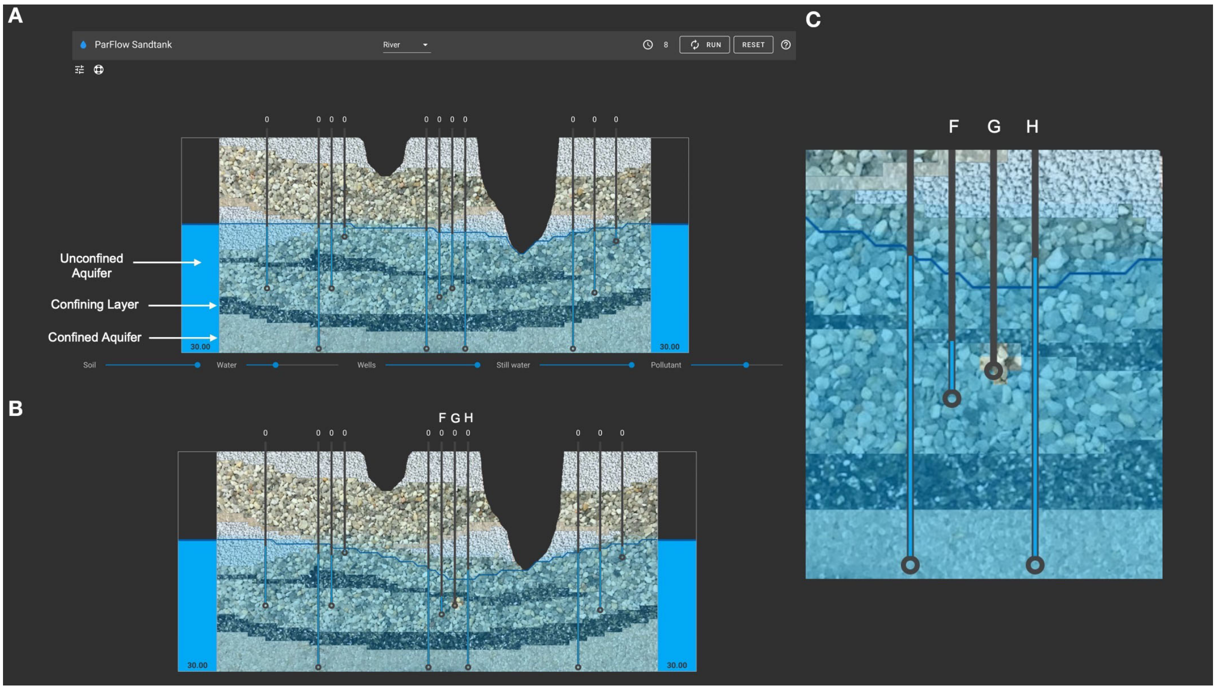

FIGURE 7
Mx. Garcia's initial ParFlow Sandtank setup and subsequent runs. **(A)** Initial setup of PFST showing a confined and unconfined aquifer. **(B)** Water levels in wells F, G, and H after students pump 5 units of water from the system. **(C)** Close up of water levels in wells F, G, and H after students pump 5 units of water from the system.

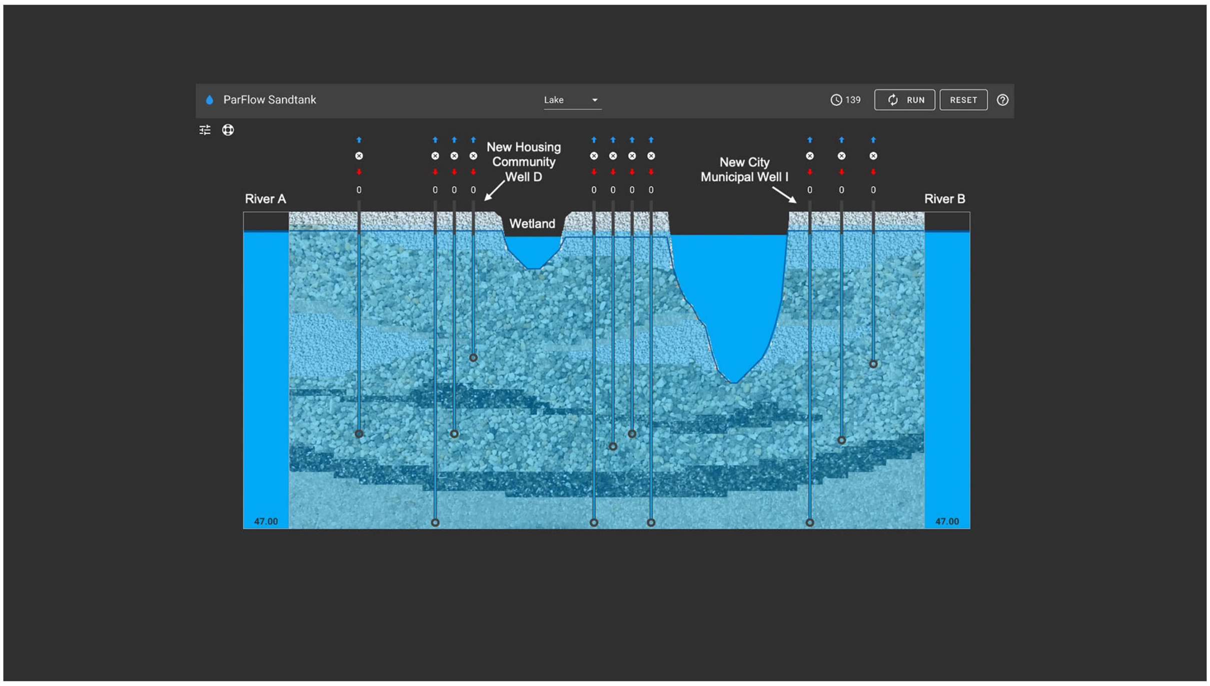

FIGURE 8
Labeled PFST features for Dr. Sandy Loam's lessons.

Sandtank. This lesson is designed for an audience with an understanding of foundational hydrology concepts prior to this activity. Dr. Loam designed a lab activity that uses the PFST to evaluate three scenarios to determine the cause of wetland dewatering in a local area (Dr. Loam uses specific rivers and locations based on her university location, but this can be altered to individual place-based lessons). For this activity, Dr. Loam describes a case where each student group is serving as a consultant to investigate the most likely cause of an increase in seasonal dewatering in a local wetland. There are three scenarios that the students explore: new housing community water use; climate change impacts; and increased groundwater demand from a nearby city (Figure 8).

Dr. Loam explains that in the first scenario a new housing community has been developed that is close in proximity to the wetland (Figure 8). This community has added to the demand for water in the area by utilizing a shallow well to pump water for community lawn irrigation, which is mostly done from late spring into early fall. Upon investigation, the students find that when they test various pumping rates (how many units of water are pumped from well D, a shallow well in close proximity to the wetland) that when the community pumps the maximum amount, the wetland is dewatered. Dr. Loam makes sure the students understand that well D and the wetland are in the same geologic unit and are therefore highly impacted by each other.

In the second scenario, Dr. Loam paints a picture of a decades long drought in the region that has resulted in less snowpack, leading to decreased flow in the river that plays a role in recharging the wetland of interest (Figure 8, River A). This scenario is of concern, for if it is the potential cause of wetland dewatering then it is likely to increase in frequency and severity. Students are instructed to simulate reductions in river flow by using the *hydraulic head sliders*, decreasing one side incrementally, running the model, then determining how low the river can go before the wetland is dewatered. This value can be compared to historical data to determine if climate change is the likely cause of the wetland dewatering.

Dr. Loam describes the final scenario, in which a nearby city has experienced significant growth and therefore increased demand for water (Figure 8). This led the city to drill a new well in a deeper geologic unit to supply additional water to the city's inhabitants. If this is the issue then the city may need to abandon the well and find other options, which may prove difficult. In this scenario, students are instructed to test pumping volumes up to 10 units from well I (a deep well in comparison to the well in the new community scenario). After testing different pumping rates from this well, the students determine that the city pumping from this well does not lead to dewatering of the wetland. Much like the community housing development scenario, Dr. Loam makes sure students understand that this well has a much smaller impact on the wetland because it is in a different geologic unit. Based on the exploration activity that the students completed using the PFST, they determine that the primary reason for wetland dewatering is over pumping from the shallow well in the new housing development; they also acknowledge that climate change can make the wetland more susceptible to dewatering as well.

These two user stories are just a small sampling of the concepts that can be demonstrated using the ParFlow Sandtank. Additional workflows and resources can be found on our project website[6].

Summary

This paper has presented the ParFlow Sandtank, an interactive educational tool that builds upon the utility of physical models to teach hydrogeology concepts, while overcoming inherent limitations. A key asset of the PFST is the variety of adjustable parameters and the subsequent real-time visualization of subsurface simulations. This can be used as a stand-alone tool or supplemented with additional teaching resources. ParFlow Sandtank is a freely available online tool that has proven to be useful in a variety of educational settings, and we hope it will continue to be used and further developed as more users with a myriad of specific perspectives and needs engage with the interface.

As we head into a future where water demand continues to outpace water availability, it is vitally important to have a society that understands the significance of this resource. Education of future scientists and engineers is one step in the right direction and the ParFlow Sandtank can contribute to this need by contributing to the collection of educational tools to support this effort. We invite you to explore the ParFlow Sandtank, a tool that will support deep dives into the world of hydrology.

Data availability statement

The ParFlow Sandtank is freely available and running on https://sandtank.hydroframe.org. The tool, along with associated resources, can also be accessed *via* https://hydroframe.org/groundwater-education-tools/ or on GitHub https://hydroframe.github.io/SandTank.

Author contributions

Conceptualization: RM, LC, and LG. Software: RM, LC, PO'L, SJ, and CC. Validation: RM, LC, PO'L, SJ, AF, CC, SC, and LG. Formal analysis and investigation: LG, AF, and SC. Resources, supervision, and project administration: RM and LC. Data curation: SJ and CC. Methodology and writing—original draft preparation: LG, RM, LC, PO'L, SJ, and AF. Writing—review and editing: RM, LC, PO'L, SJ, AF, CC, and SC. Visualization: PO'L, SJ, and LG. Funding acquisition: RM, LC, and PO'L. All authors have read and agreed to the published version of this article.

6 https://hydroframe.org

Funding

This work was supported by the National Science Foundation, Collaborative Research: Framework: Software: NSCI: Computational and data innovation implementing a national community hydrologic modeling framework for scientific discovery, under Award Number OAC-2054506. This material was also supported by the U.S. Department of Energy, Office of Science, Chicago Operations Office, under Award Number DE-SC0019609.

Acknowledgments

The authors would like to warmly thank and acknowledge Dr. Alejandro Flores for the adaptation of his contributed ParFlow Sandtank lesson exploring the potential causes of wetland dewatering.

Conflict of interest

Authors PO'L and SJ were employed by Kitware, Inc.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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frontiers | Frontiers in Education

TYPE Curriculum, Instruction, and Pedagogy
PUBLISHED 25 August 2022
DOI 10.3389/feduc.2022.959776

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OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to STEM Education, a section of the journal Frontiers in Education

RECEIVED 02 June 2022
ACCEPTED 02 August 2022
PUBLISHED 25 August 2022

CITATION
Hinckley E-LS and Fendorf S (2022) Field science in the age of online learning: Dynamic instruction of techniques to assess soil physical properties.
Front. Educ. 7:959776.
doi: 10.3389/feduc.2022.959776

Field science in the age of online learning: Dynamic instruction of techniques to assess soil physical properties

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Soil physical properties, such as soil texture, color, bulk density, and porosity are important determinants of water flow (e.g., infiltration and drainage), biogeochemical cycling, and plant community composition. In addition, they reflect the environment in which the soil developed, giving insight into climate, mineralogy, and land cover. While many soil assessments require sophisticated laboratory equipment, some can be made simply by a trained individual, requiring only practice and reference materials. For students in environmental fields, it is particularly important and empowering to learn how to make informed soil observations that provide insights from the soil pedon to the landscape and that can be done within the field setting. Drawing on updated pedagogical approaches, including active learning, small group collaboration, and metacognitive exercises, this paper presents a course module for teaching soil texture and color analysis in the field that can be modified for students from secondary through graduate school. The combination of asynchronous, pre-course readings and assessment; synchronous, in-class instruction, hands-on practice, and application activities; and post-class reflection give students the opportunity to build a strong foundation for making soil observations. This course module is suitable for both in-person and remote learning modalities and can be adapted to a number of course topics across environmental disciplines. Ultimately, the goal is to provide students with exciting, hands-on training that inspires them to learn more about soils regardless of the learning platform.

KEYWORDS

soil texture, soil color, remote online learning, active learning, environmental science, STEM education

Introduction

Accurately determining the biological, chemical, and physical properties of soils is critical to address questions across many environmental fields, including agronomy, soil science, watershed hydrology, biogeochemistry, critical zone science, and ecosystem science (see Rasmussen et al., 2018; Hammond et al., 2019; Soong et al., 2020). Often, assessing soil properties requires that samples be transported from the field to the laboratory for analysis (Gee and Or, 2002). However, observations of soil texture—the proportions of sand, silt, and clay—and soil color—an indicator of mineralogy and environmental conditions—can be made relatively easily and accurately in the field. While new Smartphone applications exist to diagnose some soil properties (e.g., LandPKS), developing one's own ability to infer information from soils based on training and expertise is valuable. It is helpful and empowering, particularly for students in environmental disciplines, to learn the simple, hands-on techniques that build confidence, capacity, and intuition in the field.

We developed the following course module to teach students interpretation of the soil texture triangle, the "texture-by-feel" method, and assessment of soil color. They combine their observations with concepts gained from asynchronous, pre-class readings to make informed guesses about the origins of soils that are previously unknown to them. We have taught this course module for many years and primarily in person (**Figure 1**), providing an engaging, tactile experience for students to learn about the world beneath their feet. However, when the COVID-19 pandemic began, we adapted it to the online (e.g., Zoom) learning environment. Even remotely, we discovered ways to make the exercise engaging, fun, and effective for achieving the desired learning objectives. We believe that it is applicable to a number of courses across environmental fields. The module can be adjusted to the focus of the course content, student level (middle school through graduate school and continuing education programs), as well as the nature of the program—from general science to research to professional programs.

Here we describe the complete course module and provide all supporting materials to teach it in person or using an online learning environment (see **Supplementary Materials**); both modalities provide multiple approaches to foster enthusiasm and curiosity about soils regardless of students' abilities or previous interest (Riener and Willingham, 2010). This approach to instruction is aligned with current best practices for increasing student learning outcomes, including: (1) flipped classroom, or assigning asynchronous pre-class content learning and assessment (Bishop and Verleger, 2013); (2) active learning or focusing on students tackling challenging activities during class, rather than listening to an instructor lecture (Bonwell and Eison, 1991; Johnson and Johnson, 2008); (3) small group work to build confidence, collaboration, and community (Towns et al., 2000); and (4) metacognitive exercises, or providing post-class opportunities for students to write and reflect on their learning (Dunlap, 2006; Zarestky et al., 2022).

Pedagogical framework

Overview

There are three main components of this in-class exercise: (1) *conceptual learning*—reinforcing the information that texture and color reflect about soils; (2) *skills building*—introducing hands-on techniques to assess soil texture and color; and (3) *synthesis/interpretation*—integrating background knowledge and evidence to determine the origin of unknown soils and the characteristics of the environment from which they came. Outside of class, students will complete pre-class readings and assessments, and post-class challenge questions and journaling to reflect on their experience and knowledge gains. This structure is consistent with flipped classroom learning, in which students come to class prepared with conceptual knowledge and can work on problems/skill-building more collaboratively (Love et al., 2015; Koh, 2019). Here, we describe the flow of the class. Depending on the length of the class period, instructors could complete this activity in one session (e.g., one 75-min to 2 h plus period), or divide it into two (e.g., two 1 h periods). It is possible to expand on one or more topics if the class time permits.

Students will come to class having read background materials on soil physical properties, as well as any topically relevant materials chosen by the instructor that link soil physical properties to broader concepts taught in the class (e.g., watershed hydrology, soil science, critical zone science, ecosystem science). This course module can be completed before or after a lecture or discussion about soil physical properties. Following the module, the instructor may choose to take the material in a number of different directions, depending on the focus of the course (as described later). However, we strongly recommend including the post-class metacognition activities (examples included in the **Supplementary Material**). We have found that having students examine their learning gains and skills acquisition not only helps to build their confidence and motivation, but also allows the instructor to adapt the following class periods to support student needs. These observations are consistent with multiple studies evaluating the use of metacognitive exercises throughout a course (e.g., weekly journaling), including Karaali (2015), Dang et al. (2018), McCabe and Olimpo (2020), among others.

Materials

Typically, we provide 3-5 unknown soils for students to use in this exercise. We have requested standard soils from

FIGURE 1
Undergraduate students **(A)** work collaboratively to describe several soil unknowns, **(B)** practice the "texture by feel" method, and **(C)** determine color analysis of soil unknowns. While these pictures show students learning the techniques in person, they can also be taught effectively using online learning platforms (Photos by E.S. Hinckley).

the Utah State University[1], or prepared soils local to our universities for analysis. Either source is useful: standard soils come with metadata and are already prepared for soil texturing, while local soils provide students with an opportunity to think about the soils' origin in a place with which they are familiar. When using local soils, we have often included 100% sand purchased from a local hardware store. Students might guess that this unknown comes from a beach or riverbank; the "trick" provides opportunities both to discuss the difference between intact, upland soil environments and others—a common misconception that upland soils are everywhere—and to handle an end member. When choosing unknowns, the key is to provide students with a range of soil texture classes to experience and practice their technique.

In addition to soils, students need a bottle filled with tap water (a sports-style squeeze bottle with straw works well), handouts explaining the techniques (see **Supplementary Material**), data table, and a copy of the Munsell color chart as a hardcopy book or via free application for Smartphones, of which there are several options available (e.g., Color Meter or Color Analyzer for iPhone).

1 https://agclassroomstore.com/soil-samples-soil-texture/

Preparation of soil unknowns

If the instructor is going to collect soils locally for this exercise, then they must be sieved through 2-mm mesh (rocks and organic matter removed), spread on pans and oven-dried at 105°C for 48-h. This procedure isolates the fraction that meets the standard definition of soil for texturing—the fine earth fraction that is ≤ 2 mm (Weil and Brady, 2016). If teaching this exercise using an online platform, it is necessary to divide each unknown soil into individual plastic bags (~200 g per bag) labeled with a code (e.g., number or letter) – and prepare one for each student. Each student will get 3-5 bags of (unique, unknown) prepared soil. If using soils obtained locally (not from a laboratory providing standards), then instructors will need to determine soil texture and color prior to teaching the activity.

The preparation and distribution of soils for this activity assumes that students will be able to pick up activity kits containing all needed materials from a central location (e.g., the university/college). If students are not able to pick up kits—for example, if they are not living near their school or university—it is possible to mail kits to them or have them collect bags of soil from their local area. Likely, they will not have access to soil processing equipment but could break up soils and remove coarse organic matter and rocks by hand, then air-dry the soils in an open bag until the class period. The instructor can discuss in class that this approximates properly prepared soils; the ability to practice and grow comfortable with determining soil texture and color will not be compromised, and it is possible to do the techniques properly and immediately with soil collected in the field.

Preparatory materials

Prior to conducting this exercise, students should complete background reading related to soil physical properties and their relationship to water flow, plant growth, and/or biogeochemical cycling. We recommend *The Nature and Properties of Soils* (Weil and Brady, 2016), Chapter 4: Soil Architecture and Physical Properties to cover the basics of soil texture and color (or equivalent). Additional texts could come from other topical areas, dependent on the focus of the course (e.g., watershed hydrology, ecosystem science, soil chemistry). The instructor may consider giving a post-reading quiz to assess students' assimilation of key concepts.

Learning environment

Learning objectives

This activity has four primary learning objectives:

1. Demonstrate ability to interpret the soil texture triangle.
2. Demonstrate ability to use the "texture by feel" method to determine different soil textural classes.
3. Demonstrate ability to determine soil color using the Munsell color chart (or Smartphone application).
4. Synthesize observations to make an informed guess about unknown soils' likely origin.

In-class exercise kits

Students will need:

- 3-5 prepared soil unknowns in plastic bags, labeled with a code (e.g., A-E or 1-5).
- Squirt bottle filled with water.
- Munsell color chart (hardcopy book or downloaded application for Smartphone, such as Color Meter or Color Analyzer for iPhone).
- Handouts with texture triangle, method for texturing by hand (as a visual flow chart).
- Assignment with instructions, question prompts, and data table.

Class plan

Students enter the main room of the online learning platform prepared with their activity kits. Worksheets that provide the instructions and data table for students' answers and interpretations may be completed online via a learning management system (e.g., Canvas or Desire2Learn) or hardcopy during the exercise, depending on the desire of the instructor. We suggest opening class by establishing small groups of three students who will work together during the breakout sessions. Students will be sent periodically into virtual breakout rooms to collaborate; the instructor, and, if present, teaching assistants, can visit these breakout rooms to check on students' progress and observe the quality of their technique.

After welcoming students, send them into breakout rooms to discuss their responses to the following prompts:

1. Why do we assess soil texture and color?
2. What can these measurements tell us about overall soil, ecosystem, or watershed function?

In ~10 min, return students to the main room and do a whole class report-out of their group's responses. Instructor and/or teaching assistants can fill in any additional gaps. This initial discussion establishes the foundation for the exercise and reinforces concepts introduced in the pre-class readings. Next, introduce the supporting materials for the in-class exercise, including how to use the soil texture triangle, read the flow chart to conduct the texture by feel method, and use Munsell color charts (see **Supplementary Materials**). At this stage, instructors may choose to give a couple of different combinations of percent sand, silt, and clay (summing to 100), so that students can practice reading the soil texture triangle; examples are also given in the worksheet provided in the **Supplementary Material**. Students may be sent into breakout rooms to practice using the soil texture triangle with their peers; smaller groups promote greater interaction in the remote environment and give the students opportunity to work through challenges together.

When the class is ready to practice the two hands-on techniques, let students know that they have bags filled with different (unknown to them) soils. First, they will determine the soil texture using the "texture by feel" method. This method uses a flow chart to guide them as they examine the soil's physical properties. The texture names on the flow chart correspond to sections of the texture triangle. In the data table, students will record their best estimate of the soil texture for each unknown.

A useful prompt for the texture by feel method is to instruct students to wet a golf ball-sized subsample of soil to the point where it develops the same consistency as cookie dough. Students will then follow the instructions on the texturing flow chart to "ribbon" the soil between their thumb pad and side of index finger to assess its clay content. As they move through the flow chart, they will also explore the "grittiness" of the soil by placing a pinch of the soil sample in their palm, wetting it to a soup-like consistency, then rubbing their index finger on the surface to estimate sand content. They will also rub a small amount of wet soil between their thumb and index finger to assess "slipperiness" or "smoothness", the amount of silt in the unknown (see **Supplementary Material**).

Second, students will determine soil color by wetting a small amount of soil (approximately the size of a pea) in one hand or on a finger and matching it to the appropriate color in the Munsell color chart. Generally, color is reported with its "wet" value. However, if determining soil color and one does not moisten it, then it would be important to report the value as "dry". At this point, remind students that there are three components of color: *hue* (spectral color, the page), *value* (lightness or darkness, labeled vertically on each page), and *chroma* (intensity, labeled horizontally on each page). Students should record these three components of color in their data table. The combination of hue, value, and chroma corresponds to a color name (e.g., 2.5YR 6/1 is "reddish gray"). The color name is on the page of the Munsell color book opposite the color chip. The instructor can have the students write the color name for each unknown soil in their data tables. Smartphone applications will provide this information, as well.

Finally, students will interpret the observations that they have made about each soil to determine the soil's origin and make an informed guess about the environment in which that soil exists/the soil creates. This final part of the exercise provides an opportunity for them to synthesize their knowledge, integrating concepts from their pre-class reading, as well as the observations that they have made for each unknown soil. Potential prompts include:

1. Does the soil likely come from an oxidizing (aerated) or reducing (water-logged) environment? (Hint: consider the color.)
2. How well does the soil likely hold water? (Hint: think about the size of the soil particles and the likely pore structure of the soil matrix when it is in an intact soil profile.)
3. Where did the soil come from in the soil profile? On the landscape? Geographically?
4. If students use soils that they collected near their home that were not provided by the instructor, then have them describe to their peers the characteristics of the soils, and have peers generate informed guesses about each soil's origin.

Following a brief demonstration of the two hands-on techniques and explaining how to make their informed interpretations of each soil, students can complete the three activities in their breakout rooms. This part of the class takes ∼40 min, depending on the number of unknowns. In our experience, students enjoy working through the flow chart and comparing ideas within their small groups; while this is going on, the instructor and teaching assistants can move in and out of breakout rooms to answer questions, check techniques, and redirect students, if necessary.

When all groups have finished keying out the unknowns and completing the worksheet, bring the class back to the main room for a whole class report out. The instructor can go through each soil unknown one by one and ask students what texture and color they selected and their interpretations of the soil's origin. These discussions tend to be lively, and, because students have worked in small groups, they participate readily with the support of their peers. If students found an unknown to be particularly difficult to decide on color or texture, prompt them to explain why. Similarly, when they offer interpretations of each soil's origin, ask them to explain their logic using background information from their pre-class reading or knowledge of the local area. For example, "I think this soil came from the base of a slope in the Colorado Foothills. It has a high clay content that is likely from accumulation of clay particles at the base of the slope, and some grittiness, which is likely contributed from the weathering of granodiorite bedrock."

We recommend that students discuss their interpretations in small groups and fill in their data tables with the group's final answers. However, they should each turn in their own work and acknowledge their group members.

After the students have completed this course module, the instructor may decide to have them explore questions that prompt further thinking (see **Supplementary Material**) or reflect on their learning experience in class with a metacognitive (e.g., journaling) activity. Such an activity can be used throughout a course, not just for one class period, to prompt reflection and solidify new concepts. In addition, student responses can be useful to guide the instructor in developing future iterations of the course; for example, to improve upon approaches to teaching the techniques for their particular population of students. Potential prompts for the journaling activity include:

1. What was challenging about learning these techniques for assessing soil properties and why? What was easier than you expected and why?
2. If you were assessing soil color and texture in the field (as opposed to from a sample in a bag), what

additional information would you have that would help your interpretations about the soil?

Reflections and synthesis

When the COVID-19 pandemic forced us to explore effective remote approaches to teaching hands-on techniques for assessing soil physical properties, we made three primary changes to the in-person approach. The first was that we needed to be more flexible regarding the example soils that students use for the texturing and color analyses. Some could pick up our pre-prepared (and keyed) soil unknowns, while others were home in quarantine and had to obtain their own. The latter challenged our goal of creating equal opportunities for students to explore synthesis and have productive group discussions. It is important to note that this flexibility was out of necessity; prior studies have noted that increased flexibility in learning approaches does not necessarily lead to higher learning gains (e.g., Thai et al., 2020). Second, using platforms like Zoom provided an opportunity for easy movement between small-group (i.e., breakout rooms) and whole class work. Thus, we incorporated more specific prompts and thought-provoking questions to ensure that students used their small group time effectively, consistent with documented research on social learning theory (see Yates et al., 2021; Yang et al., 2022 and citations within). Finally, because we could not show students the hands-on techniques in person and assess their skill mastery, we developed clearer, more relatable descriptions of the success metrics to communicate verbally and demonstrate in our own Zoom windows (e.g., Yates et al., 2021). For example, describing the ideal moisture content of the soil for hand texturing as "like cookie dough". Ultimately, we believe, such specificity improves in-person teaching and skills acquisition, as well.

During many years of teaching this course module, we have identified areas where students tend to encounter challenges, regardless of the learning platform (in-person or remote). Common pitfalls for students include not thoroughly wetting soils for the texture by feel method, causing misinterpretation of dry aggregates as sand grains; over-wetting soils, which can cause soil to fall apart and clay content to be underestimated; or working with an insufficient amount of soil in their hands. In addition, when interpreting the soils' origins, sometimes students will choose an environment that does not have an upland soil, such as suggesting that an unknown with a "sandy" texture is from the beach. However, we have found that even in the remote learning environment, these issues are relatively easy to identify and correct as the instructor and/or teaching assistants are interacting with students. Ultimately, we find that between completing this course module, as well as subsequent opportunities to practice (e.g., a practicum to assess their techniques), students can master their skills in soil texture and color analysis. The students self-report such learning gains, as well, and contrast even a remote experiential learning approach with having benefits over more traditional, lecture-based courses. For example, one student reported,

> *Being lectured on the differences in the physical characteristics of soil would not nearly have been as potent or memorable as actually participating in identifying several soil properties and types.*

Another student described how hands-on learning—even in the remote environment—helped the skills stay with them. They wrote,

> *When I learned about how water moves differently through a loamy sand versus a silty clay, there was a memory of the different textures that I had felt during the lab. Being able to reference the textures in my head allowed me to better understand why different soils influence different hydrological processes.*

The focus of the course will determine the follow-up activities that an instructor will choose to do. In our experiences, we have situated this class activity in a variety of ways. For example, one could follow with demonstrating other, more involved laboratory-based methods of soil texture analysis, such as the hydrometer method (Gee and Or, 2002). Alternatively, students could be assigned to take a field trip individually or with a partner to practice the skills that they learned, document their observations, and present them to the class. Such self-guided field trips have been used effectively in undergraduate courses within several fields (e.g., Shinneman et al., 2020; Middlebrooks and Salewski, 2021; Schwarzenbach et al., 2022). Still further, the information and skills learned within this course module could provide the basis for more complex material, such as learning about fluid flow and soil chemical transformations. Instructors may consider offering a practicum to assess the four stated learning objectives, and to provide follow-up training sessions, if necessary.

Regardless of the course focus, this activity provides a novel way to engage students in learning field methods—including through remote learning platforms—and has the potential to inspire continued engagement in a range of environmental fields. We have had many undergraduate students who have completed our courses with hands-on modules like this one and gone on to pursue an independent research project, or to apply to graduate school. For example, one student reported,

> *Doing hands-on classwork directly impacted my ability as a student and strengthened my resume when searching for jobs. My learning style is more direct and hands-on. So, when the learning material was presented to me in an experimental approach, I could retain the information better.*

Still another attributed learning these skills to success going on the job market:

> *I directly used the soil texturing and coloring skills taught in the lab in my first field-based job out of college. First, the activity gave me a direct experience that I could reference in my interview. Second, I had a solid foundation to build on because the field methods in my job used the exact same protocols (flow chart, texture triangle, and Munsell color book) as the lab. This meant that it took less training and time for me to become proficient with the method in my job.*

The majority of students who have gained hands-on training to learn about soils have simply discovered for themselves that the world beneath their feet contains a tremendous amount of information about place, and it is worthy of attention, appreciation, and conservation. The ability to cultivate such perspective, regardless of the learning modality, provides instructors with promising approaches to positively influence students' experience.

Author contributions

E-LH and SF designed the educational activities, developed the course materials, and wrote the manuscript. Both authors contributed to the article and approved the submitted version.

Funding

E-LH was supported on an NSF CAREER award (EAR-1945388), NSF Critical Zone Network Cluster award (EAR-2012669), as well as by the University of Colorado, Boulder's RIO Faculty Fellows Program Writing Group during the development of these course materials and writing of this manuscript.

Acknowledgments

We thank the many students who have taken their courses and used this module, helped them to refine it, and have gone on to pursue their own careers in environmental science.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feduc.2022.959776/full#supplementary-material

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frontiers | Frontiers in Water

TYPE Original Research
PUBLISHED 05 October 2022
DOI 10.3389/frwa.2022.958094

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OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Water and Hydrocomplexity, a section of the journal Frontiers in Water

RECEIVED 31 May 2022
ACCEPTED 08 September 2022
PUBLISHED 05 October 2022

CITATION
Jefferson AJ, Loheide SP and McCay DH (2022) Faculty perspectives on a collaborative, multi-institutional online hydrology graduate student training program.
Front. Water 4:958094.
doi: 10.3389/frwa.2022.958094

Faculty perspectives on a collaborative, multi-institutional online hydrology graduate student training program

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The CUAHSI Virtual University is an interinstitutional graduate training framework that was developed to increase access to specialized hydrology courses for graduate students from participating US institutions. The program was designed to capitalize on the benefits of collaborative teaching, allowing students to differentiate their learning and access subject matter experts at multiple institutions, while enrolled in a single course at their home institution, through a framework of reciprocity. Although the CUAHSI Virtual University was developed prior to the COVID-19 pandemic, the resilience of its online education model to such disruptions to classroom teaching increases the urgency of understanding how effective such an approach is at achieving its goals and what challenges multi-institutional graduate training faces for sustainability and expansion within the water sciences or in other disciplines. To gain faculty perspectives on the program, we surveyed (1) water science graduate program faculty who had served as instructors in the program, (2) water science graduate program faculty who were aware of the program, but had not participated, and (3) departmental chairs of participating instructors. Our data show widespread agreement across respondent types that the program is positive for students, diversifying their educational opportunities and increasing access to subject matter experts. Concerns and factors limiting faculty involvement revolved around faculty workload and administrative barriers, including low enrollment at individual institutions. If these barriers can be surmounted, the CUAHSI Virtual University has the potential for wider participation within hydrology and adoption in other STEM disciplines.

KEYWORDS

graduate education, hydrologic sciences, collaborative teaching, online education, differentiated learning, STEM

Introduction

Graduate-level courses offer students the opportunity to gain breadth and depth within a focused discipline. The hydrologic sciences are a broad field with roots in the geosciences, civil engineering, agronomy, soil science, forestry, environmental science and other allied disciplines. Faculty within the hydrologic sciences tend to specialize in niche subdisciplines spanning surface and groundwaters, quantity and quality issues, and field, laboratory, and modeling methodologies. Individual institutions rarely have departments devoted to hydrology or enough faculty to cover all of the subdisciplines at the desired depth for graduate coursework. In hydrology education, the need for complementary breadth and depth has been conceptualized as creating T-shaped professionals, who have depth of training in a specific area (the vertical bar of the T) and competencies across specialties (the broad, horizontal bar) (Uhlenbrook and De Jong, 2012; McIntosh and Taylor, 2013). Interdisciplinary water science and engineering programs that have emerged at the graduate level tend to embrace the concept of T-shaped training, but disciplinary education is still the norm at the undergraduate level and in many graduate programs (Harshbarger and Evans, 1967; Ruddell and Wagener, 2015).

Graduate programs also offer students more latitude to follow their interests in choosing courses and research topics than they may have been able to do in their time as undergraduates. In this way, graduate education is a form of differentiated instruction,which is a pedagogical framework that provides students with a range of different opportunities for learning new material in response to students' diverse interests and abilities (Tomlinson, 1999, 2001). Differentiated instruction can take the form of differentiating content, process, or product (Boelens et al., 2018). Differentiated instruction, however, is generally conceived as existing within a classroom (e.g., Tomlinson et al., 2003), and evaluation of differentiated instruction approaches within individual graduate courses has been limited (Santangelo and Tomlinson, 2009). At a graduate curricular level, differentiated instruction, through providing choice of courses and ensuring sufficient depth of training, requires faculty who are subject matter experts (Hopkins and Unger, 2017), and it often results in small class sizes for specialized subjects (Nelson and Hevert, 1992). The prohibitive costs of faculty teaching low enrollment graduate classes is a challenge for which online education may represent one potential or partial solution, especially in a collaborative, multi-institutional context.

Online education has become more prevalent over the past decade, including at the graduate level in science and engineering disciplines (e.g., Martínez et al., 2019). In a 2005 article about online teaching in the engineering field, the authors predicted that specialization and leveraging expertise among institutions would occur as online education in engineering became more common and would be used to drive down replication costs at multiple institutions (Bourne et al., 2005). The authors also recommend that engineering colleges continue to explore blended learning and partnership activities to enhance online education, thereby improving reach and access for students and improving the breadth of coverage of engineering courses (Bourne et al., 2005). To date, there has been no comprehensive assessment of the practice, trends, and potential for online education in hydrology specifically.

One type of online or remote education is multi-institutional classes. Multi-institutional classes are not new in higher education, and long-standing successful examples include classes in the less commonly taught languages (e.g., GLCA https://www.glca.org/faculty/shared-languages-program/ and Big Ten Academic Alliance https://lctlpartnership.celta.msu.edu/). Despite examples of successful multi-institutional classes and programs (e.g., Wang et al., 2005; Perkins et al., 2012; de Róiste et al., 2015), such classes remain relatively uncommon. Multi-institutional classes generally rely on distance learning technologies, and advances in technology over the past two decades, including learning management systems and video conferencing technology, have expanded the potential for multi-institutional education. Another advantage of multi-institutional classes, like online classes more generally, is that students can attend from different locations simultaneously (e.g., de Róiste et al., 2015). To provide continuity of instruction during COVID-19 pandemic restrictions, Virginia Commonwealth University's Department of Surgery initiated a virtual, multi-institutional collaborative lecture series to provide surgical residents access to synchronous lectures from experts at over 50 participating surgery programs (Metchik et al., 2021). While the program was discontinued as restrictions were lifted, Metchik et al. (2021) suggest that programs like this would dismantle disparities in surgical programs by increasing access to experts from a wide range of institutions.

Collaboration across institutions can also take the form of faculty learning communities and community-produced curriculum. Faculty learning communities are groups of faculty who collaboratively engage to enhance teaching and learning, through discussion, seminars, scholarship, and community building (Cox, 2004; Daly, 2011). Developing a faculty learning community for hydrology education and producing community-published curriculum and materials are among the "grand challenges for hydrology education in the twenty-first century" articulated by Ruddell and Wagener (2015). Previous efforts toward creating and sustaining faculty learning communities and curriculum were expressed in the Modular Curriculum for Hydrologic Advancement (Wagener et al., 2012) and special issues of hydrology journals (Missingham and McIntosh, 2013; Seibert, 2013). Several data- and modeling-driven education efforts have also been undertaken (e.g., Sanchez et al., 2016; Maggioni et al., 2020). The rapid transition to online and remote education in response to the

COVID-19 pandemic has catalyzed another flurry of innovation in hydrology education and formalized sharing of existing online hydrology education resources and efforts (e.g., Gallagher et al., 2022; Gannon and McGuire, 2022; Kelleher et al., 2022; Schwarzenbach et al., 2022; Thompson et al., 2022; Weaver et al., 2022).

This research aims to understand the perceived benefits and limitations of multi-institutional online graduate student training in the hydrologic sciences by examining faculty perceptions of an existing model from the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI). The CUAHSI Virtual University (CVU) model is one in which graduate students choose among multiple monthlong modules taught by subject matter experts (Loheide, 2020), thus adopting the pedagogical framework of differentiated instruction. Further details of the program design, history, faculty, and envisioned benefits are in Section CUAHSI Virtual University. We seek to determine whether the benefits to the CVU model are perceived as high by water science faculty, and the barriers to participation are perceived as low. If this is the case, the CVU model may serve as a template for multi-institutional graduate student training in other disciplines.

We focus on faculty perceptions, rather than those of the students, because faculty have control over course offerings and curriculum choices. To test the idea that faculty perception of benefits vs. barriers influences participation in multi-institutional graduate training programs, and therefore the success and sustainability of the programs, we surveyed both water science faculty who have participated as CVU instructors and a comparable number of water science faculty who have not participated in the program, but who were keenly aware of it through service on CUAHSI Board of Directors. Specifically, we sought answers to the following questions:

1) What do faculty perceive as benefits of CVU to participating students, faculty, institutions, and the water science community?
2) What factors influence a faculty member's decision to participate in CVU? Specifically, do faculty who choose to participate in CVU have different perceptions of benefits and/or barriers than those who choose not to participate?
3) What are the prospects for sustainability of the CVU model within and beyond water science?

CUAHSI Virtual University

Program design

CVU is an inter-institutional graduate training framework that was developed by CUAHSI with the goals of (1) increasing access to specialized hydrology courses for graduate students from participating institutions and (2) capitalizing on the benefits of collaborative training (Loheide, 2020). To enable the education of T-shaped hydrology professionals (Uhlenbrook and De Jong, 2012; McIntosh and Taylor, 2013), while acknowledging faculty limitations at individual institutions, CVU is based on the concepts of collaboration and reciprocity, in which institutions broaden their course offerings by leveraging the strengths of other universities. Loheide (2020) describes the origins and inspiration for the program.

Participation in CVU requires that a faculty member of each university offers a synchronous, 4-week, online module that covers 1-credit of content to students from any participating university (Figure 1). The subject matter covered in the module is typically based on recent research advances in the faculty member's area of expertise and is intended to be sufficiently specialized that it would be unlikely to be offered on a regular basis on most campuses. Each year 6–12 modules are offered, depending on the number of participating instructors. Each student has the flexibility to select the three modules that are best aligned with their interests and background knowledge, allowing students to differentiate their instruction (Figure 1). Specialized modules allow students to gain depth of training in a particular specialty of interest to them (i.e., vertical bar of T-shaped training), but they can also allow students to gain exposure to topics and skills in other specialties (e.g., broad and horizontal training).

Modules are taught in two 90-min synchronous class sessions per week using video-conferencing software, and instructional content is delivered through a learning management system. The structure, activities, and summative assessments of each module are designed by the individual instructor, but student-student interactions, collaboration and networking across institutions are encouraged.

While no specific pedagogy is required, many instructors use active learning approaches and inclusive practices, like whole-class and small-group discussions of journal articles and in-class collaborative assignments (e.g., jointly creating a shared Jupyter notebook). Participating faculty meet several times prior to the semester to discuss what teaching strategies have been successful in previous years based on student feedback and their own perceptions. These discussions allow instructors to build relationships with other faculty and their competencies related to online teaching. Prior to the widespread adoption of online instruction during the COVID-19 pandemic, CVU was the first exposure to online teaching for the majority of participating faculty. Beyond CVU, approaches for active learning in online science and engineering courses have been increasingly promoted and disseminated over the course of the COVID-19 pandemic (e.g., Harris et al., 2020; Venton and Pompano, 2021).

Students are expected to take three modules (typically 1 per month during a semester), typically earning three graduate credits at their home institution. Usually, the course appears as a class with a title similar to "Special Topics in Hydrology"

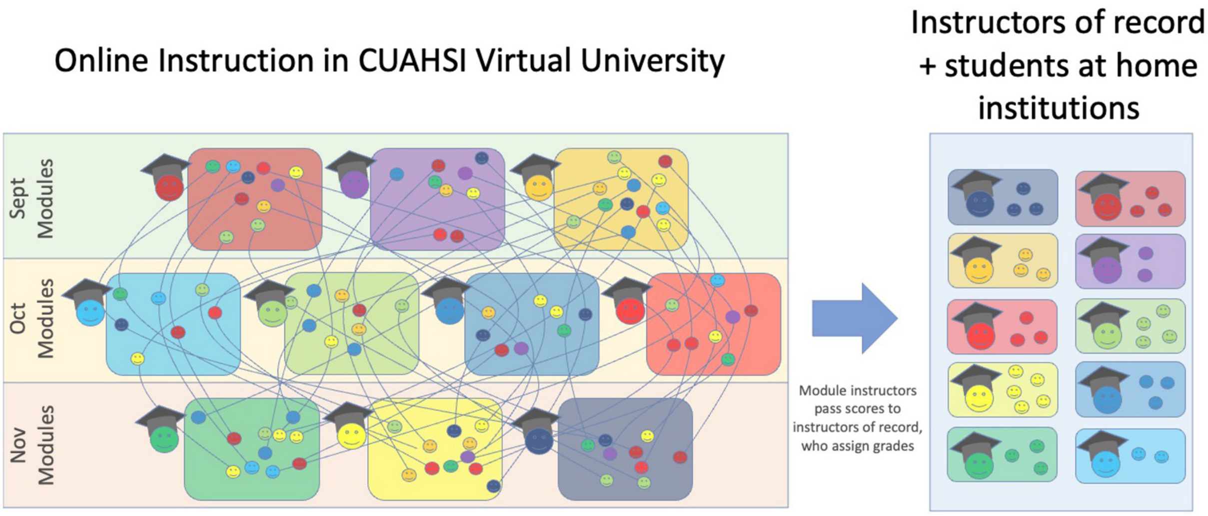

FIGURE 1
Instructors from participating universities teach month-long modules online to students (circles) from different institutions (represented by colors). Students choose the modules that interest them, resulting in differentiated instruction of content over the semester, as represented by the thin lines connecting the student icons. After the semester is over, module instructors pass scores to the instructors of record at each participating university, and these instructors assign grades to students from their home university.

in the course catalog at the home institution. The grade for the course is assigned by the instructor-of-record at the home institution based on the grading policies and culture at their university and the numerical scores that were assigned for all summative assessments (homework assignments, reading critiques, presentations, projects, quizzes, exams, etc.) for each of the modules taken by each student (Figure 1). In addition to the marks earned by students from each home institution and access to that students' work, each module instructor provides deidentified grade distributions to the instructor-of-record at the home institution.

While students take courses from instructors from across the country, it is important to note that no exchange of tuition dollars occurs, and students do not register at the other participating institutions. Rather, the students enroll at their home institutions and sign up for desired modules through CUAHSI. To maintain parity, institutional capacity is set to 15 students, and the module capacity is set to 45 students unless waived by the module instructor. To date, enrollments have never reached capacity.

CVU history and faculty

CVU started in 2017 with six modules offered to 44 students from six participating US universities. In 2021, 63 students, from 10 universities, enrolled in at least one of the 11 modules offered. Through 2021, a total of 286 graduate students have taken at least one CVU module and the average class size in a module is 15 students. Twenty-four unique modules have been offered through CVU, for a total of 43 modules taught between 2017 and 2021.

Through 2021, 23 faculty from 20 different universities have taught at least one CVU module. Of the participating universities, 19 have been located in the US and 1 in Europe. Twelve of the 23 CVU faculty have taught for 2 or more years. One faculty member has taught all 5 years. Eleven faculty have taught only one semester, with six of them being new participating instructors in 2021. Faculty departmental affiliations varied, with almost half (43%) coming from an earth sciences or geosciences-type program. Approximately 30% of faculty had an affiliation with an engineering department, while the remaining affiliations varied. Some faculty had multiple affiliations. Of the 19 US-based tenure-track faculty who have been instructors, four taught for CVU starting as assistant professors, six as associate professors, and nine as full professors.

Eligibility to teach a CVU module is limited to those who have standing as faculty members in graduate programs relevant to the hydrologic science. Participation in CVU is a bottom-up process initiated by interested prospective faculty, who then obtain permission from their institutions. CUAHSI solicits faculty participation starting about 1 year in advance, through its email list-serve and social media messages. Prospective faculty members submit a short application describing the proposed module and any prerequisite knowledge students would need, and each faculty member affirms that they have institutional permission to participate in the program. These applications are then reviewed and evaluated by CUAHSI staff and the CUAHSI

Education and Outreach Standing Committee. Evaluation is based on instructor eligibility, appropriateness of module scope for a 4-week session, and relevance of the module to water science. Feedback is provided to the potential instructor.

Envisioned benefits of CVU

Loheide (2020) enumerates the potential benefits of CVU participation for students, faculty, institutions, and the hydrologic science discipline. Potential benefits to students include (1) access to experts in specialized subdisciplines; (2) wider selection of course offerings; (3) networking and collaboration opportunities; and (4) development of new research skills. Potential benefits to participating faculty include (1) opportunities to teach in their research niche; (2) leveraging teaching effort; (3) ability to diversify educational opportunities for students; and (4) improved national visibility. Institutions potentially benefit from CVU through (1) increasing the depth and breadth of their courses, (2) improved national visibility; and (3) improved teaching efficiency. Finally, the discipline as a whole is envisioned to benefit *via* greater collaboration and faster dissemination of research innovations.

Methods

An internet-based survey was conducted using Qualtrics software in December 2021 and January 2022. Survey invitations were sent by email, with follow-up emails sent 2–3 weeks after the initial invitation. A survey was chosen as the appropriate method for this study to maximize the participation rate by minimizing expected time commitment for respondents.

Survey respondents were CVU instructors, their current department chairs, and 2017–2021 CUAHSI Board of Directors members. All members of the CUAHSI Board of Directors were faculty at institutions with graduate programs in water science, and therefore eligible to participate as instructors of CVU. Their inclusion in the survey is designed to represent faculty who were aware of CVU but had not participated in it as an instructor. Survey invitations were extended to 22 CVU faculty (participating instructors), 23 Board of Directors members who have not been CVU faculty (non-participating faculty), and 17 department chairs. The current chair of each instructor's department was contacted, regardless of who was chair at the time of CVU involvement. All survey responses were anonymous.

The survey covered faculty perceptions of CVU's benefits to participating students, faculty, and institutions, factors and concerns that influence the decision to teach for CVU, and potential benefits to the larger water community, aligning with the envisioned benefits enumerated in Loheide (2020) (Section Envisioned benefits of CVU). Survey questions were parallel where possible for participating instructors, non-participating faculty, and chairs. Our rationale for including non-participating faculty was to understand what factors influence faculty participation in multi-institutional graduate training programs and how perceptions of the benefits and barriers to participating in CVU might differ between water faculty who have and have not participated in the program.

Participating instructors were also asked the number of semesters for which they have taught in CVU, their plans for teaching in it again, and how their perceptions and concerns about teaching in CVU may have changed after they taught in it. Non-participating faculty and chairs were asked about their level of familiarity with CVU. Finally, all respondents were asked how CVU and the COVID-19 pandemic changed their perception of online classes. Survey questions are available at https://www.hydroshare.org/resource/2372f0c0a90d4061ae7f50a7f2a01cbd/.

Fisher's exact test, a non-parametric test similar to the Chi-square test useful for small datasets, was used to test differences in response among instructor and non-instructor respondents for Likert scale questions. All statistics were performed in R. Respondents were not required to answer every question, so the number of responses varies slightly across questions.

Results

Survey response rate and respondent demographics

The survey was administered to all past and current CVU faculty ("participating instructors"), CUAHSI Board of Directors members from 2017 to 2021 who had not taught for CVU ("non-participating faculty"), and department chairs of participating instructors. The survey was emailed to 63 individuals, including 22 participating instructors, 23 non-participating faculty, and 18 department chairs. A total of 37 responded to the survey, with an overall response rate of 58%. When disaggregated by experience with CVU, 18 of 22 participating instructors responded (82%) and 14 of 23 non-participating faculty responded (61%). Five of 18 (28%) department chairs completed the survey; two others replied to the email solicitation with some general thoughts about CVU but did not complete the survey.

Respondents who were non-participating faculty or department chairs were asked how familiar they were with CVU. Among non-participating faculty, 50% ($n = 7$) reported being moderately or extremely familiar with CVU, while 43% ($n = 6$) reported being somewhat familiar. One respondent (7%) reported being slightly familiar with the program. Among the five department chair respondents, three reported being somewhat familiar with CVU, one reported being moderately familiar, and one reported being extremely familiar with CVU. It is probable that department chairs who were more familiar with CVU were more likely to respond to the survey solicitation.

Participating instructors were not asked about their familiarity with the program and were assumed to be extremely familiar with it.

Among the survey respondents who have been participating instructors, 44% ($n = 8$) taught in CVU for 1 year, 44% ($n = 8$) taught for 2 or 3 years, and 11% ($n = 2$) taught in CVU for 4 years. Based on this, the survey respondents closely matched the overall instructor pool in terms of longevity of engagement with CVU, likely as a function of the high overall response rate for participating instructors (82%, $n = 18$).

Among participating instructors, 50% ($n = 9$) indicated that they planned to teach for CVU in 2022 or in future years, while 44% ($n = 8$) indicated that they were undecided. Only one respondent (5.5%) stated that they had no plans to teach for CVU in the future, commenting that a job change influenced their decision. In contrast, among non-instructor respondents, one respondent (7%) indicated that they planned to teach in CVU in the future, 50% ($n = 7$) indicated that they were undecided, and 43% ($n = 6$) indicated that they had no plans to teach for CVU in the future. At the time of survey administration, CVU applications for the 2022 semester had closed.

Benefits to participating students, faculty, and institutions

Almost all participating instructors and non-participating faculty somewhat or strongly agreed that CVU diversifies educational opportunities for students (89%, $n = 30$), increases the breadth (93%, $n = 30$), and depth (89%, $n = 30$) of opportunities for students, and increases student access to subject matter specialists (96%, $n = 30$) (Figure 2). There were no significant differences between participating instructors and non-participating faculty for these statements ($p > 0.05$). Among participating instructors, there was unanimous agreement ($n = 18$) that CVU increases breadth and access to specialists, while two instructors (of 18) somewhat disagreed that CVU increases depth of opportunity. One CVU instructor commented that CVU is "valuable for those of us in small graduate water programs" and another noted that the "students like the CVU offerings".

Student acquisition of skills was identified as an important benefit of CVU, by both participating instructors (recalling prior to their first participation) and non-participating faculty (Figure 3). Both groups largely agreed or strongly agreed that students could use skills developed in CVU for their research (thesis or manuscripts) and as part of their employment (during or following graduate school) and differences between groups were non-significant ($p = 0.73$ for research; $p = 0.12$ for employment). Participating instructors were also asked whether students had used skills developed in CVU for research or employment; 83% ($n = 15$) of participating instructors responded "yes" for research and 56% ($n = 10$) responded "yes" for employment. All the remaining responses were "unsure" for both questions. One instructor noted that "benefits to students depend on students' career trajectory".

Benefit to students was also the dominant theme of instructor answers in a free response about how teaching for CVU changed their perceptions of it. Six of 15 respondents noted the benefits to students. One instructor wrote, "I think CVU absolutely benefits the students in many ways. They have access to more experts, have the opportunity to learn different topics, and are able to network with a broader group of peers." Another instructor wrote, "I have been impressed how many thank you's I have gotten long after the class about how students have appreciated what they have learned and used it in their research. That means a lot to me."

CVU is a potential form of demonstrable broader impact associated with funded research. Recalling prior to their first involvement, 50% ($n = 9$) of participating instructors agreed or strongly agreed that CVU could fit within the broader impacts of a future proposal. In comparison, only 43% ($n = 6$) of non-participating faculty agreed or strongly agreed with that statement while considering CVU involvement (Figure 3). The difference was non-significant ($p = 0.21$). Among participating instructors considering the question retrospectively, 33% ($n = 6$) reported that CVU had been part of the broader impacts for a proposal, while 61% ($n = 11$) reported that it was likely to fit within the broader impacts of a future proposal. Three participating instructors (17%) reported it was unlikely to fit in a future proposal, while four participating instructors (22%) were unsure. All five department chair respondents indicated that teaching for CVU was likely to fit within the broader impacts of a future proposal.

Collaborations among faculty and students across institutions were envisaged as one advantage of CVU when it was launched, so we were interested in faculty perspectives on whether collaboration (projects, papers, and proposals) could be developed as a result of involvement in CVU (Figure 3). Recalling prior to involvement in CVU for the first time, a minority of participating instructors agreed or strongly agreed that a faculty collaboration (33%, $n = 6$) or student collaboration (39%, $n = 7$) could develop, and the level of agreement from non-participating faculty was similar ($p = 0.70$ for faculty collaboration; $p = 0.51$ for student collaboration). In reality, only two participating instructors (11%) reported that a faculty collaboration had developed as a result of CVU, while another two reported being unsure. Those two positive responses could represent only one collaborative pairing. The limited realization of student collaborations was similar, with three participating instructors (17%) reporting that they had occurred, and one instructor (6%) reported being unsure. However, collaborations are an outstanding feature of CVU for at least one instructor, who reported "CVU has led to deeper student-faculty and

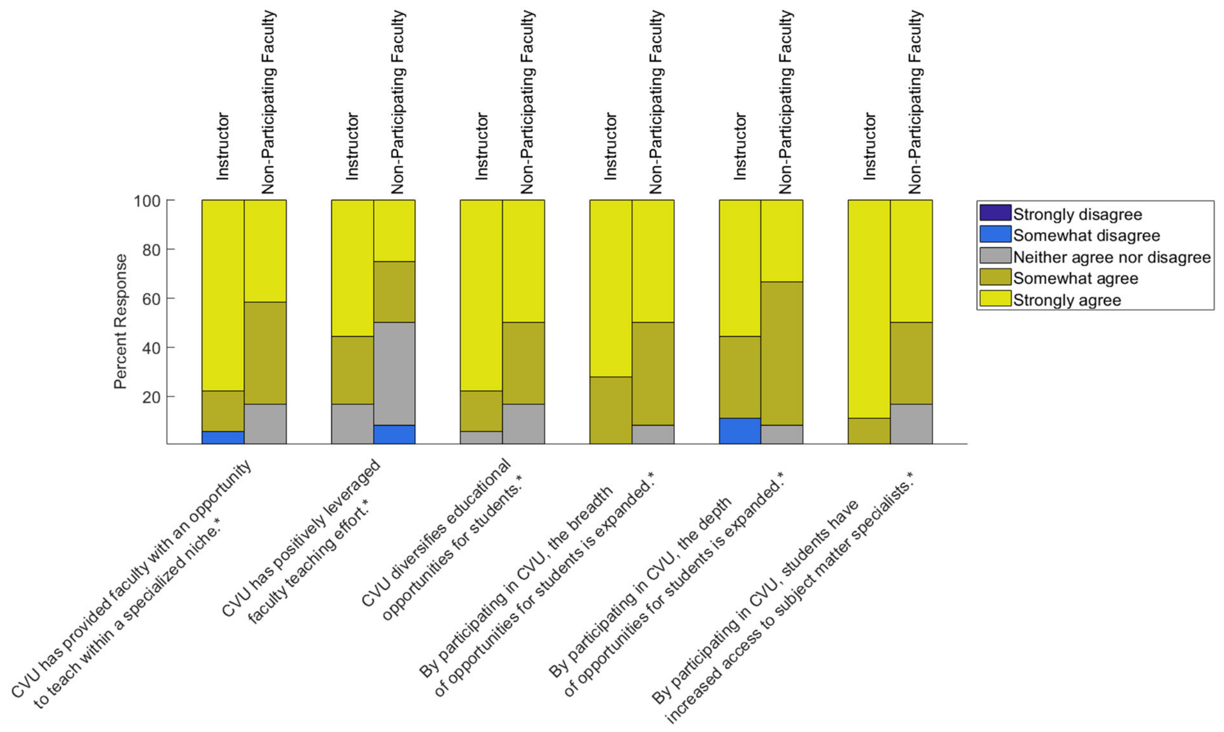

FIGURE 2
Levels of agreement to statements about benefits of CVU participation for students and faculty, as perceived by participating instructors and non-participating faculty. The asterisk symbol indicates that there were one or more non-responses to the statement.

faculty-faculty collaborations than I expected." While formal collaboration may be a rare outcome, informal connections may be more important. As one instructor noted, "the potential to connect with students in other universities was something that I didn't think about but was really what made the experience meaningful!"

Fourteen (of 18; 78%) CVU participating instructors strongly agreed that CVU offers the opportunity for faculty to teach within a specialized niche, while only 5 of 12 (42%) non-instructor respondents strongly agreed with that statement (Figure 2). The difference in the strength of agreement with this statement was statistically significant ($p = 0.049$). Despite the opportunity to teach a specialized topic, in a free response, two participating instructors described the challenges of fitting instruction into a 4-week module. One instructor wrote that they would have liked to develop a product with students from the CVU module, but that doing so "would be quite challenging as a month passes quickly". The other commented that if students didn't have the "proper background," "it was hard to bring them up to speed in such a short time".

While participating instructors overwhelmingly agreed (15 out of 18 somewhat or strongly agreed) that CVU positively leverages teaching efforts, non-participating faculty did not share that perception with six out of 12 respondents expressing either negative (somewhat disagree) or neutral responses to that statement (Figure 2). However, the difference was not statistically significant ($p = 0.17$). One instructor wrote, "My institution has embraced the CVU framework and it is now a regular part of my teaching load", while another noted "It's perhaps surprising/disappointing to hear that some of my co-teaching faculty have department chairs that resist (at least initially) their involvement. I am surprised that they don't see the potential value proposition."

Responses from the five department chairs showed similar sentiments. One commented "This is a fantastic program. Keep it up." Another indicated "There is a lot that I like about CVU, expanded access to courses for students, the high quality of the courses offered, the well-targeted and topical nature of offerings, and the short-course format makes it easy for students to fit into their programs of study."

Most participating instructors somewhat agreed that CVU has built a community of faculty (77%, $n = 14$) and community of students (50%, $n = 9$); a few (1 and 3, respectively) strongly agreed (Figure 4). Non-participating faculty responses were more neutral, with 7 (of 12) neither agreeing nor disagreeing with the statement "CVU has built a community of faculty" and 11 (of 12) neither agreeing nor disagreeing with the statement "CVU has built a community of students". The differences

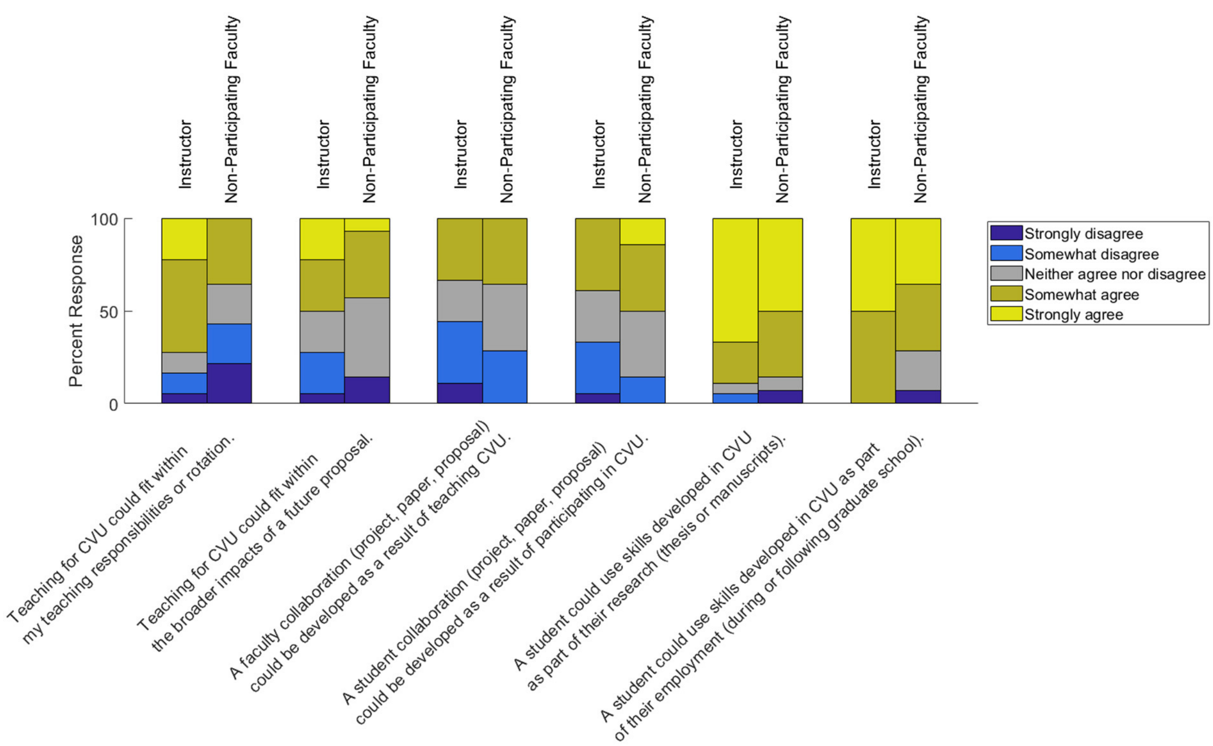

FIGURE 3
Levels of agreement to statements about outcomes from CVU participation for students and faculty. Instructors were asked to recall their perceptions prior to their first participation.

between participating instructor and non-participating faculty responses were statistically significant ($p = 0.014$ for faculty, $p = 0.0018$ for students).

When asked to consider the contributions CVU has made to the larger water science community, one CVU instructor stated "CVU is a wonderful contribution to the larger water community" while another noted "I'm not sure how widely CVU is known. But it would be great to expand it!" Most participating instructors became aware of other water graduate programs by participating in CVU (72%, $n = 13$) (Figure 4). However, CVU did not necessarily raise the national visibility of participating universities, with 67% ($n = 9$) of non-participating faculty and 50% ($n = 9$) of participating instructors neither agreeing nor disagreeing with the statement "CVU has improved the national visibility of participating universities' water programs". The difference between instructor and non-instructor responses was not significant ($p = 0.31$).

When asked to consider online instruction, participating instructors indicated that CVU changed the perception of online classes for water education, with over 55% ($n = 10$) agreeing with that statement (Figure 4). Only 42% ($n = 5$) of non-participating faculty agreed with that statement, but the difference with instructor responses was not significant ($p = 0.75$). A majority of both participating instructors and non-participating faculty agreed or strongly agreed that the COVID-19 pandemic changed their perceptions of online classes, with no significant differences between groups ($p = 0.40$). One CVU instructor wrote "Those of us who did CVU before the pandemic were way better prepared when the pandemic hit!"

Determinants of faculty participation in CVU

Perceived benefits to students were most frequently cited (40%, $n = 4$) as the biggest influence on the decision to teach for CVU in the future, by those who answered "yes" to whether they would teach for CVU in the future ($n = 10$). In contrast, benefits to students was listed as the biggest influence by only one of 22 respondents who said they were undecided or would not teach in CVU in the future. Beyond perceived benefits to students, other factors cited as the biggest influence on their positive decision to teach for CVU in the future were student participation at their university and teaching effort required vs. perceived benefit. One instructor who planned to teach for CVU in the future commented that "ability to share my specialty knowledge with students at universities who would not have access to it, and

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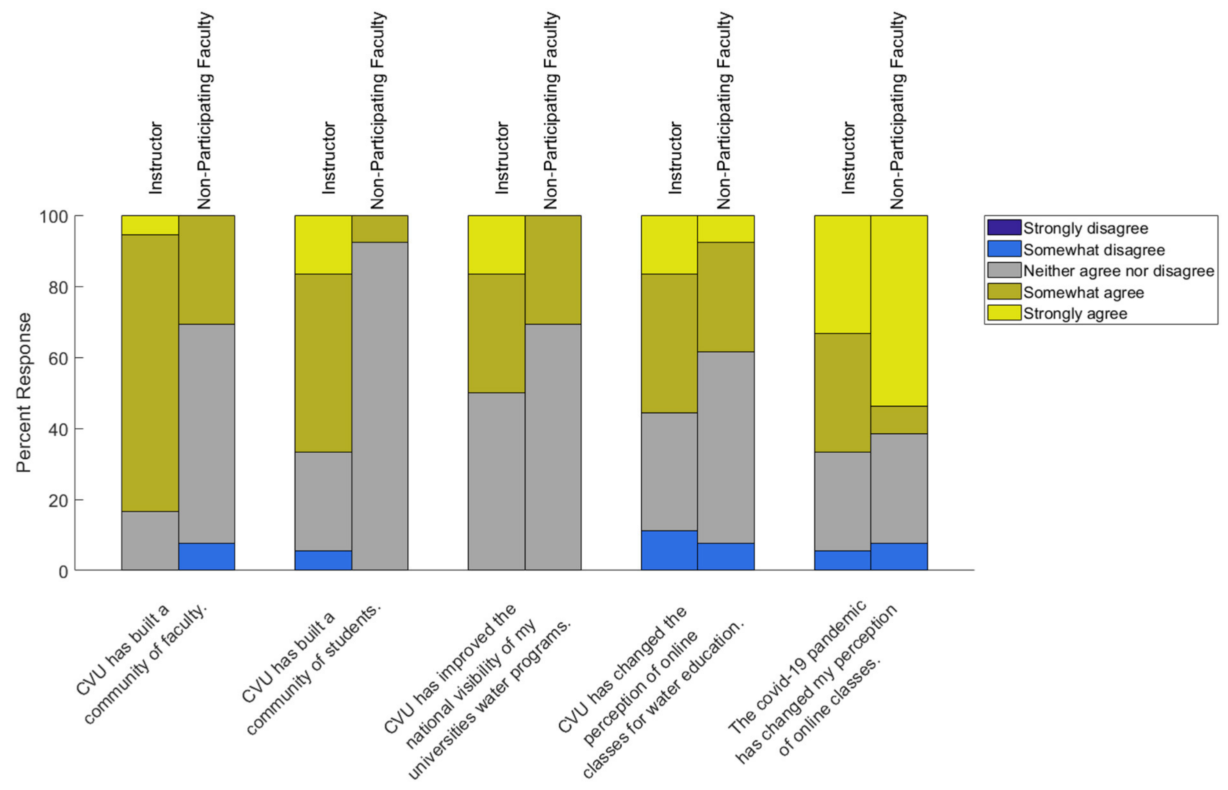

FIGURE 4
Levels of agreement with statements about CVU's role in community creation and online education.

the fact that they tell me thank you each term" was the biggest influence on their decision.

The home university plays a more important role in influencing the decision among those who have decided not to teach for CVU in the future. Of the seven respondents who said they would not teach for CVU in the future, the biggest influence for two respondents was the level of university support, for two respondents it was other classes that need to be offered at their university, and two respondents said the biggest influence was jobs that do not include regular teaching loads. Two non-participating faculty respondents cited teaching effort required vs. perceived benefits as the biggest influence on their decision.

Among those who were undecided about their future participation, the biggest influences were similar to those who have decided not to teach for CVU in the future. The level of support from their university was the most frequently cited influence. Five of seven (71%) undecided non-participating faculty respondents cited this as their biggest influence, as did two of eight (25%) undecided participating instructor respondents. Other classes that need to be offered and student participation at their university were also mentioned by more than one undecided respondent, while the remaining influences were only chosen by one undecided respondent. One undecided participating instructor noted that "teaching this enables students at my university to benefit from the offerings from other universities".

When contemplating CVU participation, the concerns held by those who went on to participate and those who did not differed somewhat (Figure 5). Institutional approval/support had the highest level of concern among non-participating faculty as they considered teaching in CVU, with 10 of 13 non-instructor respondents (77%) indicating moderate (3) or extreme (7) concern. Non-participating faculty were significantly more concerned about institutional approval/support than participating instructors ($p = 0.03$), among whom 7 out of 18 (39%) indicated moderate concern and only 1 (6%) indicated extreme concern. One non-participating faculty member noted that "I'd love to try teaching for it sometime, but right now, I don't have the time or political capital to deal with what the university would likely require for it." Over 70% of non-participating faculty respondents were moderately or extremely concerned about whether teaching in CVU would count toward workload, the time commitment, and the effort required to develop a new course. One non-participating faculty member volunteered: "My challenge is that I need more time in my day in order to be able to offer a course

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via CVU." For participating instructors recalling their concerns prior to participating for the first time, the time commitment and the effort required to develop a new course were the most concerning, with 61% ($n = 11$) of participating instructor respondents indicating moderate or extreme concern prior to their initial involvement. Fit with other classes being offered was the least concerning item for participating instructors (11%, $n = 2$ moderately or extremely concerned) and online instruction was the least concerning for non-participating faculty (15%, $n = 2$ moderately or extremely concerned). No other single concern had a statistically significant difference between groups, but when all items asking about concerns prior to participation were summed, non-participating faculty expressed significantly more overall concern ($p = 0.008$).

The ability of teaching for CVU to fit within teaching responsibilities and rotations as a potentially important determinant of participation also emerged in other questions. A majority of participating instructors (72%, $n = 13$) agreed or strongly agreed that teaching for CVU could fit within their teaching responsibilities or rotations, while only a minority of non-participating faculty (36%, $n = 5$) agreed or strongly agreed with that statement (Figure 3). The difference was not statistically significant ($p = 0.24$), but non-participating faculty offered several related comments when asked what changes would make them more likely to participate in CVU. Non-participating faculty respondents volunteered that "nothing [needs to be changed] on CUAHSI's side. It would be more about how graduate teaching loads are assigned in my department"; that they would be more likely to participate "knowing I can replace a CVU course offering with one of my regularly offered courses at my own university and still get full credit for teaching," "teaching a module in CVU would be done as an 'overload' beyond normal teaching duties," and "It would have to be on top of my current teaching load, and I just cannot handle the extra work right now."

Two non-participating faculty respondents gave specific examples of institutional barriers to involvement in CVU. One respondent stated: "Getting credit hours from "other" places to count for our students can be very hard. Students have very strict lists of acceptable courses for their MS degree and getting "other" things to count is difficult." Another respondent volunteered: "Our campus is becoming more and more "business-like" in its financial affairs; the campus is now allocating funds to units based on undergrad and grad enrollment numbers. The CVU module would be offered as an "independent study" class, and the only official enrollees would be the students at the home institution. Administrators may not fully appreciate the benefits that the students on campus are getting from their enrollment in other models at different universities." Concerns about how enrollments count were echoed in the comments offered by department chairs.

University size and diversity of offerings may also influence whether faculty choose to participate in CVU. While we did not specifically ask about university size, research activity, or discipline in the survey, two non-participating faculty respondents discussed their university context when asked what changes would make it more likely for them to participate in CVU. One wrote "I teach at a school with a lot of hydrology offerings, which I know is rare. So I love the idea of CVU, but we have so much here that it's hard to take on another class given that my students already have really amazing options." The other respondent who brought up university context wrote that "CVU may be less attractive to students and instructors from large universities with large and comprehensive water and environmental science academic programs across many colleges and departments." Nevertheless, most of the universities who have participated in CVU have moderate to large water science and engineering foci across multiple departments.

Reflecting on the institutional barriers about which many non-participating faculty expressed concern, one noted "To be clear, I view this all as a major failing of the way universities are run. CVU is a wonderful and creative program that can really benefit hydrology education."

Sustainability of the CVU model

Despite the overwhelmingly positive perceptions of CVU benefits to participating students and faculty, survey respondents expressed concern about its ability to attract sufficient enrollment to maintain university support. When participating instructors were asked "What changes would make it more likely for you to continue participating in CVU?", five out of the 15 responses discussed student enrollment. As one instructor noted, "Increased student participation at my university would help lead to broader support. In general, it's an exceptionally hard time to get support for low-enrollment graduate level classes." One department chair wrote, "I'm willing to go a year or two with low enrollments, but the participating faculty members (at least at my institution) need to ensure they are offering courses that are valuable for students at our institution as well as the virtual audience. I suspect this is a common view among dep[artmen]t heads."

Participating instructors offered a number of ideas to make their continued involvement more likely, and such ideas might offset some enrollment concerns. Among the suggestions offered were extending student participation to senior year undergraduates, creating sequences of themed modules, making modules each worth a full course credit, and advertising modules to prospective faculty as they are accepted into CVU (i.e., having a rolling application window) so that potential instructors can see what other modules are being offered before committing to participation.

Department chairs were also asked whether the CVU framework would be useful for other disciplines within their department: one somewhat disagreed, two somewhat agreed,

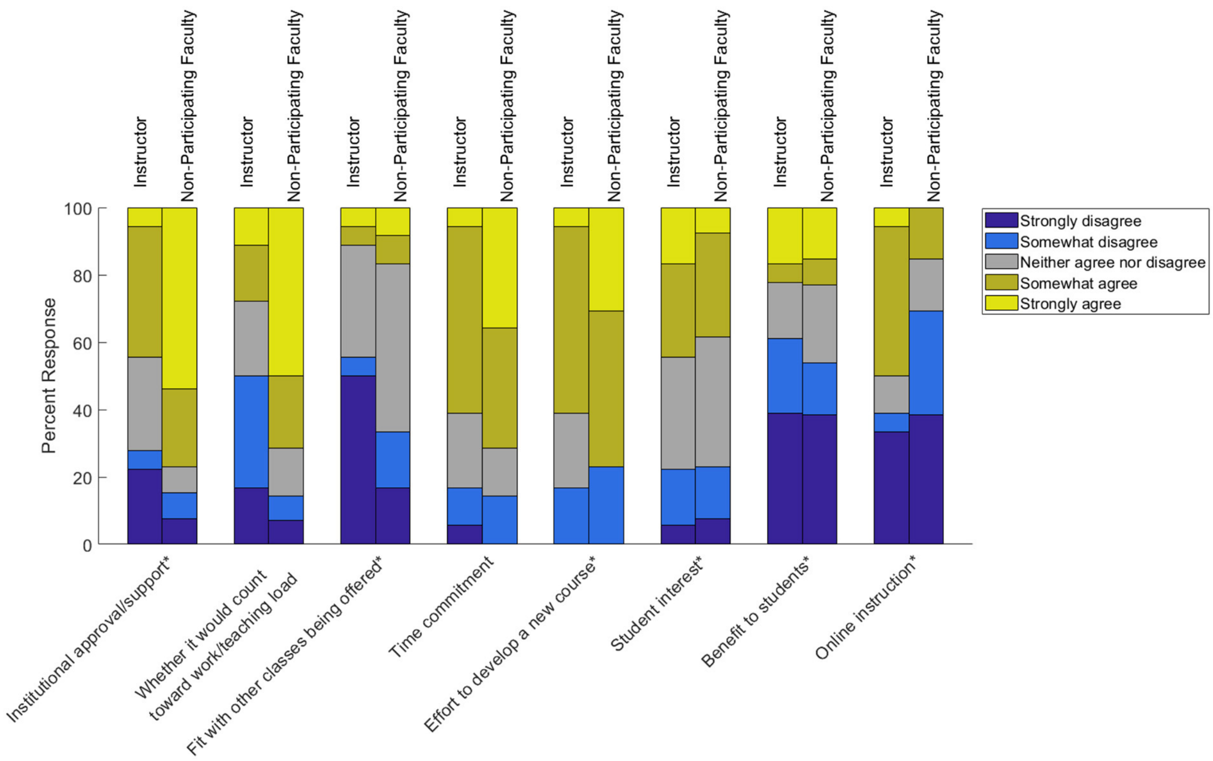

FIGURE 5
Levels of concern about various factors prior to first involvement (for instructors) and when contemplating involvement (for non-participating faculty). The asterisk symbol indicates that there were one or more non-responses to the statement.

and two provided a neutral response. We did not ask for an open-ended response to explain their reasoning.

Discussion

The benefits of CVU to participating students are at the center of the CVU design, and they emerge as the strongest and most consistent theme of survey responses. There was almost unanimous agreement that students were exposed to a greater breadth of content and had greater access to subject matter specialists because of their participation in CVU. Participating faculty also thought that CVU positively leveraged their teaching efforts, and the high degree of instructor retention suggests satisfaction with the program. Evidence for a wider appreciation of benefits to faculty and the water science community was less clear. Perceived administrative barriers around workload and enrollment are the largest challenges for sustainability and expansion of the CVU model. Despite a small sample size of survey respondents, which was influenced by the size of the CVU program, our findings suggest that the CVU model of short, specialized modules taught in a multi-institutional framework may be of interest to other science, technology, engineering, and mathematics (STEM) disciplines, particularly if ways to lower barriers to faculty participation can be identified.

CVU was envisioned to benefit students through access to experts in specialized subdisciplines of hydrology, by broadening the diversity of courses they could take, by helping them develop new research skills, and by providing an opportunity to network with students and faculty around the US (Loheide, 2020). From the perspective of participating instructors, all these objectives are being met. Among the non-participating faculty surveyed, there was also widespread agreement on the benefits to students, though the non-participant responses were somewhat less enthusiastic than among participating instructors. Lower agreement by non-participating faculty may reflect lower familiarity with the program and lack of contact with students enrolled in CVU. Multi-institutional graduate training programs may need to proactively create messages around positive student outcomes and faculty satisfaction to attract new participating faculty and institutions.

Participating instructors were unanimous that breadth of opportunity and access to experts were increased, while there was still strong, but slightly less agreement that the depth of opportunity had been increased. This suggests that participating faculty perceive that the short, specialized modules may enhance broad training across specialties (horizontal bar of T-shaped hydrologic training, sensu Uhlenbrook and De Jong, 2012) more than increase deep training (the T's vertical bar). Perceptions of greater breadth than depth could be because students studied each module for 4 weeks, rather than a typical full semester course on a topic. If sequences of modules were developed around a theme (e.g., snow hydrology, food-energy-water nexus), it's possible that the increased depth of opportunity would be more fully realized. Sequenced modules could also mitigate students' perceptions that faculty covered too much material in 4 weeks (Loheide, 2020). However, it may be challenging to implement sequences while still allowing students free choice and a high degree of differentiation of instruction based on their interests and needs.

Participating instructors were confident that students had gained skills for research, which is consistent with student responses in 2017–2019, where 67–89% of students reported that they would or might use knowledge from CVU for their research (Loheide, 2020). A smaller majority of participating instructors reported that students could use skills gained in CVU for employment. No participating instructors were aware of students not using skills gained in CVU during future employment, but 44% were unsure they had done so. This higher unsure response rate for employment may be because faculty aren't as closely tracking what skills students use in their jobs post-graduation, and it represents an opportunity for future research.

While participating instructors agreed that CVU has built a community of students, the agreement was not as universal as it was for other measures of student benefits, and non-participating faculty were almost all neutral regarding student community. Faculty perceptions of student community may be limited, as they may not be aware of student networking and community building that occur outside of class sessions and the learning management system. Online multi-institutional programs like CVU might also consider developing an optional inter-university, in-person component (e.g., reception at a disciplinary conference) as a way of fostering student community that persists beyond the semester.

Benefits to faculty from participating in CVU informed the design of the program and were envisioned to include the opportunity to teach in a specialized niche and to leverage teaching effort in that instructors offer a 3-credit course in their university's course catalog but are only responsible for delivering one credit of content (Loheide, 2020). In questions directly asking about these benefits, participating instructors almost all agreed that they were being realized, and survey respondents who intended to teach for CVU in the future also described the effort required vs. perceived benefit as important to their decision. Conversely, institutional policies prevent faculty from leveraging teaching effort through CVU appear to be a principal barrier for non-participating faculty. These results suggest that teaching for CVU or similar programs cannot be treated as an uncompensated addition to faculty workload, and that the benefit to faculty is a principal contributor to the success of the model. It is not enough that there are almost universally recognized benefits for students; faculty should also get a direct benefit from participating as instructors.

An additional, unanticipated benefit recognized by participating instructors is the development of a community of faculty through their involvement in CVU. While not formally structured as a faculty learning community, CVU includes some elements of such learning communities, including opportunities to build areas of competence related to teaching and learning and venues for relationship-building across academic units (Daly, 2011; Ward and Selvester, 2012). CVU and other multi-institutional graduate teaching efforts could consciously build in aspects of faculty learning communities, as a way to strengthen community more broadly and improve the quality of instruction. Intentional creation of faculty learning communities associated with multi-institutional graduate training programs might also attract new faculty participants to them, especially if the extra time commitment of the learning community comes with clear benefits to the participating faculty.

At the institutional level, increased national recognition of water graduate programs and research strengths are an envisioned institutional benefit of CVU (Loheide, 2020). While many participating instructors thought that CVU had improved the visibility of participating water graduate programs, non-participating faculty and department chairs were more neutral, as any enhanced visibility may is likely limited to the network of participating institutions. However, our survey captures only faculty sentiments, and CVU students may be more aware of other schools as a result of their program participation. Broader impacts on grants are another potential institutional benefit of CVU, and notably, 100% of department chair respondents saw the potential for CVU to fit within the broader impacts on a future grant proposal. If multi-institutional graduate training programs that operate by recruiting interested faculty (as CVU does) identify ways to realize and enhance benefits at the institutional level, faculty interested in participating in such programs may be able to lower barriers to their participation.

The benefits of CVU to the larger water community and discipline are less clear in our survey results, although that could be because few questions were designed to directly measure these envisioned benefits. Loheide (2020) suggests that disciplinary benefits could include greater collaboration and community awareness of research activities and faster spread and acceptance of research innovations. Longer-term, the discipline is also likely to benefit as students who participated in CVU become faculty members and other water professionals, and they bring with them the research skills and professional networks they accrued through CVU.

CVU has high retention and satisfaction among participating instructors, and considerable interest in involvement among non-participating faculty. Instructors are willing to commit to—or at least consider—teaching in the program in the future. Among those who have not previously taught in the program, most respondents are potentially open to doing so in the future, which suggests that there is potential for growth of the program. More broadly, high faculty interest and instructor satisfaction suggest that the CVU model might be attractive to other STEM disciplines.

Although non-participating faculty saw many potential benefits to students, themselves, and their institutions, they thought they could not participate in CVU, because of institutional barriers or lack of support. For example, non-participating faculty expressed higher concern overall, and about institutional approval specifically, compared to participating instructors recalling their thoughts prior to involvement in the program. While the pre-involvement concerns of CVU participating instructors may not be recalled as clearly after they successfully taught in CVU, the consistent themes expressed in non-instructor answers to both Likert-scale and open-ended questions require careful attention.

Why do non-participating faculty describe roadblocks to involvement that aren't perceived by participating instructors? We speculate that there are two possible explanations, and both may be at work across institutions. First, non-participating faculty may work at institutions where there are higher administrative or cultural barriers to participation in innovative, multi-institutional programs. Second, CVU participants may be more successful in overcoming perceived roadblocks, because of greater seniority or better informal networks and support within their university. Because we did not ask whether non-participating faculty had directly asked whether they would be allowed to participate in CVU, we cannot determine whether institutional barriers are codified or only perceived. In a few cases, non-instructor comments indicated that they had not approached their university about teaching for CVU or that they felt they lacked the capital to do so.

Whether institutional barriers to CVU participation are codified or only perceived, they may represent a significant challenge to the sustainability and expansion of the CVU model. If CVU has penetrated the universities where faculty and administration are willing to adopt an innovative, multi-institutional teaching framework, there may be little scope to expand or rotate participation. Conversely, if CVU participation is limited by current faculty awareness and interest, the potential to expand may be large, either within hydrologic science or with a CVU-like model in other disciplines. Future work should explicitly examine university policies and culture around multi-institutional teaching collaborations, perhaps in a hypothetical rather than a CVU-specific context.

Concerns about low enrollment in CVU were found across department chairs, non-participating faculty, and even some participating instructors. CVU may be seen as serving a relatively small student population per university, and with universities requiring minimum enrollments or rewarding higher enrollments, some academic units may not be easily able to justify using faculty workload to teach in the program. This tension between enrollment and workload may contribute to the institutional barriers perceived by non-participating faculty, and it may influence the type of institution that participates in CVU or similar programs. Two respondents described being at universities with large water science programs and feeling like their graduate students could take an adequate amount of hydrology from existing in-house courses. Institutions like this might have the least concerns about sufficient enrollment, but the least incentive to contribute to multi-institutional teaching efforts. Conversely, institutions with small graduate programs might gain the most from the advanced, modular CVU-like curriculum, but face the greatest challenge in achieving any required minimum enrollment.

To counter limitations to participation in multi-institutional graduate teaching that center on enrollment pressures, convincing administrators of benefits beyond enrollment (e.g., reputation) might be important. However, this was an area where the current survey did not clearly show strong results for CVU. Multi-institutional collaborative teaching efforts, like CVU could also actively recruit and promote modules that serve a broader, interdisciplinary student population, while still also fulfilling their role in providing niche disciplinary topics. For instance, CVU modules on "Geographical Information Systems for Terrain and Watershed Analysis," "Open and Reproducible Computing," and "Advances in Drone-Based Hydrology" have a technological focus with appeal beyond hydrology, while still focusing on applications to hydrologic science. However, simply offering some broadly appealing modules will not be sufficient if those modules aren't advertised at the appropriate stages to recruit new instructors and gain student registrations.

The COVID-19 pandemic was a profound test of the utility and limits of online education (e.g., Lowry et al., 2022; Thompson et al., 2022). Experience with teaching online through CVU may have helped some participating instructors be more prepared for the rapid shift to online instruction during the pandemic. While the difference was not statistically significant, participating instructors expressed more concern about online teaching prior to their first involvement than non-participating faculty, but this may reflect the fact that some participating instructors first taught in CVU before the COVID-19 pandemic, while non-participating faculty are answering with the experience of the pandemic online transition in mind. Both groups indicated that the pandemic has changed their perception of online classes, but it is unclear whether that will translate into increased faculty participation in CVU. Recruitment of participating instructors for 2022 has now occurred, and the number of participating faculty is flat or slightly below previous years, with 8 modules anticipated. This anecdotally suggests that even though faculty have gained familiarity with online instruction, institutional barriers remain and faculty may also be burned out or discouraged from teaching online as universities emphasize a return to in-person instruction in 2022.

In the long term, online education, especially with shared instructional models as found in CVU, is more resilient to disruptions than in-person instruction. While COVID-19 emphasized this resilience to university faculty around the world, online education and shared instruction also impart resilience to other health emergencies, natural disasters, and severe weather events (de Róiste et al., 2015). Proactively developing online frameworks like CVU in other disciplines and at the undergraduate level may provide a useful safety net for faculty in the event of future disruptions. The faculty and department chair perspectives in this study serve as lessons learned that could inform the development of these frameworks.

Conclusion

Multi-institutional online graduate training programs, like CVU, offer a way to provide depth and breadth of student training in disciplines, like hydrologic science, where the size of the faculty may be limited at individual institutions. CVU uses 4-week, specialized modules delivered synchronously online to allow graduate students to differentiate their learning and access specialist faculty and knowledge unavailable at their home institution. In this research, we examined CVU as a case study of multi-institutional online graduate training programs and specifically investigated how faculty who had participated in CVU, along with similar non-participating faculty, viewed the benefits of CVU and the barriers to participation.

Overall, there was a strong faculty consensus that CVU enhances the breadth of training for participating graduate students and gives them access to subject matter specialists. Participating faculty also felt they benefited through positively leveraging their teaching load and becoming part of a community of faculty. These faculty-perceived benefits to students and themselves, along with high instructor retention and interest among non-participating faculty, suggests that the CVU model has the potential for sustainability and expansion within and beyond hydrologic science.

However, non-participating faculty responses were very revealing about the limitations of the CVU model, with perceived administrative barriers around workload and enrollment emerging as the largest challenges. Finding ways to mitigate these barriers may be necessary for sustaining and growing multi-institutional graduate training programs like CVU that depend on interested prospective faculty gaining institutional approval. Emphasizing the resilience of online, multi-institutional programs to disruptions, like the COVID-19 pandemic, might be one approach to do so.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: on Hydroshare at http://www.hydroshare.org/resource/2372f0c0a90d4061ae7f50a7f2a01cbd.

Ethics statement

The studies involving human participants were reviewed and approved by Kent State University Institutional Review Board. The patients/participants provided their written informed consent to participate in this study.

Author contributions

AJ obtained IRB approval, administered the survey, and performed the statistical analysis of the results. SL created the figures. All authors contributed to the conceptualized and designed the survey and manuscript, analyzed the data, wrote sections of the manuscript, contributed to manuscript revision, and approved the submitted version.

Funding

CUAHSI Virtual University was supported by NSF Award 1849458. This material is based upon work supported by the National Science Foundation under Grant Nos. 1849458, 1855996, and 1700983.

Acknowledgments

The authors appreciate the responses from the CVU instructors, CUAHSI Board of Directors members, and departmental chairs, as well as for informal feedback and discussion since CVU was created. We thank Bridget Mulvey (Kent State University) for helpful discussions throughout the study and manuscript preparation.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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TYPE Original Research
PUBLISHED 06 October 2022
DOI 10.3389/feduc.2022.953164

OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to STEM Education, a section of the journal Frontiers in Education

RECEIVED 25 May 2022
ACCEPTED 06 September 2022
PUBLISHED 06 October 2022

CITATION
Byrd J, Gallagher MA and Habib E (2022) Assessments of students' gains in conceptual understanding and technical skills after using authentic, online learning modules on hydrology and water resources. *Front. Educ.* 7:953164.
doi: 10.3389/feduc.2022.953164

Assessments of students' gains in conceptual understanding and technical skills after using authentic, online learning modules on hydrology and water resources

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The need to adapt quickly to online or remote instruction has been a challenge for instructors during the COVID pandemic. A common issue instructors face is finding high-quality curricular materials that can enhance student learning by engaging them in solving complex, real-world problems. The current study evaluates a set of 15 web-based learning modules that promote the use of authentic, high-cognitive demand tasks. The modules were developed collaboratively by a group of instructors during a HydroLearn hackathon-workshop program. The modules cover various topics in hydrology and water resources, including physical hydrology, hydraulics, climate change, groundwater flow and quality, fluid mechanics, open channel flow, remote sensing, frequency analysis, data science, and evapotranspiration. The study evaluates the impact of the modules on students' learning in terms of two primary aspects: understanding of fundamental concepts and improving technical skills. The study uses a practical instrument to measure students' perceived changes in concepts and technical skills known as the Student Assessment of Learning Gains (SALG) survey. The survey was used at two-time points in this study: before the students participated in the module (pre) and at the conclusion of the module (post). The surveys were modified to capture the concepts and skills aligned with the learning objectives of each module. We calculated the learning gains by examining differences in students' self-reported understanding of concepts and skills from pre- to post-implementation on the SALG using paired samples *t*-tests. The majority of the findings were statistically at the 0.05 level and practically significant. As measured by effect size, practical significance is a means for identifying the strength of the conclusions about a group of differences or the relationship between variables in a study. The average effect size in educational research is d = 0.4. The effect sizes from this study [0.45, 1.54] suggest that the modules play an important role in supporting students' gains in conceptual understanding and technical skills. The evidence from this study suggests that these learning modules can be a promising way to deliver complex subjects to students in a timely and effective manner.

KEYWORDS

authentic tasks, high-cognitive demand tasks, online learning, conceptual understanding, technical skills

Introduction

Hydrologists and water resource engineers deal with intricate and complex problems that are situated in natural-human ecosystems with several interconnected biological, physical, and chemical processes occurring at various spatial and temporal dimensions. In recent years, there has been a movement to enhance hydrology education (CUAHSI, 2010). Therefore, there is a growing need to better equip the next generation of hydrologists and water resource engineers to handle such complicated problems (Bourget, 2006; Howe, 2008; Wagener et al., 2010; Ledley et al., 2015). Some of the key desired enhancements in hydrology and water resource engineering education require exposure to data and modeling tools, adoption of effective pedagogical practices such as active learning, and use of case studies to deliver real-world learning experiences (Habib and Deshotel, 2018). In their review of hydrology education challenges, Ruddell and Wagener (2015) stressed the need for structured methods for hydrology education, such as community-developed resources and data- and modeling-based curriculum. The increasing availability of digital learning modules that incorporate such attributes provide opportunities for addressing the desired enhancements. Recent examples of such growing resources in the field of hydrology and water resources include: Environmental Data-Driven Inquiry and Exploration (EDDIE; Bader et al., 2016); online modules from the HydroViz platform (Habib et al., 2019a,b); HydroShare educational resources (Ward et al., 2021); web-based simulation tools (Rajib et al., 2016); HydroFrame tools for groundwater education (HydroFrame-Education, n.d.); geoinformatics modules for teaching hydrology (Merwade and Ruddell, 2012); and the HydroLearn hydrology and water resources online modules (Habib et al., 2022).

The potential value of digital resources has been further highlighted during the COVID-19 pandemic when instructors were forced to switch to remote teaching and find resources to facilitate their teaching and support students' learning (Loheide, 2020). However, the rapid acceleration of instructional resources available *via* the internet makes it difficult for instructors to assess the quality, reliability, and effectiveness of such resources. Instructors' decisions to adopt certain digital resources are based on the digital resource's potential to enhance student learning and alignment to the instructor's learning objectives (Nash et al., 2012). Evidence of improved student learning is often cited as important factors that affect instructors' adoption of education innovations (Borrego et al., 2010; Bourrie et al., 2014). Therefore, there is a need to continuously evaluate the emerging educational resources and assess their potential impact on students' learning (Merwade and Ruddell, 2012; Ruddell and Wagener, 2015). The impact of a given instructional resource on students' learning can be assessed in terms of two key components: (a) impact on conceptual understanding of fundamental topics in hydrology and water resources, and (b) impact on technical skills that students need to identify and solve problems (Herman and Klein, 1996; Woods et al., 2000; Kulonda, 2001; Entwistle and Peterson, 2004; Sheppard et al., 2006; Yadav et al., 2014). Moreover, it is important for instructors to weigh not only the impact on students, but also the cost of the instructional resources before adopting the materials (Kraft, 2020). Costs of resources may be direct, such as subscription fees, or indirect, such as the instructor's time. Resources with high cost, even if they have an impact on student learning, may not be feasible for an instructor to adopt.

One way to support students' learning is through authentic, high-cognitive demand tasks. High-cognitive demand tasks are defined by Tekkumru-Kisa et al. (2015) as those which require students to "make sense of the content and recognize how a scientific body of knowledge is developed" (p.663). High-cognitive demand tasks, which have been widely researched in mathematics and science education, are open-ended or unstructured and challenge students to use the knowledge they have gained to engage in the problem-solving process (Stein et al., 1996; Boston and Smith, 2011; Tekkumru-Kisa et al., 2020). Low-cognitive demand tasks are those that need little to no deep comprehension; examples include tasks that involve scripts (e.g., a list of instructions or procedures) or memorization (e.g., definitions, formulae) since the task has just one correct answer or is otherwise plainly and directly stated. The level of cognitive demand of a task can also be identified with the aid of Bloom's Taxonomy (Anderson and Krathwohl, 2001). For instance, low-cognitive demand tasks can be characterized by the lower three levels of the taxonomy (i.e., remember, understand, and apply). Alternatively, tasks of high-cognitive demand are evocative of the higher levels of the taxonomy (i.e., analyze, evaluate, and create).

Authentic tasks are a subset of high-cognitive demand tasks. In contrast to problem sets, which often have one clean, neat answer, authentic tasks are ill-defined problems with real-world relevance which have multiple possible solutions (Herrington et al., 2003). Authentic can pertain to the types of problems students are asked to solve and the tools required to address those problems. Authentic tasks should involve the integrated applications of concepts and skills to emulate the tasks that professionals would perform (Brown et al., 2005; Prince and Felder, 2007). For example, if modelers use Hydrologic Engineering Center's (HEC) Statistical Software Package (SSP) to perform frequency analyses, then the authentic task should incorporate the use of that program. Within engineering education research, authentic tasks are sometimes referred to as case-based instruction. In case-based instruction, the topic of the lesson or module is embedded in a case study to allow students to draw real-world connections and apply the information in realistic problem scenarios (Prince and Felder, 2007). This approach has the potential to enhance students' understanding of principles and practices (Kardos and Smith, 1979; Kulonda, 2001) and increase their awareness of critical issues in the field (Mayo, 2002, 2004). Students who learn from cases have a higher conceptual understanding, can transfer their knowledge, and can solve real-world problems (Dori et al., 2003; Miri et al., 2007; Hugerat and Kortam, 2014). Furthermore, students benefit from the use of authentic tasks because it allows them to learn lessons while addressing problems, understand when to apply such lessons, and how to adapt the lessons for novel situations (Kolodner, 2006). Furthermore, the use of authentic problems may increase the problem's relevance for students and their enthusiasm for finding a solution, as well as provide them with the opportunity to work on open-ended questions (Fuchs, 1970; Bransford et al., 2004). Open-ended assessments, where students are asked to participate in higher-cognitive demand tasks (e.g., analyze, evaluate, and create), can demonstrate the students' level of understanding of the concepts. Authentic tasks also allow the instructor to provide opportunities for students to practice their skills and communicate about them in a professional context (Hendricks and Pappas, 1996; Pimmel et al., 2002).

These studies suggest that the use of authentic tasks in engineering education has great potential. However, there is limited research on how the inclusion of such strategies may support the development of conceptual understanding and technical skills in hydrology and water resources education specifically. The current study will evaluate a set of web-based learning modules developed as part of the HydroLearn platform (Gallagher et al., 2022; Habib et al., 2022). The modules cover a wide range of concepts and technical skills and incorporate authentic, high-cognitive demand tasks with the goal of developing students' conceptual understanding and technical skills. The research question addressed in this study is: Are there differences in students' self-reported learning gains in conceptual understanding and technical skills after participating in each of the online learning modules designed around authentic, high cognitive demand tasks?

Materials and methods

The HydroLearn platform

The HydroLearn platform[1] hosts nearly 50 authentic, online learning modules. The platform was specifically designed with a vision to influence adoption: compatibility, relative advantage, observability, trialability, and complexity (Rogers, 2003). The HydroLearn platform was developed using a deployment of the well-established open source edX platform, OpenEdx, (The Center for Reimagining Learning Inc, 2022) with hydrology education-driven enhancements, such as scaffolding wizards and templates to support the development of learning objectives, learning activities, and assessments (Gallagher et al., 2021; Lane et al., 2021). A unique feature of HydroLearn is that it allows instructors to adapt modules that were developed by other contributors and customize them for their own purposes, while following proper attribution and license requirements. This is intended to facilitate a wider use and dissemination of the learning resources beyond their own immediate developers, and thus promotes the concept of building a collaborative community of instructors around the concepts of open-source and open-access authentic learning content.

HydroLearn modules

HydroLearn modules were created purposefully to: (a) represent key topics covered in undergraduate hydrology and water resources courses, (b) be used as is or customized according to the needs of the adopter, (c) integrate web-based, open-source tools, (d) be crafted in alignment with research on curriculum design, and (e) offer support for faculty adopters. Additionally, they are easy to implement as many instructors simply assign the chosen module to be completed outside of class. Although all modules are freely available on the platform, there are indirect costs to instructors such as needing time to review the modules before deciding to use them. Most HydroLearn modules were developed and peer-reviewed during a hackathon-style immersive workshop (see Gallagher et al., 2022 for details on this process). They were designed to incorporate at least one authentic, high-cognitive demand task

1 www.hydrolearn.org

that requires students to apply the conceptual understanding and technical skills gained throughout the module to devise a solution to the task. The modules have learning objectives, instructional content, and assessment tasks aligned with those objectives.

For the purposes of this study, we examined 15 of the HydroLearn modules, which were predominantly developed collaboratively during the COVID-19 pandemic by groups of instructors (2–3 instructors per module) who then used them for teaching at their respective institutions in primarily undergraduate classes. Five modules were not developed during the pandemic, of which one was developed by an individual. We chose these because they were used during the pandemic and had been used with enough students for us to draw inferences. These modules, which were written for upper-level undergraduate and early graduate students enrolled in water resources courses, cover a broad range of topics, such as physical hydrology, hydraulics, climate change, groundwater flow and quality, fluid mechanics, open channel flow, remote sensing, frequency analysis, data science, and evapotranspiration. Most of these modules can be completed individually and non-sequentially and were assigned by instructors to be completed outside of class time. Some modules could be completed in a week's time, while others were assigned to be completed throughout an entire semester. Details about the topics, concepts and technical skills covered by the 15 modules are available in the **Supplementary material**. **Supplementary Table 1** provides a short description of each module and its authentic task(s). **Supplementary Table 2** lists the concepts and technical skills for the modules, all of which were identified by the module developers.

The modules examined in this study include a common set of characteristics: frequent self-assessment questions, learning activities structured around an authentic task, and open-source materials. All the modules contain frequent Check Your Understanding questions that allow students to assess their level of understanding of the learning material. These questions are intentionally placed to re-engage the student and provide immediate feedback (Woods et al., 2000). Another common component that the modules share is the inclusion of a set of Learning Activities, structured around an authentic task, which emulate the work a professional scientist or engineer would be doing in their career (Herrington et al., 2003). Although all the modules use open-source materials, the materials they use vary. For instance, open data and modeling platforms (Lane et al., 2021), remote sensing data and tools (Maggioni et al., 2020) professional engineering software (Polebitski and Smith, 2020), and real-world case studies that increase relevance and engagement for students (Arias and Gonwa, 2020; McMillan and Mossa, 2020).

Student participants and setting

A total of 299 participants, both graduate (n = 56) and undergraduate students (n = 243), used the 15 HydroLearn modules between the spring 2020 and fall 2021 semesters, consented to participate in our study, and had complete data. The participants in this study are the students whose instructors chose to use these 15 modules in their courses. Out of the total number of students, 57% (n = 171) identified as male, 38% (n = 113) identified as female, 1% (n = 4) identified as non-binary, 1% (n = 2) preferred not to answer, and 3% (n = 8) selected other; 77% (n = 228) identified as white, 3% (n = 9) identified as Black or African American, 2% (n = 6) identified as American Indian or Alaska Native, 16% (n = 48) identified as Asian, 1% (n = 3) identified as Native Hawaiian or Pacific Islander, 4% (n = 13) preferred not to answer, and 3% (n = 10) selected other. These students were at 15 different universities across the USA. **Table 1** provides demographic details of the study participants organized by module.

Supplementary Table 3 provides details about the universities that participated in the study. We used the most recent student population reports in conjunction with the rankings from the National Association for College Admission Counseling (CollegeData n.d.) to assign the university to a size range. We considered a university small if the student population is less than 5,000, medium for populations between 5,000 and 15,000, and large for populations greater than 15,000 students.

Data collection

Each student completed the Student Assessment of Learning Gains (SALG; Seymour et al., 2000) survey before they used the module (pre) and shortly after they finished the module's final assignment (post). The SALG is a tool that can be used to measure the knowledge and understanding of key concepts and processes that students believe they have achieved as a result of participating in a particular module (Seymour et al., 2000). It can be customized to fit any pedagogical approach or discipline. The SALG instrument has been used to assess students' gains in numerous studies, including some in the field of hydrology education (e.g., Endreny, 2007; Aghakouchak and Habib, 2010). Separate versions of the SALG were created for each module, and each version includes a list of concepts and skills aligned with the module's learning objectives (see **Supplementary Table 2**).

The SALG is divided into two scales in which students self-report their understanding of concepts and competency in employing technical skills that are the subject of the module. The concepts statement begins with, "Presently, I understand the following concepts that will be explored in this module. . ." followed by items that represent the key concepts from the

TABLE 1 Demographic details of the study participants organized by module.

Module title		Student Level		GPA				Gender					Race/ethnicity							
	Number of students	Undergraduate	Graduate/other	4.00 – 3.51	3.51 – 3.01	3.00 – 2.51	2.50 – 2.01	Male	Female	Non-binary	Prefer not to answer	Other	Spanish/Hispanic /Latino	White	Black or African American	American Indian or Alaska Native	Asian	Native Hawaiin or Pacific Islander	Prefer not to answer	Other
Assessing groundwater chemistry and suitability	9	8	1	3	4	2	0	6	3	0	0	0	0	7	1	0	1	0	0	0
Culvert design using HEC-RAS	24	24	0	6	7	8	3	16	8	0	0	0	1	19	1	0	1	0	1	0
Data science in earth and environmental sciences	11	4	7	6	4	0	1	6	5	0	0	0	1	8	1	1	0	0	0	0
Developing storm inflow and outflow hydrographs	24	24	0	6	7	8	3	16	8	0	0	0	1	19	1	0	1	0	1	0
Development of design storms	30	30	0	6	11	10	3	20	10	0	0	0	1	25	1	0	1	0	1	0
Evapotranspiration	16	16	0	2	7	7	0	12	3	1	0	0	2	10	0	1	1	1	2	0
Fluid mechanics: Bernoulli's equation	17	14	3	11	5	1	0	12	5	0	0	0	4	14	0	0	10	0	1	2
Frequency analysis in hydrology	25	18	7	12	12	1	0	13	12	0	0	0	3	23	0	0	4	1	0	0
Groundwater flow	11	6	5	7	3	1	0	6	2	1	2	0	2	7	0	0	1	0	3	0
Hydrologic droughts and drying rivers	33	26	7	8	15	6	4	11	17	0	0	5	9	24	2	2	6	1	1	2
Introduction to floodplain analysis	40	40	0	17	10	10	3	29	11	0	0	0	2	35	2	0	1	0	2	0
Physical hydrology	8	0	8	6	1	1	0	6	2	0	0	0	0	7	0	0	1	0	0	0
Quantifying runoff generation	31	31	0	6	11	11	3	21	10	0	0	0	1	26	1	0	1	0	1	0
Remote sensing applications in hydrology	50	33	17	30	13	2	4	20	24	2	1	3	8	25	0	1	17	0	3	5
Snow and climate	48	47	1	28	14	6	0	29	19	0	0	0	3	42	2	1	5	0	0	1
Total numbers	298	249	53	136	99	48	15	171	113	4	2	8	35	228	9	6	48	3	13	10
Percentages	1.00	0.84	0.18	0.46	0.33	0.16	0.05	0.57	0.38	0.01	0.01	0.03	0.12	0.77	0.03	0.02	0.16	0.01	0.04	0.03

module. Students indicate to what degree they understand each item using a 6-point Likert scale rated from 1 – Not applicable to 6 – A great deal. For example, one of the concept items for the "Hydrologic Droughts and Drying Rivers" module is "Presently, I understand the following concepts that will be explored in this module. . .drought indices." The concepts section in the SALG is followed by the skills section, which states, "Presently, I can. . ." followed by items that represent the technical skills students are exposed to through the use of the module. Students rate the skills items on the same Likert scale. "Presently, I can. . .Calculate drought indices using USGS streamflow data" is an example of a skill item from the "Hydrologic Droughts and Drying Rivers" module. A student's responses to all items within each scale (i.e., one for conceptual understanding and one for technical skills) were averaged to determine their pre- and post-module scores.

A survey's reliability is an important sign of the instrument's capacity to produce reliable and consistent results [i.e., how closely related the set of items (e.g., concepts or skills) are for all students for one module]. The internal consistency of a survey can be measured using Cronbach's alpha (Cronbach, 1984). For each scale, we determined the Cronbach's alpha (i.e., concepts and skills for each module). If the scores are reliable, they will relate at a positive, reasonably high level, with Cronbach's alpha ≥0.6 considered acceptable (Cresswell and Guetterman, 2019). The concept and skills scales' reliabilities across all modules ranged from 0.74 to 0.95.

We opted to merge data acquired from the identical modules used at different universities in the study. Data were only combined if they came from the same module (i.e., no updates or alterations at all). We made this decision for several reasons, the first of which is that the sample size is frequently insufficient for analysis, particularly in graduate-level courses. Second, by evaluating all the data for students who had completed a specific module, we were able to determine whether students felt they had attained the concepts and skills taught in that module, regardless of their university. Furthermore, because most instructors assigned the modules to be completed outside of class time, the university that used the modules was relatively irrelevant.

Data analysis

To answer our research question and investigate if the modules lead to a change in concepts or skills, we examined the difference in means from pre to post using paired samples *t*-tests. The paired samples *t*-test is commonly used to examine the difference between paired means (Zimmerman, 1997). We first tested the data to ensure it met the assumption of normality by examining the skewness and kurtosis of each scale. If a scale was found to be non-normally distributed, we used the Wilcoxon signed-rank test (Wilcoxon, 1945) instead of a paired samples *t*-test to determine whether there were statistically significant differences from pre to post (Siegel, 1956). For normally distributed scales, we moved forward with the paired samples *t*-tests.

One disadvantage of running so many tests ($n = 30$, 2 for each of the 15 modules) is that it raises the likelihood of wrongly rejecting the null hypothesis (i.e., a Type I error). To correct for the increased probability of Type I error, we employed the Benjamini–Hochberg procedure (Benjamini and Hochburg, 1995). The Benjamini–Hochberg procedure is a straightforward, sequential approach for reducing the rate of false discovery and is dependent upon the proportion of false discoveries. A discovery is the number of non-zero confidence intervals in a data set. A discovery can demonstrate that the difference noticed in the samples is not only attributable to chance (Soriæ, 1989). In this study, the number of discoveries was equal to the number of tests; therefore, the false discovery rate was reduced to α, which for this study was set at $\alpha = 0.05$. After the Benjamini–Hochberg correction factor was determined, each *p*-value had an associated Benjamini–Hochberg critical value. A variable was considered significant if the Benjamini–Hochberg correction factor was less than α.

After determining which tests were statistically significant using the Benjamini–Hochberg correction, we assessed the effect sizes to see if the changes between pre and post made practical sense (i.e., does this difference matter?). According to Warner (2012), pp. 35), "effect size is defined as an index of . . . the magnitude of the difference between means, usually given in unit-free terms; effect size is independent of sample size." According to Cresswell and Guetterman (2019), the effect size is a way of determining the strength of a study's conclusions about group differences or the link between variables. This study measured effect size using two methods: Cohen's d (Cohen, 1988) for normally distributed scales and $r_{equivalent}$ (Rosenthal and Rubin, 2003) for non-normally distributed scales. Cohen's d describes the difference between the means in terms of standard deviations for normal distributions. In educational research, a value of 0.4 or higher is considered impactful (Hattie, 2009). For each effect size, we describe Cohen's d in terms of size categories, which are small (0.2 – 0.49), medium (0.50 – 0.79), and large (≥0.8) (Cohen, 1988). Alternatively, $r_{equivalent}$ is designed specifically for non-parametric procedures (among other situations) as an indicator of effect size. The size bins for r used in this study are described as $r = 0.10$ (small effect; effect explains 1% of the total variance), $r = 0.30$ (medium effect; effect explains 9% of the total variance) and $r = 0.50$ (large effect; effect accounts for 25% of the total variance) (Field, 2018).

Results and discussion

Table 2 presents the reliability, pre- and post-mean scores and standard deviations, significance, and the effect size (Cohen's d or $r_{equivalent}$) organized by module. We found that all

TABLE 2 Reliability, pre- and post-mean scores and standard deviations, significance, and the effect size (Cohen's d or $r_{equivalent}$) organized by module.

Module	Reliability	N	Pre	Post	Sig.	Effect size
	Cronbach's α		M (sd)	M (sd)		
Culvert design using HEC-RAS						
Concepts	0.89	24	4.31 (0.77)	4.71 (0.70)	0.048*	0.74
Skills	0.88	24	3.74 (0.77)	4.44 (0.86)	0.040*	0.97
Data science in earth and environmental sciences						
Concepts	0.89	11	3.17 (0.93)	4.44 (0.54)	0.022*	0.89
Skills	0.86	11	2.86 (0.91)	4.36 (0.60)	0.023*	0.8
Developing storm inflow and outflow hydrographs						
Concepts	0.83	24	4.05 (0.56)	4.56 (0.69)	0.033*	0.63
Skills	0.88	24	3.36 (0.84)	4.48 (0.92)	0.027*	1.05
Development of design storms						
Concepts	0.95	30	4.25 (0.57)	4.74 (0.73)	0.037*	0.45
Skills	0.91	30	3.70 (0.88)	4.46 (1.02)	0.030*	0.71
Evapotranspiration						
Concepts	0.74	16	3.44 (1.00)	4.37 (0.58)	0.047*	1.3
Skills	0.78	16	3.20 (0.97)	4.34 (0.54)	0.045*	0.68
Fluid mechanics: Bernoulli's equation						
Concepts	0.82	17	2.63 (0.62)	4.69 (0.55)	0.008*	0.9
Skills	0.83	17	2.56 (0.82)	4.92 (0.53)	0.010*	1.03
Frequency analysis in hydrology						
Concepts	0.93	25	3.96 (0.74)	4.86 (0.59)	0.025*	0.73
Skills	0.92	25	3.10 (0.86)	4.81 (0.66)	0.005*	0.97
Groundwater flow						
Concepts	0.9	11	4.03 (0.94)	5.12 (0.42)	0.043*	0.94
Skills	0.93	11	3.69 (1.09)	5.17 (0.43)	0.035*	1.03
Hydrologic droughts and drying rivers						
Concepts	0.84	33	3.05 (0.73)	5.09 (0.62)	0.002*	0.89
Skills	0.82	33	2.69 (0.90)	5.21 (0.54)	0.013*	0.87
Introduction to floodplain analysis						
Concepts	0.92	40	3.69 (0.80)	5.00 (0.74)	0.020*	0.76
Skills	0.93	40	3.44 (0.96)	4.97 (0.79)	0.015*	0.78
Physical hydrology						
Concepts	0.89	8	3.99 (0.43)	4.96 (0.75)	0.050	0.85
Skills	0.94	8	3.64 (0.53)	4.66 (0.71)	0.042*	0.64
Quantifying runoff generation						
Concepts	0.96	31	4.27 (0.67)	4.81 (0.74)	0.028*	0.62
Skills	0.93	31	3.88 (0.62)	4.66 (0.91)	0.018*	0.72
Remote sensing applications in hydrology						
Concepts	0.84	50	3.90 (0.82)	5.03 (0.81)	0.017*	0.69
Skills	0.82	50	3.44 (0.98)	4.80 (0.99)	0.012*	1.54
Snow and climate						
Concepts	0.89	48	2.98 (0.76)	4.78 (0.69)	0.003*	0.86
Skills	0.79	48	3.75 (0.66)	4.80 (0.63)	0.007*	0.8
What's in your water? Assessing groundwater chemistry and suitability						
Concepts	0.86	9	2.83 (0.43)	4.33 (0.93)	0.038*	0.95
Skills	0.88	9	2.63 (0.62)	4.44 (0.94)	0.032*	0.77

*Indicates statistical significance after the Benjamini–Hochberg correction was applied.

but one of the scales had statistically significant and practically significant differences from pre to post. Only one scale (Physical Hydrology, conceptual understanding) did not have statistically significant differences from pre to post; however, it was approaching significance, p = 0.050, and the sample size was small (n = 8). Given the effect size of 0.85, the small sample size, and the p-value approaching significance, this suggests there was not enough power to detect statistical significance for this scale. A power analysis suggests that 16 students would be needed to find a statistically significant difference (Warner, 2012). To clarify, we do not have reason to think that this module is any less effective than the others. These results suggest that the students who participated in these modules felt that they had a greater understanding of the concepts and a greater ability to apply the skills after completing each module, as compared to before.

One of the most important findings of our study is the magnitude of the effect sizes. We found that only one scale had a small effect size (Development of Design Storms, conceptual understanding). The remaining scales were fairly evenly divided between medium and large effect sizes. Moreover, the fact that the effect sizes of all the t-tests we conducted were greater than the Cohen's d = 0.4 benchmark and $r_{equivalent}$ benchmark r = 0.50 typically considered impactful in education research (Hattie, 2009; Field, 2018) suggests that these modules may have a substantial practical effect on students' learning of concepts and skills.

Our results suggest that the students who participated in this study felt that they had greater conceptual understanding and technical skills after completing every one of the HydroLearn modules with the exception of Physical Hydrology conceptual understanding, as compared to before. Furthermore, the outcomes of this study align with previous research wherein students also used short modules designed to enhance their proficiency in applying technical skills to complete a task derived from the modules' learning objectives (Pimmel, 2003). Our results also support the idea that learning may be greater when conceptual understanding is directly linked to a real-world problem, and students are required to use professional tools and technical skills to propose a solution to the problem, as suggested by Brown et al. (2005) and Prince and Felder (2007). Similar to past research (Hiebert and Wearne, 1993; Stein and Lane, 1996; Boaler and Staples, 2008), our study also found that student learning was greater in courses that include high-cognitive demand tasks that stimulate high-level reasoning and problem-solving. Additionally, Kraft (2020) suggested that researchers should look not just at effect size, but at effect size compared to the cost of an educational intervention. Implementing HydroLearn modules in a water resources or hydrology course costs the instructor some time to prepare, but there are no direct costs to using these modules, as they are all freely available on our website. The findings from this study suggest that HydroLearn modules provide a very cost-effective way to improve water resources and hydrology students' understanding of key concepts and skills.

Concluding remarks

This study sought to answer the research question: Are there differences in students' self-reported learning gains in conceptual understanding and technical skills after participating in each online learning module designed around authentic, high cognitive demand tasks? The results of this study suggest that students who completed these modules reported that they had a greater conceptual understanding of key topics and developed proficiency in technical skills required to solve authentic problems. Most notably, the effect sizes of this study [0.45, 1.54] surpass the average effect size found in education research (0.40). These results suggest that the modules may relate to the growth of students' conceptual understanding and technical skills.

Instructors in the disciplines of hydrology and water resources are entrusted with preparing their students to become effective engineers in a relatively short time. We recommend that instructors consider augmenting traditional lectures with modules that use authentic high-cognitive demand tasks to develop students' conceptual knowledge and specialized technical skills, such as those hosted on the HydroLearn platform. Exposing students to authentic, high cognitive demand tasks can help them connect mathematical theories or classroom lectures to complex, real-world problems, applications, or procedures and gain a deeper understanding of fundamental topics in the field and develop the expertise needed to solve complex engineering problems.

While this study cannot directly attribute the observed gains in conceptual understanding and technical abilities to the usage of the specific module that the students completed, the positive trends that emerged from this study provide some important insights into how students' self-reported conceptual knowledge and technical skills grow following the use of an online learning module based on an authentic, high cognitive demand tasks. Moreover, this study cannot claim impact or effect based on the data collected because we did not use randomized control trials. Without randomized control trials, this study cannot make any causal claims as it is possible that participation in the courses, rather than the use of the HydroLearn modules, improved students' conceptual understanding and technical skills. Also, we cannot rule out the possibility that external factors influenced the students' self-reported results. It is possible that the students would have picked up on these concepts and skills anyway, and they simply happened to develop them between the pre and post-surveys. Finally, the exclusive use of self-report data can raise some concerns; however, this type of data is still widely used because it can be a convenient measure with some validity (Felder, 1995; Besterfield-Sacre et al., 2000;

Terenzini et al., 2001). Future research should compare a control group of students who did not participate in the modules to a group who did. Further investigation could also include performing different analyses, such as multilevel modeling, examining the impact of the modules on learning by controlling for other factors (e.g., grade point average, demographics, or motivation for learning) to try to parse out the effects of using the module on students' learning.

Data availability statement

The datasets presented in this article are not readily available. Per the institutional IRB, the dataset collected cannot be shared or hosted on any server that is not owned by the university. Inquiries can be directed to EH, emad.habib@louisiana.edu.

Ethics statement

The studies involving human participants were reviewed and approved by the University of Louisiana at Lafayette Institutional Review Board. The patients/participants provided their written informed consent to participate in this study.

Author contributions

JB collected the data, performed the analysis, and contributed to the writing of the manuscript. MG conceived and designed the analysis and contributed to the writing and editing of the manuscript. EH conceived and designed the overall approach and contributed to the writing and editing of the manuscript. All authors contributed to the article and approved the submitted version.

Funding

This study was supported by the National Science Foundation (NSF) IUSE Award #1726965. The HydroLearn project was supported by the National Science Foundation under collaborative awards 1726965, 1725989, and 1726667.

Acknowledgments

We acknowledge and sincerely appreciate the efforts of all HydroLearn fellows who have contributed modules to the HydroLearn platform. We would also like to thank all Fellows and faculty who have collected and shared their student data. Lastly, a very special thank you goes to the students who participated in the study.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feduc.2022.953164/full#supplementary-material

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