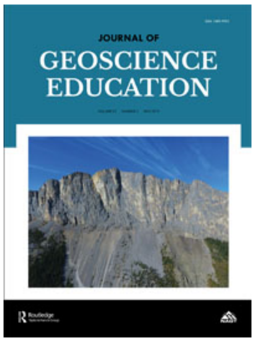

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Using student conceptions about groundwater as resources for teaching about aquifers

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ABSTRACT

Despite the need for public understanding about groundwater resources, groundwater is among those topics that instructors most struggle to teach at pre-college and college levels. Although constructivist theories suggest student-held conceptions can be used as teaching tools for active learning, there remains a question about how to draw out and incorporate these conceptions into actual class instruction. This study aims to answer the question: How can student conceptions about groundwater be used as teaching tools by drawing on a *resource perspective* of learning and *backward design*? The work utilizes the *design study* methodology. College-student work, college-classroom activities, and instructional records of a college-level instructor were examined to reconstruct and describe an instructional sequence about groundwater that was iteratively designed over five years using a resource perspective and backward design. This study helps bridge the gap between theory and practice by describing the design of an instructional sequence about groundwater and analyzing it within the framework of a resource perspective. *General* best practices, such as prior knowledge checks and predict-observe-discuss demonstrations, are translated into *domain-specific* instructional activities for teaching about groundwater and aquifers. Students' responses to such activities reveal student-held conceptions and can be used to further guide instruction and inform ongoing curriculum design. Student-held conceptions are a key component of the proposed resource-perspective-based backward design model for instructional design.

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Groundwater; conceptions; resource perspective; instructional design; active learning

Introduction

The United States utilizes groundwater for a variety of purposes (Maupin et al., 2014) and aquifers provide more than 80% of its residents with their drinking water (Kenny et al., 2009). Threats to the quality and quantity of this water are due to agricultural and industrial contamination (Mackay & Cherry, 1989; Wakida & Lerner, 2005) and pumping rates that exceed natural recharge rates (Oude Essink, 2001). An understanding of groundwater and aquifers is therefore among the "ideas of Earth Science that all citizens should know, determined by the Earth Science research and education communities [so that they are able to] make informed and responsible decisions regarding Earth and its resources" (Earth Science Literacy Initiative, 2009).

However, groundwater and related concepts are among content areas that instructors most struggle to teach (Hewson, 1981; W. B. Meyer, 1987). Consistent with constructivist theories of teaching and learning (Ausubel & Ausubel, 2000; Driver & Erickson, 1983; Powell & Kalina, 2009), it has been suggested that student-held conceptions about groundwater could be used as teaching tools (Bar, 1989; W. B. Meyer, 1987). However, Bar (1989) and W. B. Meyer (1987) both pose the question of *how* it could be done. Despite more than 30 years of research describing theory-supported and empirically-tested instructional "best practices," the question about how to translate *general* "best practices" into teaching *domain-specific* concepts (e.g., groundwater) remains relevant not only in K-12 grades but also at the college level. A recent literature review of the geoscience education research literature supports the continued need for studies on student cognition and their use as teaching tools (Arthurs, 2018). Indeed, "the translation process often remains elusive" (National Research Council, 2012, p. 180).

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The question about how instructors could utilize student-held conceptions about groundwater as teaching tools likely persists for at least two reasons. First, a more comprehensive and coherent knowledge base about domain-specific student-held conceptions does not exist (National Research Council, 2012). Although student conceptions about groundwater have been described in different and unrelated contexts, until recently a more comprehensive and coherent knowledge base of such student-held conceptions did not exist (Arthurs & Elwonger, 2018). Second, little is known about how science instructors translate documented learning theories and general "best practices" into domain-specific teaching practice (Beach, Henderson, & Finkelstein, 2012), such as teaching about groundwater and aquifers. The present study is part of a larger project undertaken in response to the two aforementioned gaps in knowledge. The first question is addressed in another study (Arthurs & Elwonger, 2018). The second question is addressed herein. The driving research question of this study is: Drawing on a constructivist theory (i.e., resource perspective) and backward design, how can student conceptions about groundwater be used as teaching tools during classroom instruction? The purpose of this study is not to evaluate the impact of an instructional intervention on student learning but rather to answer the driving research question through the examination of an instructional sequence designed with a resource perspective and backward design in mind for an introductory-level college geoscience course.

Theoretical framework

Resource perspective

Constructivist theories of learning share a common foundation that recognizes students do not come to the classroom *tabula rasa* and new learning is constructed in the context of their prior knowledge (Bransford, 2000). When that prior knowledge conflicts with expert-defined knowledge, it is often referred to as a "misconception." In other words, it is an incorrect conception that needs to be replaced (H. Meyer, 2004).

Alternatively, a resource perspective on teaching challenges instructors to think about students' prior knowledge as "conceptual resources" students bring to the learning environment (Hammer, 2000). Accordingly, the term "alternate conception" is more appropriate than "misconception" as it respects the students' ideas without simply dismissing them as incorrect (Gilbert & Watts, 1983). Within a constructivist approach, a resource perspective challenges instructors to more deeply understand students' ideas and to engage those ideas in an active learning process. This perspective frames the design and implementation of the instructional sequence about groundwater.

Backward design

Backward design is a process for designing an instructional *unit of study* (Wiggins & McTighe, 2011). In this research study, the unit of study is a week-long instructional sequence about groundwater and aquifers. The backward design model comprises three steps. First, define learning goals for the unit of study. Second, develop assessments that measure the degree to which students achieve the learning goals. Third, design activities that aid students in achieving the learning goals. Along with a resource perspective, backward design was used to inform the design the instructional sequence. Furthermore, its utility as a model for instructional design is discussed.

Methodology

Design study

All researchers "bring to inquiry" [Creswell, 2014, p. 35-36]) with them a worldview or "a set of beliefs that guide action" [Guba, 1990, p. 17]. Pragmatism, as described by Creswell (2014), is the worldview that grounds the design and conduct of the present study. Pragmatism is concerned with the intended consequences or applications of research (Creswell, 2014). The intended application of this study is to help stimulate discussion and continued research about how students' conceptions can be used as tools for teaching and how science instructors translate documented learning theories and general "best practices" into domain-specific teaching practice (Beach et al., 2012). Pragmatism also lends the researcher freedom of choice to use any and all available approaches that will help to solve a problem or answer a question (Creswell, 2014). This study utilizes the methodology of *design study*.

The design study methodology is associated with earlier terms such as design experiments, design research, design-based study, and design-based research (Confrey, 2012). The design study methodology is used for "the close study of a single learning environment […] as it occurs in naturalistic contexts" (Barab, 2012, p. 153). The "designed context is subject to test and revision, and successive iterations" (Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003, p. 9). The design process permits the researcher to not only understand the world as it is but to change it in useful ways to meet local needs (Barab & Squire, 2004). This methodology connects design interventions with existing models or theories as well as tests and generates models or theories. That is, in addition to meeting local needs, it is "concerned with using design in the service of developing broad models of how humans think, know, act and learn" (Barab & Squire, 2004, p. 5).

According to Confrey (2012), a research study based on the design study methodology (i.e., design-based study) is an "investigation of educational interactions provoked by use of a carefully sequenced and typically novel set of designed curricular tasks studying how some conceptual field, or set of proficiencies and interests, are learned through interactions among learners with guidance" (p. 135-136). These studies are akin to case studies in that they examine a single bounded case of complex interactions in detail over extended periods of time (Confrey, 2012; Yin, 2013). They are also akin to ethnographies in that the researcher is a participant observer (Barab, 2012; Confrey, 2012). An expert in ethnographic and education research, external to this study, provided a peer review of the methodology and methods for the study, and the expert noted that the selected methodology and methods are appropriate for answering the stated research question.

The case: An instructional sequence about groundwater

The *focal case* (Stake, 1995) for this design-based study is a one-week long (i.e., three 50-minute meetings) instructional sequence about groundwater and aquifers. It is set within the context of a 15-week long introductory-level college course titled *Environmental Geology* taught at a large state university in the USA. The course satisfies requirements for the environmental studies major and university natural science requirement. The course comprised four major modules: (i) what is science and how do scientists know what they know; (ii) how do Earth processes, particularly natural disasters, impact people; (iii) how does the Earth, particularly its natural resources, allow people to live the way we do; and (iv) how do people impact the environment? The instructional sequence about groundwater and aquifers was implemented within the module about natural resources and in a unit about water resources.

Methods

Locating the study

The subject of this study is the final iteration of a week-long instructional sequence about groundwater. The development of the sequence was an iterative process of design, implementation, and revision. The development process occurred at two large state universities in the USA over six iterations of implementation over five years. The universities are located in south USA and central USA. Both institutions are Carnegie doctoral-research universities. The class enrollment in the south USA ranged from 233 to 312 students, and in the central USA it ranged from 48 to 79 students. The designer and instructor was the same individual across all iterations of the development process. At both universities, the course was taught in an auditorium setting. The last iteration of the instructional sequence is the focal case of this study.

Designing the instructional sequence

The design of the instructional sequence utilized backward design. The learning goals pertaining to groundwater in the water resources unit include students being able to: (i) explain where drinking water pumped from the subsurface originates from, (ii) describe the relationships between impermeable rocks and water-bearing rocks in the subsurface, and (iii) draw three types of aquifers from which drinking water may be pumped. To facilitate student attainment of these learning goals, the instructional sequence was designed with a resource perspective.

Applying a resource perspective to the design of the instructional sequence required instructor awareness of student-held preconceptions about groundwater. The instructor was aware of student-held conceptions in the published literature, e.g., groundwater is an underground lake or stream of water (Mattingly, 1987). However, that knowledge alone was insufficient to design an instructional sequence about groundwater and aquifers for using a resource perspective. A resource perspective depends on drawing out students' thinking. Thus, the instructional sequence in every iteration of design and implementation included activities that elicited students' ideas about groundwater.

A systematic study of these ideas (Arthurs & Elwonger, 2018) reveals students conceive groundwater as residing in underground lakes, caves, reservoirs, streams, or layers of water. They also conceived it to be water intermixed with dirt/soil, water in between small sediments, or water inside rock. That study also shows these conceptions are held by other students in different regions and different grade levels from 4th grade to college (e.g., Ben-Zvi-Assarf & Orion, 2005; Dickerson & Dawkins, 2004; Reinfried, 2006; Schwartz, Thomas-Hilburn, & Haverland, 2011). It also found the following recurring conceptions every semester:

1. Groundwater exists as large continuous bodies of water in large openings underground.
2. Rocks are solids and therefore are unable to hold water inside them.
3. The underground contains soil or dirt and groundwater is mixed with it.

With the development process framed by a resource perspective, these conceptions were incorporated into the instructional sequence by translating *general* "best practices" into *domain-specific* activities about groundwater and aquifers.

Data sources

Consistent with the design study methodology (Confrey, 2012), this design-based study utilized student work, classroom assessments, and instructional records as sources of data. The data sources are: (i) course syllabus, (ii) PowerPoint presentations and detailed lesson plans, (iii) copies of instructions and handouts for in-class activities, and (iv) instructor's notes about how in-class activities unfolded and student contributions to in-class discussions. Student performance data beyond their contribution to in-class discussions are discussed in a different article (in preparation) coming out of the larger aforementioned project. Also consistent with the design study methodology (Confrey, 2012), this design-based study examined successive iterations of a week-long instructional sequence about groundwater. The data were collectively examined to reconstruct and describe an instructional sequence about groundwater that was iteratively designed over six iterations and five years.

Data analysis

Recall that design-based studies are a type of case studies research. Creswell (2007) states that analyses of data for case studies research can involve either a holistic analysis of the entire case or an *embedded analysis* of specific aspects of the case. In this study, an embedded analysis of only data pertaining to the research question is performed (refer to Data Sources section above). The data were analyzed to provide a description of the instructional sequence and to illustrate how student-held conceptions about groundwater were incorporated into classroom instruction.

Results

Focal conception-based instructional sequence and activities

Framed within a resource perspective, the instructional sequence about groundwater and aquifers comprises general "best practices" that actively elicit, engage, and utilize student-held conceptions (Table 1). Three in-class activities compose the sequence. Each activity engages aforementioned student-held conceptions. The overall design goal was to develop a scaffolded process of learning (Holton & Clarke, 2006; Shepard, 2005) that builds on student-held conceptions (Bransford, 2000).

First in-class activity: prior knowledge checks

Prior knowledge checks are a type of general formative activity described by Angelo and Cross (1993). The prior knowledge checks developed for the instructional sequence on groundwater were intended to challenge students' conceptions that groundwater exists as continuous bodies of water in large underground openings. The first prior knowledge check asked: "Where does water that people drink come from?" Students discussed this with their neighbor(s). After about two minutes, the instructor convened a whole-class discussion where students shared their ideas. As they did, the instructor recorded the ideas on the blackboard (e.g., "river," "rain," "bottled water," etc.).

Anticipating that one or more students would say, "aquifer," the instructor designed a follow-up prior knowledge check. This was a multiple-choice item intended to probe what students think when they hear the word "aquifer" and to prime students to think about groundwater residence (i.e., where water resides and is found in the subsurface). This prior knowledge check asked:

Which one of the ideas is most similar to your idea? An aquifer looks like …

A. An underground river or tunnel with water flowing through it
B. An underground pool or giant cave filled with water
C. A mixture of sand and water in a bucket
D. My idea is not similar to any of these choices

Students used colored cards to vote (O'Connor, 2013). The instructor estimated the percentage of the

Table 1. Instructional sequence about groundwater and aquifers.

Class #	Week #	General Best Practice	Domain-Specific Activity	Prompt or Item
23	8	Prior knowledge check	Draw free-form concept sketch	In preparation for next week, draw and label a picture of how water* is naturally store below the ground. *water that is pumped from the ground to drink
24	9	Prior knowledge check	Paired & whole-class discussion	Where does water that people drink come from?
		Prior knowledge check	Vote on polling question	Which one of the ideas is most similar to your idea? An aquifer looks like … A. An underground river or tunnel with water flowing through it B. An underground pool or giant cave filled with water C. A mixture of sand and water in a bucket D. My idea is not similar to any of these choices
		Interactive demonstration	Complete predict-observe-discuss worksheet	What do you think will happen when 3 drops of water are placed on each of these rocks? A. The water run off or stay on the surface B. The rock will absorb the water C. Both A and B will happen D. Something else will happen
25	9	Interactive demonstration	Discuss predict-observe-discuss worksheets	What kinds of predictions did we make as a class? [Display and discuss compilation of class predictions. A few folks referred to "pores" and "porosity" – but what are they. We'll talk about that now (lecture next).]
		Prior knowledge check	Discuss prior knowledge checks	What is an aquifer? [Display and discuss prior-knowledge free-form sketches. Let's see how closely these ideas match geoscientists' ideas about aquifers (lecture next).]
		Concept sketch	Draw base-form synthesis concept sketches	How are all three types of aquifers related to one another in a "bigger picture"? On your handout, (1) shade in where each of the three types of aquifers would occur and (2) be sure to label each aquifer that you shade in.
26	9	Concept sketch	Discuss base-form synthesis sketches	How are all three types of aquifers related to one another in a "bigger picture"? [Display and discuss examples of base-form sketches. Then, fill in a projected base-form sketch, to show how and where each type of aquifer is emplaced, and the various possibilities (i.e. no single correct answer).]
27	10	Homework	Complete & discuss	[Discuss homework questions for which <70% of the class answered correctly.]
32	11	Mid-term exam	Complete post-module-instruction check	In the figure below, (1) draw in a confined aquifer, perched aquifer, and unconfined aquifer; (2) draw in a drinking water well that pumps water out of the unconfined aquifer; (3) label each aquifer, the water table, and the potentiometric surface.
45	16	Final exam	Complete post-course-instruction knowledge check	Draw and label a sketch that shows the position of the following with respect to one another: confined aquifer, unconfined aquifer, perched aquifer, water table, potentiometric surface, impermeable layers, and wells.

class that voted for each answer choice. After reporting the approximate percentages, the instructor validated students' ideas by stating that water can indeed occur underground as described in the first three answer options. The instructor went on to state that an aquifer has a specific geologic definition, that the concept of an aquifer would be further pursued during this week of instruction, and then the instructor segued into the next in-class activity.

Second in-class activity: Interactive demonstration

Interactive demonstrations are described as a three-step activity: (i) predict, (ii) observe, and (iii) discuss by Crouch, Fagen, Callan, and Mazur (2004). The interactive demonstration activity designed for the instructional sequence about groundwater was intended to aid students in realizing rock has the capacity to hold water even though it is, as they said, "solid." In particular, the results of this in-class activity were used to segue into a discussion about the concepts of "permeable" and "impermeable." Prior to playing the prerecorded video demonstration, the instructor asked using PowerPoint:

What do you think will happen when 3 drops of water are placed on each of these rocks?

A. The water will run off or stay on the surface
B. The rock will absorb the water
C. Both A and B will happen
D. Something else will happen

The instructor also distributed a worksheet (Figure 1) for students to record their predictions and reasoning, and then passed around the rock specimens for students to handle before watching the video demonstration with the same rock specimens in it. After students inspected the specimens and completed their worksheets, they watched the video. Before the second

Name: ______________________________ Date: ________________

Rock and Water

(1) Predict what will happen to the water when three drops of water are placed on each of the rocks. Record your predictions in the table below.

	Rock Name	PREDICTION for what happens to the water (circle one)
1	granite	**(A)** runoff/stay on surface. **(B)** be absorbed. **(C)** both A & B. **(D)** something else
2	basalt	**(A)** runoff/stay on surface. **(B)** be absorbed. **(C)** both A & B. **(D)** something else
3	sandstone	**(A)** runoff/stay on surface. **(B)** be absorbed. **(C)** both A & B. **(D)** something else
4	marble	**(A)** runoff/stay on surface. **(B)** be absorbed. **(C)** both A & B. **(D)** something else

(2) Using the table below, describe your reason(s) for the prediction that you made for each of the rocks.

	Rock Name	Describe your REASON(S) for each prediction
1	granite	
2	basalt	
3	sandstone	
4	marble	

Figure 1. Worksheet to support interactive demonstration.

class meeting in this instructional sequence, the instructor tallied the students' predictions and summarized their associated reasons. This tallied information was discussed in the next class meeting.

For the second day of the instructional sequence, the activities were designed to aid students in discovering solid rock can hold water. To begin the interactive lecture, the instructor presented and facilitated a discussion about the tallied student responses. At the end of the discussion, the instructor pointed out that a few people made reference to "pores" and "porosity" in their reasons and asked, "But what are they?" The instructor stated that they would now learn more about what these terms mean in a geologic sense and proceeded with a mini lecture about "pores," "porosity," "primary porosity," and "secondary porosity."

Following the mini lecture, the instructor asked, "What is an aquifer?" To begin addressing this question, the instructor displayed anonymized concept sketches that students submitted the week before as the initial prior knowledge check to this week's instructional sequence to facilitate class discussion. The concept sketches represented different ideas about groundwater residence (e.g., underground caves and streams). Following the discussion, the instructor said, "Let's see how closely these ideas match geoscientists' ideas about aquifers." The mini lecture addressed karst formations such as underground caves and provided a formal definition for aquifers: An aquifer is a body of rock or sediment that is porous, permeable, and saturated enough to supply water to wells, springs, and perennial streams (Reichard, 2010).

Students were then shown a photograph of an underground cave that was partially filled with water and asked whether it was an aquifer. The instructor wrote "YES" and "NO" on the board, asked students to vote "YES" or "NO" by raising their hands, and then recorded the tallies on the board. Following this, the instructor facilitated a whole-class discussion that was prompted by the instructor asking students about their reasoning, "Whether you voted 'yes' or 'no,' what are some reasons why this might not be an aquifer?"

Third in-class activity: Concept sketch

Following the above discussion, the instructor delivered a mini lecture in which students were reminded what it means for rock to be "permeable" or "impermeable" and in which the instructor described "perched," "unconfined," and "confined" aquifers separate from one another. After individually discussing each type of aquifer, the instructor asked students to synthesize the information by completing a concept sketch that was already partially drawn for them on a worksheet (Figure 2). This activity was also designed as part of an effort to aid students in realizing that aquifers are made of "porous" and "permeable" rock that can hold water. It asked:

> How are all three type of aquifers related to one another in a "bigger picture"? On your handout, (1) shade in where each of the three types of aquifers would occur and (2) be sure to label each aquifer that you shade in.

The instructor collected, reviewed, and selected representative examples for discussion during the next class meeting.

During the third day of the instructional sequence, the instructor began class by asking, "How are all three types of aquifers related to one another in a 'bigger picture'?" Five different anonymized concept sketches

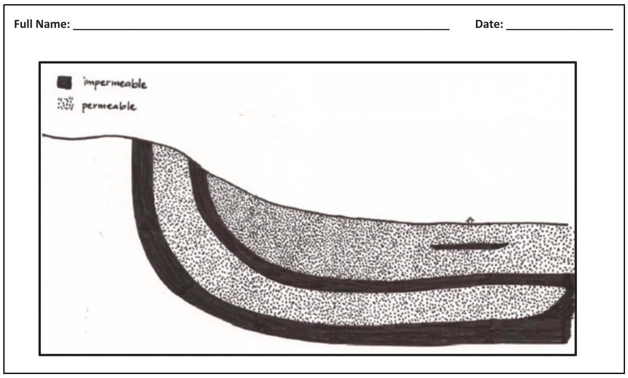

Figure 2. Worksheet to support concept sketching activities.

were selected and scanned for class discussion. Each sketch was displayed using PowerPoint and discussed sequentially. Students were asked to identify what about each sketch could be changed in order to make it more scientifically accurate. After the discussion, the instructor used a DocCam to project the instructor's real-time shading on a blank worksheet. While doing so, the instructor asked students what kind of aquifer was being shaded in. At this time, students also asked questions they had about how to place different aquifers relative to the "permeable" and "impermeable" layers and how water enters aquifers.

Successive iterations of design and revision

The focal case described above, consistent with the design study methodology, was the product of successive iterations of design and revision. Examination of each earlier previous iteration permits a view into the history behind the development of the focal instructional sequence, including what the instructor learned and what informed instructor decisions to make subsequent changes or not. The data sources used to reconstruct and examine each earlier iteration include: the course syllabus, PowerPoint slides and detailed lesson plans, copies of instructions and handouts for in-class activities, and the instructor's notes about how in-class activities unfolded and student contributions to in-class discussions. Collectively, drawing on these data sources, the described observations about changes to the instructional sequence can be made relative the focal conception-based instructional sequence and activities described above.

First in-class activity: Prior knowledge checks

The first prior knowledge check, "Where does water that people drink come from?", remained unchanged through all iterations. The instructor retained it in the original form from one iteration to the next because she believed it was a useful way to engage students with something they know about that would then draw them into more geologically-oriented discussions. The follow-up prior knowledge check that asks, "Which one of the ideas is most similar to your idea? An aquifer looks like …" also remained the same through all iterations. The instructor did not change this follow-up prior knowledge check because she found it was a helpful way to begin moving into directly learning about what her students thought about aquifers.

There were, however, two aspects of the first in-class activity that were not held constant through all iterations. First, only during the first iteration another follow-up prior knowledge check was inserted in between the checks described above. Students were asked to: "Individually, draw a simple diagram that illustrates how you imagine water might be stored under ground in an aquifer. Also, write a brief description to explain your reasoning. When you are finished, talk with your neighbor and share your ideas with each other." Students were asked to submit their completed work on their way out of class. With a desire to facilitate student learning through improvements in the lesson, the instructor was curious to see whether discussion with classmates might noticeably change the concept sketches at that early stage of the instructional sequence compared to pre-instructional sequence concept sketch students were asked to draw the week prior. Upon finding there was no noticeable difference, the instructor decided not to do this again in subsequent iterations, believing the in-class time together could be spent in other ways that would be more meaningful for both student and instructor learning. During that iteration, the instructor did not yet know what exactly those other ways would end up being.

Second, only during the second iteration, the instructor also asked students to write down their lists of ideas for where water that people drink comes from. Again with a desire to facilitate student learning through improvements in the lesson, she was curious to see whether any ideas were written down that were not shared in the whole-class discussion. Upon finding that there were not notable differences, the instructor decided there was no value added in collecting the students' lists in subsequent iterations.

Second in-class activity: Interactive demonstration

The "What is an aquifer?" question changed during the second iteration. Specifically, digital scans of actual student work were projected and discussed (see Figure

S1 in the Supplementary Materials). This modification was retained in subsequent iterations because the instructor learned students liked seeing their and their peers' anonymized sketches and ideas as the direct subject of discussion, which stimulated the discussion in ways that helped her learn more about their current thinking about aquifers and helped students see the range of ideas that exist.

The predict-observe-discuss interactive demonstration about what happens when three drops of water are placed on different types of rocks was changed in three ways throughout the six iterations. First, the wording of the first multiple-choice answer was changed from "(A) The water will run off the surface of the rocks" to "(A) The water will run off or stay on the surface." The instructor decided to make this change after listening to what students said during the whole-class discussion. Several students said that the water would "stay" on the rocks and that was not an option originally presented in the multiple-choice answer options. The instructor also thought the reasons why water might run off or stay on a rock were similar enough for the purposes of the discussion that they could be placed in the same answer option. This change was made during the second iteration and remained so in successive iterations. Second, the order of the multiple-choice answers was changed from "(C) Something else happens" and "(D) Both A and B will happen" to "(C) Both A and B will happen" and "(D) Something else will happen." The instructor made this decision because she though that the answer choice C fit better after choices A and B in the revised version. The instructor did not notice any obvious changes in the variety of students' votes based on the order change. This change was made during the fifth iteration and remained so in the sixth iteration. Third, the manner in which students recorded their votes and reasoning changed throughout the iterations. During the first and second iterations, students were asked to write down the letter they voted for with colored cards on a sheet of their notebook paper and turn it in after class. During the third iteration, students were asked to write down the letter they voted for on a notecard that the instructor provided and turn it in after class. During the fourth iteration, the instructor provided a ½-sheet handout upon which students could record their vote and their reasoning and students' completed handouts were collected before students watched the demonstration. The handout remained unchanged in successive iterations.

The reasons for these changes are attributed to the instructor's time available for developing course materials, desire to more efficiently sort hard copies of student work, and desire to have students commit to the reasoning behind each prediction before testing their prediction. In terms of course material development time, during the first iteration, the instructor was creating *all* course materials from scratch. Although she had wanted to create a handout during the first iteration, she ran out of time before the class meeting and thought having students write their responses on their notebook paper would be satisfactory. During the second iteration, the instructor created another in-class activity and, with limited time to create more materials, decided to continue having students write their responses on their notebook paper instead of creating a handout then. During the third iteration, the instructor did not create a new activity for this instructional sequence and had a class with about 70 students, as opposed to the more than 200 students per class in each of the earlier iterations. With the relatively smaller class, the instructor decided to experiment with using 3-x5-inch notecards to more efficiently sort hard copies of student work, compared to notebook paper that students often tore out of their spiral notebooks and that would get stuck to one another as a consequence. For this activity in the third iteration, the instructor passed out the notecards for each student to write on and she liked how quickly they were sorted. She considered having students bring notecards of their own for subsequent iterations, but she was able to create a ½-sheet handout during the fourth iteration because she had material development time to do so and was also curious to see whether the quality of student responses might change if they had a handout compared to a blank sheet or notecard. Interestingly, she found that on the whole students more clearly articulated their reasoning for each prediction on the ½-sheet handout. This finding was useful to her because she was able to learn even more about the ideas that students had about rock properties that might impact their capability for holding water. It was also during the fourth iteration that a more formal debriefing to the predict-observe-discuss handout was introduced. During the debriefing, digital scans of examples of completed student handouts were projected and discussed. This change remained intact in successive iterations because the instructor liked how well the discussion unfolded when the class could see actual examples of students' work and discuss them as a whole class. Also, students provided the instructor with feedback that the discussion was helpful to them as well.

Third in-class activity: Concept sketch

This activity uses a ½-sheet handout with a partially drawn sketch and asks students, "How are all three types of aquifers related to one another in a 'bigger picture'?" This activity was designed and used during the fourth iteration. The instructor designed this activity because she observed students in previous iterations consistently were confused by how different aquifers are classified and their relationship to one another and had available material development time. She thought if she provided students with a partially complete sketch of a scenario that showed where permeable and impermeable rock are located, then the students could focus on thinking about where water might reside relative to the shown rocks. The instructor liked that the student-completed handouts allowed her to learn common ways that students were thinking about the three aquifer types and, then, guide a discussion where the whole class walked through different examples of student thinking and then together arrived at a more scientifically accurate understanding of three different types of aquifers, how they compare or relate to one another, and how they are recharged. Figure S2 in the Supplementary Materials shows examples of some student sketches.

Based on instructor's notes, prior to the fourth iteration, the instructor knew students were "not grasping the distinctions between the three different aquifer types" but she didn't understand why not. The students' sketches helped her to better understand the many ways students conceptualized the location of these three aquifer types relative to permeable and impermeable rock and relative to one another. Knowing how students were thinking about the different types of aquifers allowed the instructor to have a discussion with students using concrete examples of what they thought and compare them to scientific conceptualizations for each type of aquifer.

Discussion

Alternative approaches

The reader may be interested in a discussion of alternative approaches and the merits of the approach applied to this study. To address these interests, it is first necessary to note that the definition of two terms defined in the instructional decisions to enable active learning strategies or IDEALS theory (Arthurs & Kreager, 2017) are adopted for this discussion. First, an *approach* is a general philosophy or principle for guiding instructional decisions. An approach concerns high-level decision making about the general manner with which to undertake instruction and involves deciding to use a transmissionist approach, a constructivist approach, or some combination of these two end-member approaches. An *activity* is concerned with low-level instructional details that relate to the implementation of a specific learning task(s).

With these definitions in mind, let us consider several empirical studies that represent a variety of different activities used for teaching and learning various aspects of groundwater at different grade levels in different geographic locations. Thomas and Svihla (2017) studied how a two-day (i.e., two class meetings) experiential learning activity that involved taking a "watershed walk" around the lecture building impacted students in a college environmental science course (enrollment = 79). Unterbruner and colleagues (2016) studied how hundreds of Austrian seventh graders and teacher-training students used multimedia learning software on an individual basis outside of class to independently learn about groundwater. Endreny (2010) studied how a place-based inquiry unit on watersheds impacted a class of 33 fifth graders in a school in northeast USA. Mays (2010) studied the impact that a one-week module on stochastic groundwater modeling had on a graduate groundwater hydrology course with enrollments of eight to 14 students. Assaraf and Orion (2009) conducted a *design study* to describe the development of the "Blue Planet" program for hundreds of junior high school students in Israel. Reinfried (2006) conducted a quasi-experimental study with teacher education students in a German college classroom setting that utilized a physical groundwater model (treatment group = 16, control group = 14). Pederson (1979) studied the impact of fieldtrips with classes of of 25 to 35 college students enrolled in an introductory-level geology course in central USA.

Although a comparison of the aforementioned studies with the present study can help illustrate similarities and differences, it is beyond the scope of this study to assign merit to the different activities developed. What might have merit is largely contextually informed, and there is no direct way in the present study to compare how earlier studies' activities and the present studies' activities perform in different contexts. That is, for example, it could be that an activity that resulted in positive learning outcomes in a small class might not have a positive effect in a large class and vice-versa.

Nevertheless, several observations can be made to compare and contrast earlier studies with the present study as well as the activities developed in those studies with the activities developed in this study. First, the purposes of most of the earlier studies and the present study are not the same. The purpose of almost all these earlier studies was to determine the impact the activities had on student learning. The exception is the study by Assaraf and Orion (2009), which had the purpose of outlining the design process behind an instructional program. In that regard, its purpose is unique to both the other studies and this one. Recall the purpose of the present study is to answer the research question: *Drawing on a constructivist theory (i.e., resource perspective) and backward design, how can student conceptions about groundwater be used as teaching tools during classroom instruction?* However, Assaraf and Orion's study is similar to the present study in that they both utilize a design study methodology. Third, like the present study, these earlier studies involved activities aimed at providing students with active learning opportunities (Arthurs & Kreager, 2017) and most were also designed with a constructivist approach in mind. Also, the previous studies were implemented in small- to medium-sized classes (i.e., enrollments of eight to 79 students), whereas the present study also included large classes (i.e., enrollments with more than 200 students). Lastly, among all previous studies' activities were tasks that required specialized apparatus (e.g., Reinfried, 2006), specialized software (e.g., Mays, 2010; Unterbruner, Hilberg, & Schiffl, 2016), and/or a field-trip or other outdoor activity (Endreny, 2010; Pederson, 1979; Thomas & Svihla, 2017). This contrasts with the activities in the present study, which required no specialized apparatus or software and for which all tasks were completed entirely inside the classroom/auditorium. These similarities and differences surely have different implications for the activities' effectiveness in contexts beyond those in which they were developed, effectiveness both in terms of instructors' ability to implement them and in terms of the impact on student learning. Thus, the similarities and differences in lessons about groundwater opens the door to an area of potential future research.

Constructivist teaching and learning

The design of the week-long instructional sequence about groundwater and its activities are grounded in a constructivist approach to teaching and learning that explicitly emphasizes a resource perspective. Constructivist approaches to teaching and learning are student-centered, integrate students' prior knowledge in hermeneutic whole-class discussions between the students and teacher (Davis, 1997; Yorke, 2003). Furthermore, they provide instructional scaffolding (Shepard, 2005) that promotes independent self-scaffolding (Holton & Clarke, 2006). The instructional sequence and activities were designed and implemented to facilitate active learning about groundwater and related concepts by eliciting and engaging student-held conceptions. Importantly, the design process also positioned the instructor in the role of learner and designer. As a learner, the instructor discovered more about student thinking in a particular conceptual field, consistent with a design study methodology (Confrey, 2012). As a designer, she applied what she learned about student thinking and what she learned about the usefulness of each activity to various iterations of change. These activities and any changes to them were aimed at improving the local context of teaching and learning, consistent with a design study methodology (Barab & Squire, 2004), and were intended to be formative.

Analysis of the results reveals the activities in the instructional sequence support classroom instruction that is formative. "Instruction" means the combination of teaching and learning [… and] refers to any activity intended to create learning (Black & William, 2009, p. 7). Classroom instruction is formative to the extent that:

> evidence about student achievement is elicited, interpreted, and used by teachers, learners, or their peers, to make decisions about the next steps in instruction that are likely to be better, or better founded, than the decisions they would have taken in the absence of the evidence that was elicited. (Black & William, 2009, p. 7)

Consistent with a resource perspective (Hammer, 2000) the instructional sequence and activities show how the instructor elicited students' ideas to facilitate student thinking and class discussion. In addition, they help to answer this study's driving research question by illustrating how *general* "best practices" for teaching (e.g., prior knowledge checks) can be translated into *domain-specific* contexts for teaching about groundwater and aquifers.

Instructional design

Consistent with the design study methodology, the present study contributes to the testing and generation of theories and models (Barab & Squire, 2004). As previously discussed, backward design is a three-step model for the instructional design process (Wiggins & McTighe, 2011) used to frame the design of the week-long instructional sequence about groundwater and aquifers. The first step is the articulation of instructor-defined learning goals. These goals inform the design of assessments and both, in turn, inform the design of learning activities. Reflection on its use in this design study revealed previously unnoticed limitations of the model. First, students' conceptions are not present in the model. Additionally, the model is not explicit about types of assessment (e.g., formative) and how they might overlap with learning activities. Given the theorized importance of student-held conceptions in constructivist theories of teaching and learning, designing formative activities and classroom instruction only on the basis of instructor-defined learning goals may be less than optimal.

For example, instructors may become susceptible to expert blind spots (Nathan & Petrosino, 2003) and the reverse Dunning-Kruger effect (Klymkowsky, 2017). An expert blind spot is the tendency for domain experts who are instructors to be unaware of the cognitive challenges novices confront in developing expertise. The reverse Dunning-Kruger effect is "the tendency for instructors […] to overestimate what the people they are talking to are prepared to understand, appreciate, and accurately apply" (Klymkowsky, 2017). By way of example, a common novice conception is that rocks do not hold water inside them because they are "solid" (Arthurs & Elwonger, 2018) but a hydrologist with 20 years of experience might have forgotten that he thought the same thing when he was first learning about geology and/or might be unaware that others do not share expert hydrologists' understanding that rocks are capable of holding water. An implication of such an expert blind spot in teaching is that the expert hydrologist could unconsciously assume his students know the fundamental "given" in hydrology that rocks do have the capability of holding water within them. Operating under this assumption might, in turn, result in the reverse Dunning-Kruger effect such that, for example, the hydrologist pitches his lectures and assignments at a level the students are not prepared to engage with in productive ways and ends up "talking over their heads."

To address potential limitations in relying only on instructor-defined learning goals to support learning through the implementation of summative activities, modifications to the original backward design model are proposed herein. This *resource-perspective-based backward design* model (Figure 3) is a conceptual model that includes student-held conceptions in the instructional design process. Modifications to the original model include: (i) specifying that the "assessments" in the box model are summative assessments (which may also include post-tests administered as diagnostic pre-tests) and (ii) emphasizing that the "activities" in the original model are mainly formative

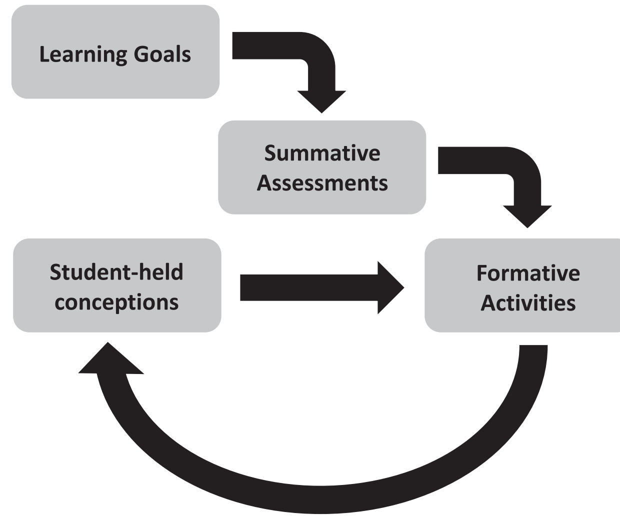

Figure 3. Conceptual model. Resource-perspective-based backward design model for instructional design.

activities. The activities are not only designed, they are also implemented. In this way, the "activities" are also tied to student-held conceptions through classroom instruction and can serve to both reveal and change students' conceptions as well as inform subsequent formative activities.

Potential generalizability

Studies conducted using the design study methodology generally have constraints to their generalizability as a "whole package" because they are conducted in a local context with variables that might not hold in other contexts and because naturalistic settings have many so-called confounding variables (Barab, 2012). Nevertheless, the iterative nature of the design and implementation of the instructional sequence presented herein provides evidence for its potential generalizability. In particular, the instructional sequence was implemented in introductory-level Earth science courses at two different regional universities, in two different regions of the US, and in courses with class enrollments ranging between 48 and 312 students. This suggests that the instructional sequence may be implemented in different regional universities and classes that range in size.

Additional evidence of the instructional sequence's potential generalizability comes in the form of the student-held conceptions that were incorporated into the instructional sequence. As previously noted, these conceptions were also identified in other regions and different grade levels (e.g., Arthurs & Elwonger, 2018; Ben-Zvi-Assarf & Orion, 2005; Dickerson & Dawkins, 2004; Reinfried, 2006; Schwartz et al., 2011). This suggests that the instructional sequence may be implemented in different regions and even in pre-college classes. The same evidence suggests that the instructional sequence or parts of it may also be useful in other courses for different fields of Earth science that study groundwater (e.g., environmental science, geography, hydrology, etc.) Although studies conducted using the design study methodology have constraints to generalizability as a "whole package," the developed theories or models, artifacts, and practices that they produce can be generalizable for other instructors and students (Barab, 2012). The products of this study include the instructional sequence, the activities, and the resource-based backward design model for instructional design.

Conclusion

The theoretical value of incorporating student-held conceptions about groundwater into classroom instruction has been long recognized, as has the need for research that describes *how* to actually do so in practice (Bar 1989; W. B. Meyer, 1987). The findings of this study help to bridge this gap between theory and practice. Consistent with a design study methodology and framed with a resource perspective and backward design, this study:

- Used successive iterations of design in naturalistic settings to demonstrate how student-held conceptions about groundwater residence can be incorporated into classroom instruction about groundwater and aquifers.
- Illustrates how *general* "best practices" for teaching can be translated into *domain-specific* contexts for teaching about groundwater and aquifers to meet local instructor needs and goals.
- Shares the instructional sequence and activities that were designed using a *resource perspective* so that others may utilize it or parts of it for instruction and/or research.
- Supports the development of broad models of how humans think, know, act and learn (Barab & Squire, 2004) by proposing a *resource-based backward design* model for instructional design that builds on Wiggins and McTighe's (2011) original *backward design* model.

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