Drawing As A Method To Facilitate Conceptual Change In Earth Sciences Education

Leilani A. Arthurs, University of Colorado at Boulder, USA
Chelsie M. Kowalski, University of Colorado at Boulder, USA
Justin M. Elwonger, University of Nebraska – Lincoln, USA

ABSTRACT

Communicating even fundamental scientific concepts can be challenging. Furthermore, student mental models are often difficult to uncover even by the most talented teacher or researcher. Drawing is a universal process skill widely used by scientists to refine their conceptions about a wide range of topics, communicate ideas, and advance scientific thought in their disciplines. Just as drawing is useful to scientists for refining their conceptions, it has the potential to be useful for revealing misconceptions when teaching from a conceptual change perspective of science students' mental models. Using a design study methodology and framed within the knowledge integration perspective of conceptual change, this longitudinal study investigates the efficacy of a delimited-sketch activity on the conceptual change of novices' mental models about groundwater residence. A delimited-sketch activity, the focal case of this study, involves (i) students drawing to expand upon a provided partially-drawn concept sketch and then (ii) collectively debriefing the ideas communicated in the completed student-expanded concept sketches. The activity's efficacy at facilitating conceptual change is tested with two different sample populations at two different large public universities in the USA. The first population is drawn from an introductory-level college geoscience course designed for non-science majors and the second population is drawn from a similar course designed for science majors. The activity has a large significant impact on moving students away from novice-like toward more expert-like conceptions of groundwater residence. The impact is observed even two months after the activity concludes.

Keywords: Geoscience Education Research; Conceptual Change; Groundwater

Scientists are learners or, if you will, life-long students of their science disciplines. As learners, they draw to lay out preliminary ideas, further develop and refine their ideas, and communicate their findings to others. History captures some of past scientists' work, and museums preserve them until this day. DaVinci drew to better understand and characterize the human anatomy (DaVinci, 2013; Zollner, Nathan & DaVinci, 2019). Muir drew to capture and communicate the beauty of the flora, fauna, and the pristine outdoors (Limbaugh & Lewis, 1986; Muir, 1992). Lyell drew to better understand and represent landscapes and their evolution (Lyell, 1853; 1990). For these scientists and others like them, drawing is an important part of their learning process and conceptual development. Thus, the conceptual development of other learners, such as science students, may also benefit from the act of drawing. In this research, we examine the potential impact of drawing on science students' conceptual development. To do this, we first define more precisely what drawing is.

"There is no consensus in the literature on the definition of 'drawing,' and many terms (e.g., sketch, diagram, external representation, external model, visualization, illustration, picture) are used differently in different papers" (Quillin & Thomas, 2015). For the purposes of the present study, a drawing is defined as an agent-generated external two-dimensional visual representation of structures, relationships, and/or processes. The agent can be the instructor, student, or a combination thereof. The two-dimensional visual representation can be generated using chalk and blackboard, paper and pencil, touchscreen and stylus, human agent and computer software, etc. This definition is similar to that described by Quillin and Thomas (2015) but differs in its recognition that drawings can be created by an instructor, the combined efforts of different students, and the combined efforts of an instructor and students. In other words, a single drawing can have more than a single contributor to its creation.

Several types of drawing tasks are used in science classes. The drawings associated with these tasks range from being entirely instructor-generated to entirely student-generated. Perhaps the most frequently used drawing task involves giving students an already-complete drawing and having them label specified parts of it. This already-complete drawing will have been created or selected by the instructor. For example, students can be given an already-complete drawing of a flower with arrows pointing to different parts of the flower. Students are then asked to label the arrows to indicate they know where the stamen, pistil, sepal, and anther are.

Another type of drawing involves giving students a blank paper and having them draw and label a concept sketch. Johnson and Reynolds developed the idea of a concept sketch and describe it as a "simplified sketch illustrating the main aspects of a concept or system, annotated with concise but complete labels that (i) identify the features, (ii) depict the processes that are occurring, and (iii) characterize the relationships between features and processes" (Johnson & Reynolds, 2005, p. 86). These are entirely student-generated sketches. Johnson and Reynolds (2005) describe the advantages of using entirely instructor-generated concept sketches, list the procedures for having students draw student-generated concept sketches, and state an advantage to student-generated concept sketches is active engagement with the material and peers.

In this article, we build on the work of Johnson and Reynolds (2005) and introduce a new type of drawing that we call an *instructor-mediated concept sketch*. An instructor-mediated concept sketch involves giving students a partially complete diagram and having them further build upon, revise, transform, and label it. We refer to this partially complete diagram as a *base-form sketch*. We refer to structured sketch activities that include two parts (draw then debrief) as *delimited-sketch activities*. In the first part, students draw an instructor-mediated sketch. In the second part, the instructor guides students through a debriefing discussion where they dissect and examine selected examples of students' instructor-mediated concept sketches. Similarly, two-component activities that ask students to draw student-generated concept sketches and are followed with a debriefing discussion are referred to as *free-sketch activities*.

For some time, it was naturally assumed that the act of drawing improves knowledge organization and learning outcomes (Paris, Lipson & Wixson, 1983). More recently, there is "growing interest in drawing as it reflects new understandings of science as a multimodal discursive practice" (Ainsworth, Prain & Tytler, 2011). Research conducted on the potential relationships between drawing and learning utilizes a range of methods. The specific drawing method of choice is variable including, for example, drawing with paper and pencil (e.g., Alesandrini, 1981) and arranging cut-out figures and organizing them into a pictorial representation (e.g., Lesgold, Levin, Shimron & Guttman, 1977). The method of assessing outcomes also varies and include post-intervention tests of comprehension (e.g., Alesandrini, 1981), recognition (Rasco, Tennyson & Boutwell, 1975), and free recall (Kulhavy et al. 1985). In addition, participant populations are also different, ranging from first grade (e.g., Lesgold, Levin, Shimron & Guttman, 1975) to college students (e.g., Snowman & Cunningham, 1975). Also, the disciplinary science domain of interest varies. They include, for example, biology (e.g., Anderson, Ellis & Jones, 2014; Glynn & Muth, 2008; Rais, Aryani & Ahmar, 2018), chemistry (e.g., Chittleborough & Treagust, 2007; Nyachwaya et al. 2011; Wu & Rau, 2018), earth science (e.g, Gobert & Clement, 1999; McLaughlin, 2018; Shepardson, Choi, Niyogi & Charusombat, 2011), engineering (e.g., Alias, Gray & Black 2002; Newcomer Raudebaugh, McKell & Kelley, 1999), and physics (e.g., Anzai, 1991; Maries & Singh, 2013).

Few studies on drawing and learning are empirical. Work by Van Meter, Aleksic, Schwartz & Garner (2006) is among such studies. They use controlled experiments to investigate relationships between drawing and learning. Their focus is on how drawing supports learning from text, where "drawing is a strategy in which readers construct a pictorial representation of concepts described in text." They found, for example, fifth and sixth graders were able to generate more accurate drawings and had better recall of scientific text with illustrations after comparing their student-generated drawings with a provided illustration and assistance in making the comparisons than students who only read the scientific text with illustrations, students who were instructed to create a drawing after reading a page of text, and students who were instructed to create a drawing after reading a page of text and then instructed to compare their drawing with a provided illustration (Van Meter, 2001).

Empirical research related to drawing is an area of ongoing need for further understanding the connections between drawing and learning broadly construed (Ainsworth, Prain & Tytler, 2011; Jee et al. 2014). The peer-reviewed literature yields little empirical data to elucidate potential connections between drawing and learning. Furthermore, there is a notable absence of research that investigates the connections between drawing and learning in naturalistic settings of actual classroom instruction. It is therefore not surprising that research-based recommendations for how to implement drawing as a method to facilitate learning are also lacking. This study aims to addresses these gaps by (1) describing how drawing was implemented to facilitate conceptual change in the naturalistic settings of two different introductory-level Earth Science courses at two different institutions of higher education, (2) analyzing the impact drawing had on students' conceptual understanding, and (3) providing empirically-supported and theory-grounded recommendations for using students' drawings to facilitate science learning and conceptual change.

The overarching research question driving this study is: How efficacious is drawing as a method for facilitating conceptual change in Earth Sciences education? To help answer this broader research question, the specific research question this study aims to answer is: How efficacious is a delimited-sketch activity at facilitating the conceptual change of students' mental models about groundwater residence over time in the naturalistic settings of actual classroom instruction? The purpose of this study is not to compare different approaches to teaching students about groundwater residence and the approaches' relative strengths and weaknesses; rather, the scope of this longitudinal study focuses on how students' ideas about groundwater residence evolve over time and how that evolution is made visible in their drawings.

THEORETICAL FRAMEWORK

The theoretical framework for this study is the *knowledge integration perspective* of conceptual change. It brings together cognitive, social, and temporal considerations to provide a more complete understanding of conceptual change (Linn, 2008). Furthermore, it argues certain practices that promote student learning should be a part of classroom instruction. These practices include (i) utilizing personally relevant problems; (ii) creating opportunities to make individual student thinking visible; (iii) providing opportunities for students to learn from each other by sharing, discussing, and evaluating each other's ideas; and (iv) creating opportunities for students to reflect on and monitor their performance (Linn, 2008).

Unlike other conceptual change perspectives that advance the notion of revolutionary or rapid conceptual change (Linn, 2008), the knowledge integration perspective suggests that learning is gradual because students need to grapple with their own perhaps confusing and conflicting ideas (Linn, 2008). It takes time for students to more fully understand their own ideas and how they integrate or not with the ideas learned in class. Furthermore, the knowledge integration perspective argues "that variability in student ideas is fundamentally a valuable feature and that instruction designed to capitalize on the variability … has potential for facilitating conceptual change" (Linn, 2008, p. 715). Consequently, this perspective also promotes the practice of characterizing the repertoire of student-held ideas and "adding the right ideas to the mix held by students … as a way to increase the efficiency and effectiveness of instruction" (Linn, 2008, p. 716).

The knowledge integration perspective of conceptual change is well aligned with constructivist theories of learning, which agree students do not come to the classroom as blank slates and, instead, come with pre-existing ideas and new learning is constructed in the context of these ideas (National Research Council, 2000). The preconceptions students bring with them to the classroom form the basis of students' mental models. The mental models are conceptual models that help explain how the world around them works (Norman, 1983). Depending on the target domain, associated mental models may be readily subject to revision and even fluid in a noncommittal sense but they may also be associated with persistent deeply rooted pre-existing ideas that are not readily changed.

The knowledge integration perspective of conceptual change is especially well aligned with the *resource perspective* of constructivism, which views students' prior knowledge as "conceptual resources" that are valuable in the learning environment (Hammer, 2000). When student's prior knowledge is incongruent with expert-defined knowledge, it has traditionally been referred to as a "misconception." Such terminology suggests student thinking is wrong and needs replacement with a correct conception (e.g., Meyer, 2004). Like Hammer (2000), Gilbert and Watts (1983) recognize value in students' prior knowledge and have long argued for use of the term "alternate conception" in lieu of "misconception" because it communicates respect for and value in students' ideas without dismissing them as simply wrong. As Arthurs noted, a resource perspective “challenges instructors to more deeply understand students’ ideas and to engage those ideas in an active learning process” (2019, p. 162).

The knowledge integration perspective is utilized in this study to (i) help frame the instructor’s design and implementation of the delimited-sketch activity and (ii) frame the discussion about conceptual change that may have occurred as a result of students’ participation in the delimited-sketch activity. For example, this perspective postulates social interactions promote conceptual change and, thus, the activity is designed to include not only independent thought but also social interactions in the form of debriefing discussions. It is also used to frame how data are collected and analyzed. For example, this perspective posits conceptual change is gradual and, thus, this work is designed as a longitudinal study that examines students’ conceptions at several different points in time. Finally, the knowledge integration perspective of conceptual change is discussed in terms of the extent to which the empirical data supports what it postulates.

METHOD

The larger project of which the present study is a focused subcomponent utilizes a design study approach. This design permits using “the close study of [teaching and learning] in naturalistic contexts, to develop new theories, artifacts, and practices that can be generalized to other schools and classrooms” (Barab, 2012, p. 153). Confrey (2012) states such research 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). Furthermore, such research utilizes instructional records, classroom assessments, and student work to understand the “prior knowledge the students bring to the task, how students and teachers interact, how records and inscriptions are created, how conceptions emerge and change, what resources are used and how teaching is accomplished over the course of instruction” (p. 136).

Like case studies, the design study approach supports the detailed examination of one or more bounded cases of complex interactions over extended periods of time (Confrey, 2012; Yin, 2013). The focal case of the present study is a delimited-sketch activity about groundwater residence. As with ethnographies, this methodology views the researcher as a participant observer in these studies (Barab, 2012; Confrey, 2012). An expert in mixed methods research who was external to the project peer reviewed the methodology and methods and indicated they are appropriate for answering the stated research questions.

As the present study reported here is part of a larger project that utilizes the design study approach, the development of delimited-sketch activity took place over six different course iterations over five years. The details about what, how, and why the activity was iteratively developed, implemented, and analyzed are thoroughly discussed in Arthurs (2019). In the interest of space considerations for the present article, these details are not reiterated. The scope of the present study is to determine the impact of the final version of the delimited-sketch activity has on how students’ conceptualizations of groundwater residence change over time.

The focal case of this study is the implementation of a delimited-sketch activity as an instructional method for teaching students about groundwater residence. The activity was part of a one-week unit of study (i.e., three 50-minute class meetings) on water resources. The unit of study on water resources was part of a five-week module on natural resources. The details of its iterative design over five years at two large universities in the United States are described in Arthurs (2019). As the focal case for the present study, the delimited-sketch activity was implemented in two different introductory-level Earth Science courses at two different large public universities. Both courses were taught by the same instructor. One course was designed for non-science majors seeking to fulfill their general education natural science requirements at a university in midwestern USA. Another course was designed for science majors seeking to fulfill a general education requirement at a university in western US.

Study Participants

Two different sample populations are examined for this study. Students from a course for non-science majors make up Population A in the study. From this course, 29 out of 48 students both (i) consented to their course work being used for research and (ii) completed the pre- and post-instruction assessments. Students from a course for science majors make up Population B; however, non-science majors were also able to enroll in it. From this course, 17 out of 24 both (i) consented to their course work being used for research and (ii) completed the pre- and post-instruction assessments. The demographics for each sample population are summarized in Table 1. There is a self-selection bias because students volunteered to have their work considered in this study and because students need to have been present in class on both days when the pre- and post-instruction assessments were administered. Despite the self-selection bias, the sample populations are representative of the total student body in the courses from which they were drawn in terms of gender, race, class standing, and major. The two sample populations, however, are notably different demographically from one another. For example, Population B has a larger percentage of males and science majors than Population A.

Table 1. Participant demographics for each sample population. Population A is derived from a course designed for non-STEM majors. Population B is derived from a course designed for STEM majors.

Demographic		Population A % (n=29)	Population B % (n=17)
Gender	Male	45	71
	Female	55	29
Class Standing	Freshmen	41	47
	Sophomore	17	29
	Junior	24	0
	Senior	17	18
	Unclassified	0	0
	Graduate	0	6
Race	Asian	14	29
	Caucasian	79	47
	Other	7	24
Major	STEM*	41	65
	Non-STEM	59	35
First generation		21	12
International		10	29

*STEM: science, technology, engineering, and mathematics

Delimited-Sketch Activity

The delimited-sketch activity that is the focal case for the present study took place in two different courses during two different semesters, each 15 weeks long and followed by a final-exams week. The activity took place in both courses during the ninth week of instruction. It is an in-class activity that had two components.

Part 1 consisted of students drawing a student-expanded concept sketch. Students were asked to draw upon and label a provided base-form sketch (Figure 1) to help synthesize information about three different types of aquifers presented in a mini lecture. The prompt for this activity is shown in Table 2 (see T_2 prompt).

Part 2 consisted of a debriefing session to collectively examine and discuss selected (and anonymized) student-expanded concept sketches. Part 2 of the activity took place in the class meeting following the class meeting in which Part 1 occurred. In between these two class meetings, the instructor reviewed the concept sketches, looked for commonly occurring ideas, and selected a few concept sketches to guide a discussion about the ideas represented in them.

Consistent with the knowledge integration perspective of a conceptual change model, the delimited-sketch activity has cognitive, social, and temporal dimensions. Cognitively, it is designed to address student preconceptions that emerged from a prior knowledge check administered in class the week prior to the unit of study on water resources and to help move students toward more expert-like ways of thinking about groundwater residence. Socially, the first part of the activity is mainly an individual task that requires personal reflection on what they already know about groundwater, but the second part depends on social interactions between the instructor and students as well as peer interactions between students. Temporally, the activity takes place over two different class meetings and contributes to students' continually evolving ideas about groundwater during the remainder of the semester.

Figure 1. Base-form sketch used in the focal delimited-sketch activity. From ''Using student conceptions about groundwater as resources for teaching about aquifers by L. Arthurs, 2019. Copyright 2019 by the Journal of Geoscience Education. During implementation of this activity, students are told the little house is intended to provide a sense of scale for the underground rock features. They are also told the blank space on the left to bottom represents an area for which there is no geologic data and they should not draw in that space for the present activity.

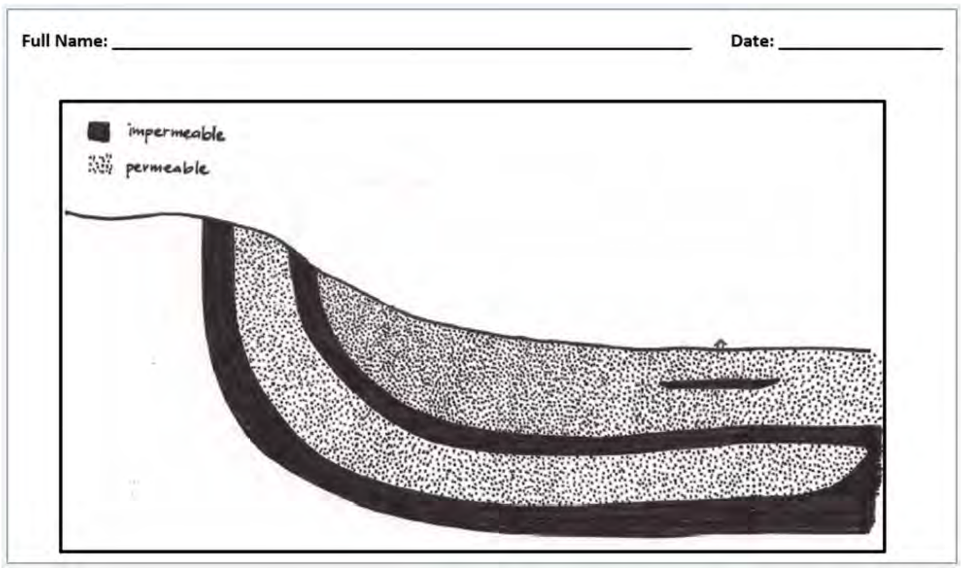


Table 2. Items used to prompt students to draw out their ideas about groundwater and how it is naturally stored underground.

Time Point	Item	Type of Concept Sketch
T_1	In preparation for next week, draw and label a picture of how water* is naturally stored below the ground. *water that is pumped from the ground to drink	Student-generated
T_2	How are all three aquifers related to each other in a "bigger picture"? Let's give it a try! Use color pencils if you brought some. On your handout: Shade in where the each of the three types of aquifers would occur. Be sure to label each aquifer that you shaded in. Note: There is a little house sketched in for reference, to help you visualize the size and extent of the aquifers.	Instructor-mediated
T_3	In the figure below, (1) draw in the confined, perched, and unconfined aquifers; (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; and (4) in the space below, answer the following question: "What does it mean for a rock to be impermeable?" by completing the sentence: For a rock to be considered impermeable, it means that ….	Instructor-mediated
T_4	Draw and label a sketch that shows the position of the following geologic structures with respect to one another: confined aquifer, unconfined aquifer, perched aquifer, water table, potentiometric surface, impermeable layers, porous and permeable layers, and wells as needed to illustrate certain relationships.	Student-generated

Data Sources

This study utilizes students' completed work and instructional records as sources of data. Specific sources of data for this study include instructor lesson plans, student responses to paper-and-pencil in-class activities and exams, and instructor notes about in-class activities and discussions. The main sources of data are concept sketches produced as part of a free-sketch activity, the delimited-sketch activity, and exams (mid-term and final). Additional sources of data are instructor lesson plans and notes.

Concept sketches were collected at up to four different periods in time during the semester. The first time (T_1) was the week before the unit of study on water resources began. The second time (T_2) was during the first component of the delimited-sketch activity (i.e., during the drawing component, not the debriefing component). The third time (T_3) was during a mid-term exam, three weeks after the unit of study on water resources. The last time (T_4) was during the final exam, eight weeks after the unit of study on water resources. The prompts presented to students at each of these time points are shown in Table 2).

To characterize overall conceptual change, student-generated concept sketches produced prior to and after student participation in the delimited-sketch activity (i.e., at T_1 and T_4) are analyzed. At T_1, the instructor administered a prior knowledge check (Angelo & Cross, 1995) to get a clearer idea of what students already knew about groundwater residence and to inform subsequent instruction. Students were asked to draw a student-generated concept sketch to illustrate and help explain how they envision the natural underground storage of groundwater that is pumped out of the ground for drinking water. At T_4, students were again asked to draw a student-generated concept sketch during the final exam, to provide the instructor information about how their original mental models might have changed during the semester.

To gain insights into the longitudinal development of students' mental models, concept sketches produced during three or four time points during the semester are analyzed. For Population A, concept sketches were collected at all four time points. For Population B, concept sketches were collected at only three time points during the semester (T_1, T_2, and T_4). In other words, the mid-term for Population B at T_3 did not prompt students to draw a sketch about groundwater residence.

The concept sketch activities initiated at T_1 and T_2 were formative assessments. That is, they were in-class activities used to extract student ideas with which to inform follow-up feedback and instruction. For both courses, class participation was part of the overall final course grade. Most in-class activities, including the free-sketch activity and delimited-sketch activity initiated at T_1 and T_2, respectively, were worth up to two points towards an individual students' final course grade. The maximum two points were assigned not necessarily for scientifically accurate responses but for demonstrated good-faith effort in clearly communicating their ideas. Selected student responses were anonymized and later displayed on PowerPoint for class discussion to (i) highlight the diversity of student-held mental models and (ii) provide a basis for building on those ideas through follow-up in-class activities and discussions.

The concept sketch items at T_3 and T_4 were part of summative assessments (i.e., exams). As with the in-class activities, these sketch-based exam items were worth up to two points. Consistent with the traditional implementation of summative assessments, students' responses to exam items were not debriefed during class time; however, students were invited to meet with the instructor to review and discuss their individual exams. About 10% of students in Population A and 18% in Population opted to go over their individual exams with the instructor.

Data Analyses

Three rubrics were used to systematically conduct diagrammatic analyses (Gobert, 2000) and textual content analyses (Sapsford, 1999) of the collected concept sketches. Rubrics A and B facilitated course-grained analyses of the concept sketches, aimed at characterizing the overall mental model represented and the pattern of mental model it falls under, respectively. Rubric C, on the other hand, facilitated a fine-grained analysis of the concept sketches which examines individual features in each concept sketch.

Categories of mental models and patterns of these categories were identified by Arthurs and Elwonger (2018) and Rubrics A and B, respectively, are based on their findings. Examples of mental model categories include: groundwater resides underground (i) in large openings in rock, (ii) as rivers or streams, and (iii) intermixed with dirt. The four patterns of mental models include: (i) separate pattern, (ii) composite internal pattern, (iii) composite external pattern, and (iv) mixed pattern. The separate pattern includes mental models where aquifers are conceptualized as all water. The composite internal pattern and the composite external pattern include mental models where aquifers are conceptualized as being composed of water and rock (most expert-like conceptions). The mixed pattern includes mental models where aquifers are conceptualized as slurries of water and dirt. Rubrics A and B were applied to only the pre-instructional concept sketches collected at time point T_1.

Rubric C was applied to concept sketches collected at all time points. It was developed to evaluate concept sketches against an expert conceptualization of groundwater and groundwater residence. The course textbook (same textbook used in both courses; Reichard, 2010) describes the three types of aquifers in which groundwater resides: perched aquifers, unconfined aquifers, and confined aquifers. Rubric C is based on the descriptions associated with each (Table 3). The maximum raw score possible is "6" and raw scores are translated into percentages for the final score (e.g., 6 points equals 100%). The more expert-like a mental model represented in a concept sketch, the higher the final score. After one researcher developed Rubric C, two research assistants with geology backgrounds reviewed the rubric for content, clarity, and organization. One research assistant applied the rubric to 10% of the concept sketches from Population A and the other to 100% from Population B. They discussed their codes with the first researcher as part of the process of refining Rubric C. This process contributes to the rubric's trustworthiness (Guba, 1990).

Using a process of double coding, one researcher applied Rubrics A, B, and C to the concept sketches collected at T_1. She also applied Rubric C to concept sketches collected at T_2, T_3, and T_4. Double coding ensures the repeatability of coding results (Krefting, 1991). The two coding sessions were spaced approximately a week apart, which served as a forgetting period where results from the first coding session were forgotten, and the sketches were coded a second time using the same rubric (Krefting, 1991). Agreement between the resultant codes from these two coding sessions was >95% for concept sketches collected at each time point. Where codes were not matched, the researcher contemplated the disparity while re-inspecting the relevant concept sketch and assigned a final code.

To further check and recheck the first researcher's coding results, another researcher independently applied Rubric C to all concept sketches. The two researchers then compared their coding results to establish interrater agreement (LeBreton & Senter, 2008). A comparison of codes assigned by the two researchers produced high interrater agreement (>84%) prior to discussion. Where codes were not matched, the two researchers discussed the disparities and resolved their differences, with a post-discussion interrater agreement of 100%. The final scores assigned to the concept sketches were used for statistical analyses.

To determine what overall conceptual change might have occurred as a consequence of participation in the delimited-sketch activity, data collected at T_1 and T_4 were analyzed as a pre-post comparison. To characterize the longitudinal development of students' mental models, data collected at T_1, T_2, T_3, and T_4 were analyzed. Potential statistically significant differences between time points were determined using a two-tailed T-test. The effect size was determined by calculating Cohen's d. In addition, potential statistically significant differences between the two sample populations were explored.

RESULTS AND DISCUSSION

To answer our research question about how efficacious the delimited-sketch activity is at facilitating the conceptual change of students' mental models about groundwater residence over time, multiple sources of data and rubrics were used. The primary sources of data used to answer this specific research question include a prior knowledge check, the delimited-sketch activity itself, a mid-term exam, and the final exam. Three different coding rubrics were used to analyze student drawings generated with these data sources. The multiple sources of data and rubrics used permit tight triangulation of data, thus supporting the study and its findings' trustworthiness as discussed by Guba (1990) and Krefting (1991).

Table 3. Rubric describes the method of scoring the student-generated and instructor-mediated concept sketches.

Type of Aquifer	Location Criteria	0 Point	0.25 Point	0.5 Point	1 Point
Perched aquifer	rests on layer of impermeable* rock above water table or an unconfined aquifer	Not shown	Incorrect location (e.g., inside unconfined aquifer)	Partially correct. Above unconfined AQ but does not have bottom impermeable layer.	Correct location, but incorrect lateral extent (i.e., drawn as a "packet") or points at general location
Unconfined aquifer	rests on layer of impermeable rock and/or has vertical pore connection to atmosphere	Not shown	Incorrect location (e.g., envelopes a confined aquifer)	Partially correct. Below unsaturated zone, but does not rest on impermeable rock layer.	Correct location but incorrect lateral extent (i.e., drawn as a "packet") or points at general location)
Confined aquifer	rests between two layers of impermeable rock and has no vertical pore connection to atmosphere	Not shown	Incorrect location	Partially correct. Has top impermeable layer, but not bottom impermeable layer.	Correct location but incorrect lateral extent (i.e., drawn as "packet") or points btw 2 impermeable layers) and/or incorrect vertical extent (i.e., GW does not fill vertical space btw impermeable layers)

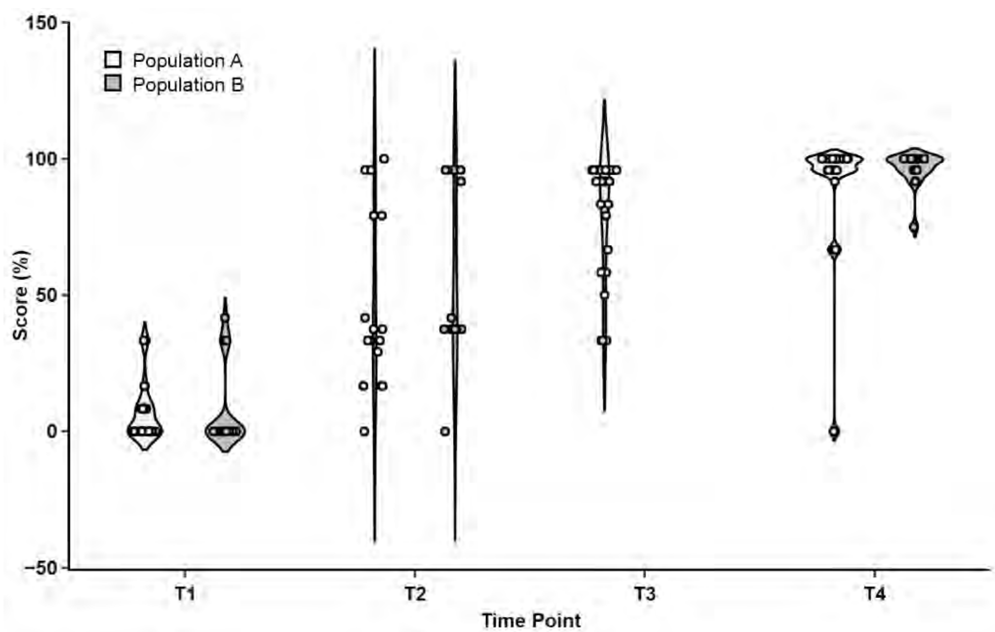
Type of Aquifer	Location Criteria	1.5 Points	1.75 Points	2 Points
Perched aquifer	rests on layer of impermeable* rock above water table or an unconfined aquifer	NA	NA	Correctly positioned in terms of location and lateral extent
Unconfined aquifer	rests on layer of impermeable rock and/or has vertical pore connection to atmosphere	NA	Mostly correct location, but vertical extent abuts with a permeable layer thus creating a confined AQ	Correctly positioned in terms of location and lateral extent
Confined aquifer	rests between two layers of impermeable rock and has no vertical pore connection to atmosphere	Correct or mostly correct lateral extent, below unconfined aquifer but missing bottom impermeable layer	Correct location and mostly correct lateral extent	Correctly positioned in terms of location and lateral extent

*impermeable = includes very low permeability
NA = no description associated with these point attributions

Conceptual Change over Time

How students' conceptions about groundwater residence evolved as a function of time was examined using Rubric C to analyze the concept sketches collected at T_1, T_2, T_3, an T_4. The violin plot shown in Figure 2 illustrates the rates at which students' conceptions changed during the period of study. The preponderance of students' novice-like conceptions at T_1 (the week before the delimited sketch was implemented) is shown in the clustering of data points near the 0% score, and it is notable that no concept sketch received a score higher than 50%. The concept sketches collected at T_2 were collected immediately after a mini lecture about three different types of aquifers. The distribution of scores at T_2 show the mini lecture helped to slightly move student thinking toward more expert-like ways of conceptualizing groundwater residence (there is a small cluster in the distribution near the 50% score). It also shows the mini lecture had a highly differential impact on student thinking, with scores ranging from 0% to 100%.

Figure 2. Results of Rubric C are illustrated as a violin plot. It illustrates conceptual change over a time period of about two months, as Population A (course for non-science majors) and Population B (course for science majors) move away from more novice-like mental models at T_1 towards more expert-like mental models of groundwater at T_4. T_1 represents week 0 in the time period of interest (a prior knowledge check is administered the week before the delimited sketch activity is implemented), T_2 represents week 1 (delimited sketch is implemented), T_3 represents week 4 (a mid-term exam is administered) , and T_4 represents week 9 (final exam is administered). This analysis and visualization used BioVinci version 1.1.5 developed by BioTuring Inc., San Diego California USA, www.bioturing.com. Circles overlain on violin plots represent relative distribution of data points.



Between T_2 and T_3, the instructor facilitated a debriefing session to discuss examples of the base-form sketches that students completed at T_2. The instructor began the lesson by asking, "How are all three types of aquifers related to one another in a 'bigger picture'?" About three different anonymized concept sketches were selected to discuss each type of aquifer and scanned for class discussion. The concept sketches were 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 or projected PowerPoint slides onto a white board 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 where different types of aquifers exist relative to the "permeable" and "impermeable" layers and how water enters aquifers.

By T_3 (mid-term exam administered), the majority of students' concept sketches from the course for non-science majors achieved scores greater than 50%. The mid-term exam in the course for science majors did not include the same item that asked students to draw a concept sketch. By T_4 (the week of the final exam, nine weeks after T_1), the overwhelming majority of the concept sketches students generated in both courses achieved scores greater than 90%. Figure 2 illustrates gradual conceptual change, from students holding more novice-like mental models toward holding more expert-like mental models of groundwater.

This finding supports the knowledge integration perspective of conceptual change. Recall, unlike other perspectives of conceptual change, the knowledge integration perspective suggests learning is gradual because students must grapple with their own perhaps confusing and conflicting ideas (Linn, 2008). Additionally, our findings show that simply lecturing about the concept at hand (i.e., T_2) is insufficient for facilitating the development of more expert-like conceptions among most students. The data as summarized in Figure 2 show students held strongly to their preconceptions and the conceptual change toward expert-like ways of thinking took most students about two months (i.e., time between T_1 and T_4) to achieve.

Students' Initial Conceptions

The pre-instructional student-generated concept sketches (collected at T_1) were analyzed using Rubric A (Figure 3) and reveal the most prevalent pre-instructional mental model for both sample populations is: Groundwater that we pump for drinking water resides in large open underground reservoirs or "pockets" (student language). The second most prevalent pre-instructional mental model for Population A is groundwater resides as underground "lakes" (student language) (e.g., Figure 4.a), whereas the second most prevalent one for Population B is groundwater resides underground as layers of water or "streams" or "rivers" (student language). Results from analyzing the drawings using Rubric B (Figure 4) show that the most common pattern of mental models prior to instruction is the separate pattern. Although water does exist in such underground features, these features are not typically a source of drinking water.

Figure 3. Results of Rubric A reveal a wide range of different mental models held by students prior to formal instruction about groundwater. Sums for each iteration do not necessarily add up to 100% because the number of different mental models each student represented in their sketches ranged between 0 and 3.

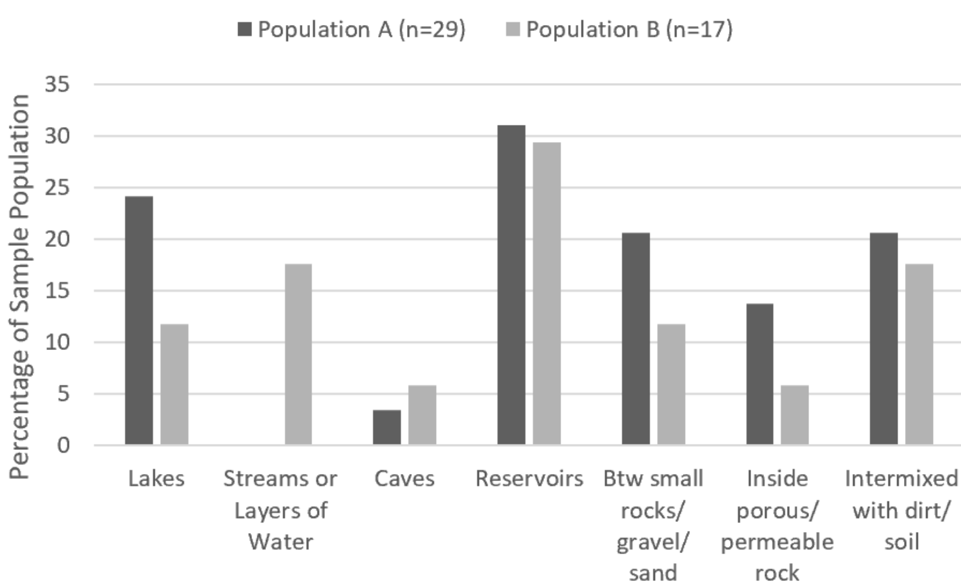
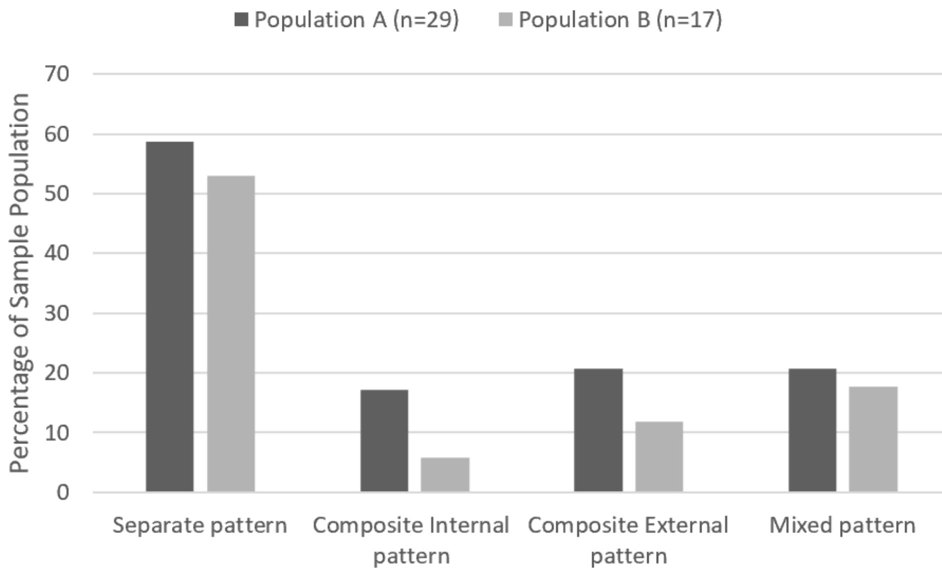


Figure 4. Results of Rubric B reveal all four patterns of mental models are represented prior to instruction in both sample populations. Sums for each iteration do not necessarily add up to 100% because the number of different mental models each student represented in their sketches ranged between 0 and 3.



The pre-instructional mental models identified here contribute to an existing very small corpus of work using drawings to characterize students' mental models about groundwater. Among the earliest of such studies, if not the earliest, was Dickerson and Dawson's (2004) study conducted in North Carolina (USA) and titled, *Eighth Grade Students' Understandings of Groundwater*. They emphasize no intervention is associated with the study and that students were asked to create their concept sketches after a lesson about groundwater. In 2005, Ben-zvi-Asarf and Orion, collected student drawings to learn about Israeli junior high school students' preconceptions about the water cycle. In 2006, Reinfried conducted a quasi-experimental study to determine the impact of an instructional intervention on German college students' understanding of groundwater. In 2011, Schwartz, Thomas-Hilburn & Haverland collected drawings from fourth graders who participated in the Arizona Water Festival program (USA). In 2018, Arthurs and Elwonger conducted the largest study to date to use student-generated concept sketches to systematically characterize college students' pre-instructional conceptions about groundwater residence.

The findings of the present study add to this growing body of knowledge to understand students' conceptions of groundwater and its residence using drawings. It shows the same types of preconceptions appear in two additional populations, providing more data that shows such conceptions span geographic regions and grade levels. Furthermore, at least in the United States (US), the fact that college students hold the same preconceptions as fourth graders is likely, at least in part, a product of the fact that less than 30% of US high school graduates complete an Earth Science course and many college students never take a geoscience course (Morris, 2019). Given the essential role that groundwater resources play in society now and in the future, the persistence of novice-like conceptions of groundwater and its residence compromises the informed decision-making processes critical for the effective management of groundwater resources. Thus, instructional interventions designed to move students away from more novice-like conceptions towards more expert-like conceptions have the potential to ultimately help support the effective management of groundwater resources in the future.

Students' Posttest Conceptions

The student-generated concept sketches drawn during the final exams (collected at T_4) were analyzed using both Rubric A and Rubric B. The analysis with Rubric A shows the overwhelming majority of participants in both the course for science majors and the course for non-science majors came to hold mental models in which they conceptualize groundwater residing within very small pore spaces that make up the underground rock media, instead of very large openings or holes underground. Using Rubric B, these mental models are associated with the composite internal pattern and composite external pattern. The mental models and patterns of mental models apparent at T_4 reflect expert-like ways of conceptualizing groundwater and its residence. By T_4, the vast majority of students had moved beyond more novice-like conceptions characterized by the separate pattern of mental models. In doing so, they are prepared to understand more complex hydrological concepts involving groundwater and aquifers such as residence time, flow rates, mass balance between recharge and discharge, etc.

Individual Conceptual Changes

Insights into individual students' trajectory of conceptual change is observable in the sequence of concept sketches they completed during the period of study. To provide examples of what these individual trajectories look like, four individual student's sequence of concept sketches were randomly selected and are shown in Figures 5, 6, 7, and 8. The trajectory of conceptual change captured in all four sequences of concept sketches show students begin with more novice-like conceptions about where groundwater that is pumped for drinking resides underground, and all sequences end with notably more expert-like conceptions. Novice-like ideas illustrated in these examples include water being held in large underground caves (Figure 5), in underground lakes (Figure 6), in large openings in underground soil (Figure 7), and in underground layers or rivers of water (Figure 8).

Although all four trajectories end with notably more expert-like conceptions, the mental models of groundwater residence held by these four individuals did not change at the same rate. For example, the trajectory shown in Figure 5 shows the individual's conception of groundwater residence quickly moved to being highly expert-like right after the mini lecture at T_2 and maintained that high level of understanding through T_3 and T_4. On the other hand, the trajectory shown in Figure 7 shows the most gradual change compared to the other three examples. The trajectories shown in Figures 6 and 8 changed at rates in between those shown in Figures 5 and 7.

Figure 5. One student's conceptual change over time regarding groundwater residence. Panels (a) and (d) are student-generated concept sketches collected at T_1 and T_4, respectively. Panels (b) and (c) are instructor-mediated concept sketches collected at T_2 and T_3, respectively.

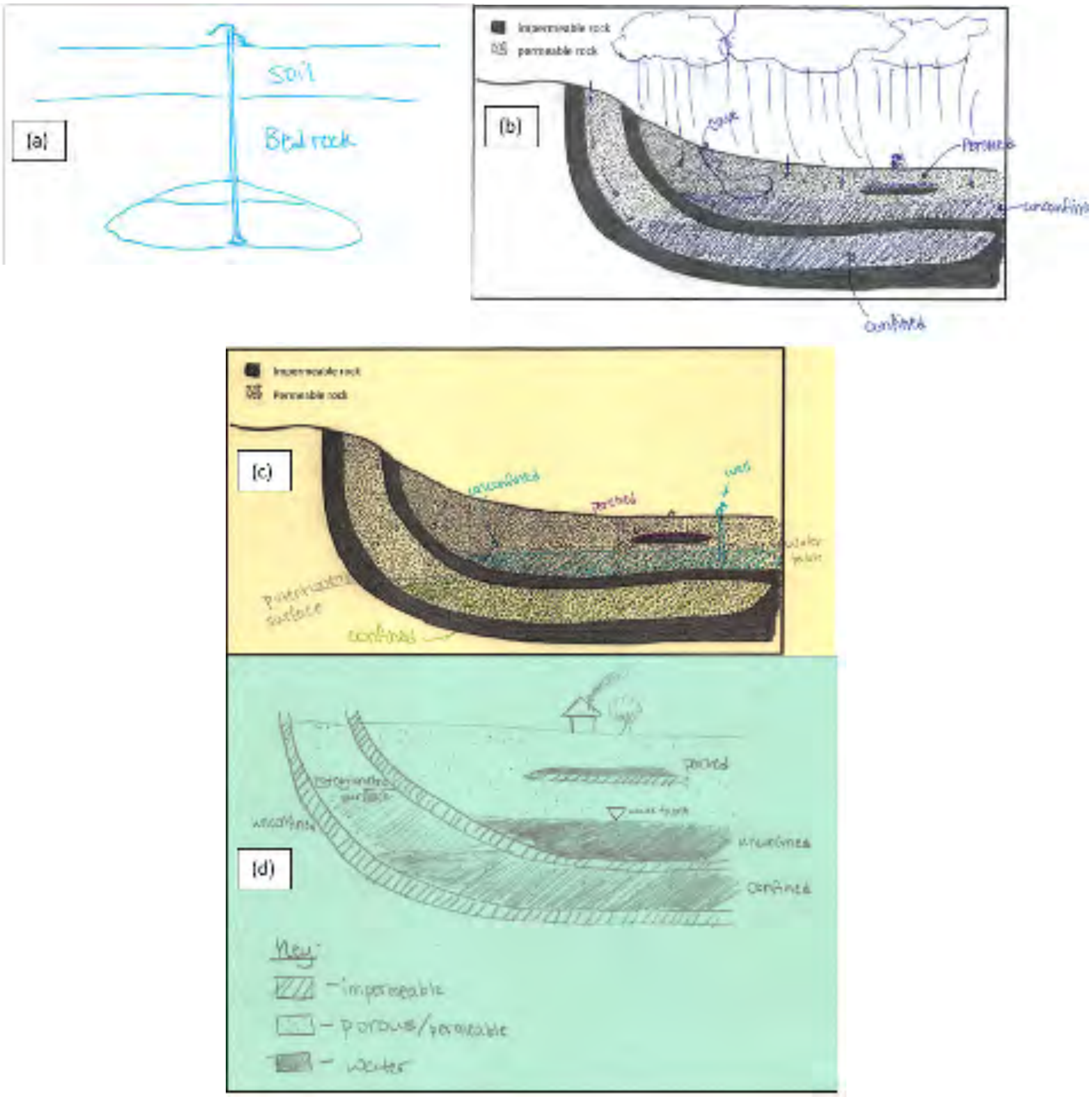


Figure 6. One student's conceptual change over time regarding groundwater residence. Panels (a) and (d) are student-generated concept sketches collected at T_1 and T_4, respectively. Panels (b) and (c) are instructor-mediated concept sketches collected at T_2 and T_3, respectively.

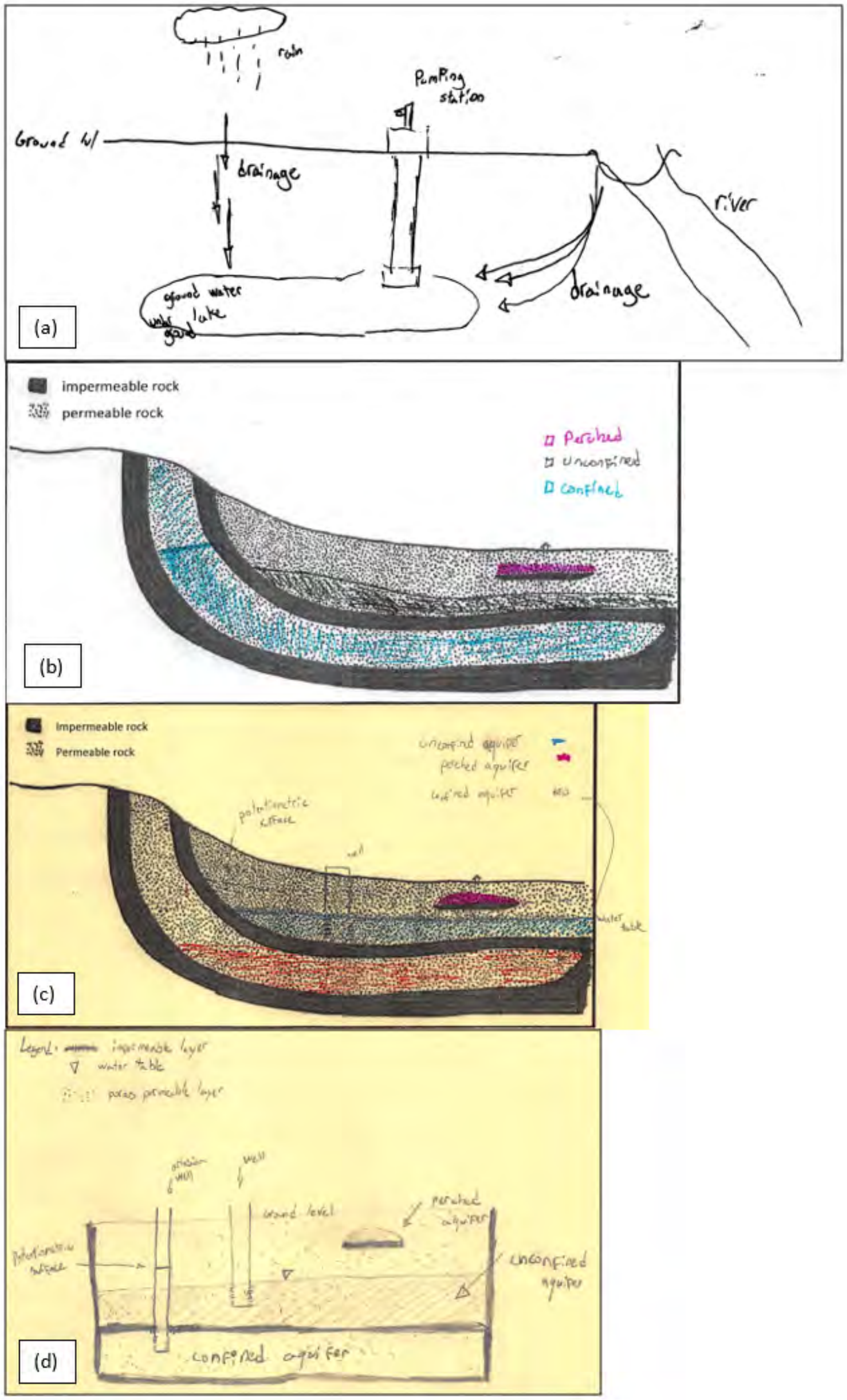


Figure 7. One student's conceptual change over time regarding groundwater residence. Panels (a) and (d) are student-generated concept sketches collected at T_1 and T_4, respectively. Panels (b) and (c) are instructor-mediated concept sketches collected at T_2 and T_3, respectively.

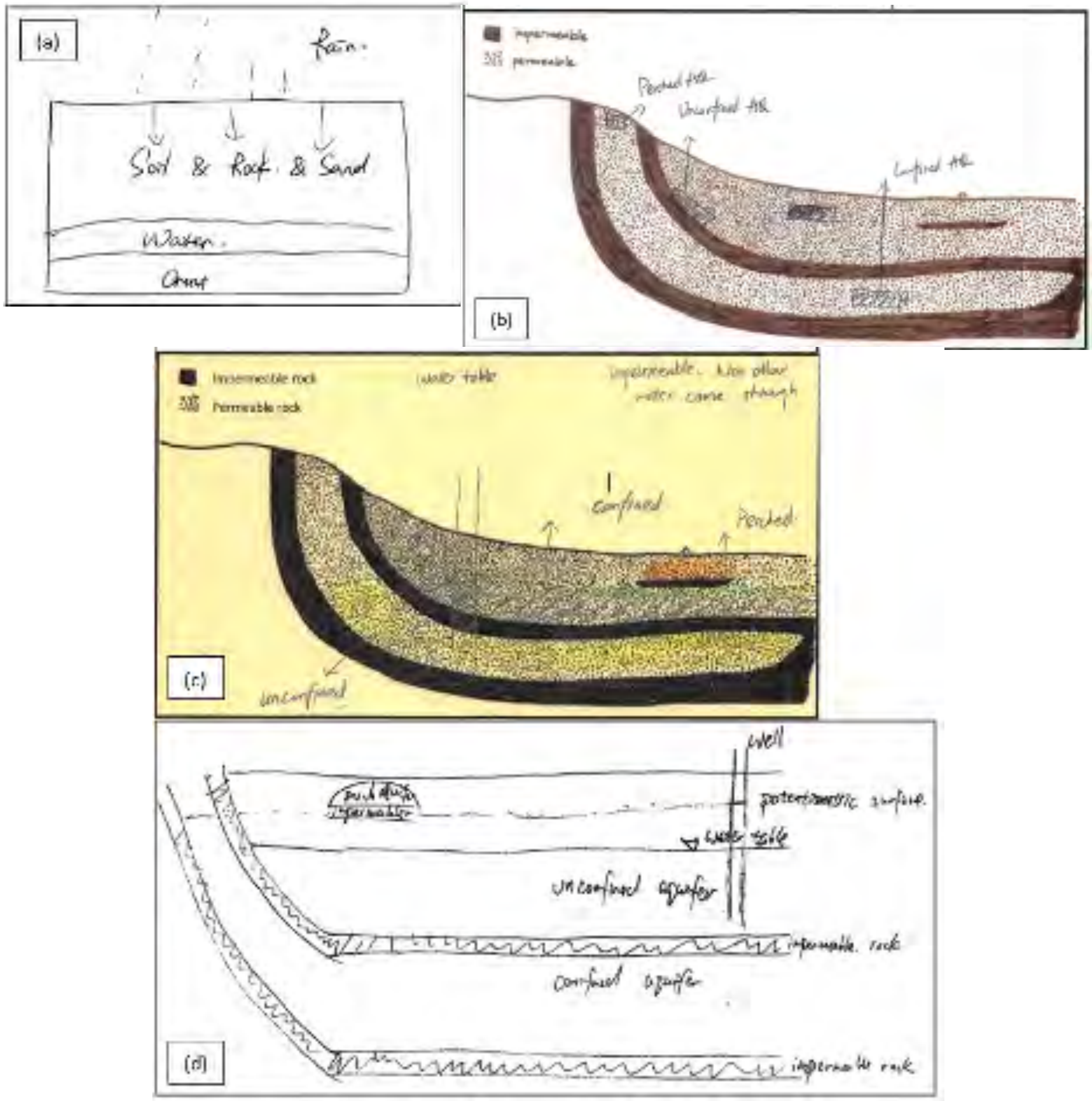
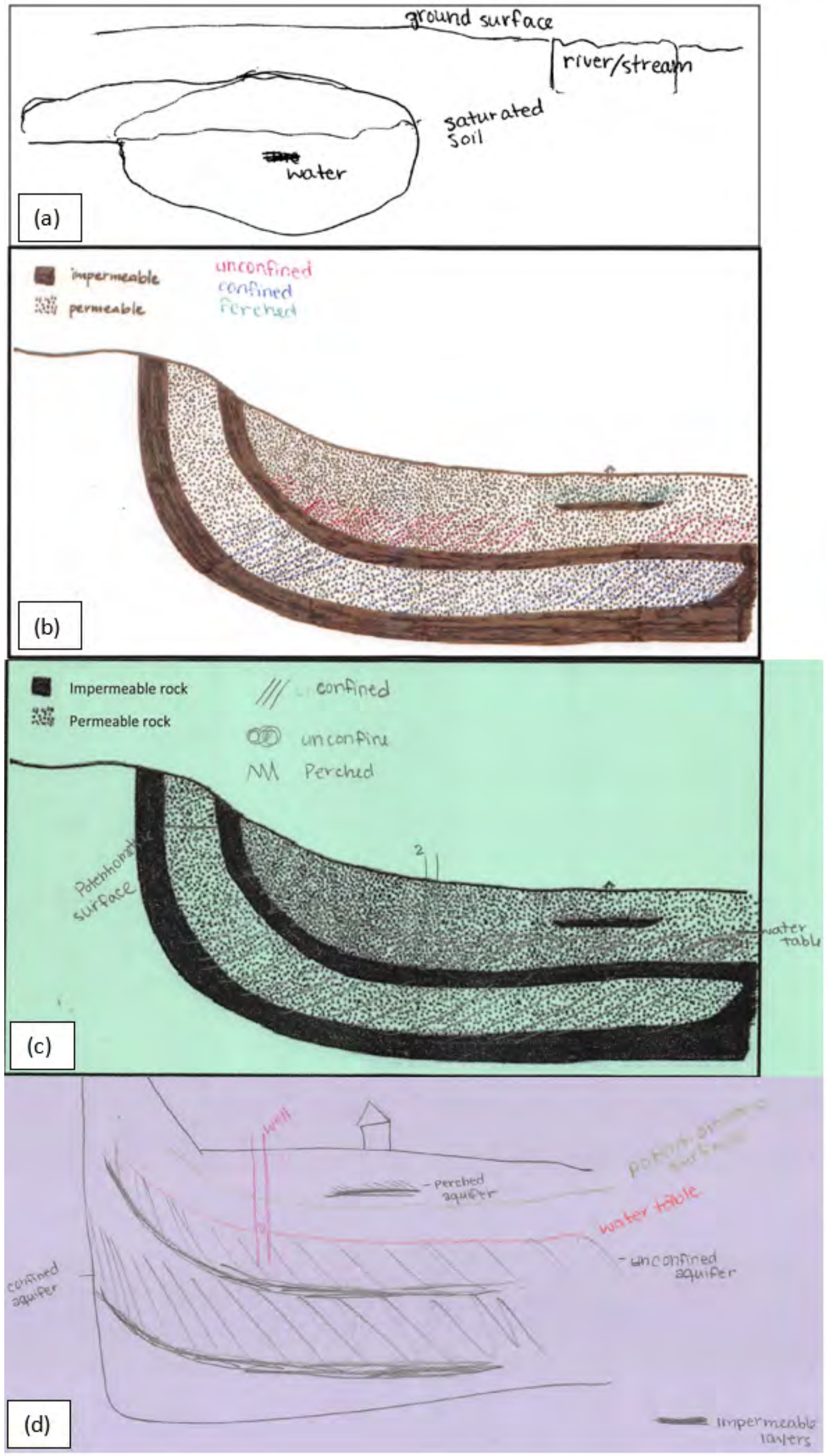


Figure 8. One student's conceptual change over time regarding groundwater residence. Panels (a) and (d) are student-generated concept sketches collected at T_1 and T_4, respectively. Panels (b) and (c) are instructor-mediated concept sketches collected at T_2 and T_3, respectively.



Overall Conceptual Change

The overall conceptual change associated with using the delimited-sketch activity were determined for both sample populations by comparing Rubric C scores for the student-generated concept sketches created at T_1 and T_4 (Table 4). The results show a large and significant (< 0.00001) positive shift towards more expert-like mental models about groundwater residence for the sample populations. The delimited-sketch activity had a significant positive impact on students who are non-science majors and those who are more inclined toward science.

It is important to note that, as with all in-class activities in the two participating courses, the instructor-provided base-form sketches that students completed at T_2 which were part of the delimited-sketch activity were never returned to students. Although they were never returned to the students, both populations of students participated in a debriefing discussion about these sketches, where several different students' sketches were anonymized, inserted into PowerPoint slides, and projected for class discussion. Even if some students recorded notes, including drawings, during the debriefing discussion (which is unknown because students' class notes were not collected and analyzed as a part of this study), the data presented in Figure 2 and in Table 4 strongly support the conclusion that the delimited-sketch activity implemented as it was (with or without students sketching them into their own notebooks) in both courses is highly effective at facilitating conceptual change.

Table 4. Rubric C analysis of free-form concept sketches created before using the two-part base-form concept sketch activity at T_1 and nine weeks later at T_4 reveals significant positive shifts toward more expert-like mental models for students in iterations with Population A (course for non-science majors) and Population B (course for science majors).

Iteration (n)	T_1 Avg. Score (%)	T_1 Standard Error (%)	T_4 Avg. Score (%)	T_4 Standard Error (%)	t-value	p-value	Cohen's d
A (29)	4.74	9.56	86.3	4.37	-17.3	< .00001	4.54
B (17)	8.82	4.55	98.0	1.96	-21.6	< .00001	6.18

Possible Reasons for Efficacy

Although the results indicate the delimited-sketch activity is highly effective at facilitating conceptual change, they do not on their own explain *why* it is so efficacious. The knowledge integration perspective of conceptual change (Linn, 2008), which provides the theoretical framework for the present study, argues certain classroom practices facilitate conceptual change. The delimited-sketch activity was designed with these practices in mind and perhaps this explains its efficacy. First, it utilizes the *personally relevant question* about where the majority of citizens across the US obtain their drinking water. Second, asking students to complete the instructor-provided base-form sketch after the mini lecture is an opportunity to *make individual student thinking visible* and, thereby, an opportunity for students to wrestle with the ideas just presented and begin integrating them into their existing mental models by committing what they think to paper for later discussion . Third, the debriefing discussion that occurs after students complete the instructor-provided base-form sketch is structured for *students to learn from each other by sharing, discussing, and evaluating each other's ideas.* Lastly, activities linked to the delimited-sketch activity were opportunities for students to *reflect on and monitor their performance*; these included the prior knowledge check the week before the delimited-sketch activity was implemented, debriefing discussion that was the second part of the delimited-sketch activity, as well as homework and exam questions that pertained to concepts addressed in the delimited-sketch activity.

Instructor Benefits

While delimited-sketch activities can benefit student learning and facilitate conceptual change, they also confer practical benefits for instructors trying to uncover student thinking. From the present study, we identify at least four such benefits. First, using a base-form sketch allows instructors to highlight key features they want all students to work with. In this way, instructors can provide more targeted scaffolding for their students. Second, using a base-form sketch proffers some degree of uniformity in the instructor-mediated concept sketches. Compared to entirely student-generated concept sketches, this uniformity can facilitate a faster review or inspection of students' concept sketches, thus permitting more timely feedback to students. Third, the degree of uniformity proffered by the base-form sketch facilitates faster scoring of students' completed drawings. Finally, instructors' communication of abstract concepts and/or spatially oriented concepts is facilitated using base-form sketches.

Implementation Recommendations

Using drawings to effectively facilitate conceptual change requires going beyond simply having students draw something for the sake of drawing. Drawing activities should be purposeful, designed with specific learning goals in mind. Furthermore, they require creating a learning environment conducive to drawing (Quillin & Thomas, 2015). Based on our work, we believe how drawing tasks are framed and graded help create such a learning environment. They also require careful implementation. Listed below are stepwise recommendations for using delimited-sketch activities to facilitate conceptual change among science students.

1. Determine commonly occurring preconceptions related to the conceptual field of focus (e.g., groundwater). This can be achieved using a free-sketch activity as was done in the case described herein. Other formative assessments such as multiple-choice survey items or free-response prompts may be used, in addition or instead of, to gain insights into a class's prior knowledge and preconceptions.
2. Determine whether preconceptions can be addressed in follow-up instruction using a delimited-sketch activity. Based on the case described herein, delimited-sketch activities are effective for addressing concepts that involve a spatial component. That is, they are useful for illustrating the relative position of key features of a conceptual field in a sketch relative to one another.
3. Design a base-form sketch that contains baseline features upon which you will ask students to expand. The base-form sketch is designed to directly addresses a targeted preconception (in this case, solid rock cannot hold water within it).
4. Design the instructional context, including what will precede and follow, the delimited-sketch activity.
5. Explain to students what the base-form sketch illustrates. That is, walk them through the different features already illustrated. Instruct them to add to it and/or modify it so that their finished sketch shows how they are thinking about the conceptual field of focus. Instruct students to label their sketch and/or write one or two brief sentences to help further explain their sketch and thinking if they wish. Explain to students that their sketches will help the instructor better understand what they are on track with and where it might be helpful to provide follow-up instruction. If points are assigned to completed student work, explain how points are assigned.
6. Review the completed sketches. Select several examples for class discussion. Remove student identifiers.
7. Provide follow-up instruction by debriefing the instructor-mediated concept sketches. Show actual examples of student work and have students discuss the strengths and limitations of each example.
8. End the debriefing of the instructor-mediated concept sketches by showing an example of student work that is most representative of scientifically accurate mental model of the conceptual field of focus.

LIMITATIONS

Potential limitations of this study readers might find are three-fold. They include the study being conducted in naturalistic settings, the study using drawings as a method for communicating ideas, and the activity being tested in only two different contexts. Here, we briefly address each of these potential limitations.

This research utilized a design study methodology, which utilizes naturalistic settings (i.e., authentic learning environments). Such settings are complex and contain multiple interacting and potentially confounding variables (Dede, 2012). Nevertheless, such studies provide valuable perspectives and insights that cannot be obtained under contrived and laboratory experiments in controlled conditions. As Barab (2012) states, "If researchers only study that which takes place in controlled conditions, they run the risk of developing artificial meanings and interactive dynamics that are so free of contextual realities that they may not be able to inform real-world practice" (p. 154).

In this study, drawing was used as a form of communication to convey students' ideas. Like other forms of communication, there is the possibility for the imperfect conveyance of ideas (Clement, 1982; Henriques, 2002;

Osborne & Wittrock, 1983). Nevertheless, drawing is a well-established technique for studying mental models and cognitive development (e.g., Piaget & Cook, 1952; Piaget, 1956).

According to Barab (2012), design studies have constraints to generalizability as a "whole package" but the developed artefacts and practices can be generalizable for other instructors and students. The artefacts this study produced are records of student-held mental models about groundwater that are comparable to previous studies (e.g., Ben-zvi-Asarf & Orion, 2005; Dickerson & Dawson, 2004; Reinfried, 2006; Schwartz et al. 2011). The practices developed include the delimited-sketch activity and recommendations for implementation. Evidence of the generalizability of the efficacy of the delimited-sketch activity comes from replicable results during its implementation in two different courses at two different institutions with two different student populations. It suggests that its implementation in other similar contexts (e.g., introductory-level college Earth Science courses) has the potential to similarly support conceptual change around the concept of groundwater residence.

CONCLUSION

The overarching research question behind this study is: How efficacious is drawing as a method for facilitating conceptual change in Earth Sciences education? To help answer this broader research question, the specific research question this study investigated is: How efficacious is a delimited-sketch activity at facilitating the conceptual change of students' mental models about groundwater residence in the naturalistic settings of actual classroom instructional environments. This research is based on the design study methodology (Barab, 2012; Confrey, 2012).

Conceptual understanding of groundwater residence was examined at four different time points during the introductory-level Earth Science courses for non-STEM majors and three time points in the introductory-level Earth Science course for STEM majors. For this study, data about student-held conceptions of groundwater residence were collected using instructor-mediated concept sketches and completely student-generated concept sketches. The multiple sources of data and rubrics used permit tight triangulation of data, thus supporting the trustworthiness (Guba, 1990; Krefting, 1991) of the study and its findings.

This study contributes to our deeper understanding of the connections between drawing and learning, particularly concerning conceptual change. Based on our review of the literature, this is the first longitudinal study that contributes to the conceptual change knowledge base in hydroscience by focusing on students' drawings to show how their conceptions gradually evolve as a function of time in the naturalistic settings of actual classroom learning environments.

The results of this study indicate drawing is an efficacious method for facilitatiing conceptual change. They show the delimited-sketch activity stimulated a large and significant (<0.00001) positive shift towards more expert-like mental models about groundwater residence for both sample populations when comparing their results from T_1 (prior knowledge check) to T_4 (final exam administered). The results of this study also show there is a wide range in the rate individuals undergo conceptual change (Figures 2 and 5-9), away from novice-like conceptions toward more expert-like conceptions about groundwater residence.

The findings of this study and resultant recommendations can be applied by Earth Science educators to help students learn about groundwater resources. Arthurs and Elwonger (2018) show that US college students hold the same preconceptions as elementary school students. Given the essential role groundwater resources play in today's world and the future, the persistence of novice-like conceptions of groundwater and its residence compromises the informed decision-making processes critical for the effective management of groundwater resources. Thus, instructional interventions designed to move students away from more novice-like conceptions toward more expert-like conceptions, like the delimited-sketch activity studied herein, have the potential to ultimately help prepare future policy makers and resource managers to effectively manage our groundwater resources. To more fully understand the connections between drawing and conceptual change, similar studies in other naturalistic geoscience education settings and targeting different geoscience domains and topics are needed.

ACKNOWLEDGEMENTS

We extend thanks and appreciation to the students who willingly consented to participate in this study. This material is based upon work supported by the National Science Foundation under Project Number 1821709. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

AUTHOR BIOGRAPHIES

Leilani A. Arthurs is an Assistant Professor of Geological Sciences at University of Colorado at Boulder whose scholarship focuses on Geoscience Education Research (GER). She has conducted GER for more than ten years. E-mail: Leilani.Arthurs@Colorado.edu (corresponding author).

Chelsie M. Kowalski is a university research assistant at the University of Colorado at Boulder.

Justin M. Elwonger was an undergraduate researcher during this study at the University of Nebraska – Lincoln, USA. He is now an Earth Science certified schoolteacher.

REFERENCES

Ainsworth, S., Prain, V., & Tytler, R. (2011). Drawing to learn in science. *Science*, *333*(6046), 1096-1097. doi: 10.1126/science.1204153

Alesandrini, K. L. (1981). Pictorial–verbal and analytic–holistic learning strategies in science learning. *Journal of Educational Psychology*, 73, 358–368. http://dx.doi.org/10.1037/0022-0663.73.3.358

Alias, M., Gray, D. E., & Black, T. R. (2002). Attitudes towards sketching and drawing and the relationship with spatial visualisation ability in engineering students. *International Education Journal*, *3*(3), 165-175.

Anderson, J. L., Ellis, J. P., & Jones A. M. (2014). Understanding early elementary children's conceptual knowledge of plant structure and function through drawings. *CBE – Life Science Education*, *13*(3), 375-386. https://doi.org/10.1187/cbe.13-12-0230

Angelo, T.A., & Cross K.P. (1993). *Classroom assessment techniques: A handbook for college teachers*. San Francisco: Jossey-Bass Publishers.

Anzai, Y. (1991). Learning and use of representations for physics expertise. *Toward a general theory of expertise: Prospects and limits*, 64-92.

Arthurs, L. A., & Elwonger, J. M. (2018). Mental models of groundwater residence: A deeper understanding of students' preconceptions as a resource for teaching and learning about groundwater and aquifers. *Journal of Astronomy & Earth Sciences Education* (JAESE), 5(1), 53-66.

Arthurs, L. A. (2019). Using student conceptions about groundwater as resources for teaching about aquifers. *Journal of Geoscience Education*, 67(2), 161-173. doi: https://doi.org/10.1080/10899995.2018.1561111

Barab, S. (2012). Design-based research: A methodological toolkit for the learning scientist. In R.K. Sawyer (Ed.), *The Cambridge handbook on the learning sciences* (pp. 153-169). New York, NY: Cambridge University Press.

Ben-zvi-Assarf, O., & Orion, N. (2005). A study of junior high students' perceptions of the water cycle. *Journal of Geoscience Education*, 53(4), 366-373. https://doi.org/10.5408/1089-9995-53.4.366

Chittleborough, G., & Treagust, D. F. (2007). The modelling ability of non-major chemistry students and their understanding of the sub-microscopic level. *Chemistry education research and practice*, *8*(3), 274-292. doi: 10.1039/B6RP90035F

Clement, J. (1982). Students' preconceptions in elementary mechanics. *American Journal of Physics*, 50, 66-71. https://doi.org/10.1119/1.12989

Confrey, J. (2012). The evolution of design studies as methodology. In R.K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences* (pp. 135-151). New York, NY: Cambridge University Press.

Da Vinci, L. (2013). H.A. Suh (Ed.), *Leonardo's Notebooks: Writing and Art of the Great Master*. New York, NY: Black Dog & Leventhal.

Dede, C. (2012). Scaling up: Evolving innovations beyond ideal settings to challenging contexts of practice. In R.K. Sawyer (Ed.), *The Cambridge handbook of learning sciences* (pp. 551-566). New York, NY: Cambridge University Press.

Dickerson, D., & Dawkins, K. (2004). Eighth grade students' understandings of groundwater. *Journal of Geoscience Education*, 52(2), 178-181. https://doi.org/10.5408/1089-9995-52.2.178

Gilbert, J. K., & Watts, D. M. (1983). Concepts, misconceptions and alternative conceptions: Changing perspectives in science education. *Studies in Science Education*, 19(1),61–98. https://doi.org/10.1080/03057268308559905

Glynn, S., & Muth, K. D. (2008). Using drawing strategically: Drawing activities make life science meaningful to third- and fourth-grade students. *Science and Children*, *45*(9), 48-51.

Gobert, J. D. (2000). A typology of causal models for plate tectonics: Inferential power and barriers to understanding. *International Journal of Science Education*, 22, 937-977. https://doi.org/10.1080/095006900416857

Gobert, J. D., & Clement, J. J. (1999). Effects of student-generated diagrams versus student-generated summaries on conceptual understanding of causal and dynamic knowledge in plate tectonics. *Journal of Research in Science Teaching: The Official Journal of the National Association for Research in Science Teaching*, *36*(1), 39-53. https://doi.org/10.1002/(SICI)1098-2736(199901)36:1<39::AID-TEA4>3.0.CO;2-I

Guba, E. G. (1990). The alternative paradigm dialog. In E.G. Guba (Ed.), *The paradigm dialog* (pp. 17-30). Newbury Park, CA: Sage.

Hammer, D. (2000). Student resources for learning introductory physics. *American Journal of Physics*, 68(S1), S52–S59. https://doi.org/10.1119/1.19520

Henriques, L. (2002). Children's ideas about weather: A review of the literature. School Science and Mathematics, 102(5), 202-215. https://doi.org/10.1111/j.1949-8594.2002.tb18143.x

Jee, B. D., Gentner, D., Uttal, D. H., Sageman, B., Forbus, K., Manduca, C. A., ... & Tikoff, B. (2014). Drawing on experience: How domain knowledge is reflected in sketches of scientific structures and processes. *Research in Science Education*, *44*(6), 859-883.

Johnson, J. K., & Reynolds, S. J. (2005). Concept sketches—Using student-and instructor-generated, annotated sketches for learning, teaching, and assessment in geology courses. *Journal of Geoscience Education*, *53*(1), 85-95. https://doi.org/10.5408/1089-9995-53.1.85

Krefting, L. (1991). Rigor in quantitative research: Assessment of trustworthiness. American Journal of Occupational Therapy, 45, 214-222. doi:10.5014/ajot.45.3.214

Kulhavy, R. W., Lee, B., & Caterino, L. C. (1985). Conjoint retention of maps and related discourse. *Contemporary Educational Psychology*, 10, 28–37.

LeBreton, J. M., & Senter, J. L. (2008). Answers to 20 questions about interrater reliability and interrater agreement. *Organizational research methods*, 11(4), 815-852. https://doi.org/10.1016/0361-476X(85)90003-7

Lesgold, A. M., Levin, J. R., Shimron, J., & Guttman, J. (1975). Pictures and young children's learning from oral prose. *Journal of Educational Psychology*, 67, 636–642. http://dx.doi.org/10.1037/0022-0663.67.5.636

Limbaugh, R. H., & Lewis, K. E. (Eds.). (1986). *The Guide and Index to the Microform Editions of the John Muir Papers, 1858-1957*. United Kingdom, Sommerset: Chadwyck-Healey Incorporated.

Linn, M. C. (2008). Teaching for conceptual change: Distinguish or extinguish ideas. In S. Vosniadou (Ed.), *International Handbook of Research on Conceptual Change* (pp. 694-722). New York, NY: Routelage.

Lyell, C. (1853). *Principles of geology: Or the modern changes of the earth and its inhabitants considered as illustrative of geology*. London, United Kingdom: J. Murray.

Lyell, C. (1990). *Principles of geology* (Vol. 1). Chicago, IL: University of Chicago Press.

Maries, A., & Singh, C. (2013). To use or not to use diagrams: The effect of drawing a diagram in solving introductory physics problems. In *AIP Conference Proceedings* (Vol. 1513, No. 1, pp. 282-285). AIP.

Meyer, H. (2004). Novice and expert teachers' conceptions of learners' prior knowledge. *Science Education*, 88(6),970–983. https://doi.org/10.1002/sce.20006

McLaughlin, J. A. (2018). What's hidden beneath? Using spatial sketching and feedback to help deepen students' understanding of Earth's subsurface. *The Science teacher*, *54*(3).

Morris, A. R. (2019, September). Whole student mentoring of undergraduate students in school and careers. In B. Pratt-Sitaula, Preparing undergraduates: Data-rich introductory teaching modules and connecting content to geoscience careers. Short course conducted at the meeting of the Geological Society, Phoenix, Arizona.

Muir, J. (1992). *John Muir: The eight wilderness discovery books*. United Kingdom, London: Hodder & Stoughton.

National Research Council. (2000). *How People Learn: Brain, Mind, Experience, and School: Expanded Edition*. Washington, DC: The National Academies Press.

Newcomer, J. L., Raudebaugh, R. A., McKell, E. K., & Kelley, D. S. (1999, November). Visualization, freehand drawing, solid modeling, and design in introductory engineering graphics. In *FIE'99 Frontiers in Education. 29th Annual Frontiers in Education Conference. Designing the Future of Science and Engineering Education. Conference Proceedings (IEEE Cat. No. 99CH37011* (Vol. 2, pp. 12D2-1). IEEE.

Norman, D. A. (1983). Some observation on mental models. In D. Gentner & A.L. Stevens (Eds.), *Mental Models* (pp. 7-14). Hillsdale, HJ: Laurence Erlbaum Associates, Inc.

Nyachwaya, J. M., Mohamed, A. R., Roehrig, G. H., Wood, N. B., Kern, A. L., & Schneider, J. L. (2011). The development of an open-ended drawing tool: an alternative diagnostic tool for assessing students' understanding of the particulate nature of matter. *Chemistry Education Research and Practice*, *12*(2), 121-132. doi: 10.1039/C1RP90017J

Osborne, R. J., & Whittrock M.C. (1983). Learning science: A generative process. *Science Education*, 67, 489-908. https://doi.org/10.1002/sce.3730670406

Paris, S. G., Lipson, M. Y., & Wixson, K. K. (1983). Becoming a strategic reader. *Contemporary Educational Psychology*, 8, 293–316. https://doi.org/10.1016/0361-476X(83)90018-8

Piaget, J., & Cook, M. T. (1952). *The origins of intelligence in children*. New York, NY: International University Press.
Piaget, J., (1956). The child's conception of space. New York, NY: Macmillan.
Quillin, K., & Thomas, S. (2015). Drawing-to-learn: a framework for using drawings to promote model-based reasoning in biology. *CBE—Life Sciences Education*, *14*(1), es2,1-es2,16. https://doi.org/10.1187/cbe.14-08-0128
Rais, M., Aryani, F., & Ahmar, A. S. (2018). The influence of the inquiry learning model and learning style on the drawing technique of students. *Glob. J. Eng. Educ*, *20*(1), 64-68.
Rasco, R. W., Tennyson, R. D., & Boutwell, R. C. (1975). Imagery instructions and drawings in learning prose. *Journal of Educational Psychology*, 67, 188–192. http://dx.doi.org/10.1037/h0077014
Reichard, J. (2010). *Environmental Geology* (1st ed.). Dubuque, IA: McGraw-Hill Higher Education.
Reinfried, S. (2006). Conceptual change in physical geography and environmental sciences through mental model building: The example of groundwater. *International Research in Geographical and Environmental Education*, 15(1), 41-61. https://doi.org/10.2167/irgee186.0
Snowman, J., & Cunningham, D. J. (1975). A comparison of pictorial and written adjunct aids in learning from text. *Journal of Educational Psychology*, 67, 307–311. http://dx.doi.org/10.1037/h0076934
Wu, S. P., & Rau, M. A. (2018). Effectiveness and efficiency of adding drawing prompts to an interactive educational technology when learning with visual representations. *Learning and Instruction*, *55*, 93-104.
Sapsford, R. (1999). *Survey research*. London: Sage Publishing.
Schwartz, K.L., Thomas-Hilburn, H., & Haverland, A. (2011). Grounding water: Building conceptual understanding through multimodal assessment. *Journal of Geoscience Education*, 59, 139-150. https://doi.org/10.5408/1.3604827
Shepardson, D. P., Choi, S., Niyogi, D., & Charusombat, U. (2011). Seventh grade students' mental models of the greenhouse effect. *Environmental Education Research*, *17*(1), 1-17. https://doi.org/10.1080/13504620903564549
Van Meter, P. (2001). Drawing construction as a strategy for learning from text. *Journal of educational psychology*, *93*(1), 129. http://dx.doi.org/10.1037/0022-0663.93.1.129
Van Meter, P., Aleksic, M., Schwartz, A., & Garner, J. (2006). Learner-generated drawing as a strategy for learning from content area text. *Contemporary Educational Psychology*, *31*(2), 142-166. https://doi.org/10.1016/j.cedpsych.2005.04.001
Yin, R. K. (2013). *Case study research: Design and methods*. Thousand Oaks, CA: Sage.
Zollner, F., Nathan, J., & DaVinci, A. (2019). *Leonardo da Vinci: The Complete Paintings and Drawings*. Germany, Cologne: Taschen.

NOTES