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Groundwater Education: An Investigation of Students' Use of a Groundwater Modeling Tool

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GROUNDWATER EDUCATION: AN INVESTIGATION OF STUDENTS' USE OF A GROUNDWATER MODELING TOOL

by

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Groundwater is a critical resource for life on Earth. However, our groundwater resources are at risk due to human activities, making this a topic of importance within K-12 and undergraduate environmental education. Yet, students hold alternative conceptions and may have limited awareness about groundwater systems. One way to support students' learning is by incorporating computer-based modeling tools into classrooms. Here, we explore the use a groundwater modeling tool, the Hydrogeology Challenge (HGC), among two age groups of students: seventh grade students and undergraduate students. In the seventh-grade population, we investigated how students relate or map model components to their real-world phenomena. We found that students struggled with aspects of the model relating to natural components and processes of groundwater systems. In the undergraduate population, we explored how students think spatially about aspects of the groundwater model. We compared two semesters of students: 1 semester with no intervention, and 1 semester with a spatial thinking intervention. We found that the intervention helped students to think spatially in certain aspects, such as concepts of space. However, students in both years still struggled with other aspects of spatial thinking, such as tools of representation and reasoning. Overall, these studies have implications for teaching and learning about groundwater.

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Chapter I: Introduction

Earth's water resources are critical for all life and for various human activities such as agriculture, energy and industrial purposes, domestic purposes, and more. However, for centuries, human activities have negatively impacted our water resources. With the onset of the industrial revolution, these impacts intensified. Throughout time, more and more water sources were affected, and people became more aware of issues such as water quality. A notable example of this is the Hudson river, which in 1969, was discussed in newspapers as being so polluted it was a threat to health (Cronin, 2019). The Cuyahoga River in Ohio is another well-known case. In June of 1969, the river set fire due to industrial pollution, and has since become a well-known event in environmental history. Before the 1970's, issues relating to water quality were managed by states and cities rather than the federal government. The Federal Water Pollution Control Act of 1948 was in place but had limited power and was not easily enforceable. However, over time, human and environmental health concerns have led to the federal government taking action to improve water quality (Keiser & Shapiro, 2019). During 1972, the Clean Water Act was passed to eliminate pollution in navigable waters. During 1974, the Safe Drinking Water Act was passed to protect drinking water from contamination. Since these two major acts were put into place, they have generally helped to improve the quality of various water sources in the US (Keiser & Shapiro, 2019).

However, still, decades after these laws were put into place, we continue to face water-related environmental issues and should reflect on the shortcomings of current policies (Cronin, 2019). The water crisis in Flint, Michigan is one current and well-known example of this. This issue illustrates how the Safe Drinking Water Act can fail to be successfully implemented and enforced, leaving people with unsafe and contaminated drinking water (Butler et al., 2016). Besides this case, there are also many other water-related issues throughout U.S. affecting both humans and the environment that should be focused on. Over half of the rivers, streams, lakes, and ponds assessed in the US are considered to have impaired quality (EPA, 2018), and groundwater resources are at risk of impairment as well. Furthermore, overconsumption also poses a threat to our surface and groundwater resources (UNESCO, World Water Assessment Program, 2020). These problems will likely be exacerbated with climate change and our expanding population. Tackling these complex socio-hydrologic issues (SHIs) will take increased efforts, and we should prepare future citizens and leaders to deal with these problems effectively.

For citizens here in Nebraska, groundwater is a particularly important component of the water cycle to be knowledgeable about. The High Plains Aquifer is one of the largest freshwater groundwater resources in the world, and it provides us with both irrigation and drinking water (Dennehy et al., 2002). However, the groundwater levels in certain regions of the aquifer have been declining for decades and will continue to decline without changes to current management practices (Haacker et al., 2016). According to the USGS, the groundwater in various regions in Nebraska is also at risk for nitrate contamination due to agricultural activities (USGS, 1999). Conservation, protection, and management of groundwater resources are SHIs that citizens in Nebraska will be faced with in the future.

We should increase awareness about these issues and prepare our communities to make science-informed decisions surrounding water-related problems. As such, water literacy, or the culmination of water knowledge, behaviors, and attitudes (McCarroll &

Hamann, 2020), is increasingly important to our society. It is important to increase water literacy among students, who are tomorrows citizens, so they can make environmentally responsible decisions (Covitt, 2009). The public should understand water and water systems if we are going to successfully confront water management issues in the future (Attari et al., 2017), since many of these may require input or even support from the public. Research has shown that students who know more about groundwater tend to show more concern for the resource (Pan & Liu, 2018), meaning efforts to increase water literacy have the potential to give rise to more environmentally conscious students. Overall, water literacy is important at all ages, from K-12 through adulthood (McCarroll & Hamann, 2020). Water is already an important topic in both K-12 (NGSS, 2013) and undergraduate education.

My research takes place in both K-12 and undergraduate contexts. Prior research shows there has been ongoing efforts to improve teaching and learning about water in both K-12 and undergraduate education settings. For example, at the K-12 level, researchers have used lab-based research projects (Villegas et al., 2010), technology-based approaches (Unterbruner et al., 2016), and educational interventions aimed at misconceptions (Reinfried et al., 2015) to help students learn about water systems. Similar approaches have been implemented at the undergraduate level. Researchers have implemented technology-based learning (Habib et al., 2012; Li & Liu, 2003), experiential learning (Thomas & Svihla, 2017), and interdisciplinary course content (Willermet et al., 2013) to enhance teaching and learning about water in undergraduate courses. However, there is room for improvement, particularly within groundwater education. Groundwater may not be emphasized in science standards (Dickerson et al., 2007) or in textbooks (Pan

& Liu, 2018) as much as other parts of the water cycle. Furthermore, students of all ages have various inaccurate or incomplete ideas about water systems, particularly about groundwater (Arthurs, 2019; Sadler et al., 2017). To address these issues, our research aims to enhance teaching and learning about groundwater systems.

Computer-based modeling is one strategy that can be implemented in K-12 and undergraduate settings to foster student learning about groundwater. Since groundwater cannot be readily observed, computer-based models may be a particularly useful approach. Prior research shows that technology-based modeling approaches have been used to teach about various Earth systems in K-12 settings. For example, researchers used technology-based modeling tools to teach about climate (Svihla & Linn, 2012) and about groundwater (Unterbruner et al., 2016). These tools can be used with undergraduate populations as well. For example, computer-based groundwater models can help undergraduates explore real-world groundwater issues (Li & Liu, 2003). Other computer-based visualization tools have also been used in undergraduate classrooms to help students learn about water (Habib et al., 2012). However, even though technology-based tools are available for use, they are often underutilized by instructors (Songer, 2007).

The aim of my work is to enhance students' model-based learning about groundwater across the K-16 continuum. Specifically, we use the Hydrogeology Challenge (HGC), a computer-based tool, to help students learn about groundwater movement. Students learn about groundwater flow direction, gradient, and horizontal velocity, along with many other groundwater characteristics. This modeling tool was developed by the Groundwater Foundation, and its original purpose was for a Science Olympiad event. However, this tool has potential to enhance groundwater education in the classroom setting as well, which we explore in our studies. The model allows students to learn about groundwater movement in various locations, one being the High Plains Aquifer, which is well suited for students in Nebraska.

Here, we explored the use of the HGC among two age groups of students in Nebraska. First, we investigated model use among seventh grade students in a Nebraska middle school as part of the *Water Education Leaders for Secondary Science* (WELS^2) project at the University of Nebraska-Lincoln. To explore the HGC in a seventh-grade setting, we developed a curriculum module surrounding the groundwater model. This study set out to explore how students relate, or – map – various model elements to their real-world phenomena. This mapping process refers to a student's ability to conceptualize model elements as their real-world phenomena. Students must understand and make connections between the real-world water system and the representations within the model. The design of this unit allowed for us to evaluate and explore this.

Second, we explored its use with undergraduate students in an introductory water course at the University of Nebraska-Lincoln as part of a 4-year NSF IUSE *Engaged Student Learning: Exploration* grant (DUE-1609598) that supported the initial design, implementation, and study of the course, particularly its emphasis on the use of data-driven, computer-based water systems modeling tools to enhance students' socio-hydrologic reasoning. This course, *Water in Society*, is focused on teaching students about hydrological concepts and their importance in the social world. This course is interactive and student-centered. For this study, we again explored students use of the HGC. However, in this study we implemented a spatial thinking approach. This approach was informed by prior experiences with students in the course from past semesters, and from our middle school study. We developed a multi-week module surrounding the HGC, involving various spatial thinking activities designed to foster their understanding and use of the model. This study was guided by a theoretical framework which defines spatial thinking as a student's ability to understand concepts of space and tools of representation, and their ability to reason (NRC, 2006). Our intervention focused on these aspects of spatial thinking in relation to the groundwater model, and we evaluated each of these aspects among students. Though prior research has shown that students may struggle to think spatially within various science domains (Hegarty, 2014; Kali & Orion, 1996), there is little research about spatial thinking surrounding groundwater.

Chapter II: Investigating Groundwater: Middle School Students' Mapping Data-Driven, Computer-Based Models to Socio-hydrologic Phenomena

Abstract

Groundwater is a critical component of the global water cycle and standards-based topic within science education. However, students articulate an array of ideas about groundwater systems, including their natural and human elements. One way to support students' learning about groundwater systems is through the use of data-driven, computer-based modeling tools in technology-enabled science learning environments. To use models to reason productively about groundwater, students must be able to interpret the relationship between the model and the phenomena it represents. Here, we report findings from a study conducted in 7th-grade classrooms (n=209) during implementation of a 3-week curriculum module designed around a data-driven, computer-based groundwater modeling tool – the Hydrogeology Challenge. Students completed a series of tasks using the model to reason about and engage in problem-solving about a real-world, scenario-based water challenge. Here, we focus on how students relate – or map – elements of the model to the components of the authentic water-related phenomena they represent. We conducted quantitative and qualitative analyses of student artifacts and interviews. Findings suggest that students could more easily interpret and understand model elements which represent human dimensions of groundwater systems, such as wells, than they could elements that represent natural dimensions and processes, such as contour lines or groundwater flow direction. These findings provide important insights

into students' model-based reasoning about groundwater and teaching and learning about coupled human-hydrological systems.

2.1 Introduction

Water is a critical natural resource that is vital to all life, making water education essential for helping cultivate water literacy in today's students, who will be tomorrow's global citizens. Although many Americans are concerned about water issues, such as water quality and availability, many do not feel confident in their knowledge of the water cycle (Duda et al., 2005). This can be problematic since the decisions people make in everyday life have an impact on natural resources and environment, including water resources. With Earth's growing human population and changing climate, water resources are under increasing pressure. This is particularly the case for groundwater, which is a critical dimension of the water cycle and water resource in many parts of the world. For example, the High Plains Aquifer in the American Great Plains region provides residential water to 82% of the 2.3 million people living within its boundaries and 30% of groundwater used for agricultural irrigation (Dennehy et al., 2002). However, groundwater levels in the aquifer have been declining for decades and groundwater quality is a significant issue for those living in this region. As such, groundwater movement and contamination present a socio-hydrological issue (SHI), meaning a contemporary challenge associated with natural water systems and their human dimensions, about which, policymakers, water scientists, and consumers must make informed decisions.

To make informed decisions about these and other SHIs, individuals should possess a sound understanding of the natural water cycle and water as a resource for human use. Water is an important topic in standards for K-12 science teaching and learning (NGSS Lead States, 2013). However, research has shown that students express an array of ideas about water and Earth's water systems (Abbott et al., 2019; Arthurs, 2019; Ben-Zvi Assaraf & Orion, 2005; Covitt et al., 2009; Dickerson et al., 2005; Dickerson & Callahan, 2006; Forbes et al., 2015b; Lally & Forbes, 2019; Sadler et al., 2017; Shepardson et al., 2009; 2007b). Specifically, students tend to focus on surface water while ignoring or deemphasizing groundwater (Arthurs, 2019; Pan & Liu, 2018; Sadler et al., 2017; Zangori et al., 2017). Students who have a better understanding of groundwater systems tend to recognize the impacts of overexploitation and express greater concern about water conservation (Pan & Liu, 2018). Having a connected understanding of water in the environment is essential for responsible decision making about environmental issues (Covitt et al., 2009), including SHIs. Since most students develop their ideas about groundwater from school-based experiences in formal classroom settings (Pan & Liu, 2018), it is important to optimize approaches to teaching and learning about groundwater through the design of research-based learning tools, as well as effective, standards-aligned curriculum and instruction.

One way to support students' learning about groundwater is through the use of groundwater models, particularly technological tools that enhance visualization and investigation, which hydrologists use extensively to study water systems, including groundwater. Scientific modeling is one of eight Science and Engineering Practices emphasized by the *Next Generation Science Standards* (NGSS Lead States, 2013), in which students across the K-12 grades should engage. This is particularly true for teaching and learning about water (Forbes et al., 2015b; Schwarz et al., 2009), however, few such resources are available for K-12 teachers and students. To address this need, we developed and pilot tested a middle school science curriculum module that engaged 7th-grade students in learning about groundwater through the use of the Hydrogeology Challenge (HGC), a data-driven, computer-based groundwater modeling tool that helps students develop understanding of groundwater flow and how groundwater contamination might occur in an aquifer. The purpose of this study is to understand how 7th-grade students relate – or map – elements of the HGC to real-world water-related phenomena as part of their model-based reasoning. Mapping refers to students' abilities to representationally relate components of a model to their parallel real-world phenomena. Using curriculum-embedded modeling tasks completed by students during the module, as well as interviews, we aim to better understand how students interpret the model's representational elements, a foundational skill that underlies model use for investigation and evidence-based reasoning about groundwater systems that include both natural and human dimensions. We asked the following research questions:

(1) To what extent do students accurately map model elements onto components of real-world groundwater phenomena?

(2) How do students conceptualize natural and human dimensions of groundwater systems through this model mapping process?

2.2 Background and Prior Research

2.2.1 Research on Teaching and Learning about Water

There has been significant prior research on teaching and learning about water in K-12 science learning environments. This research has shown that students articulate an array of ideas about groundwater storage and movement. A common idea among students is that groundwater occurs as an underground lake or pool (Sadler et al., 2017; Zangori et al., 2017), including among middle school students (Ben-Zvi Assaraf & Orion, 2005), as well as undergraduate science majors (Arthurs, 2019; Dickerson & Callahan, 2006). Many do not fully grasp that groundwater is held in the spaces and crevices of rock and soil, or see no relationship between groundwater and the surrounding substrate (Ben-Zvi Assaraf & Orion, 2005). Furthermore, this research has shown that students generally do not focus on groundwater in their reasoning about water and water systems (Ben-Zvi Assaraf & Orion, 2005; Covitt et al., 2019; Shepardson et al., 2009; 2007b). For example, research on students in the U.S. Midwest found that only about 27% of the students incorporated groundwater into their illustrations of the hydrologic cycle (Shepardson et al., 2009). They showed water storage in lakes and oceans much more often than in groundwater. Other research has shown that when students are asked to portray the water cycle, they tend to focus on atmospheric components of water systems, such as rainfall and evaporation, rather than groundwater (Ben-Zvi Assaraf & Orion, 2005). Students are challenged to follow or trace water as it moves through different parts of the water cycle, especially parts that are invisible to them, such as aquifers (Covitt et al., 2019), and they may not understand how groundwater is connected to the environment or other components of water systems (Pan & Liu, 2018). However, having a comprehensive understanding of these connections is important when learning about environmental systems (Shepardson et al., 2007a; Tsurusaki & Anserson, 2010).

Why might students exhibit these scientifically inaccurate ideas about groundwater? Research has shown that groundwater is not emphasized to the same degree as other aspects of the water cycle in science education standards (Dickerson et al., 2007), and textbooks tend to highlight water storage in lakes and oceans, rather than groundwater (Pan & Liu, 2018). When textbooks do illustrate groundwater, they may do so as a blue pool of water underground (Unterbruner et al., 2016). These underemphasized and/or inadequate representations of groundwater in textbooks and other curriculum resources may contribute to the ways in which students conceptualize groundwater. Teachers may also possess a limited understanding of groundwater, as most have not received formal instruction about groundwater concepts, and they may choose to underemphasize this component of water systems in instruction (Forbes et al., 2015a; Dickerson et al., 2007). Finally, students may not emphasize groundwater because they have many more personal experiences with visible, surface water, such as oceans, rivers, lakes, and streams, in their day-to-day experiences outside of the classroom (Sadler et al., 2017). Overall, research has shown that groundwater is a particularly difficult aspect of the water cycle for students to comprehend and reason about, making it an important focus of ongoing innovation in water education efforts.

2.2.2 Scientific Models and Modeling

One approach to supporting students' learning about groundwater is through the use of models, which hydrologists use to understand, explain, and manage water resources. In K-12 contexts, modeling can be defined as a practice of science in which students use and construct models that allow them to represent ideas or explanations (NGSS Lead States, 2013). By this definition, modeling includes a wide array of practices using various physical, computational, and conceptual modeling tools, such as analogies, diagrams, physical models, mathematical models, or, in the context of this study, computer-based models. Research has shown that model-based experiences of many kinds can be effective for students across the K-16 spectrum in an array of disciplinary domains (Kenyon et al., 2008; Lally & Forbes, 2020; 2019; Rutten et al., 2012; Schwarz & White, 2005; Svihla & Linn, 2012; Unterbruner et al., 2016). For example, data-driven, computer-based modeling tools been used successfully to help middle school students learn about climate (Svihla & Linn, 2012) and groundwater (Unterbruner et al., 2016).. Models help students visualize and investigate complex systems, including both inputs and outputs, as well as how changes in one or more system components can impact processes and mechanisms underlying a given system.

Despite this, these kinds of models, and opportunities for students to engage in meaningful, technology-driven modeling practices to support their evidence-based reasoning about natural phenomena, are relatively rare in middle school classrooms (Schwarz et al., 2009). Even when these and other kinds of models are available, however, many factors can impact their effectiveness, including features of the tools themselves, how teachers design instruction around them, and their purpose in the broader teaching and learning context (Barowy & Roberts, 1999; Cosgrove & Schaverien, 1997; Rapp & Uttal, 2006; Treagust et al., 2002; Van Driel & Verloop, 2002). One critical modeling challenge for students involves their use of two-dimensional (2-D) representations to visualize three-dimensional (3-D) concepts (Clark et al., 2008; Mackintosh, 2005; Rapp et al., 2007; Taylor et al. 2004), a core feature of many scientific models and particularly important to the study of complex Earth systems.

A critical precursor to students' effective model-based reasoning is their ability to conceptualize how components of a model reflect real-world phenomena and how the model serves as a bridge between theory and the physical world. This *mapping* process is central to our *mechanism-based* theoretical and analytical framework for scientific modeling (Forbes et al., 2015b; Schwarz et al., 2009), which is grounded in broader, NGSS-aligned perspectives on scientific modeling. A critical element of this perspective revolves around the representational nature of the model itself. Models, as tools, represent real-world phenomena in particular ways that may be more or less accessible to students and, as such, may influence their model-based reasoning. While different models may represent phenomena in different ways, in many cases, particularly in the geosciences, they represent 3-D natural phenomena, such as geospatial features and processes, in two dimensions. Students must learn to effectively use models, but also construct, revise, and evaluate them, where appropriate, reflective of their representational affordances and limitations. To better students' model-based reasoning about natural and human dimensions of groundwater systems, specifically, we must first understand how they make sense of the tools they use. Here, we focus on how middle-school students relate – or map – features of a data-driven, computer-based model onto components of coupled human-natural groundwater systems when using the model to investigate and explain groundwater-related phenomena.

2.3 Methods

This independent convergent mixed methods study (Plano, Clark, & Ivankova, 2015) was conducted in the context of a multi-year professional development program for middle- and secondary science teachers focused on model-based approaches to teaching and learning about water. The goals of the program were threefold: a) to help teachers learn about water systems and data-driven, computer-based modeling tools, b) translate this knowledge into meaningful learning opportunities for students through curriculum and instruction, and c) positively impact students' learning about water systems.

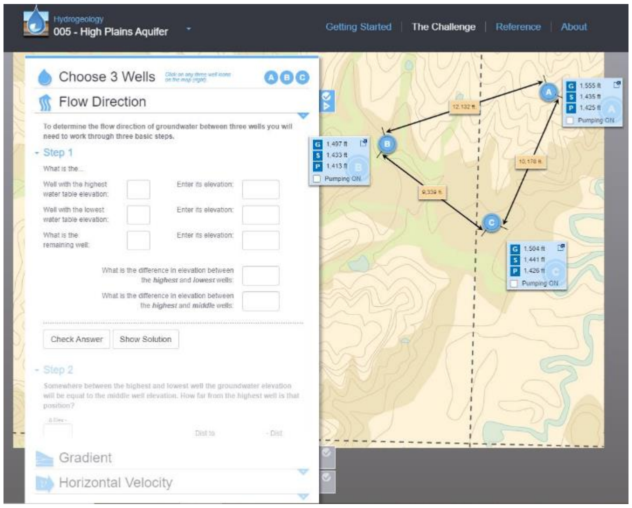
2.3.1 Context/participants

This study took place in a single middle school in a suburban school district in a single Midwestern state in the U.S. It involved two 7th-grade teachers, each of whom was a participant in the professional development program and taught multiple class periods of 7th-grade science. Study participants (n=209) were students in these teachers' classrooms experiencing the standards-based, 7th-grade science curriculum. While we did not collect demographic information on these students, district-level statistics show that the student population is predominantly Caucasian (87%), 5% Hispanic or Latino, 2% Black, and 3% Asian. In this district, 4.2% of households have an income below the poverty level, 5.9% of households have Food Stamp/SNAP benefits, and there is a 16:1 student to teacher ratio.

2.3.2 The Modeling Tool

The HGC, shown in Figure 2.1, is a computer-based groundwater modeling tool that introduces students to groundwater concepts. Originally developed for use with secondary-level Science Olympiad events, it has yet to be empirically studied in any formal classroom setting. Students use the HGC to learn about groundwater characteristics, such as flow direction, gradient, and horizontal velocity, and relationships between groundwater flow and various other model elements, such as soil type, hydraulic conductivity, and elevation. The model allows students to explore groundwater resources in several different areas, one being the High Plains Aquifer, and utilizes authentic regional hydrologic data. All visuals in the model are 2-D overhead views of well fields, such as the visual in Figure 2.1. In Figure 2.1, topographic contours are displayed in the background. Water table contours are displayed in the model as students work through the process of determining flow direction. To begin a scenario, students choose three wells. Next, students use the water table elevations at the wells, and the distance in between the wells, to determine the direction of groundwater flow. Students then calculate the gradient along the flow direction. The horizontal velocity, or the rate at which groundwater is flowing, is calculated using Darcy’s Law. Hydraulic conductivity and porosity values, used in Darcy’s Law, are provided for each well in the model. Finally, using the information they have found, students make predictions about the direction a contaminant spill might flow, and which wells may be impacted by contaminants given the other variables.

Figure 2.1
The Groundwater Modeling Tool



Note. Screenshot of the Hydrogeology Challenge (HGC).

2.3.3 The Curriculum Module

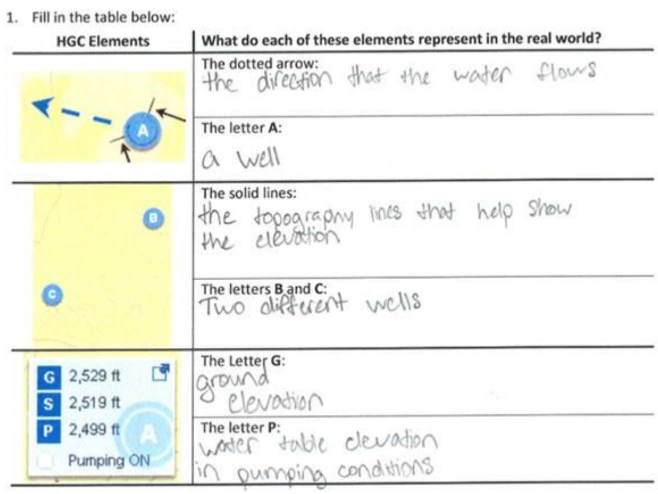
The authors and one of the teachers worked collaboratively to develop a 3-week instructional sequence grounded in use of the HGC, which was implemented by both teachers. As one of the Science and Engineering Practices in the *Next Generation Science Standards*, students should engage in scientific modeling to learn about Earth's systems, including water (NGSS Lead States, 2013). These performance expectations were central to the design of the curriculum module. Module lessons involved an array of whole-class, small group, and individual activities in which students explored fundamental concepts related to groundwater and were afforded opportunities to use the HGC to explore these components and processes. The class met regularly throughout this 3-week instructional unit. Lessons and activites focused on both groundwater concepts and the HGC model itself. First, students were a) introduced to core, underlying, water-related concepts and b) an introduction to the model. This included a series of short exercises in which students used the model to explore various groundwater phenomena, developing familiarity with the model while reinforcing key disciplinary ideas. Second, as a motivating context to apply what they had learned, students were asked to use the HGC to investigate an environmental hazard scenario involving a contaminant spill specific to the region in which the study was conducted.

2.3.4 Data Collection

2.3.4a Student Task

Throughout the curriculum module, students completed and submitted a series of tasks associated with module activities. In the first part of the task, students responded to a series of closed- and open-ended prompts focused on fundamental groundwater concepts associated with non-model-based module learning activities. Next, they practiced using the HGC and developed skills navigating the interface, model variables, and saving model output. Finally, students were tasked with investigating the scenario, as part of which they were asked to find the flow direction and explain how they determined it. Using this information, they made predictions about which wells were in danger of contamination from a contaminant spill in the area. Lastly, students made claims about groundwater flow and explained factors which might influence it. They addressed questions and included both numerical and graphical model output to support their reasoning about groundwater flow and the contaminant spill. As part of the student assignment, students were asked to examine six elements of the modeling tool interface shown in Figure 2.2 and identify what each represents in the real world. The elements they were asked to identify were: flow direction representation, wells, topographic contour lines, and representations of ground elevation and water table elevation during pumping conditions. The purpose of this portion of the task was to provide evidence for how students mapped the various model elements onto the real-world components of the groundwater system underlying the scenario. Student tasks (n=209) were collected from each student in the classrooms of both teachers, which were later saved electronically and anonymized with codes that refer to their class period and student number. For example, student 1-20 would refer to student #20 in class period #1.

Figure 2.2
Example Student Artifact



Note. Portion of the student task that was analyzed in this study.

2.3.4b Student Interviews

Interviews (Bell, Osborne, & Tasker, 1985) were also conducted with a subsample of students at the end of the module (n=15), which were audio-recorded and transcribed. The transcripts were anonymized and given code names such as student A, B, C and so on. The purpose of the interviews was to gain a better understanding of how students interpret model elements and outputs, including the model elements in Figure 2.2. Students were randomly-selected to participate in interviews, each of which was approximately 20 minutes in duration, in which students were asked to review their completed student task and respond to interviewer questions. The interviews were semi-structured (Patton, 2001) based upon a pre-determined protocol but with opportunities to probe students' thinking as interviews progressed. Interview questions asked students to describe the HGC elements in Figure 2.2, as well as what they liked/disliked, what they would change about the model, how they used it, and how it relates to the water cycle.

2.3.5 Data Analysis

One portion of a student task, shown in Figure 2.2, was analyzed in this study. A scoring rubric was developed and modified through preliminary data analysis and was used throughout the scoring process. Each student's six responses from the task (Figure 2.2) were scored for accuracy and given a score of 2, 1, or 0. A score of 2 was given to students who correctly identified what the model element represented in the real world. Partially correct answers were given a score of 1, and inaccurate responses were given a 0. Interrater reliability (IRR) of a 10% sample was assessed between two coders. There was a high level of IRR shown by a high Cohen's kappa (k=0.836) and a 90% agreement between the coders in the first round of coding. After the IRR check, one coder completed the remainder of the responses. Questions were paired up to make three question sets for the statistical analyses, shown in Table 2.1. The scores of these combined question sets were added to give a total score, making the highest possible score 4 per question set. These three question sets were analyzed quantitatively using non-parametric statistical tests as the data did not meet the assumption of normality. Statistical Package for the Social Sciences (SPSS) was used for the data analysis. Scores for each of the three question sets were compared between the two classrooms using a Mann-Whitney U test. No statistically significant differences in students' scores were observed between classes (U = 4819.500, p = .132; U = 4992.000, p = .276; U =

5045.000, p = .335), meaning student scores do not differ between teachers. Scores were therefore treated as a single dataset for the remainder of the analyses.

Table 2.1

Question Set Descriptions and Themes

	Questions included	Description	Initial Codes
Question set 1	(#2) The letter A (#4) The letters B and C	Includes questions about groundwater wells, human-made parts of a groundwater system	Wells
Question set 2	(#1) The dotted arrow (#3) The solid lines	Includes questions about groundwater flow direction, a process, and contour lines, a natural aspect of the model	Flow direction and surface topography
Question set 3	(#5) The letter G (#6) The letter P	Includes questions about elevation value representations, specifically ground elevation and water table elevation in pumping conditions, natural aspects of groundwater systems	Ground and water table elevation

Student tasks and interviews were also analyzed qualitatively. No qualitative data analysis software was used. Initial codes were based upon the three question sets shown below in Table 2.1. Code queries were performed on student responses to each question set to isolate data. This secondary data analysis aided in grouping qualitative data for each of the question sets to complement and align with quantitative findings from scoring of the student tasks. These subsets of data were then open-coded through a stepwise process of data representation, reduction, and verification (Marshall & Rossman, 1999; Merriam, 2009; Patton, 2001; Strauss & Corbin, 1998) to qualitatively characterize students' mapping of the HGC elements onto real-world elements of this SHI. As definitive patterns emerged, the data was reduced to isolate and illustrate key themes within and across the initial codes. We tested emergent themes by seeking and accounting for conflicting data that contradicts claims about students' mapping. This process continued until dominant patterns for students' mapping were refined and substantiated. Joint coding was conducted between two authors on a 10% sample of the data. Interrater reliability reached 85% before discussion and 100% after discussion. After this, one coder completed the remainder of the coding.

2.4 Results

2.4.1 To What Extent Do Students Accurately Map Model Elements Onto Components of Real-world Groundwater Phenomena?

In research question #1, we asked, 'To what extent do students accurately map model elements onto components of real-world groundwater phenomena?'. To address this question, we present results of quantitative analysis of student tasks. Mean scores and descriptive statistics for scores on student tasks for the three question sets are shown in Table 2.2. Question set scores, as shown in Table 2.2, were analyzed to determine the extent to which students were able to accurately identify what real-world components of groundwater systems the model elements represented. Students scored highest on question set 1, and lowest on question set 2. Results of a Wilcoxon Sign-Rank test show that differences between these scores were statistically-significant. Students scored higher on question set 1 than they did on both question set 2 ($Z = -7.383$, $p = <.001$) and question set 3 ($Z = -5.183$, $p= <.001$). Differences between scores on question sets 2 and 3 were not statistically-significant ($Z= -1.489$, $p = .136$). When looking at individual item scores, shown in Table 2.2, the two items on which students scored highest (questions #2 and #4) are included in question set 1, which asks students to identify the wells. Students scored lowest on question #3, which asked them to identify topographic contour lines. Overall, these results suggest that students scored significantly higher on questions about wells than they did on questions about groundwater flow direction, topographic contour lines, or elevation representations, meaning there were several model elements that students struggled to map onto real-world phenomena. Results of qualitative analyses, presented in the sections that follow, help illuminate these trends observed in the results of quantitative analyses.

Table 2.2

Descriptive Statistics for Students' Model Task Scores (N=209)

	Mean	Standard Deviation	Minimum	Maximum
Question set 1	3.00	1.617	0	4
#2	1.51	0.058	0	2
#4	1.49	0.060	0	2
Question set 2	2.02	1.301	0	4
#1	1.32	0.067	0	2
#3	0.70	0.063	0	2
Question set 3	2.23	1.801	0	4
#5	1.18	0.057	0	2
#6	1.05	0.065	0	2

**p < 0.1.

2.4.1a Wells

For question set 1, students were asked to identify the groundwater wells in the model. Students who received the highest scores for this question set responded with answers such as ‘a well” (Student 1-6). Students who received a score of 1 wrote responses such as “water source” (Student 8-5) or “place of the water” (2-26). These students were able to recognize a source of water, but they did not specifically identify the wells as the structures which provided access to the water. Students who received the lowest scores did not recognize the wells or show an accurate understanding of wells as a water source. These students gave responses such as "point where the water starts" (Student 2-23) and "stopping points" (6-24), "position on a map" (Student 2-12), and "it is a waterfall…" (Student 5-13). These responses do not accurately describe the wells as water sources and some of the responses also show inaccurate understandings of how groundwater flows by describing the well as the starting or stopping point of groundwater. Since both items in question set 1 focused on wells, trends in students' responses were largely consistent across these two individual items.

2.4.1b Flow Direction and Topography

In question set 2, the primary struggle was with the topographic contour lines (question #3), on which students scored lowest of all items. Very few students identified these model elements specifically as contour lines. Most students who received the highest scores gave answers such as "elevation" (Student 2-1). Students received a score of 1 for providing responses that did not show full understanding of contour lines such as "sand elevations" (Student 8-16) and "steepness" (Student 2-17). These answers are partially correct but not complete. Students who received a score of zero provided a wide range of answers unrelated to contour lines such as "water paths" (Student 1-23), "the water" (Student 5-20). The other question in this set (question #1) asked students to identify an arrow representing groundwater flow direction. Students who received the highest scores wrote answers such as "the way the water is going to travel" (Student 5-3) and "the direction the water flows" (Student 6-5), showing they understood what the arrow meant. Students received a score of 1 for providing answers that were related to water but did not show a full understanding of groundwater flow direction. For example, some students did not mention anything about direction in their response, such as “water flow” (Student 1-18). The lowest scores were given to students who wrote responses unrelated to groundwater flow direction. Some of these students identified the flow direction arrow representation as the direction of something other than water, such as “the direction of another well” (Student 6-19). Some gave vague answers such as “pointing somewhere” (Student 8-4), which does not show an un understanding that the arrow represents groundwater flow direction.

2.4.1c Ground and Water Table Elevation

For question set 3, students were asked to identify elevation value representations in the model, one for surface elevation (question #5) and one for water table elevation (question #6). Students who received high scores gave answers such as “ground elevation” (Student 2-1) and “water table elevation pumping conditions” (Student 6-14). Students were given partial credit for answers that were incomplete such as “elevation” (2-23), “elevation in certain places” (5-19) and “pumping” (Student 2-9). None of these responses specify whether they are referring to water table or ground elevation, but they do show partial understanding of the concept. Students who received the lowest scores gave various incorrect answers, including references to types of measurements other than elevation. For example, student responses included “how large the area is” (Student 5-12) and “how far to the next well” (Student 5-20). As with question set #1, trends in students’ responses were largely consistent for question set #3 due to the similar focus of its two constituent items.

2.4.2 How Do Students Conceptualize Natural and Human Dimensions of Groundwater Systems Through This Model Mapping Process?

In research question #2, we asked, 'how do students conceptualize natural and human dimensions of groundwater systems through this model mapping process?'. To address this question, student tasks and interviews were analyzed qualitatively. Results of these analyses yielded three key themes: natural components, human components, and processes of groundwater systems, described here and shown below in Tables 3-6. In terms of model *components*, many students exhibited a more robust understanding of the model components which represent <u>human</u> dimensions of groundwater systems, primarily the wells. For example, when asked how this model could be used with younger students, one student suggested starting with the easier concepts, referring to the wells, "I'd probably start them with what I … knew the best, these letters. I would probably start with that. … 'Cause those are probably the easiest ones" (Student N). Another student mentioned "Well I know the blue circles were telling where the wells are…" (Student J) when asked about the model representations. When asked what the model was showing them, one student answered "Yeah, it shows … locations or wells on the map and you click them and it tells you more about them" (Student P), indicating an understanding of the wells and the information given with the wells. Another student suggested that the wells were relatively easy to identify in the model, saying, "And then the letters represented the wells, so …I just knew that." (Student N). Most students could easily identify the well representations in the model. These results contributed to students' relatively higher scores on question set 1, shown in Table 2.2.

However, a smaller number of students failed to recognize the well representations, shown below in Table 2.3. The most common misinterpretation involved students referring to the wells as other types of water sources, such as “it is a waterfall” (Student 5-13), and “water flow” (Student 8-11). A less common answer involved students referring to the well representation as a place where water flow starts or ends. For example, one student referred to the well as “the beginning” (Student 6-14). A small number of students also identified the wells as spots/locations on a map, or a place of interest. One student recognized the well as an important location but did not mention it was a well, saying “represents a certain point they want you to look at” (Student 5-7). Overall, these findings suggest that most students recognize the human dimensions of groundwater systems as shown in the HGC.

Table 2.3

Themes and Examples from Student Tasks for Wells (Questions #2 and #4)

Themes	Examples	# of occurrences
Water/water source	“Place of water tunnel” (Student 5-22) “It is a waterfall” (Student 5-13 “Different water holes you are directed to” (Student 5-7)	21
Beginning or ending point of water flow	“Where the water starts” (Student 2-13) “The second and third places water will flow” (Student 6-1) “Stopping points” (Student 6-24) “The destination” (Student 6-15)	12
Point on map	“It’s a landmark” (Student 6-11) “Position on a map” (Student 2-12) “Location” (Student 8-12)	9
Refers to values given at wells, instead of well	“The lowest elevation point” (Student 1-12) “The two highest elevations” (Student 8-24)	13

Don't know/no answer	43
Unsure/does not fit into category	12

However, also in terms of *components*, students exhibited greater challenges interpreting the model components representing natural dimensions of groundwater systems, particularly the contour lines and representations of elevation. When asked about the elevation representations (G and P), some students mentioned they were unsure why they needed this information. For example, when asked how to improve the model, one student said, "I don't know why we needed to know the distances and elevation of the wells and things like that." (Student N). Another student replied "Well I feel like the letters on there didn't really tell us what it was. So I feel like we didn't really need those like the "g" and the "p" or something like that." (Student A). Some students described the elevation values as measurements other than elevation, shown in Table 2.4, such as "length" (Student 5-28), "height" (Student 6-28) and "how long the water is pumped for" (Student 6-1). Some of these students may have seen the "feet" label and described other types of measurements that may use the same unit. Other students may have been confused about the letter provided. For example, some students provided responses such as "amount of precipitation" (Student 5-27), "precipitation" (Student 6-23), and "maybe perimeter" (Student 6-10) possibly referring to other measurements that start with "p".

Table 2.4

Themes and Examples from Student Tasks for Elevation (Questions #5 and #6)

Themes	Examples	# of occurrences
Wrong item being measured/wrong type of measurement	"Amount of groundwater" (Student 5-17) "Gradient" (Student 8-4) "Maybe perimeter" (Student 6-10)	52

	"How long the water is pumped for" (Student 6-1) "How large the area is" (Student 5-12) "Length" (Student 5-28) "Height" (Student 6-28) "Precipitation" (Student 2-23)	
Refers to the well or the values given, instead of "G" and "P" meanings	"A well" (Student 2-11) "Highest elevation" (Student 5-21) "Lowest elevation" (Student 1-18)	32
Incomplete description	"Pumping" (Student 2-9)	41
Don't know/no answer		78
Unsure/does not fit into category		4

The primary challenge within natural components revolved around identifying and describing contour lines in the modeling tool, as shown in Table 2.5. When asked about the HGC, one student replied "Well, the map is sorta confusing with the lines. I think those are contour lines, right?" (Student M). A common misconception was that the contour lines were distance measurements (34 occurrences). Many students gave answers such as "distance from one well to another" (Student 5-16). Another common idea involved students identifying the contour lines as water (33 occurrences). Most students gave answers similar to "water flow" (Student 5-23) or "path of water flow" (Student 6-14), and did not specify whether they were referring to ground or surface water. The few students who did specify gave answers such as "flow of groundwater" (Student 2-19), "where the groundwater goes" (Student 8-28), and "rivers" (Student 8-8). Students also referred to the contour lines as landscapes (22 occurrences). Some students in this category interpreted the lines as a specific type of landscape, for example, "where the mountains are" (Student 2-2) and "land or desert" (Student 2-25). A smaller number of students (7) explained the contour lines as connections between wells by giving answers such as “pipes” (Student 5-16) or “connecting lines” (Student 2-14). Overall, these results suggest contour lines, in particular, were challenging for students to interpret and use in their model-based reasoning about the groundwater scenario.

Table 2.5

Themes and Examples from Student Tasks for Contours (Question #3)

Themes	Examples	# of occurrences
Distance	"How far apart the wells are from each other” (Student 1-25) "Distance between wells“ (Student 5-19) “Distance” (5-6)	34
Water	“Water flow” (Student 5-23) “The water paths” (Student 1-24) “Flow of groundwater” (Student 2-19) “Rivers” (Student 8-8)	33
Landscape	“Where the mountains are” (Student 2-2) “Land or desert” (Student 2-25) “Land” (Student 8-11)	22
Connection between wells	“Pipes” (Student 5-16) “Connecting lines” (Student 2-14) “Water lines or pipes” (Student 1-1)	7
Incomplete description		7
Don’t know/no answer		26
Unsure/does not fit into category		6

Finally, students were challenged to understand *processes* of groundwater systems, specifically flow direction. As shown in the results of quantitative analyses, students were able to interpret the flow direction symbol in their tasks, but the few who struggled gave answers such as “tells where the other wells are” (Student 8-28), “distance from one well to another” (Student 2-28), “direction of the pipe” (2-24) and other similar answers shown in Table 2.6. Some of these students recognized the arrow as a direction but were unaware that it was flow direction. Further analyses suggest that students have difficulty understanding the concept of flow direction, even though most could interpret the symbol. Some students were not able to explain flow direction. When asked if there was anything troubling about the modeling tool, for example, one student replied, “flow direction” and later explained “I did not find out what the flow direction was” (Student Q). Other students described finding the flow direction but did not seem to understand how or why this was the answer. For example, in the following quote, the student, (Student K), describes the process of how they came to find flow direction, but shows little understanding of why flow direction was perpendicular to the contour line.

> “So, I entered those in and then I just entered the elevation in, did that real quick, and then when a lot of us were getting stumped on the direction, the sheet told us that it has something to do with either a parallel or a perpendicular line. So, I rotated it around and made it parallel and it didn't work, so I tried the perpendicular line and that worked” (Student K).

First, they tried making flow direction parallel to the line, and when this did not work, they tried it the opposite way. The response suggests that the student may not understand what the water table contour line is or why groundwater flows perpendicular to it. Similarly, another student describes learning that flow direction was perpendicular to the line, but they do not show an understanding of what the line represents, which suggests a limited understanding of flow direction.

> "I knew some of it before. But I didn't necessarily know that the flow direction is perpendicular to one of the lines. And I forgot what the lines are called" (Student L)

These responses suggest that some students are unaware of why the flow direction is perpendicular to the water table contour line, meaning they may not have a complete understanding of the relationship between these parts of groundwater systems. Some students suggested their answers were guesses. When asked how they figured out flow direction, one student replied, "Probably just a lucky guess" (Student F). Another answered "I kind of just guessed because I assumed that was the water's path because of the lines and previous knowledge I guess. I just kind of guessed" (Student C). Many students also suggested flow direction as a difficult or confusing part of the modeling tool. For example, some students specifically mention struggling to find flow direction, "And then step three was a little confusing, of trying to find where the direction of the groundwater would be…" (Student M). Another student responded similarly, suggesting that making the prediction was difficult, "I used those pictures to help me, but also on the compass one, I didn't really understand how to try to make my prediction first. I didn't understand it" (Student O). These findings suggest that students may have been challenged to conceptualize the process of groundwater flow, even though many were able to identify and interpret its representation in the modeling tool.

Table 2.6

Themes and Examples from Student Tasks for Flow Direction (Question #1)

Themes	Examples	# of occurrences
Distance	"The feet in between the wells" (Student 5-6) "Represents distance from one well to another" (Student 5-16) "Distance" (Student 1-14)	5
Direction (other than flow direction)	"The direction of another well" (Student 6-19) "Direction of the pipe" (2-24) "Pointing somewhere" (Student 8-4)	5
Incomplete description	"Direction the line is going to travel in" (Student 1-1) "Water flow" (Student 8-16)	46
Don't know/no answer		29
Unsure/does not fit into category		6

2.4.3 Summary of Results

Overall, study results suggest that students show relatively higher levels of understanding about the human dimensions of groundwater systems than their natural components and processes. Many students were able to recognize and identify wells in the model but struggled with natural dimensions of groundwater systems. Students had difficulties interpreting contour lines, elevation values, and processes of groundwater systems, or groundwater flow direction, though most were able to identify its representation within the HGC.

2.5 Discussion

Water systems, including groundwater, are critical for human activity. Water systems and their human dimensions are a core topic in standards for science teaching and learning across the K-12 continuum (NGSS Lead States, 2013). Developing a robust understanding of both managed (e.g., human-influenced) and natural dimensions of contemporary water systems is critical to make decisions about contemporary SHIs and develop water literacy. The use of models is one important approach to enhancing teaching and learning about water systems. However, prior research has shown that students of all ages, as well as members of the public (Duda et al., 2005), may articulate a wide array of ideas about water, particularly groundwater. To address this need, and help tomorrow's global citizens develop water literacy, students should be afforded productive opportunities to learn about water systems in K-16 classroom settings through the use of data-driven, computer-based modeling tools that mirror those used by water scientists.

Though research has shown modeling can be an effective approach to teaching and learning across various disciplines (Kenyon et al., 2008; Svihla & Linn, 2012; Rutten et al., 2012), including about water (Habib et al., 2012; Lally & Forbes, 2019; Unterbruner et al., 2016), implementing modeling in the classroom can be challenging (e.g. Barowy & Roberts, 1999; Treagust et al., 2002; Van Driel & Verloop 2002). Specifically, regarding complex Earth systems, students are often challenged to translate 2D representations into 3D conceptual understanding (Clark et al., 2008; Mackintosh, 2005; Rapp et al., 2007; Taylor et al. 2004), and must therefore be actively supported to do so. Findings presented here provide important insights into middle-school students' model-based reasoning about coupled human-hydrological systems, specifically how 7^{th}-grade students map components of a data-driven, computer-based modeling tool onto real-world phenomena in order to engage in model-based reasoning about a groundwater SHI. These findings not only yield insights into usability of the HGC, but also build upon and contribute to a broader body of work focused on teaching and learning about water across the K-16 continuum (Arthurs, 2019; Ben-Zvi Assaraf & Orion, 2005; Covitt et al., 2009; Dickerson et al., 2007; Dickerson & Callahan, 2006; Forbes et al., 2015a; 2015b; Lally & Forbes, 2019; Sadler et al., 2017; Shepardson et al., 2009; 2007b; Zangori et al., 2017).

Results presented here illustrate aspects of coupled human-water systems for which students possess relatively high levels of understanding. In response to our first research question, we found that students were more easily able to recognize and map the human dimensions of groundwater systems in the model than natural components, including system processes. In general, these findings align with prior research, which has shown that students often emphasize components of water systems more so than the underlying processes (e.g. Forbes et al., 2015b; Lally & Forbes, 2019). They also reinforce the notion that students may likely recognize features of models with which they are most familiar, either from school-based learning or everyday life. However, our findings extend this research by show that students have relatively developed understandings of the human components of groundwater systems, specifically, compared to natural components. Though our findings do not specifically illustrate students' understanding of how wells might interact with groundwater, they do show that students are able to interpret these representations in the model with relative ease compared to natural components. As humans continue to alter the environment, it becomes increasingly important that students understand how humans interface with and impact the natural environment, including water systems (Covitt et al., 2009; Tsurusaki & Anserson, 2010). This is particularly important since previous research has found that students, as well as members of the public, tend to ignore the human components of water systems unless prompted to do so (Abbott et al., 2019; Duda et al., 2005; Shepardson et al., 2007a), de-emphasizing their inherent socio-hydrologic nature. To fully grasp and be able to reason about SHIs such as the one foregrounded in this study, students should recognize the fundamental role of humans and human activity in socio-hydrological systems.

Study findings also illuminate aspects of coupled-human water systems with which students struggled, particularly the natural components and processes. Prior research has shown that students may deemphasize or struggle with parts of the water cycle that are not visible to them, such as groundwater (e.g. Ben-Zvi Assaraf & Orion, 2005; Covitt et al., 2009; Pan & Liu, 2018; Shepardson et al., 2009; Zangori et al., 2017), which may have made the natural components in this model difficult to recognize. One specific challenge for students was identifying and describing contour lines in the HGC, a task that requires translating 2-dimensional representations into three-dimensional concepts. Prior research reinforces this study finding, as students may often struggle to translate 2-D representations into 3-D concepts (Clark et al., 2008; Mackintosh, 2005; Rapp et al., 2007; Taylor et al. 2004), whether in a technology-mediated environment or not.

As a result, students articulated an array of ideas related to contour lines that align with findings from research on students' alternative ideas about water systems. For example, some students misinterpreted contour lines as other features of water systems, such as rivers. The idea that groundwater flows like an underground river or stream is a common conception students convey (Unterbruner et al., 2016). Some students also referred to the contour lines as mountains even though the HGC scenario was specific to a non-mountainous area. Previous research has shown that students tend to think of the water cycle happening in mountainous areas rather than the landscapes they live in (Shepardson et al., 2009). Students also confused the contour lines with pipes or connecting lines between wells, and though they did not specifically state whether they thought groundwater moved through these pipes, this same idea has been documented among other students (Dickerson et al., 2005). Overall, these natural components of groundwater systems, which required translation from 2D representations to 3D conceptual understanding, were observed to present significant representational and conceptual challenges for many students in this study. This finding highlights the importance of the representational aspects of models to enable their use as explanatory tools by students. The mapping process is critical for students if they are to engage effectively model-based reasoning about a system and its underlying phenomena (Forbes et al., 2015b; Schwarz et al., 2009).

2.6 Limitations and Implications

Results provide insight into representational features of the model that may be more or less helpful for middle school student users. A logical assumption, supported by theory and prior research, is that students must first understand how a given model represents elements of the real world to be able to use the model to reason about systems-related phenomena (Cosgrove & Schaverien, 1997). This mapping ability is a central epistemic element of modeling as a science and engineering practice (Forbes et al., 2015b; Schwarz et al., 2009). Study findings provide insight into how the HGC, and others like it, may be designed and/or modified to address representational challenges students in this study experiences. For each of the various elements in the HGC, students were asked to translate a 2-D representation into 3-D conceptual understanding. Results show this was easier for some elements (i.e., wells) than for others (i.e., contours and groundwater flow). It is possible that some model features were more challenging than others because of how they are displayed within the model. It is also possible that these phenomena are more challenging to grasp and that interpreting contour lines and other natural components and processes may require a higher level of thinking than, for example, wells. Collectively, these results, informed by findings from prior research, highlight potential usability factors and areas for ongoing refinement of the HGC for use in middle-school science learning environments. Insights from study findings should be examined further through comparisons with high school and undergraduate students to investigate similarities and differences in observed results that may help disentangle any developmental factors from those attributable to the model itself.

Subsequent studies may also explore the affordances and constraints of HGC design features that may help further enhance students' model-based reasoning about groundwater. Translating 2-D representations into 3-D concepts can be scaffolded through, for example, shading and stereo visualization (Rapp et al., 2007) and color enhancement (Taylor et al. 2004), neither of which the HGC employs in its current design. Additionally, the level of detail in the graphical representation must be appropriate both to the developmental level of the student user and the task at hand. Using maps with too many features or details may be cognitively overwhelming for novice students (Clarke, et al, 2008). In the case of the HGC, both surface and water table contours were displayed simultaneously and without strong features to distinguish them from one another, creating challenges for students who did not have prior experience with contour maps. Additionally, when using complex visualizations, students may tend to focus on the color or shape of a representation rather than the underlying concept of what it represents (Rapp & Uttal, 2006). As shown in the results, some students here referred to the wells as water, possibly based upon on the blue color of the well representations. Consideration of colors and shapes of model representations may also help students' mapping of these elements. A strong implication of these results, however, is that models such as the HGC should provide both 2-D and 3-D visualizations of the system and its underlying phenomena to support students in making this conceptual leap.

Finally, study findings point to the importance of other classroom factors in supporting students' use of such models. While we did not investigate the influence of such factors in this study, students' use of modeling tools like the HGC can be envisioned as part of a more comprehensive set of teaching and learning resources in the broader classroom learning environment, Coupling the use of a computer-based model like the HGC with other models, including physical models, may be particularly useful as an intermediate step in helping students make representational connections with the real-word phenomena. Incorporating lessons about topography, contour maps, and elevation into class before using 2-D models may also help students make these connections. Additionally, teachers undoubtedly serve a critical role in mobilizing and orchestrating an array of resources and pedagogical strategies that support students to navigate through multiple representations to make sense of underlying phenomena. While we did not observe different student outcomes between the two teachers involved in this study, future research should specifically investigate instruction as it relates to implementation of model-based curriculum and students' use of associated resources.

2.7 Conclusion

Contemporary science is increasingly defined by the use of complex, computer-based, data-driven models, including in hydrology and the water sciences. Furthermore, scientific modeling is one of eight Science and Engineering Practices emphasized by the *Next Generation Science Standards* (NGSS Lead States, 2013) and there is evidence that using models in the classroom can promote students' learning (Schwarz & White, 2005). As such, students can be afforded opportunities to use these models to learn about the natural world, including water systems. This is particularly the case with groundwater, which is a particularly vital water resource in some areas (Dennehy et al., 2002) that is increasingly at risk due to human activities and that research has shown both to be challenging for students to reason about and a dimension of water systems that they tend to de-emphasize (Arthurs, 2019; Ben-Zvi Assaraf & Orion, 2005; Covitt et al., 2019; Shepardson et al., 2009; 2007b; Sadler et al., 2017; Zangori et al., 2017). Groundwater education is therefore important to help students develop a connected understanding of natural and human dimensions of water system, which is essential when making decisions about SHIs (Covitt et al., 2009). Since most students develop their ideas about groundwater from school-based experiences (Pan & Liu, 2018), modeling should be a core feature of K-12 teaching and learning about groundwater. To use models to reason about groundwater, including both natural and human dimensions of these systems, students must first understand what the components of a model represent in the real world. As such, these findings have potential implications for the design of technological tools and technology-enabled science learning environments that can enhance teaching and learning about water systems, including curriculum design and instructional practice.

Chapter III: An Investigation of Undergraduate Students' Spatial Thinking about Groundwater

Abstract

Undergraduate students may possess underdeveloped knowledge about water systems, particularly groundwater. The use of models and modeling have been employed in undergraduate classrooms to support students' learning about water. However, effective modeling requires spatial thinking skills, which undergraduate students may need to develop. To address this need, we developed a multi-week intervention involving an array of spatial thinking activities to support undergraduate students' use of a computer-based groundwater modeling tool in an intro-level undergraduate water course. Students used the model to complete a task involving a groundwater contaminant scenario. Here, we report findings from a comparative study conducted in two consecutive semesters: Year 1 (n=56) and Year 2 (n=46), the latter of which involved the intervention. We explored their understanding of space, representation, and reasoning (NRC, 2006) by conducting quantitative and qualitative analyses on student tasks and interviews. Findings suggest that students in year 2 better articulated concepts of space. However, students in both years exhibited relatively limited understanding of representation and reasoning abilities about groundwater. Overall, these results suggest students struggle with certain aspects of spatial thinking in relation to this groundwater model. These findings have implications for undergraduate teaching and learning about groundwater.

3.1 Introduction

The topic of water is an important focus of STEM and environmental education (Earth Science Literacy Initiative, 2010; NGSS Lead States, 2013). However, learners hold many scientifically-inaccurate conceptions about water and water systems across the continuum from ‘K-gray’, including K-12 students, undergraduate students, and adults (e.g. Canpolat, 2006; Duda et al., 2005; Sadler et al., 2017). Of the many components of Earth’s water system and water-related concepts, groundwater has been shown to be a particularly challenging aspect of the water cycle to learn about since it is not readily observable (Arthurs, 2019; Dickerson & Callahan, 2006; Sibley et al., 2007; Zangori et al., 2017). And while water education is important at all levels, it is particularly essential as a core component of undergraduate education for STEM majors as a core component of disciplinary and technical expertise (King et al., 2012), but also for both STEM majors and non-majors as a core component of scientific literacy (McCarroll & Hamann, 2020). At the postsecondary level, many unique approaches to undergraduate water education have been implemented, including the use of models and visualizations to help students engage with, investigate, and explain complex water systems (Forbes et al., 2018; Gunn et al., 2002; Habib et al., 2012; Lally & Forbes, 2020; 2019; Li & Liu, 2003). However, understanding and using such models effectively is challenging, requiring students to think spatially and interpret two-dimensional (2-D) representations in three dimensions (3-D) (Clark et al., 2008; Hegarty, 2014; Rapp et al., 2007; Swenson & Kastens, 2011; Taylor et al., 2004). In terms of groundwater education, specifically, there is a need for increased focus on students’ spatial abilities (Dickerson et al., 2007). Yet, broader research suggests modeling is generally underemphasized in undergraduate geoscience education (Lally et al., 2019). There is therefore much work to be done to not only afford undergraduate students model-centric, water-focused learning experiences, but to also better understand how to do so effectively through instructional design.

To address these challenges, we developed a multi-week instructional intervention involving an array of activities to better support undergraduate students' use of a data-driven, computer-based groundwater modeling tool in an introductory-level, interdisciplinary, undergraduate water course (Forbes et al., 2018; Lally & Forbes, 2020; 2019; Owens et al., 2020). This tool has been used since the inception of the course as part of an instructional module designed to support students' reasoning and spatial thinking about abstract concepts related to properties and characteristics of groundwater. To develop understanding of groundwater flow through the use of the modeling tool, students must use spatial thinking skills to navigate the model and the representations within it. While a sizable body of research has focused on supporting students' spatial thinking across disciplines, including at the undergraduate level (Black, 2005; Collins, 2018; Gold et al., 2018; Golledge, 2002; Hegarty, 2014; Kali & Orion, 1996; Lee & Bednarz, 2009; Ormand et al., 2014; Reynolds et al., 2006), relatively little research has focused on the role of spatial thinking in undergraduate groundwater education, despite arguments for the importance of spatial thinking in this disciplinary context (Dickerson, et al., 2007). Informed by our own prior experience with the course module and tool, we developed the multi-week intervention to address specific challenges we observed as course instructors in students' use of the modeling tool and model-based spatial thinking skills related to groundwater concepts. Here, we investigate students' spatial thinking about groundwater in two consecutive iterations of the course, the second of which involved the instructional intervention, by addressing the following research questions:

1. To what extent does undergraduate students' spatial thinking about groundwater improve as a result of the intervention in an undergraduate water course?
2. How do students use spatial thinking abilities to reason about groundwater in two consecutive iterations of the course?

3.2 Background and Prior Research

3.2.1 Undergraduate Teaching and Learning about Groundwater

Students of all ages exhibit a range of scientifically-inaccurate ideas about water, water systems, and water resources (e.g. Baumfalk et al., 2019; Canpolat, 2006, Dickerson & Callahan, 2006; Sadler et al., 2017), including undergraduate students (Arthurs 2019; Cardak, 2009; Sibley et al., 2007). Groundwater may be a particularly challenging aspect of the water cycle to learn about, even among students who have completed undergraduate geosciences coursework (Dickerson & Callahan, 2006). A common misconception observed among undergraduate students is that groundwater occurs as an underground lakes, caves, streams, or other reservoirs (Arthurs, 2019; Cardak, 2009). Students may not recognize groundwater as part of the water cycle because it is typically not directly observable (Sibley et al., 2007). When students do recognize groundwater in the water cycle, they may not understand how it is connected to other parts of these broader water systems, viewing it as separate from other water systems (Cardak, 2009). Students may struggle to develop accurate ideas about how groundwater occurs because they struggle to conceptualize how rock can hold water underground (Arthurs, 2019). Overall, findings from prior research shows that there is a need to further support students' learning about groundwater.

One effective strategy for supporting teaching and learning about groundwater is through the use of models and visualizations. Geoscientists, including hydrologists, use various types of representations and graphical displays, such as maps and models, to display and make meaning of data. Model-based experiences, including the use of data-driven, computer-based modeling tools, can help students learn about water in various educational contexts, from K-12 to undergraduate classrooms (e.g., Baumfalk et al., 2019; Gunn et al., 2002; Habib et al., 2012; Lally & Forbes, 2020; 2019; Unterbruner et al., 2016; Williams et al., 2009). Research has shown that computer-based groundwater models afford undergraduate students opportunities to explore real-world problems and learn hands-on about groundwater systems while also introducing them to current hydrology research (Li & Liu, 2003). Computer-based multimedia tools have also been shown to help undergraduate students improve their conceptual knowledge surrounding groundwater systems (Unterbruner et al., 2016). Technology-based approaches, such as the use of GIS, have been used to effectively teach about water, as well (Kingston et al., 2012). However, many courses lack opportunities to use models and research suggests modeling is more broadly underemphasized in undergraduate geoscience education (Lally et al., 2019; Merwade & Ruddell, 2012). Even when such tools are available in undergraduate classrooms, students must be supported to use them effectively and make meaning from their representations of data (Kastens et al., 2016).

3.2.2 Spatial Thinking in Undergraduate Geoscience Education

A core component of modeling and understanding model representations is spatial thinking. Spatial thinking refers to the ability to think about the locations and shapes of objects, their relations to one another, and how they move in space. These skills may be particularly beneficial to novice undergraduate students, as they may be important for success in introductory STEM courses and degree programs (Uttal & Cohen, 2012). Specifically, in the geosciences, research has shown that among undergraduate students, there is a possible relationship between certain spatial abilities and conceptual knowledge, including Earth science topics related to water (Black, 2005). One particularly important spatial thinking skill within the geosciences involves conceptualizing 3-D structures based on 2-D representations (Golledge, 2002). Yet, despite the importance of spatial thinking, undergraduate students often struggle to think spatially and understand the spatial representations which are used to teach in various fields of science (Hegarty, 2014; Kali & Orion, 1996). Visualizing and interpreting 2-D representations, such as contour and elevation maps, in 3-D has shown to be challenging for learners (Clark et al., 2008; Rapp et al., 2007; Swenson & Kastens, 2011; Taylor et al., 2004). Often, students view maps or other 2D representations as photographs or pictures rather than a representation of actual data (Swenson & Kastens, 2011). Interpreting these representations of 3-D structures entails more than simply understanding symbols (Clark et al., 2008). Students must recognize the spatial data in the representation and be able to mentally transform it into something with meaning (NRC, 2006). These abilities require students to employ mental rotation, penetrative thinking, and disembedding (Ormand et al., 2014), all skills related to visualization 2D representations in three dimensions. These skills may be particularly important for students to productively use a 2D groundwater model and understand the representations within it.

Prior research also provides insight into how these spatial thinking abilities and skills can be supported through undergraduate instruction (e.g. Gold et al., 2018; Hegarty, 2014; Reynolds et al., 2006; Titus & Horsman, 2009). For example, textbooks may lack spatial thinking exercises (Jo & Bednarz, 2009; Scholz et al., 2014), so instructors may need to explicitly address them through instruction. Researchers have also developed spatial thinking workbooks to incorporate into undergraduate geology, mineralogy, and stratigraphy courses, which have been successful in increasing students' spatial abilities (Ormand et al., 2017). Another study implemented a module to foster undergraduate students' spatial thinking skills with computer-based activities involving topographic maps and block diagrams, which improved their spatial abilities and eliminated gender differences (Reynolds et al., 2006). Research also shows that incorporating short weekly lessons throughout the semester helped students' spatial skills in undergraduate geology courses (e.g. Gold et al., 2018; Titus & Horsman, 2009). The use of GIS tools has also been beneficial to students spatial thinking abilities (Lee & Bednarz, 2009). Students are able to interpret contour maps more easily after they have been allowed to practice with multiple map formats with the same data being portrayed (Taylor et al., 2004). Collectively, these studies point to promising approaches to undergraduate Earth systems education that enhance students' spatial thinking skills. However, none is specific to water systems or groundwater, thus prompting a need for more research (McNeal & Petcovic, 2020).

3.3 Theoretical Framework for Spatial Thinking

According to the National Research Council (NRC, 2006), spatial thinking is a way of problem solving comprised of three primary subcomponents: *concepts of space*, *tools of representation*, and *reasoning*. *Concepts of space* provides the conceptual framework within which data can be formed and structured into its entirety. To understand space, the student should understand the various properties of the space they are evaluating or learning about. Properties of space might include things such as location, dimensionality, proximity, or other patterns. Knowing about space might also entail recognizing and elaborating on relationships among geologic components such as knowing different ways of calculating distance. Space will differ with the field of study and students will need to learn different geologic knowledge depending on what is being studied. *Tools of representation* is also an important component of spatial thinking. According to the authors, representation might show what is, what might be, or what should be. This could be the map of a city or a building plan for future construction. To understand these, students must understand the relations between the representations and their real-life parts. Students can do this by perceiving and analyzing both the static and dynamic properties and relationships. They must transform representations to make predictions or detect trends. Representations can be internal, such as a mental image, or external such as a printed map. Finally, students must be able to use the information about space and representation to engage in *reasoning* about a problem. There are various types of ideas students can reason about, depending on the field being studied. Students can reason about either the results of a change or the process of the change itself, or they can be hypothetical scenarios. Like here, the NRC's framework for spatial thinking has been used in prior research on spatial thinking (e.g. Jo & Bednarz, 2009; Scholz et al., 2014).

3.4 Methods

3.4.1 Context and Participants

This study was conducted in the context of an introductory, interdisciplinary undergraduate water course at a large Midwestern university (Forbes et al., 2018; Lally & Forbes, 2020; 2019; Owens et al., 2020). The course has been offered annually in the spring semester for four years. Students in this course are from both STEM and non-STEM majors, including environmental studies, agribusiness, sociology, fisheries and wildlife, and many more. Student demographics for Year 1 and Year 2 are shown below in Table 3.1**.** The class meets three times each week for two whole-group lecture sessions led by faculty members and one smaller-group lab or recitation session facilitated by graduate assistants. Class periods are 50 minutes each. This course was designed to foster students water literacy by focusing on both science concepts and civic engagement. The student outcomes for this course are to (1) explain hydrologic concepts and engage in scientific practices, and (2) analyze and reason about socio-hydrologic systems and issues. This course design adheres to a 'flipped' model (Lally & Forbes, 2019), focusing on active learning and student engagement during class meetings. Students often view pre-recorded lectures and other material before class through the university's course management system (CMS). Class meetings involve hands-on activities, such as group discussion, problem solving, feedback, and other student-centered activities. Over the course of the semester, students' complete various projects and have many opportunities to learn from and collaborate with peers. For example, students design infographics to communicate about contemporary socio-hydrologic issues. They also complete various projects using computer-based models to learn and reason about complex water-related phenomena, including the one foregrounded in this study. These projects revolve around real-world water-related scenarios, where students apply their knowledge to make decisions. Overall, the various course projects are meant to afford students opportunities to develop water literacy.

Table 3.1

Student Demographics

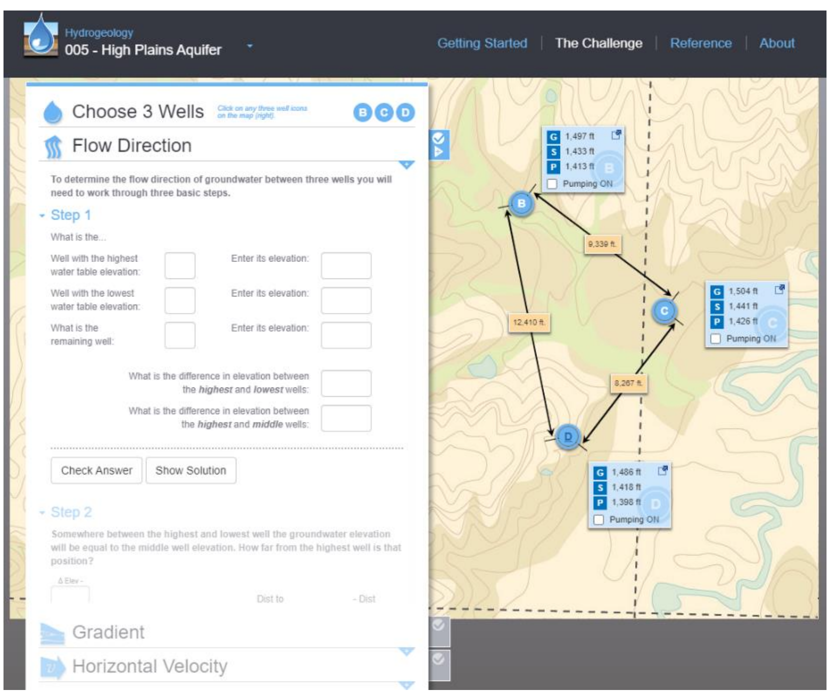
	# of Students Enrolled	Gender		Major		Academic Level			
		M	F	STEM	Non-STEM	Freshman	Sophomore	Junior	Senior
Y1	58	34	24	52	6	5	21	20	12
Y2	48	24	24	45	3	2	4	28	14

3.4.2 Student Task

This study focuses on one multi-week course module in which students use a computer-based groundwater model to learn about groundwater characteristics and reason about a socio-hydrologic issue. In Year 1 and Year 2, students used the model to learn about groundwater and complete a final task using the model, shown in Figure 3.1. The task asked students to use the model to reason about a groundwater contamination scenario and answer a series of both closed- and open-ended questions, as well as include graphical model output. This task helped students to learn about various groundwater properties such as flow direction, velocity, and gradient. The task was designed around subcomponents of spatial thinking (NRC, 2006). First, for *concepts of space,* students were asked to use the model to help them think about spatial concepts related to groundwater flow. Students calculated distances between various wells in the model, calculated groundwater travel times between various wells in the model and described why these spatial concepts were important to know and understand. Second, for *tools of representation*, students had to use the model to estimate the groundwater flow direction from a particular well. To do so, they had to interpret a 2-D contour map display, elevation changes, and various geologic structures in the model. They were then asked to provide the flow direction and describe how they used the model to find this. Last, students were asked to *reason* using information from the model. They had to reason about a hypothetical pollutant scenario and predict which groundwater wells in the model might be in danger of contamination if a spill were to occur.

Figure 3.1

Groundwater Flow Model



3.4.3 Intervention

In Year 2, we designed and implemented a new, class-based instructional intervention as part of the course module prior to students' completion of the model-based task. The intervention was intended to better foster students' spatial thinking skills and enhance their understanding of groundwater concepts through the model-based course module. In week 1, students completed a series of learning activities focused on groundwater spatial concepts and representations. Before each class period, students viewed videorecorded lectures in the online course management system to learn about various aquifer and groundwater concepts and answered reflection questions relating to the lecture material. This prepared them for class and allowed for in-class time to be focused on the interactive, hands-on activities. Both paper and technological tools were used in this intervention, as past research has shown paper and technology may help students with different spatial abilities (Collins, 2018). First, students were first introduced to surface topography and contour lines. In class, they completed an interactive Google Earth activity, which allowed them to overlay contour lines over land features onto a location of their choosing. This assignment focused on various spatial concepts related to topography and contour lines. Throughout the activity, instructors guided small-group discussions about the spatial concepts in this lesson. At the end of the activity, students compared their maps and responses with peers. Last, we concluded with a whole-class discussion and short lesson about the spatial concepts learned that day. On day two, we focused on groundwater and aquifer spatial concepts. In class, students completed a small-group activity surrounding water table contour maps where they drew contours and predicted groundwater flow direction. Throughout class, instructors guided small-group discussions at various points in the activity. Last, we concluded with whole-class discussions about these spatial concepts. In a third, final whole-class meeting, students were introduced to the groundwater model and engaged in a discussion about how the spatial concepts and representations we had learned about related to the model itself. They completed tasks to help them practice and connect the ideas from the instructional intervention to the model. Instructors assisted as students worked in small groups throughout class. Overall, this intervention allowed students to gain experience thinking spatially about the concepts in the groundwater model. Finally, in week 2, students completed their final task using the model, which was described above.

3.4.4 Data Collection

Student tasks were collected from Year 1 (n=56) and Year 2 (n=46). The student tasks, which were completed and submitted by student within the CMS at the end of the module, were identical in both years. These artifacts were later saved electronically and anonymized by the project team before analyses began. Interviews were also conducted in Year 1 (n=15) and Year 2 (n=10) with subsamples of students who volunteered to participate after all student tasks were completed. The purpose of the interviews was to gain more in-depth understanding of students' ideas about groundwater and the model. The interviews were semi-structed (Patton, 2001) based upon pre-determined interview questions grounded in student tasks but with opportunities to probe students' responses and reasoning. The interviews were conducted either in person or virtually, were around 20-30 minutes in duration, and were audio-recorded and transcribed. Copies of the transcribed interviews were also saved electronically and anonymized.

3.4.5 Data Analysis

A scoring rubric was developed and modified during preliminary data analysis. It was designed to analyze students' use of spatial thinking within the model-based task. The development of this rubric was guided by our theoretical framework (NRC, 2006). Three separate scores were given for each subcomponent of spatial thinking: concepts of space, tools of representation, and reasoning. A score of 0, 1, or 2 was given for each subcategory. Scores of 0 were given when there was little to no evidence of the spatial thinking ability in the response. Scores of 1 were given for partial evidence, and scores of 2 were given to students who showed clear evidence of the spatial thinking skill. Scored data includes a sub score for each of the three subcomponents of spatial thinking and an aggregate mean score. Interrater reliability (IRR) was assessed between two coders for a 10% sample of the data until 90% agreement was reached (k=0.827). Both years of student task data were analyzed and scored. Student tasks and interviews from both years were also analyzed qualitatively. Code queries were performed to isolate data. Initial codes were based on the three subdimensions of spatial thinking (NRC, 2006). The qualitative data were first coded into categories according to the three subdimensions of spatial thinking by using thematic analysis (Clark & Braun, 2014). When students discussed ideas related to one of these subdimensions of spatial thinking, it was labeled with the code. Coded data were queried to organize student responses into the three codes. Next, we further analyzed qualitative data within each of these three initial codes. We labeled emergent patterns within each of the three initial codes. This process allowed us to create a narrative and that described differences and similarities in students' spatial thinking between the two years. This process also allowed us to confirm and corroborate our quantitative results.

3.5 Results

In research question #1, we asked, "To what extent does undergraduate students' spatial thinking about groundwater improve as a result of the intervention in an undergraduate water course?" To address RQ #1, we first analyzed spatial thinking scores by combining Year 1 and Year 2 scores. Results show that students scored higher on concepts of space (M=1.696, SD=0.483) than both tools of representation (M=0.941, SD=0.642) and reasoning (M=0.902, SD=0.498). Observed differences between concepts of space and both representation, $t(188) = 9.48$, $p = < .001$; $d = 1.329$, and reasoning, $t(202) = 11.56$, $p = < .001$; $d = 1.618$, were statistically-significant. However, the observed difference between representation and reasoning was not statistically significant, $t(190) = 0.48$, $p = 0.626$; $d = 0.067$. Next, we analyzed spatial thinking scores between years 1 and 2 (Table 3.2). While overall spatial thinking scores were higher in Year 2 than Year 1, the observed difference was not statistically-significant. However, individual subcomponents of spatial thinking were also analyzed by year. Students in Year 2 scored significantly higher on concepts of space, though differences in scores between Year 1 and 2 for tools of representation and reasoning were not statistically-significant. Students in both years had relatively low scores in these two subcategories, compared to their scores on concepts on space. Overall, these results suggest that a) gains were observed in the subdimension of spatial thinking for which students exhibited the greatest strength (concepts of space) and b) there was no observable improvement in the aspects of spatial thinking with which they struggled the most.

Table 3.2

Year 1 and Year 2 Spatial Thinking Scores and Statistics

	Year 1		Year 2						
	M	SD	M	SD	*p*	t-stat	t-crit two tail	df	*d*
Space	1.607	0.528	1.804	0.401	0.035	2.141	1.984	99	0.420
Representation	0.839	0.654	1.065	0.611	0.075	1.799	1.984	98	0.357
Reasoning	0.910	0.499	0.869	0.499	0.673	-0.422	1.985	94	0.082
Total	3.375	1.153	3.739	0.929	0.080	1.766	1.983	100	0.347

In research question #2, we asked, "How do students use spatial thinking abilities to reason about groundwater in two consecutive iterations of the course?". Here, we present results of qualitative analyses to address this question. First, as shown in findings for RQ#1, measurable improvement was observed in students' spatial thinking for *concepts of space* from Year 1 to Year 2. Results show that students in Year 2 were more knowledgeable about groundwater flow and travel time from one well to another. Most students in Year 2 were able to correctly calculate the travel times of a contaminant spill at a well to the nearest and farthest wells and explain why this was important to know. For example, one student (2-02) in Year 2 explained,

> It is important to approximate this value because it would help environmental scientists of how much time it would take for one well to contaminate other sources in order for them to take appropriate preventative measures. Also, knowing the approximate travel time

> can tell us when to take appropriate measures before it is too late to do so.

This student was also able to correctly calculate the travel times between wells. Students in Year 2 more aptly recognized certain travel times as improbable or unlikely due to their understanding of spatial concepts that influence groundwater movement, such as water table elevation and well distances. For example a student (2-K) in Year 2 explained how the model helped them to recognize that groundwater not only moves, but that it moves slowly, “I didn’t know that it could move maybe from one place to another even though we found out it is kind of moves at a slow speed.” However, students in Year 1 struggled more with these groundwater movement calculations. For example, one student (1-19) from Year 1 answered that groundwater would move a distance of 2,397 feet, from one well to another, in just “342.42 days”, a fast travel time for groundwater, making the velocity about 7 feet per day. Another student in Year 1 (1-36) calculated the travel time to the nearest well (2,397 feet away) to be “…3 days”, and “…8 days” for the farthest well (5,161 feet away). Another student (1-51) calculated very similar travel times for both the nearest and farthest wells. Even though one of these wells is further away from the first well by thousands of feet, this student calculated the travel times to be “3,424 days” and “3,612 days” for the two wells, respectively. Some students failed to complete the calculations at all, possibly because they did not know how. When asked about properties that influence groundwater flow in the model, students in Year 1 discussed factors that were not in the model. For example, student 1-R says,

> Can I say activity like what's happening on the surface? Like what they're doing because if they are like building a house and the huge, whatever will be around, I guess then that's going to make this soil shaking…

Similarly, one student in Year 1 (1-B) identified various possible factors influencing groundwater flow, including "Soil texture, precipitation of course, the ground cover, the climate, precipitation, the way the aquifer is made and its contents, and of course human activities." However, some of these environment characteristics were not provided in the model. Rather than discussing important *concepts of space* in the model, these answers show that students discussed factors such as weather, vegetation, and construction activities which were not in the model or irrelevant to determining flow direction. Another student from Year 1 (1-Q) questioned if groundwater might be moving in an underground pipe system, and if the size of the pipe might influence flow, saying,

> I can say topography and maybe the size or where the water was moving. I don't know how I can say this, but when they may be, if for instance, if pipe is small, then the water tends to move faster than when it's really large. So I don't know how, how ground water moves. Does it move in the pipe like underground?

Another student from Year 1 (1-M) seemed unsure whether ground elevation or water table elevation might influence groundwater movement in the model, "The elevation, like the land elevation, the ground elevation. Mostly the ground elevation and the water table between one spot and another. Cus water usually wants to move from higher elevation to lower elevation." They accurately describe that water will move from high to low elevation, however they might not have recognized that they needed to use only water table elevation to determine groundwater flow. In contrast, student (2-M) from Year 2 described how they learned from the model that there were differences in the ground and water table elevation values, saying,

> … I think I probably would've assumed that surface elevation is the elevation of the water underground where kind of like in sync or in pan, I don't know if that makes sense but kind of like the same, when they are not.

Overall, these results show that students in Year 1 exhibited a more limited understanding of *concepts of space* within the groundwater model than students in Year 2, suggesting that students in Year 2 benefited from the intervention.

Second, students were more consistently challenged with *tools of representation* in both years. Some students misinterpreted model representations. For example, a student misinterpreted the water table contour line (the grey line), saying, "It will flow on an angle of 90 degrees which is perpendicular to the gray line that represents the distance from ac point to well F" (Student 2-09). Many students were also unable to name specific representations from the model in their explanations of how they derived groundwater flow direction. For example, one student explained the process of determining flow direction, but failed to identify any important model elements, “The direction of the flow is 96°. I know through the [model name] because the blue dotted line is perpendicular to the grey line” (Student 1-19). Instead of explaining how they used the water table contour line and the direction, they referred to these model representations as the blue and grey lines. Similarly, another student (1-L) described the lines as helpful to their calculations, but seemed unsure of what the lines represented, “…the interesting thing I think that I learned is the flow direction and things like that, and how we kind of use between the wells there was lines that were drawn and then it just kind of helped you calculate.” These students were able to find flow direction but may have struggled to interpret and understand the model representations that allowed them to do so. Some students understood the grey line represented a contour line but were unsure of the how it was important to groundwater flow, “I don’t really remember like how I used the contour lines” (Student 2-O). These responses show students to struggle with contour lines, along with other model representations. Overall, these results show that students in both years struggled to interpret tools of representation in the model. Some students discussed the difficulties of interpreting the 2D model, which may have been a reason for struggling with this aspect of spatial thinking. For example, student 2-M says,

> I definitely at first struggled with the [model] like conceptually because it is like a flat 2d model, and you have to kind of think about it in a 3d sort of way which was really hard for me.

Student 1-K had similar concerns, “It was hard to visualize the water table elevation just because it was flat, and I like to be able to see things I guess like in 3D…”. These results suggest students struggled with the 2D nature of the model, possibly making it difficult to interpret the representations. However, some students did discuss elevation within the model, but they provided oversimplified explanations of groundwater flow. For example, one student explained “The spilled diesel will likely follow the same path as the underground water, since it is a fluid that will travel with respect to elevation and gravity. Therefore, it will travel East (approximately 91 degrees)” (Student 1-51). This student understood elevation played a role in flow direction but failed to explain groundwater flow in terms of specific model representations.

Third, like *tools of representation*, students in both Year 1 and 2 struggled with *reasoning*. Students were tasked with reasoning about which wells might be in potential danger if a contaminant spill occurred in a location on their maps. Some students were able to reason using multiple pieces of spatial data from the model. For example, one student wrote, “Well F will be in higher danger compared to A as it is located few feet from well A. The diesel will flow from high elevation to low elevation; therefore, there is high chance that all wells will be exposed though well F in particular is at high risk” (Student 1-02). This student was able to recognize that eventually, all surrounding wells would be in danger because they reasoned using information about both distance between wells and water table elevation. However, many students struggled to articulate and defend a line of reasoning using all the necessary spatial data and information within the model. For example, many students used only one type of spatial information from the model. Student 1-19, for example, wrote, “I think it’s well F because it is near well A”, referring to spatial information about distance from the model. Another student (Student 2-18) gave a similar answer, writing, “The well in proximity to well A where the spill occurred is in potential danger, and that is well F. This is the case because there is less distance between the well A and F than there is between well A and C. So, the diesel will easily flow from A downwards to east towards well F”. Both students referred to spatial information about distance, however, they failed to reason about other spatial data, particularly water table elevation. By only using information about distance, they did not recognize the other wells that were in potential danger of contamination. Reciprocally, some students only reasoned using spatial data about elevation, “Well F beings that it has a lower elevation than A where the oil was spilled and since that is the flow direction of the water” (Student 2-44). Many students failed to consider multiple types of spatial information in their reasoning. Student 2-M reflected on the model by discussing how complex groundwater movement is, saying, “I think it helped me to learn that there’s a lot more factors to it than I originally realized…”. The complexity of groundwater concepts may have made it hard for students to reason with multiple pieces of model information. These results show that many students struggled to reason using all necessary spatial information, and sometimes relied strongly on certain pieces of information while leaving others out.

3.6 Discussion

Water is an important part of undergraduate education that helps prepare the next generation of water scientists (King et al., 2012; NGSS Lead States, 2013), but also cultivates water literacy in tomorrow’s engaged citizens (McCarroll & Hamann, 2020).

Undergraduate students should not only learn core water-related concepts, but also how to use that knowledge to reason about and address real-world, water-related challenges. However, research has shown that students of all ages, as well as adults, hold alternative conceptions about water, the water cycle, and socio-hydrologic systems (e.g. Canpolat, 2006, Cardak, 2009; Duda et al., 2005, Sadler et al., 2017), including groundwater (Arthurs, 2019; Dickerson & Callahan, 2006; Sibley et al., 2007; Zangori et al., 2017). An array of unique approaches have been implemented to support undergraduate students - both water science majors and non-majors – to learn about water systems (Forbes et al., 2018; Kingston et al., 2012; Noll, 2003; Smith et al., 2006; Thompson et al., 2012; Wagener et al., 2012; Williams et al., 2009), including modeling (Gunn et al., 2002; Habib et al., 2012; Lally & Forbes, 2019; 2020; Li & Liu, 2003). However, interpreting visualizations and representations requires fairly robust spatial thinking abilities (Dickerson et al., 2007) and, thus far, little research has focused specifically on spatial thinking about groundwater (McNeal & Petcovic, 2020). Here, in the context of an introductory-level, interdisciplinary undergraduate water course, we developed and implemented a multi-week intervention designed to address this challenge by supporting students' development of spatial thinking skills specifically related to groundwater concepts and a data-driven, computer-based groundwater modeling tool. Findings presented here provide important insights into undergraduate students' spatial thinking about groundwater systems, specifically in the context of the computer-based groundwater model used by students. These findings contribute to research about spatial thinking within the geosciences (Black, 2005; Gold et al., 2018; Golledge, 2002; Hegarty, 2014; Kali & Orion, 1996; Lee & Bednarz, 2009; Ormand et al., 2014; Ormand et al., 2017; Reynolds et al., 2006; Uttal & Cohen, 2012), and teaching and learning about water (Forbes et al., 2018; Kingston et al., 2012; Lally & Forbes, 2020; 2019; Merwade & Ruddell, 2012; Noll, 2003; Smith et al., 2006; Thompson et al., 2012; Wagener et al., 2012; Williams et al., 2009).

First, students in Year 2 showed a better understanding of the subcomponent of spatial thinking *concepts of space* as compared to students in Year 1. These results suggest that the intervention was successful in improving students' understanding of spatial dimensions of groundwater-related concepts. Students in Year 2 could calculate pollutant travel times between wells with relative ease and explain why these calculations were important. To complete this portion of the task, they had to understand various spatial concepts such as well locations, possible flow direction, distances between various wells, gradient, and elevation differences between wells. Our findings align with prior research which has shown that students perform better on questions that involve comprehension of orientation and direction, identification and comparison of various spatial information, than those that involve transformations, or mental visualizations (e.g. Clark et al., 2008; Collins, 2018). These kinds of skills may be easier skills for students to learn, which students have suggested themselves in prior research (e.g. Collins, 2018). Spatial concepts (i.e., *concepts of space*) are the building blocks of spatial thinking overall, making them an important first step for students to understand (NRC, 2006). Students in Y2 may have also gained more accurate ideas about groundwater movement, shown by their more accurate calculations of groundwater travel times. The misconception that groundwater moves like an underground river or stream is common among students, whereas accurate ideas of groundwater existing within porous rocks are less common (Unterbruner et al., 2016). On average, students in Y1 calculated unrealistic travel times as compared to students in Y2 did not have this issue as often. The unrealistic travel times in Y1 may relate to ideas about groundwater moving like an underground river or stream, rather than moving slowly. Students in Y2, who performed better on *concepts of space*, may have been able to quickly recognize unrealistic travel times if they made a calculation error.

However, second, students in both years struggled with *tools of representation* and *reasoning*. To think spatially about groundwater flow, students need to understand the representations within the model. Students should be able to make meaning from the data representations, however, novice undergraduate students may struggle with this (Kastens et al., 2016). Students misinterpreted representations, oversimplified them, and sometimes showed little understanding of specific model parts. Some students specifically pointed out that the 2-D nature of the model was challenging. Students must use a water table contour line to determine groundwater flow direction, though the model also has surface contours in the background. Within the geosciences, recognizing 2-D representations as their 3-D structures is considered an important spatial skill (Golledge, 2002). However, interpreting these 2-D representations may be difficult for students (Rapp et al., 2007; Taylor et al., 2004). Research shows that students may grasp surface contour lines and topography spatially, and tasks involving transformations are challenging for students (Clark et al., 2008), and it is possible this is also the case for water table contour lines. Students have been shown to misinterpret elevation representations in other settings as well. For example, when students were asked to interpret a global elevation map, they misinterpreted the map as showing water, temperature, or weather, rather than elevation data. The authors note that students had more misconceptions surrounding the oceanic parts of the map than the land surface and suggest that this may be because most earth science curricula focuses on continents and land (Swenson & Kastens, 2011). It is possible that students also struggle with representations of groundwater because of this. Furthermore, they may not have much prior experience with this, as many geography textbook activity questions do not allow opportunities for students to use *tools of representations* (Jo & Bednarz, 2009; Scholz et al., 2014). Overall these findings align with prior studies that discuss students may struggle interpreting and visualizing 2D representations as the real-life, complex, 3D geologic features (Clark et al., 2008; Rapp et al., 2007; Taylor et al., 2004; Swenson & Kastens, 2011).

Third, students in both years were also challenged to *reason* about groundwater. The modeling task required students to higher leveled processes of reasoning (Scholz et al., 2014) by asking them to use the information from the model to make a prediction. Specifically, the task here asked students to predict which wells in the model might be in danger and to explain their reasoning. Accurately reasoning about this hypothetical scenario would have required students to reason with multiple pieces of spatial information from the model representations. Prior research has found that students may struggle when asked questions that require them to synthesize multiple assumptions, details, or features from maps (Clark et al., 2008). Since students struggled to understand tools of representation as well, it is possible this hindered their ability to further reason using the model. It is possible for students to perform well on some spatial tasks, while performing poorly on others (e.g. Ormand et al., 2014). However, students need to move beyond understanding spatial concepts and information, they must also use spatial representations and reason with spatial information (Jo et al., 2010; NRC, 2006). Though there has been evidence of spatial thinking improving as a result of interventions, many of these studies used quantitative pre/posttest to measure spatial abilities (e.g. Gold et al., 2018; Ormand et al, 2014; Reynolds et al., 2006; Titus & Horsman, 2009). Our study results may be difficult to compare to studies that used quantitative measures, such as the STAT, considering we explored spatial thinking in the context of groundwater using open-ended student tasks and interviews.

3.7 Implications and Conclusion

Results presented here provide some evidence for how our instructional intervention may have been successful, and other ways in which it was not. These findings have implications for similarly designed undergraduate learning experiences focused on groundwater. First, the instructional intervention may not have been sufficient in duration. While the immediate objective here was to directly target a course assignment which had proven challenging for students in the past, it is likely that a longer, more systematic emphasis on spatial thinking could have been developed and infused throughout the course. Prior research supports this perspective, in which longer-term instructional interventions have been found to enhance students' spatial abilities (e.g. Gold et al., 2018; Reynolds et al., 2006; Titus & Horsman, 2009). Additionally, other existing elements of course may contribute to this broader goal, for example, where students use multiple data-driven, computer-based models to investigate water throughout the semester. Research has shown that the use of these and similar technological tools may help improve spatial abilities (Hegarty et al., 2014; Lee & Bednarz, 2009). Students also may have benefited from other instructional strategies besides the ones implemented here, such as fieldwork or 3-D physical models of groundwater. These may have helped further developed their spatial abilities surrounding groundwater by allowing them to experience these concepts with sight and touch as well (Dickerson et al., 2007). Additionally, Scholz and colleagues (2014) recommend that students should be asked high-level spatial thinking questions. These would involve complex spatial concepts, the use of tools of representation, and require them to use high levels of reasoning, such as making predictions (Scholz et al., 2014). These elements of spatial thinking may need to be emphasized and addressed in other areas of the course throughout the entire semester to better support development of students' spatial abilities. While many of these are long-standing elements of our course (Forbes et al., 2018; Lally & Forbes, 2020; 2019), we continue to explore how they can be used synergistically to specifically support students' development of spatial thinking skills.

Second, these results illustrate the need to focus on specific subdimensions of spatial thinking for which students may need particular support - *tools of representation* and *reasoning*. Prior research has illustrated how students employ spatial thinking to understand and reason about an array of Earth systems and geoscience concepts (Black, 2005; Gold et al., 2018; McNeal & Petcovic, 2020; Ormand, et al., 2017; Reynolds et al., 2006; Titus & Horsman, 2009). The study presented here contributed to this body of research through its unique focus on groundwater. However, because we found no evidence of the impact of the instructional intervention on students' understanding of representation and their reasoning about groundwater, it is necessary to learn more about how these spatial thinking abilities are most effectively employed for this particular topic. Researchers might explore what characteristics of groundwater models and tools allow students to better comprehend and use *tools of representation,* since this was particularly challenging for students. Since our study explored the subdimensions of spatial thinking in the context of one groundwater tool, researchers may want to explore how students spatial thinking differs with more commonly used representations of groundwater, such as textbook diagrams. This might help us understand students spatial thinking about groundwater in a broader sense. Research might also explore how these subdimensions of spatial thinking relate to students' conceptions about groundwater. Findings from subsequent research will help inform the design of undergraduate learning experiences, including this course, that better support students' development of these critical subdimensions of spatial thinking (NRC, 2006).

Chapter IV: Conclusion

Overall, the broader goal of both studies presented in this thesis was to investigate students' understandings of groundwater in the context of the HGC model. Both studies illustrate how students think about the model. We found that both seventh graders and undergraduates struggle to comprehend certain elements of the HGC. Our findings show that there is a need for increased efforts to support students use of computer-based models, such as the HGC. Here, even with our intervention, undergraduate students still struggled with the model. These findings have implications for future efforts to support students learning about groundwater. Students of all age groups should be encouraged and supported to develop the skills needed to understand and use models. Though our studies focus on a groundwater modeling tool, similar modeling tools are used to teach about various other topics in the sciences as well. Therefore, comprehension of models and representations is an important ability for all students to acquire.

Though there is a substantial age difference between the populations of our two studies, we found similarities in the struggles that students had with the HGC. For example, students in both age groups seem to struggle with the 2D nature of the model. Certain elements of the model were particularly challenging for students, possibly because they required students to translate a 2D representation and relate it to a 3D real-world object. This finding aligns with prior research which suggests students struggle to interpret 2D representations (Clark et al., 2008; Rapp et al., 2007; Taylor et al., 2004). Since we found this among both age groups, this suggests the possibility that students may need assistance in developing these skills over time, throughout their educational careers. Spatial thinking skills are clearly important for comprehending representations used to teach within the geosciences.

Our findings from our undergraduate study show that we may not have provided students with enough time and practice to develop spatial skills. To help them develop these abilities, students may need more direct practice and intervention to help them acquire the necessary skills over time. Rather than a short-term spatial thinking unit, such as the one in our undergraduate study, students may need support with spatial thinking throughout longer periods of time and within multiple subject areas to get more practice. This might involve incorporating spatial thinking activities into all modules of a course throughout a semester. Students would then have opportunities to use these skills with various settings and contexts, which would be beneficial. Since spatial skills are important for geosciences overall, it would make sense to incorporate this into all areas of a course, rather just one small unit.

Physical groundwater models may have also supported students learning about groundwater in our studies. For example, a groundwater flow model may have been beneficial. These are physical models that allow students to watch how groundwater actually travels in a groundwater system. Students can visualize how pumping at a well would affect groundwater movement. They can also visualize possible contamination by adding food coloring to the water. Other physical models that could be used are virtual reality topography sandboxes. These interactive tools that display a contour map onto the sandbox. As you move the sand and form different landscapes, a projector displays contours onto the sand according to what you build. This could potentially be beneficial to students who struggle to interpret contour lines.

Here, we explored students understanding of a groundwater model, but future research might also consider how spatial skills relate to groundwater content knowledge. A pre/post groundwater knowledge test might also be implemented along with a spatial thinking intervention to help us understand if spatial skills are important for overall understanding of groundwater systems. For example, students of all ages tend to have misconceptions about groundwater systems (Arthurs, 2019; Ben-Zvi Assaraf & Orion, 2005; Cardak, 2009; Covitt et al., 2019), so there is a need to support students in this area. Future research studies could explore if improvements to students' spatial skills might also help them conceptualize groundwater more accurately. The relationship between groundwater knowledge and spatial thinking skills could be important to future efforts in teaching and learning about groundwater systems.

Future research should also explore spatial thinking about groundwater systems among multiple age groups. This might be useful to compare how spatial skills differ among varying ages of students within this same area of study. A study involving middle school, high school, and undergraduate students may be beneficial. This might help us to understand how students think spatially about groundwater at various stages of their educational career. This can help instructors to continue developing relevant course material to better support students learning about groundwater systems throughout their lifetimes. The development of a framework illustrating which spatial skills should be developed for certain age groups may also be helpful. Spatial thinking could then be more effectively emphasized throughout K-12 and undergraduate science courses to ensure students develop these skills.

Furthermore, both of our studies were limited in various ways. Both studies used convenience sampling and are therefore hard to generalize about. Our intervention treatment in the second study was non-random, which is another limitation making it difficult ensure that differences found between the two student groups are caused by the treatment. Though a true-experimental design may not be realistic for many educational settings, future research could consider these various limitations better.

Overall, there is a need for more research about students' understandings of models and representations of groundwater. The literature has shown that students of varying ages struggle to conceptualize groundwater, therefore further research would be beneficial for instructors within the geosciences who teach about groundwater systems. Here, we have provided multiple suggestions for continuations of this research. Improving groundwater education will hopefully provide students with the knowledge necessary to make informed decisions about water-related environmental issues. With our water resources continually at risk, water literacy becomes increasingly important. Improvements to teaching and learning about groundwater is an important component of improving overall water literacy.

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