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GEOSCIENCE EDUCATION RESEARCH: TRENDS AND APPLICATIONS IN UNDERGRADUATE COURSES

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GEOSCIENCE EDUCATION RESEARCH: TRENDS AND APPLICATIONS IN UNDERGRADUATE COURSES

By

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A DISSERTATION

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GEOSCIENCE EDUCATION RESEARCH: TRENDS AND APPLICATIONS IN UNDERGRADUATE COURSES

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University of Nebraska-Lincoln, 2020

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Water resources are progressively under pressure from anthropogenic uses. Students need to learn about water systems as they are the future decision-makers and problem solvers who will be faced with unknown challenges in the future. The overarching goals of this dissertation were: 1) to identify ways in which geoscience instructors are incorporating systems thinking and science modeling in their teaching along with the accompanying methods for improving systems thinking and modeling implementation and 2) explore how the implementation of science modeling and systems thinking increase student evaluation of models and the understanding of hydrologic content. Data for these studies came from the Geoscience Educators Research (GER) 2016 survey data, student assignments and interviews surrounding the Water Balance Model, and student responses from a sociohydrologic systems thinking assignment.

First, GER survey data was analyzed with significant variation observed in reported frequency of science modeling and systems thinking (SMST) practices with the highest levels of SMST reported in the atmospheric and environmental sciences, those who emphasize research-based, student centered pedagogical methods, those who recently made course revisions, and those who reported high levels of participation in educational professional development.

Therefore, to test if this was replicable in subsequent work, we examined a course at UNL, SCIL 109: Water in Society, a novel course. Courses in SCIL (Science Literacy) are housed in the College of Agricultural Sciences and Natural Resources, are interdisciplinary, and include both human and scientific dimensions. A case study emerged from this data presenting the use of a computer-based water model over three iterations of SCIL 109. Results indicate that students regardless of year in college, gender, or major can effectively reason about the Water Balance Model. Specific investigation into student performance and reasoning surrounding the Water Balance Model indicate that model evaluation and understanding of core hydrologic content increased from 2017 to 2018 in part due to a flipped classroom format. Finally, the systems thinking assignment from SCIL 109 was studied using mixed-methods to investigate student operationalization of a sociohydrologic system. Results show that students scored highest on problem identification from their written work and mechanism inclusion form their drawn models. Each of these studies contributes to the overall body of knowledge surrounding undergraduate geoscience education.

DEDICATION

To Matt,

thank you for always supporting, encouraging, and believing.

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PREFACE

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Chapter 3 is published: Lally, D., Franz, T., & Forbes, C.T. (2020). Undergraduate education about water and climate change: Students' use of a water balance model. *Journal of Sustainability Education*, *22* (March 2020). Used with permission.

Chapter 4 is published: Lally, D., Forbes, C. (2019). Modeling water systems in an introductory undergraduate course: Students' use and evaluation of data-driven, computer-based models. *International Journal of Science Education. 41*(14), 1999-2023. Used with permission.

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CHAPTER 1

INTRODUCTION

The Need for Scientific Literacy

The frontier of scientific inquiry and global interconnectedness merge at the point where new problems are discovered and confronted (McFarlane, 2013). This point reflects the nexus for collaboration to solve global problems through, among other solutions, the cultivation of scientific literacy in citizens of the global community. Scientific understanding and its dissemination should be approached in a way that maximizes its potential for use by all people in their everyday lives, including the decisions they make (McFarlane, 2013; Smith, Edwards, & Raschke, 2006).

Everyday encounters with natural phenomena, the purview of science, make up the vast majority of the public's scientific experience. Activation of prior knowledge depends on learners having experienced scientific phenomenon in formal and informal education settings and everyday events (McFarlane, 2013; Smith, Edwards, & Raschke, 2006). The connections students learn to make between their lived experiences and new information are what lead to scientific literacy. Formal K-16 classroom settings is one context to help students make those connections. Teaching students to solve problems based on scientific literacy needs to take into account the lived cultural experiences of the individual (Feinstein, 2010; Murcia, 2008; Roth & Mullen, 2002). It is valuable for students to experience the impact of science on their everyday lives in the context of unpredictability and skepticism and to use science in scenarios where these two features are inherent (Feinstein, 2010; Murcia, 2008). Scientific literacy requires combining skills such as the use of scientific information and ideas including the way science is used and shaped by community (Murcia, 2008). Learning to use scientific information more effectively could enhance student access to innovative scientific research and primary data.

Teaching and Learning about Water

A central theme within the majority of today's most pressing global challenges is that of water. Clean water is critical to maintain all levels of life on Earth. Hydrology includes the study of water, all of its components, its movement, and storages (Wagener, et al., 2012). Sociohydrology is the study of the impact of humans on water and water systems (Sivapalan, Savenije, & Blöschl, 2012; Tewksbury, Manduca, Mogk, Macdonald, & Bickford, 2013; Wagener, et al., 2012). The impact of humans on water processes was long discounted and included in more nebulous titles such as "external forcings" or it was neglected altogether (Sivapalan, Savenije, & Blöschl, 2012, p. 1271). The result is a critical need for the acknowledgement of human interactions with water systems and study as a standalone field. The actions of people on water systems has had both positive and negative impacts. Nonetheless, humans may not identify the ramifications of changes to hydrologic system services for years or decades. Knowing that the price of an item does not reflect the true hydrologic cost on the environment is going to need to be part of the discussion and solution moving forward (Sivapalan, Savenije, & Blöschl, 2012). Involving students in these types of discussions at the introductory level sets the stage for thinking and learning surrounding the Food-Energy-Water (FEW) Nexus in later years.

The interaction of hydrologic and geologic systems is hydrogeologic systems. Standards related to hydrogeologic systems and water science are found throughout the K-12 performance expectations and calls have been made for the support of hydrogeologic systems understanding research (Earth Science Literacy Initiative, 2010; National Research Council, 1996; National Science Foundation, 2005; NGSS Lead States, 2013). Still, even with efforts aimed at reforming hydrogeology standards for K-12 education, students (Schaffer, 2013) and adults present with alternate conceptions related to water (Duda et al., 2005). These and other underdeveloped skills need reinforcing, as misconceptions can be durable, even in the face of confounding evidence. For students to change their conceptions to more closely match content requires iterative experiences with often-complicated material in order to overcome their alternate conceptions (National Research Council, 2012). Students need to be able to conceptualize the water cycle, but they must also know how resources and living things interact through various cycles (NGSS Lead States, 2013). For example, rather than labeling parts of the water cycle, students should also be able to account for the movement of unseen water and how humans interact with water in various, sometimes inadvertent ways (Covitt, Gunckel, & Anderson, 2009). However, past research has shown gaps in student understanding of core hydrological concepts (Covitt et al., 2009; Halvorson & Wescoat, 2002). These gaps can be addressed through the exploration of a sociohydrologic issue (SHI).

Modeling and Systems Thinking

Effective teaching aimed at reducing alternative conceptions surrounding water and incorporating science-based teaching strategies, specifically, systems thinking, and scientific modeling, are needed at the post-secondary level. Modeling is a way to make natural processes accessible and to practice skills such as making and testing hypotheses, model evaluation, comparison, and to link scientific content with the real-world (Forbes et al., 2015a; b). Modeling can take the form of computer-based, diagrammatic, physical, and analogies among others (Bybee, 2011; Coll et al., 2005). While systems thinking is the process of considering all of the interwoven feedbacks, effects, human interactions, and the ever-evolving nature of a natural systems. Systems thinking products can be both diagrammatic and written descriptions which explore the relationships between components, mechanisms and natural phenomenon (Jordan et al., 2014b). Modeling and systems thinking can be ways to engage students in both content and skill development.

Benefits of Modeling and Systems Thinking. Many hydrogeologic processes occur underground, making them difficult for students to imagine, the inclusion of computer-based water models can remove this hurdle to understanding (Singha & Loheide II, 2011). In spite of these difficulties, every community and individual participates in the hydrologic cycle; we must be cognizant of the impacts of our actions. Computer-based models allow students to both learn to hypothesize based on evidence and demonstrate their understanding of a process (Calvani, Cartelli, Fini, & Ranieri, 2008; Sins, Savelsbergh, van Joolingen, & van Hout-Wolters, 2009). This is particularly the case with hydrogeologic phenomena and sociohydrologic systems.

Students in the classroom report the use of computer-based models is engaging because, with a rudimentary understanding of hydrogeologic processes, they can explore multiple hypotheses, develop policies, and run multiple scenarios quickly (Gunn, Mohtar, & Engel, 2002; Williams, Lansey, & Washburne, 2009; Zigic & Lemckert, 2007). Thus, students incorporate the nature of science as they test ideas while simultaneously applying content knowledge.

Supporting Modeling and Systems Thinking in Classroom Settings. Do college instructors incorporate these types of methods across the board and with the frequency they are needed in introductory geoscience courses? Just as education reform efforts at the K-12 level aimed at increasing scientific fluency in students exist (NRC, 2012), cutting-edge instruction and research is also needed from postsecondary faculty (Somerville & Bishop, 1997). Some instructors engage in strategies such as systems thinking and science modeling more than others, yet these two scientific habits of mind are critical to geoscience education and the geosciences (Lally et al., 2019).

However, there is a lack of computer-based water model use in introductory courses despite evidence that their inclusion can aid students in using higher order thinking skills than are often found in undergraduate curricula (Singha & Loheide II, 2011). Similarly, undergraduate students’ ability to operationalize hydrologic systems, particularly the unseen components, interactions, and repercussions, fall on a broad spectrum (Sibley et al, 2007). Modeling skills are overall underdeveloped when students begin post-secondary education (Forbes, Zangori, & Schwarz, 2015). Computer-based modeling skills may be even more underdeveloped because of their lack of use in K-12 education and introductory post-secondary courses (Gunn, Mohtar, & Engel, 2002; Williams, Lansey, & Washburne, 2009). Worsening the lack of modeling skills is the lack of core hydrologic knowledge students in K-16 demonstrate (Ewing & Mills, 1994; Forbes, et al., 2018).

Often, theoretical models are used to teach hydrologic content, this can make it harder for students apply what they are learning to daily decision making activities (Canpolat, 2006). One of the manifestations of this difficulty is for students to both compartmentalize cycles such as the water, rock, or carbon, and parts of cycles within themselves, even though there are definitive links between them (Batzri, Assaraf, Cohen, & Orion, 2015; Canpolat, 2006).

Systems thinking falls within a student’s zone of proximal development permitting active learning to occur (Danish, et al., 2017). The large and small group discussions surrounding a systems thinking model allows individual students to critically evaluate their individual model and revise it. However, not all students will reach the same level of analysis (Danish, et al., 2017). Students which are new to systems thinking are more likely to think exclusively about the big patterns and surface level descriptions of a system (Danish, et al., 2017). In applying systems thinking in a classroom, students are often asked to explain their systems thinking model either verbally or in a written format. Students at the introductory stage of systems thinking are highly influenced by pre-existing ideas and are likely to use many available resources such as readings or peers to complete a systems thinking model (Danish, et al., 2017). Students can benefit from discussing and learning how mechanisms or processes can be transferred from one component to another component within a system, this type of thinking will increase the complexity and accuracy of their systems model (Hmelo-Silver, et al., 2017).

Equally important to developing the skills of modelling and systems thinking is the assessment of how and the extent to which students use and evaluate computer-based water models and evaluate systems thinking models. Developing model use and evaluation skills is an iterative process strengthened by active learning strategies, hydrologic content knowledge development, and learning to transfer concepts across varying scales and manifestations (Gunckel, Covitt, Salinas, & Anderson, 2012; Smith, Edwards, & Raschke, 2006). Qualitative data is helpful in understanding how students reason about hydrogeologic systems. Based on this qualitative data, it may be beneficial, to incorporate student ideas into content and teaching methods where possible.

Students who do not understand basic hydrologic content and who do not possess modeling skills are at a distinct disadvantage in geoscience courses because of the large role it plays in many systems. The studies presented here combine identifying how and the extent to which undergraduate students learn basic hydrologic content via model based reasoning and systems thinking to gain insights into patterns which can be used to develop future courses and refine teaching methods.

Gaps in the Literature

More research about hydrologic science teaching strategies and how students learn hydrologic science is still needed to learn methods particular to hydrology which increase student learning (Thompson, Ngambeki, Troch, Sivapalan, & Evangelou, 2012). First, defined gaps exist in what we know about effective teaching and learning in undergraduate geoscience courses, specifically surrounding the ways instructors implement modelling and systems thinking as well as the extent to which these strategies are employed in undergraduate courses. I work to address these gaps through first quantifying the "how" and "to what extent" geoscience instructors are incorporating modeling and systems thinking into post-secondary courses. Second, gaps exist in our understanding of how postsecondary students engage in computer-based modeling and how to support undergraduate students' model-based reasoning about water systems. These gaps are addressed through two studies using quantitative and qualitative analyses of a computer-based modeling assignment and related interviews to explore student understanding and needs. Third, explicit gaps exist in our understanding of the links between students' use of systems thinking to operationalize and model SHS, as well as their metacognitive evaluation of systems thinking. A qualitative and quantitative analysis of student reasoning and operationalization of a sociohydrologic issue through a diagrammatic model and written description work serve to being to address the related systems thinking gaps. Overall, work here is focused on geoscience faculty systems thinking and science modeling practices, student computer-based water model use and evaluation, and systems thinking operationalization of a regional socioscientific issue.

Theoretical Framework

Scientific Teaching in Undergraduate STEM

Each of the theories I selected contribute to my design of curriculum and instruction and are core elements of effectively designed undergraduate courses. Constructivist learning theory, the zone of proximal development, and metacognition support both vertical alignment of course content and student centered learning environments. Vertically aligned material is designed with the course goals for the student at the forefront of each course decision. Student centered learning is the product of scientific teaching strategies which are demonstrated to enhance learning and skill development in undergraduate students. Furthermore, scientific teaching strategies also lend themselves to hydrogeologic language development, modeling skills, and systems thinking based decision-making.

Working to enhance student-thinking skills requires activation of many individual skills that are fostered through different theories and pedagogical strategies. Applying the same theory or method to each type of skill would be frustrating and ineffective. It is the correct application of theory matched to specifically selected pedagogical methods which results in the achievement of a course learning goal. The contribution of theory to practice results in enhanced student ability to learn the skills needed for accurate and robust understanding.

Constructivist Learning Theory

Learning begins in infancy and continues throughout life, with our experiences building on one another to develop increasingly complex ideas, patterns, and skills. Learning progressions are a way of defining the continuing development of a concept within students (Gunckel, Covitt, Salinas, & Anderson, 2012). As part of the progression of growing from novice to proficient, learners incorporate life experiences into the facts, skills, and ideas they encounter in formal education (Fosnot & Perry, 1996; Gunckel, et al., 2012; National Research Council, 2007,). Learners are then, a summation of all their life experiences including formal and informal education opportunities. These opportunities each play a part in the development of the learner's understanding because they are the foundation from which new understanding is built. It would be easy and convenient if learning was similar to advancing floors in an elevator, but it is more similar to a rollercoaster ride. Initially, learners begin at a starting point, an early experience with an idea or something familiar, and then they progress in fits and starts, adding and subtracting ideas and understanding as they grow in their clarification of understanding (Fosnot & Perry, 1996; Mislevy, 2006).

Constructivism as a theory for learning is rooted in the idea that learners continually develop over time as the result of experiences. There is no defined end, but steady building, editing, and revising of an existing thought structure (Fosnot & Perry, 1996). Constructivist learning benefits from active learning strategies in which students grapple with an idea themselves or with others instead of individually (Somerville & Bishop, 1997). However, we know that learning is not straightforward and that there are times when what we experience and know come into contrast with new information. When this contrast or disruption of equilibrium occurs, in which the learner is faced with new information at odds with what they previously knew, something has to change (Fosnot & Perry, 1996). This disruption and its relation to previous knowledge results in the learner thinking about how they can reconcile both the old and new ideas (Fosnot & Perry, 1996). It is in this thought process where growth occurs. Growth can happen at any point in a learner's life, but the most growth happens when a learner is ready for a new level of mastery.

Zone of Proximal Development

Meeting students where they are in their academic progress is often a goal of an instructor when beginning new content. Students have experience, even if tangentially, with ideas and content that needs to be taken into account. The goal of beginning where a student's mastery ends and where assistance on the next level task is needed is the zone of proximal development (Vygostky, 1978). This type of readiness is an extension of constructivism. As students demonstrate their self-sufficiency with a task, they are simultaneously demonstrating their readiness for help in learning the next more difficult task in progress to content mastery. As students grow in their ability to successfully master content, they build on experiences with ideas and revise their understanding of concepts, some of which are contrary to previously held ideas.

Students need time to revise their understanding of a concept in order to think about and make new connections between ideas. The time spent reorganizing information can result in one of three outcomes: preservation of the original alternate idea, maintenance of two distinct theories about the same idea, or the development of a new more accurate reorganized understanding of a concept (Fosnot & Perry, 1996). The goal of education is the gradual growth of a more informed, nuanced understanding of a concept through progressively more challenging and engaging work. The brain seeks novelty, learning new ideas then transforming chaos into order (Fosnot & Perry, 1996, Vygotsky, 1978), working within a student's zone of proximal development is a way to harness this intrinsic behavior. Just as constructive learning is a looped system, so is the zone of proximal development. Learners are constantly moving into and out of their zone of proximal development for given tasks and concepts (Moll, 1992).

Metacognition

Teaching students to think about their own thinking is another way to promote constructive learning in the classroom. Learning to assess development in content proficiency is important for students to be able to determine the gaps in their own understanding (Flavell, 1979; White & Fredericksen, 1998). Learning this skill helps students understand that they control their own learning and can change course when learning strategies are not working. Students who unsuccessfully toil with content may not have ever learned metacognitive skills and often find them useful because they can govern their own learning and identify that they are capable of mastering content (White & Fredericksen, 1998). Learning self-assessment practices is a process, similar to learning course content (Flavell, 1979). By consistently revisiting, understanding, and comparing it against the desired outcome, students can construct higher proficiency in both content and metacognitive mastery.

Not only does critically evaluating one's gaps in learning and skills increase understanding, but it also helps students to become more certain in their ability (White & Ericksen, 1998). Building confidence in students helps them to feel like they are capable and in control of learning more advanced material. Picking the right approach to solve a problem is the first step in building knowledge by determining patterns and consistencies in solutions (Flavell, 1979). Knowing the correct strategy to use in solving a problem or learning content is critical to building content mastery. Growing in metacognitive skill reduces the likelihood of the persistence of alternate conceptions because of the ability to identify knowledge that is inconsistent with other facts or skills (Flavell, 1979). Learning to identify where there are misconceptions is just as important as learning the correct content. Building a skillset then is equally comprised of learning material and learning how to process it.

Research Questions and Studies Overview

I conducted four studies to address gaps in the current understanding of the frequency, support, and implementation of science modeling and systems thinking within post-secondary, geoscience classrooms. Specifically, there are gaps in our understanding of the ways in which and the frequency with which instructors implement science modeling and systems thinking in undergraduate geoscience courses. Gaps exist in our understanding of how postsecondary students engage in computer-based modeling and how to support undergraduate students' model-based reasoning about water systems. Explicit gaps also exist in our understanding of the links between students' use of systems thinking to operationalize and model SHS, as well as their metacognitive evaluation of systems thinking. Each of these studies explores the implementation of science modeling, systems thinking, or both within the context of undergraduate geoscience classrooms (Table 1.1).

In the first study, I investigated how geoscience instructors, nationwide, engage in scientific modeling and systems thinking as well as the factors, which predict and explain the extent to which they engage in scientific modeling and systems thinking (Chapter 2). The second study concentrated on the overall modeling skills that were developed across three iterations of the course, SCIL 109, and explicitly described the implementation of the Water Balance Model and associated assignment. In the third study, I explored comparatively the extent to which students in two iterations of the course, SCIL 109: Water in Society, increased in both model-based reasoning skills and conceptual understanding of regional water balance as well how they differed in model-based reasoning (Chapter 4). In the fourth study, I examined the operationalization and modelling components, mechanisms, and patterns found in a systems thinking model and description of a real-world Sociohydrologic issue as well as how students self-evaluated their model limitations (Chapter 5). Each study is presented as its own manuscript and as a piece of the larger dissertation, where Chapter 6 contributes a summation of the studies and the conclusions drawn.

Individual studies are guided by their own specific research questions, but overall questions governed the studies as a whole:

1. How are geoscience instructors incorporating systems thinking and science modeling in their teaching and what are strategies for improving systems thinking and modeling implementation?
2. How does the implementation of science modeling and systems thinking increase student understanding of basic hydrologic content and help students grow in their critical evaluation of models?

Table 1.1 *Overview of Studies*

Chapter	Population	Topic	Research Questions
2	Post-secondary geoscience instructors	Survey analysis of the factors influencing the prevalence of systems thinking and science modeling components in geoscience classes.	1. To what extent do geoscience instructors report engaging in scientific modeling and systems thinking? 2. What instructor- and course-level factors help predict and explain the extent to which geoscience instructors report engaging students in scientific modeling and systems thinking?
3	Undergraduate introductory water students	The use of the Water Balance Model and active learning strategies demonstrate how all students can learn to effectively engage with models.	1. What differences exist between gender, major, and year in college and Water Balance Model project score? 2. How are students reasoning about precipitation, PET, and contour lines using the Water Balance Model?
4	Undergraduate introductory water students	A between years comparative study of student use and evaluation of the Water Balance Model.	1. To what extent do students' a) model-based reasoning and b) conceptual understanding of hydrology differ between Years 1 and 2? 2. How does students' model-based reasoning differ between Years 1 and 2?
5	Undergraduate introductory water students	Systems thinking operationalization and model analysis of a water related issue.	1. What systems thinking modeling components, processes, and mechanisms do students emphasize in drawing a model of a real-world scientific issue? 2. What do students operationalize surrounding a real-world socio-hydrologic issue? 3. How do students evaluate their own systems thinking models of real-world socio-hydrologic issue?

CHAPTER 2

NATIONAL GEOSCIENCE FACULTY SURVEY 2016: PREVALENCE OF SYSTEMS THINKING AND SCIENTIFIC MODELING LEARNING OPPORTUNITIES

Worldwide, there continues to be a growing emphasis on effective undergraduate teaching and learning in science, technology, engineering, and mathematics (STEM). Increasingly, STEM policymakers, faculty, industry leaders, and university administrators are recognizing the importance of well-developed and effective undergraduate STEM programs in meeting the needs of the STEM workforce and cultivating scientifically literate citizens. Students in post-secondary institutions should learn the skills and concepts necessary to be competitive in the job market and a productive member of society. To be effective in any future endeavor, students need to be able to analyze information, problem-solve in the context of ill-defined socio-environmental challenges, and integrate multidisciplinary concepts in their reasoning about Earth systems (Mosher, et al., 2014). These needs suggest undergraduate geoscience education is in an important position to positively impact society.

A central element of effective undergraduate geoscience teaching and learning involves scientific modeling and systems thinking (SMST). As Arnold and Wade (2015) note, “Systems thinking is a set of synergistic analytic skills used to improve the capability of identifying and understanding systems, predicting their behaviors, and devising modifications to them in order to produce desired effects. These skills work together as a system.” (pg. 671). Systems thinking in geoscience education is beneficial because students learn to think about a system from multiple viewpoints (Danish, Saleh, Andrade, & Bryan, 2017). As students develop geoscience understanding, the complexity of these systems can be explored with increasing depth, demonstrating the interconnectedness of systems and spheres of Earth. Scientific modeling is a critical component of systems thinking that contributes to holistic understanding in the geosciences. It involves the use of historical data and future, empirically based predictions for systems-related phenomena, each of which temporally examine system interactions (Troy, Konar, Srinivasan, & Thompson, 2015; Kastens et al., 2009), often with support from technological tools. SMST approaches help to support students' development of robust mental models of how Earth systems interact.

However, little is known about how SMST practices are taught in undergraduate geoscience courses. There is still a need to know more about SMST, specifically, how and why it is implemented by instructors, how often they include it in their courses, and what types of SMST practices are most common in undergraduate classrooms. While studies of individual courses or instructional interventions may provide empirical insights into SMST in geoscience education (Forbes et al., 2018; Gunn, Mohtar, & Engel, 2002; Williams, Lansey, & Washburne, 2009), few efforts have attempted to document where, when, why, and how SMST elements are being emphasized in undergraduate geoscience courses, as well as factors that can help explain and/or predict these trends. The purpose of the present study, in which we analyze survey data from a national sample of geoscience faculty in the United States, is to begin to address these questions. Specifically, we ask the following research questions:

1. *To what extent do geoscience instructors report engaging students in scientific modeling and systems thinking?*
2. *What instructor- and course-level factors help predict and explain the extent to which geoscience instructors report engaging students in scientific modeling and systems thinking?*

UNDERGRADUATE TEACHING AND LEARNING IN THE GEOSCIENCES

Educational experiences that prepare future problem solvers require affording all students opportunities to learn how to think scientifically, particularly in undergraduate classrooms (National Research Council [NRC], 2012), including the geosciences. Over the last half-century, geoscience education has undergone significant change in its purpose and organization (Libarkin, 2006; Tewksbury, et al., 2013). Historically, geoscience education was designed primarily to develop future geoscientists. However, given the inherent opportunities it affords students to engage in evidence-based reasoning about Earth systems (Somerville & Bishop, 1997; Tewksbury et al., 2013), geoscience education also plays an important role in helping students develop scientific literacy. With increasing emphasis on teaching and learning in the geosciences and the development of geoscience education research (GER) as a field of inquiry in recent decades, geoscientists and geoscience educators are more strongly positioned than ever to efficiently and effectively evaluate and assess the efficacy of teaching and learning practices on these two parallel outcomes of geoscience education.

Beginning in the early 2000s, purposeful efforts have been made to define target outcomes of geoscience education. Partnerships between various organizations, including the National Science Foundation, the National Oceanic and Atmospheric Administration, the American Association for the Advancement of Science, the Earth Science Literacy Initiative, and U.S. Department of Energy, among others, have contributed to the development of standards, principles, and frameworks for general Earth science literacy (Earth Science Literacy Initiative, 2010), climate literacy (U.S. Global Change Research Program, 2009) and energy literacy (U.S. Department of Energy, 2012). In each of these documents, SMST is prioritized as a core experience and outcome for learners at all levels, including undergraduate geoscience education. In the Earth Science Literacy Principles (Earth Science Literacy Initiative, 2010), for example, SMST is central to the definition of Earth Science Literacy, in which “An Earth science-literate person understands fundamental concepts of Earth’s many systems” (Earth Science Literacy Initiative, 2010, p. 2). They also emphasize the need for students to “construct and refine computer models that represent the climate system” (U.S. GCRP, 2009) and “think in terms of energy systems” (U.S. DoE, 2012). The development of these documents instantiates and enhances the importance placed on SMST within the context of geoscience education.

The landscape of geoscience education is changing in parallel with broader undergraduate STEM education reform efforts in the United States (NRC, 2012). Not only are geoscientists in academia expected to do impactful scientific research, but in order to remain competitive and relevant, they must also engage in innovative instruction (Somerville & Bishop, 1997). However, educators need help finding and learning to use best practices in geoscience education. As such, geoscience instructors are increasingly participating in professional development opportunities to develop new skills that enhance geoscience education (Manduca et al., 2017). However, the reach and impact of these opportunities is not evenly distributed. For a variety of reasons, some instructors engage in these opportunities with greater frequency than others (Libarkin & Anderson, 2005; Macdonald, Manduca, Mogk, & Tewksbury, 2005). Despite the literature and resources available to geoscience instructors, more work is needed to understand which instructional strategies are the most beneficial to students. Understanding the use of SMST practices by instructors and the associated impacts on student learning is one area that warrants further study.

SCIENTIFIC MODELING AND SYSTEMS THINKING

Scientific modeling and systems thinking are two interrelated practices and 'habits of mind' central to the geosciences and geoscience education. Systems thinking is the study of the interplay between the subsystems comprising an overall system (Bawden, Macadam, Packham, & Valentine, 1984; Scherer, Holder, & Herbert, 2017). Systems thinking involves the explicit description of the system as a whole and the links between its constituent parts and processes (Arnold & Wade, 2015). Processes occur simultaneously through both large and small-scale interactions and feedbacks (Assaraf & Orion, 2005). Learning how to think about the interactions between systems, the far-reaching effects of a system, and the dynamic nature of systems are all ways to demonstrate scientific literacy. Both are core components of the work of geoscientists and critical outcomes for undergraduate STEM education, particularly in the geosciences.

A primary mechanism to investigate systems is through models. Scientific models are inherently simplified versions of complex systems. Modeling is a way in which students can both learn to make predictions based on evidence and communicate their understanding of a phenomenon (Baumfalk et al., in press; Schwarz, et al. 2009). Contemporary science, particularly the geosciences, is heavily reliant on computer-based models to support research on complex systems and overlapping components of socioscientific issues makes modeling more difficult (Troy, Konar, Srinivasan, & Thompson, 2015). However, models do offer the opportunity to hypothesize and experiment with varying outcomes of a model in the pursuit of a suite of potential solutions. Research suggests there are a number of ways to help students succeed in the use of computer-based models. Students reported the presence of an instructor as beneficial even if they are working in groups on a modelling problem (Zigic & Lemckert, 2007). Students express interest in computer-based models and report that they add to understanding of complex processes, describing them as useful; they also report that participation in class and the skill of the instructor are key components to computer-based model learning (Williams, Lansey, & Washburne, 2009). Instructors have an important role to play in developing student modeling skills, despite students' seeming familiar with technology overall. Learning SMST practices is a valuable way to help students transition from learning facts to generating new ideas and solutions to problems.

There are several concrete ways instructors can help students develop systems thinking skills. Spending time discussing not only the mechanisms and patterns surrounding components, but also the scale of certain features, helps students make systems thinking connections (Hmelo-Silver et al., 2017; McNeal, Miller, & Herbert, 2008). Sometimes it is difficult for students to conceptualize how all of the components of a system might be connected or the ways seemingly disparate components are connected, including in the geosciences (Macdonald, Manduca, Mogk, & Tewksbury, 2005). The more instructors engage students in discussion about areas of difficulty, the more detail they will be able to include in their systems thinking models. Not every cause and effect will have the same impact on a system, so instructors explicitly teaching students to evaluate the size of the impact and the range of likely effects of an interaction can help increase precision in their model development. Instructors can provide opportunities for discussing and learning how mechanisms or processes can be transferred from one component to another component within a system, this type of thinking will increase the complexity and accuracy of student systems models (Hmelo-Silver et al., 2017). The ways instructors can help students increase SMST skill are known, but gaps still exist in the ‘how’ and ‘to what extent’ this set of important practices is emphasized in undergraduate geoscience courses.

METHODS

Survey Instrument

This study is based upon data from the 2016 administration of the National Geoscience Faculty Survey. The 2016 survey was designed by a research team involving leadership from the National Association of Geoscience Teachers (NAGT) along with three NSF-funded professional development projects (On the Cutting Edge, InTeGrate, and SAGE 2YC). This survey, as well as earlier versions administered in 2004, 2009, and 2012, are publically available. Data derived from the first three distributions of the Geoscience Faculty Survey were reported by Macdonald and colleagues (2005) and Manduca and colleagues (2017). The 2016 survey, which provides information about undergraduate geoscience course instructors and course characteristics, has open response and Likert-style questions which probe instructor teaching and learning practices from general strategies to specific actions, as well as demographic info about respondents. The survey consisted of 209 questions with a median completion time of 14.4 minutes. Respondents answered questions about their: 1) disciplinary focus, teaching background, and institution; 2) introductory level course teaching strategies; 3) major teaching; 4) learning new teaching methods, active learning strategies included, course changes; 5) communication within the geosciences community and their reasons for attending teaching workshops; 6) use of online resources, articles published, and conference presentations. Respondents provided information about the year in which they received their terminal degree, how many years they have been teaching at the postsecondary level, their position title, and how many courses they teach. In terms of their course, they were asked about how many students the course serves, its format (i.e., face-to-face vs. online), if they had instructional support in the form of teaching assistants, and if there was a lab section associated with the course.

The focus of this study is on opportunities in undergraduate geoscience courses for students to engage in SMST practices. The survey included a set of nine items in which respondents were asked to identify one or more sets of practices in which they engaged students in their courses through ‘yes’ or ‘no’ responses. Practices included: 1) discussion of changes in a system, 2) feedback loop analysis, 3) system mapping, 4) exploration of systems with computer models, 5) building predictive models, 6) discussions of implications and predictions, 7) discussions of scale and interactions, 8) distinguishing current processes and results of history, and 9) description of system parts and relationships. These nine items serve as the measure for the outcome variable of interest in this study – scientific modeling and systems thinking (SMST).

Sampling

The 2016 survey was administered to set of respondents based upon a national sample of geoscience faculty. The target population was identified from publically available records and membership lists associated with relevant U.S. geoscience departments at 2- and 4-year institutions (community colleges, liberal arts colleges, Research Intensive Universities), professional communities, geoscience education listservs maintained by SERC, and previous and current geoscience education projects serving postsecondary geoscience faculty, including On the Cutting Edge (n=10,910). Full-time faculty, adjunct faculty, instructors, and lecturers were eligible for surveying. Individuals included in the sample met the requirements of actively teaching postsecondary geoscience courses and having legitimate functioning email addresses. From these resources, a sample of 9,596-geoscience faculty were identified as eligible. The participants included members of the American Geological Institute, SERC Cutting Edge participants, Geosciences Two-year College list, the SAGE Two-Year College List, SERC Early Career List, and meteorology faculty.

Data Collection and Analysis

From this sample, 200 randomly selected individuals were contacted via email and invited to participate in a pilot administration of the 2016 survey, of which 33 individuals responded. The results from the pilot survey were used to modify wording of some of the survey items to be sent to the remaining 10,910 individuals. After the pilot, the remaining individuals in the sample were invited to complete the survey. All individuals received email copies of the survey, were contacted up to four times to complete the survey, and those completing the survey did so electronically. Of these potential participants, 27.3% (N=2615) of the 9,596 eligible individuals answered one or more questions on the survey. The findings reported here are based on the sample of respondents who completed all items used as data for this study (n=2056), a response rate of 21.4%. Respondents were primarily from research/doctoral and master's institutions. However, the response rate was lowest among research/doctoral institutions and highest among all other institution types. Fewer individuals in the sample population described their disciplinary focus as oceanography or atmospheric science than geology, which accounted for 81% of the sample. Demographic characteristics of respondents are presented in Appendix 2.A.

The survey dataset was compiled and imported into SPSS software for statistical analyses. We used inferential statistical methods to evaluate relationships between the outcome of interest – reported SMST practices in undergraduate geoscience courses – and a variety of other faculty- and course-level variables as reported by respondents in the survey. Standard parametric tests rely on the underlying assumptions of normal distribution and equal variances (or standard deviation) for the variables subject to analysis. Here, the distribution of scores for our outcome variable of interest - SMST - exhibited both Skewness (0.16) and Kurtosis (-0.62) values falling between -1 and 1, indicated scores were normally distributed. Therefore, the utilized correlation, t-tests, and ANOVA to assess relationships between variables from the survey data.

Pearson correlations were conducted to assess the STRENGTH and DIRECTION of relationships between two variables from the same individuals for analyses within groups. Reported correlation (*r*) values fall between -1 and 1 and indicate the extent to which two variables are linearly related within a single sample or group. Additionally, t-tests and ANOVAs (with Tukey's post hoc tests) were conducted to compare mean SMST scores and subscores between groups of survey respondents. The *t*-test and one-way analysis of variance (ANOVA) are appropriate tests for comparing mean of variables involving two or more groups. A t-test is used to assess whether the means of two groups are *statistically* different from each other. The *t*-statistic is the ratio of mean difference and standard errors of the mean difference t-test. For a comparison of more than two group means, the ANOVA is the appropriate method of analysis. The F ratio is the ratio of mean square values where the larger the F ratio, the larger the difference in variation between the groups tested for a given variable. Tukey's post hoc tests are then run on individual pairings of groups used in the ANOVA to establish statistically-significant differences between the individual groups. Through these analyses, we observed that most instructor-level factors and course-level factors identified in the survey were not related to the SMST course elements reported by respondents. However, instructor-level and course-level factors that exhibited statistically-significant relationships with the outcome of interest – SMST course elements – are summarized in Table 2.1.

Table 2.1
Survey Items and Independent Variables Associated with Reported Scientific Modeling and Systems Thinking Course Elements

Variable	Description
20_COMP	SMST course elements
S16_1	Geoscience subdiscipline of faculty respondent
S16_25_COMP	Number of changes made to course content in past 2 years
S16_27_COMP	Number of changes made to teaching methods in past 2 years
PRESENTRESEARCHR	Number of meetings presented scientific research within the past two years
NUMPUBLISHR	Number of articles about research published in the past two years
TALKCONTENT	Frequency of conversation with colleagues about course content over the past two years
ATTENDTEACHTALKSR_2	Number of talks on teaching methods, other topics related to science education, or geoscience education attended in the past two years at professional meetings, on campus, or at other venues
ATTENDWRKSHPR	Number of workshops related to improving teaching attended in the past two years
PRESENTTEACH	Number of presentations of research on teaching methods or student learning at meetings within the past two years

NUMARTICLES	Number of articles published about educational topics within the past two years
TRADLECb	Frequency of use of traditional lecture
LECDEMOb	Frequency of use of demonstration
INDIVQUESTb	Frequency of use of individual student questions
ALLQUESTb	Frequency of use of asking whole-class questions
SMALLGRPDISb	Frequency of use of small-group discussion
WHOLEGRPDISb	Frequency of use of whole-class discussion
INCLASSb	Frequency of use of in-class assignments

Based upon these analyses, a multiple regression model was constructed to investigate the extent to which instructor- and course-level variables identified as significant through t-tests, ANOVAs, and correlations (Table 2.3) predict reported SMST elements in undergraduate geoscience courses. A multiple linear regression is used to model the relationship between two or more independent, or predictor, variables and a single, dependent variable by fitting a linear equation to observed data. It provides an R^2 value (between 0 and 1) which represents the percentage of variance in the dependent variable explained by the predictor variables used in the model. The objective of these analyses is to infer probabilities that statistically significant relationships observed in this population that would be predictive of those in the broader population of undergraduate geoscience instructors. Consistent with the purpose of multiple linear regression, these results both a) explain the strength of the relationship between predictor variables and the outcome variable of interest (SMST), as well as how increasing values of predictor variables would help predict increasing SMST in undergraduate geoscience courses. All analyses involved two-tailed tests with significance at the $p < .05$ level and Cohen's d as the reported measure of effect size. Means (M) and standard deviations (SD) are reported as descriptive statistics for variables of interest.

RESULTS

Overview of Results

In the sections that follow, we present results from analysis of the survey data to address our research questions. Overall, primary findings are summarized as follows:

- On average, geoscience faculty members report including fewer than four SMST practices in their undergraduate classes
- SMST practices are more commonly emphasized in courses for geoscience majors than non-majors, but only slightly
- Faculty from atmospheric science/meteorology, environmental sciences, and hydrology report emphasizing the most SMST practices, while those from geology report the fewest
- Faculty who report being significantly engaged in instructional innovation (course revisions, attuned to research and best practices in geoscience education, and seeking out instructional support) and identify with a community of geoscience educators report more emphasis on SMST practices than those who do not
- These variables account for approximately 17% of the observed variance in reported SMST practices emphasized in undergraduate geoscience courses

Reported Scientific Modeling and Systems Thinking Course Elements

In research question #1, we asked, "*to what extent do geoscience instructors report engaging students in scientific modeling and systems thinking?*". To address this question, we analyzed frequencies with which survey respondents reported SMST elements in their undergraduate geoscience courses. Response frequencies for the nine (n = 9) survey items that comprised the composite SMST scale are presented in Table 2.2.

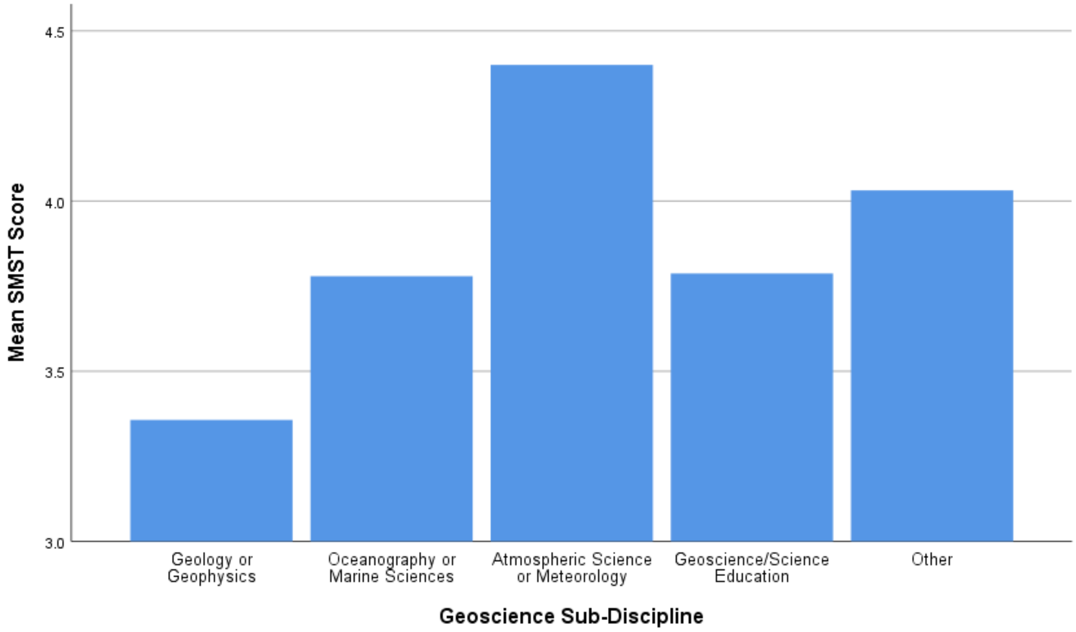
Table 2.2
Frequencies of Reported Scientific Modeling and Systems Thinking Course Elements

Item	*Are there elements in your course that enable your students to:*	Percentage (%)	SD
1	Discuss a change that has multiple effects throughout a system	54	.50
2	Analyze feedback loops	34	.47
3	Make systems visible through causal maps	26	.44
4	Explore systems behavior using computer models	20	.40
5	Build predictive models	22	.41
6	Discuss relationship between implications and predictions	42	.49
7	Discuss complexity of scale and interactions	59	.49
8	Distinguish outcomes of current processes from results of prior history	42	.49
9	Describe a system in terms of its parts and relationships	64	.48

As shown in Table 2.2, there was variation in how frequently these course elements were reported by survey respondents. The most commonly reported course element was *describing a system in terms of its parts and relationships* (Item #9), with over 60% of survey respondents reporting emphasizing this element as a part of their course. At the low end of the continuum, only 20% survey respondents reporting *using computer models to explore systems behavior* (Item #4). The frequencies for the remaining items each fell somewhere in between these two ends of the range of reported SMST practices. Standard deviations for these items ranged between .4-.5, with a majority between .45-.5.

To generate a single, composite score for our outcome variable of interest – scientific modeling and systems thinking (SMST) course elements – we summed scores for the nine items in Table 2.2. This composite SMST score, with a range of 0-9, provides an overall measure of reported opportunities for students to engage in scientific modeling and systems thinking in undergraduate geoscience courses. To address reliability and validity of the composite score, or scale, we conducted principal component and Monte Carlo simulations which confirmed that the nine items represented a single factor. Reliability analyses show this scale to have moderate to high internal consistency (Cronbach's $\alpha = 0.68$). As such, the nine items are treated as a single reliable factor for composite SMST score in the analyses that follow. Overall, survey respondents reported a mean of 3.61 SMST course elements in their classes (SD = 2.22). Nearly 50% of respondents reported three or fewer course elements supporting scientific modeling and systems thinking, while only 10% reported seven or more. A frequency distribution for respondents' composite SMST course elements is shown in Figure 2.1.

Figure 2.1. *Frequencies of composite score for reported scientific modeling and systems thinking course elements.*



Reported Scientific Modeling and Systems Thinking Course Elements

In research question #2, we asked, "*what instructor- and course-level factors help predict and explain the extent to which geoscience instructors report engaging students in scientific modeling and systems thinking?*". In the sections that follow, we describe instructor- and course-level variables for which statistically-significant relationships were observed in the 2016 survey.

Course components and SMST

Respondents were asked whether they had made changes to the *content* and *teaching methods* in their courses within the past two years. For those who reported making such changes to either *content* and/or *teaching methods*, they then responded 'yes' or 'no' to a set of 10 additional items describing types of changes they might have made to course content and teaching methods. Findings from analysis of these survey items suggest that changes made to the *content* and *teaching methods* in geoscience courses, as well as the extent of those changes, were positively associated to the opportunities afforded students to engage in SMST in these courses. A higher number of respondents reported making changes to *course content* and *teaching methods* than those who did not, meaning a majority of respondents indicated changing aspects of their courses in the recent past. As shown in Table 2.3, those instructors who reported making more changes to *course content* also tended to make more changes to their *teaching methods*. Additionally, for those who reported making these changes, the number of changes made was positively correlated to the use of SMST course elements, for both *course content* and *teaching methods*. Overall, the more instructors were actively modifying the content taught in their courses, as well as their approaches to teaching it, the more SMST opportunities they reported for students in their courses, as shown in Table 2.4. Respondents were asked to identify whether their undergraduate course was an introductory course for students majoring in a geoscience degree program or introductory course for a broader population of students. Those who completed the survey in respect to an undergraduate course they taught for geoscience majors reported including more SMST elements in their courses than those teaching introductory courses for non-majors, as shown in Table 2.5.

Table 2.3

Correlations between Changes to Course Content, Changes to Teaching Methods, and SMST

Variables	1	2	3
1. Changes to course content	–		
2. Changes to teaching methods	.45***	–	
3. SMST	.36***	.21***	–

*$p < .05$. **$p < .01$. ***$p < .001$.

Table 2.4

Results of T-tests and Descriptive Statistics for SMST by Changes to Course Content and Teaching Methods

Outcome	Group						95% CI for Mean Difference			
	Changes			No Changes						
	M	SD	n	M	SD	n		t	df	d
SMST (course content)	3.75	2.22	1585	3.13	2.14	432	-.848, -.379	-5.13*	2015	0.28
SMST (teaching methods)	3.78	2.21	1128	3.42	2.21	885	-.549, -.160	-3.58*	2011	0.16

* p < .001.

Table 2.5

Results of T-tests and Descriptive Statistics for SMST by Course Audience (Geoscience Majors or Non-Majors)

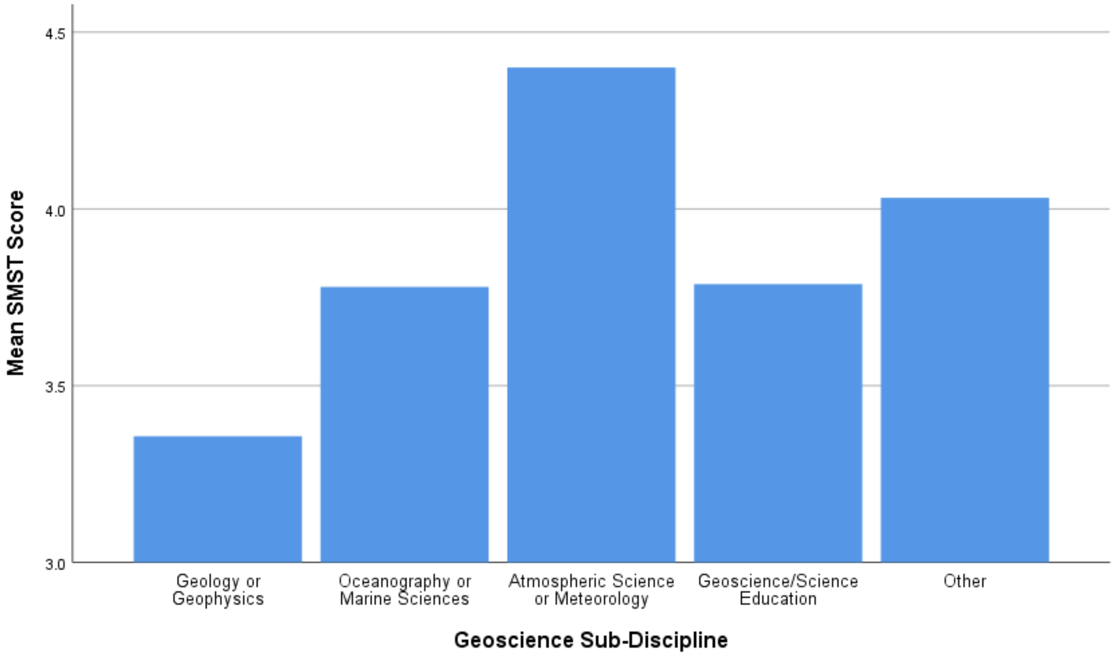
Outcome	Group						95% CI for Mean Difference			
	Majors			Non-Majors						
	M	SD	n	M	SD	n		t	df	d
SMST	3.73	2.25	1024	3.5	2.2	1032	-.427, -.043	-2.4*	2054	0.1

* p < .001.

Disciplinary profile and SMST

In the survey, respondents were asked to characterize their geoscience subdisciplinary orientation into one of the following categories: *(1) Geology or Geophysics (2) Oceanography or Marine Sciences (3) Atmospheric Science or Meteorology (4) Geoscience Education/Science Education (5) Other (please specify)*. For the *Other* category, respondents could include a brief description of their disciplinary focus within the geosciences. Respondents who selected the *Other* category identified primarily as environmental science, hydrology and hydrogeology, geography, soil science, and geochemistry faculty. Overall, findings suggest respondents from the atmospheric sciences, meteorology, and other self-classified categories (e.g., environmental science, hydrology, etc.) reported engaging students in more SMST course elements than did instructors from geology, oceanography, and geoscience education, , $F(4, 2050) = 13.5$, $p = .009$. Mean SMST scores by subdiscipline are shown in Figure 2.2. Post hoc comparisons indicated that the mean score for *Atmospheric Science or Meteorology* had the highest reported number of SMST course elements and was significantly different than the *Geology or Geophysics* category, which had the fewest number of SMST course elements. The mean score for *Other, please specify* was the second highest and was also significantly different than the *Geology or Geophysics* category. The *Oceanography or Marine Sciences* and *Geoscience Education/Science Education* did not significantly differ from the each other or the other categories. A student in a course taught by an instructor from atmospheric science, meteorology, environmental science, or hydrology would be significantly more likely to experience SMST course components than a student in a geology/geophysics course.

Figure 2.2. *Mean scientific modeling and systems thinking course elements reported by instructors from geoscience subdisciplines.*



Faculty teaching profile and SMST

A set of analyses were conducted on survey items and composite variables focused on respondents' overall engagement in activities associated with the improvement of undergraduate instruction. In general, respondents who reported a higher level of engagement in undergraduate geoscience teaching and instructional innovation generally reported more opportunities for students to engage in SMST practices in their courses. These findings suggest that instructors with significant levels of engagement in professional development experiences focused on undergraduate geoscience teaching report more SMST opportunities for students in their courses than do other faculty. For example, respondents were asked two questions about the number of a) geoscience teaching presentations and b) workshops they had attended in the past two years (0) *None* (1) *1 or 2* (2) *3 or 4* (3) *5 or 6* (4) *7 or 8* (5) *9 or 10* (6) *11 or more*.

Respondents who reported attending presentations, *F*(6, 2003) = 4.09, *p* < .001, and workshops, *F*(5, 1996) = 4.77, *p* < .001, on geoscience teaching methods and/or student learning at a professional conference in the past two years also reported incorporating more SMST elements into their courses than those respondents who had not attended presentations on geoscience teaching topics (see Table 2.6). For those respondents who reported attending presentations and/or workshops, there is evidence that attending more was associated with higher reported SMST than only attending a few. Post hoc comparisons indicated that those instructors who attended nine (9) or more *presentations* on geoscience teaching reported higher implementation of SMST course elements than those who had attended only one or two teaching presentations. Similarly, they show that those respondents who attended nine (9) or more *workshops* on geoscience teaching reported higher implementation of SMST course elements than those who had attended only one or two teaching workshops.

Table 2.6
Results of T-tests and Descriptive Statistics for SMST by Attendance at Presentations of Geoscience Teaching

Outcome	Presentations on Geoscience Teaching						95% CI for Mean Difference			
	Attended			Did Not Attend						
	M	SD	n	M	SD	n		t	df	d
SMST (Presentations)	4.12	2.21	471	3.48	2.20	1525	.409, .863	-5.49*	1994	0.30
SMST (Workshops)	4.10	2.20	589	3.43	2.18	1420	.363, .932	5.12*	2009	0.28

* p < .001.

Finally, respondents were asked how strongly they affiliate with a community of geoscience educators with shared goals, philosophies, and values for geoscience education; (1) *Not at all* (2) *To a little extent* (3) *To some extent* (4) *To a great extent*. Findings suggest that those geoscience faculty members who identify with a community of geoscience educators to at least a moderate degree report more SMST course elements than those who do not, $F(3, 1996) = 13.2$, $p < .001$. Post hoc comparisons indicated that respondents who identified with a community of geoscience educators *to a great extent* reported more SMST course elements than did respondents who reported identifying with a community of geoscience educators *to some extent*, *to a little extent*, or *not at all*. Respondents who reported identifying with a community of geoscience educators *to some extent* also reported more SMST course elements than did those reporting the lowest two categories. No statistically-significant difference was observed between the two groups that reported identifying with a community of geoscience educators to the least extent. The stronger an instructor's sense of identity as part of the geoscience education community, the more SMST course components they report in their undergraduate geoscience courses.

In Manduca and colleagues' (2017) paper analyzing results of previous administrations of the survey, the following items from Table 2.3 were used to identify subgroups of faculty based upon factor analyses:

1. Number of meetings presented scientific research within the past two years
2. Number of articles about research published in the past two years
3. Frequency of conversation with colleagues about course content over the past two years

4. Number of talks on teaching methods, other topics related to science education, or geoscience education attended in the past two years at professional meetings, on campus, or at other venues
5. Number of workshops related to improving teaching attended in the past two years
6. Number of presentations of research on teaching methods or student learning at meetings within the past two years
7. Number of articles published about educational topics within the past two years

They identified three groups of respondents who differed in their teaching and research roles, participation in teaching-related professional development, and self-described instructional identities. These faculty groups (Manduca et al., 2017, pg. 3) were:

(1) Education-focused faculty who reported significant activity related to improving teaching (their own and/or others)

(2) Geoscience research–focused faculty who reported significant geoscience research activity

(3) Teaching faculty who reported lower levels of activity in both geoscience research and activity related to improving teaching

Consistent with Manduca and colleagues (2017) previous study, education-focused faculty made up the smallest percentage (18%) of respondents, while teaching faculty were the largest group (43%), with geoscience-research focused faculty comprising 39% of respondents in the 2016 survey.

Findings show that reported SMST course elements vary by faculty group, $F(6, 2009) = 16.5$, $p < .001$. Post hoc comparisons indicated that teaching faculty reported fewer SMST course elements than both education-focused and geoscience research-focused faculty. Though education-focused faculty reported slightly more SMST course elements than did geoscience research-focused faculty, this observed difference was not statistically-significant. These results indicate that both geoscience education- and geoscience research-focused faculty reported incorporating equivalent SMST opportunities for students in their courses, and both groups do so more than teaching faculty.

Instructional Profiles and SMST

A set of analyses were also conducted on survey items and composite variables focused on respondents' reported teaching practices. In general, respondents who reported greater use of research-based STEM instructional practices (i.e., active learning) as opposed to more traditional teaching methods generally reported more opportunities for students to engage in SMST practices in their courses.

Respondents answered a series of items regarding the extent to which they used particular forms of instruction in their classes as *(1) Never (2) Once (3) Several times (4) Weekly (5) Every class*. Overall, findings suggest that those geoscience instructors who report using more research-based, student-centered instructional approaches more frequently also report more SMST course elements in their courses. Post hoc comparisons indicated that respondents using lecture in *every class period* reported fewer SMST course elements than those who reported *never* using lecture, as well as those who reported using lecture *weekly* or several times, *F*(4, 1936) = 7.16, *p* < .001. Similarly, post hoc comparisons indicated that respondents who report *never* using small group discussion also report fewer SMST course elements than those who use this instructional strategy at all, including only occasionally, *F*(4, 1925) = 19.7, *p* < .001. Respondents who report using small group interactions *weekly* reported the most SMST course elements in their course. Instructors who reported spending a greater percentage of class time on student activities, questions, and discussion (*r* = 0.132, n = 2033, *p* < .001) also reported incorporating more SMST course elements in their courses. Though a modest correlation, it does contribute to cumulative evidence from the survey data suggesting a positive relationship between student-centered instruction and SMST opportunities for students in geoscience courses.

In Manduca and colleagues' (2017) paper analyzing results of previous administrations of the survey, the following items from Table 2.3 were used to identify subgroups of faculty based upon factor analyses:

1. Frequency of use of traditional lecture
2. Frequency of use of demonstration
3. Frequency of use of individual student questions
4. Frequency of use of asking whole-class questions
5. Frequency of use of small-group discussion
6. Frequency of use of whole-class discussion
7. Frequency of use of in-class assignments

They identified three groups of respondents who differed in their teaching styles. These faculty groups (Manduca et al., 2017, pg. 3) were:

(1) Active learning: faculty reporting frequent use of small group discussion, whole-class discussion, or in-class exercises with or without the use of any other methods

(2) Active lecture: faculty reporting frequent use of demonstrations and/or posing questions with or without traditional lecture

(3) Traditional lecture: faculty reporting infrequent use of strategies other than traditional lecture

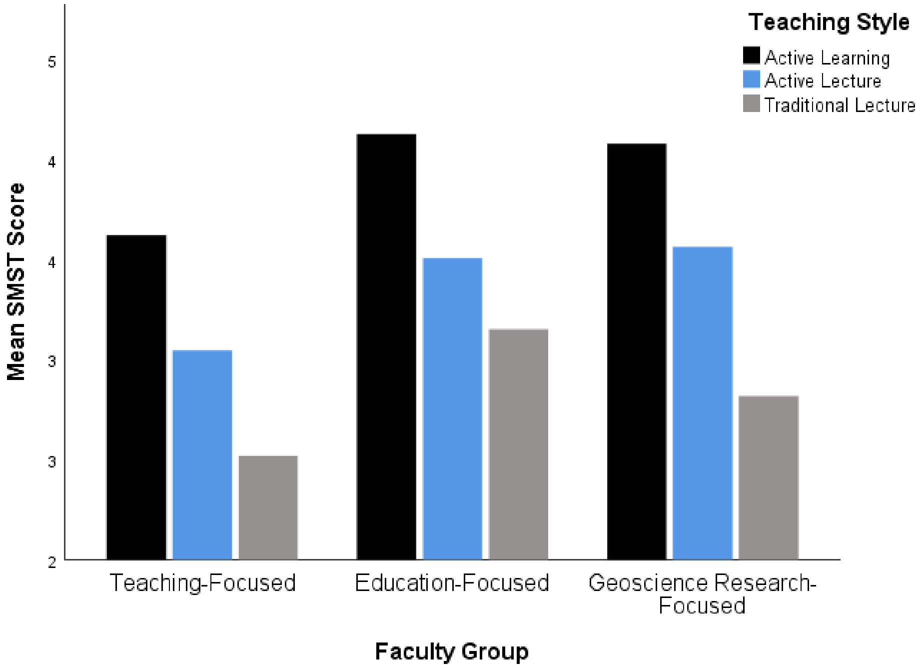
Consistent with Manduca and colleagues (2017) previous study, faculty classified as active learning made up the largest percentage (60%) of respondents while those classified as traditional lecture were the smallest (11%). 29% of respondents were classified as active lecture in the 2016 survey.

Findings show that reported SMST course elements vary by faculty teaching profiles, $F(2, 1962) = 38.4$, $p < .001$. Post hoc comparisons indicated that geoscience faculty characterized as active learning reported more SMST course elements than both faculty identified as active lecture and traditional lecture. Additionally, faculty identified as active lecture reported more SMST course elements than did those identified as traditional lecture. Overall, these findings suggest that geoscience instructors who were utilizing more active learning strategies also reported providing students more opportunities to engage in SMST and that these opportunities increased in conjunction with the respondents' reported use of student-centered instructional strategies.

A Predictive Model for Reported Scientific Modeling and Systems Thinking Course Elements

The results presented thus far illustrate relational trends in the 2016 survey data for both survey respondents and the courses they teach in respect to reported SMST course elements. These results suggest that both education- and research-focused faculty using active learning strategies report including the greatest number of SMST course elements in their courses. There are few observed differences between these two groups except for those who fall into the traditional lecture category, for which education-focused faculty report more SMST course elements that geoscience research-focused faculty. In contrast, teaching faculty of all types of instructional profiles report including the fewest SMST course elements. These results are summarized in Figure 2.3.

Figure 2.3. *Composite mean SMST score for teaching style categorized by faculty types.*



Given these statistically-significant associations, we sought to develop a predictive model for SMST course elements in undergraduate geoscience courses. A standard multiple regression analysis was conducted to evaluate how well instructor- and course-based variables predicted respondents' reported emphasis on SMST course elements in undergraduate geoscience courses. Co-variates includes independent variables discussed in previous sections as associated with the outcome variable of interest (SMST course elements), including respondents' subdiscipline, and number of changes to both course content and teaching methods, and those that comprised categories for both faculty type and teaching style identified in Manduca and colleagues' (2017) previous study. Of the 17 predictor variables included in the regression model, 10 had a significant ($p < .01$) zero-order correlation with SMST and had significant ($p < .05$) partial effects in the full model. A zero-order correlation means there were no control variables among SMST and the 17 predictor variables. Partial effects are the statistical result of holding one variable constant to determine if it is a potential cause of correlation between other components. The estimated intercept for SMST course elements (β = 1.252) indicates the expected number of SMST course elements for a survey respondent with average scores on these 17 predictor variables. The model was able to account for 17% of the variance in reported SMST course elements, $F(9, 2010) = 21.12$, $p = .007$, $R^2 = .17$, 95% CI [.69, 2.3]. The results of the regression are presented in Table 2.7 and Appendix 2.B.

Table 2.7
Results of Multiple Linear Regression for Predictors of Reported SMST Course Elements in Undergraduate Geoscience Courses (N = 2056)

Variable	Description	*β*	Std. Error	*t*	*p*
(Constant)	SMST course elements	1.252	.348	**3.601**	.000
S16_1	Geoscience subdiscipline of faculty respondent	.171	.031	**5.558**	.000
S16_25_COMP	Number of changes made to course content in past 2 years	.258	.026	**10.104**	.000
S16_27_COMP	Number of changes made to teaching methods in past 2 years	.063	.027	**2.343**	.019
PRESENTRESEARCHR	Number of meetings presented scientific research within the past two years	.049	.030	1.670	.095
NUMPUBLISHR	Number of articles about research published in the past two years	.069	.025	**2.701**	.007
TALKCONTENT	Frequency of conversation with colleagues about course content over the past two years	.200	.056	**3.546**	.000
ATTENDTEACHTALKSR_2	Number of talks on teaching methods, other topics related to science education, or geoscience education attended in the past two years at professional meetings, on campus, or at other venues	.027	.034	.805	.421
ATTENDWRKSHPR	Number of workshops related to improving teaching attended in the past two years	.010	.041	.254	.800

PRESENTTEACH	Number of presentations of research on teaching methods or student learning at meetings within the past two years	.372	.126	**2.950**	.003
NUMARTICLES	Number of articles published about educational topics within the past two years	-.020	.083	-.245	.807
TRADLECb	Frequency of use of traditional lecture	-.088	.120	-.726	.468
LECDEMOb	Frequency of use of demonstration	.125	.102	1.224	.221
INDIVQUESTb	Frequency of use of individual student questions	.252	.100	**2.519**	.012
ALLQUESTb	Frequency of use of asking whole-class questions	-.119	.111	-1.070	.285
SMALLGRPDISb	Frequency of use of small-group discussion	.237	.121	**1.949**	.051
WHOLEGRPDISb	Frequency of use of whole-class discussion	.441	.110	**3.993**	.000
INCLASSb	Frequency of use of in-class assignments	.021	.109	.194	.846

The model illustrates the predictive power of variables already identified in these analyses as associated with reported SMST course elements. Variables that were most strongly predictive of SMST course elements revolve directly around reporting and implementation of classroom instruction. These include respondents’ presentations of research on geoscience teaching and learning (10%), as well as reported instructional practices, such as student questions (8%) and the use of small-group (10%) and whole-class (9%) discussion. Collectively, one-unit increases to each of these variables resulted a 1.23 unit increase in reported SMST scores, highlighting the particular importance of these variables underlying both faculty type and instructional style profiles. Other variables, such as geoscience subdiscipline (2.5%), number of changes to course content (2%) and teaching (2%), and frequencies of conversations with colleagues about teaching (4.5%), were also shown to be statistically-significant predictors of reported SMST course elements, but to a lesser degree. However, not all variables that comprised the faculty type and instructional style profiles were shown to predict reported SMST course elements. Presentations of research at conferences, attendance at teaching presentations or workshops, nor publishing articles on teaching methods, were not observed to predict reported SMST course elements. More teacher-centered instructional approaches, such as lecture, demonstration, and instructor questioning, were also not observed to predict reported SMST course elements. Overall, results from this model provide a profile of geoscience faculty using research-based teaching methods in their courses and actively disseminating their work to colleagues as most predictive of emphasizing SMST in their undergraduate courses.

Summary of Results

Overall, results illustrate average levels of SMST course elements reported by geoscience faculty members teaching undergraduate geoscience courses, as well as which are most commonly emphasized and by whom. Respondents who are actively revising the content and teaching in their courses, attending workshops and presentations on effective instruction, reading geoscience education research, and using more reform-based instructional strategies in their classrooms generally report a stronger emphasis on SMST practices in their courses. These trends are slightly stronger in courses for geoscience majors and are consistent for both education- and research-focused faculty members, particularly in geoscience subdisciplines of atmospheric science, meteorology, environmental sciences, and hydrology. Collectively, these factors help account for less than 20% of the variation expected in reported SMST practices emphasized by geoscience faculty teaching undergraduate geoscience courses, suggesting that one or more other factors are responsible for the remaining differences in SMST in undergraduate geoscience courses.

DISCUSSION

Introductory STEM courses are often the last opportunity for K-16 students to learn universally beneficial skills, such as engaging in evidence-based scientific reasoning and learning to think scientifically (Somerville & Bishop, 1997; Tewksbury et al., 2013), in formal classroom settings. Consequently, there has been a growing recognition of the need for STEM faculty to not only conduct research in their disciplines, but also deliver high quality education (NRC, 2012), particularly in the geosciences (Somerville & Bishop, 1997). To address this need, more geoscience faculty than ever before are taking advantage of professional development opportunities (Manduca et al., 2017). All types of faculty - education-, research-, and teaching-focused - are increasingly attending teaching seminars and workshops to enhance their instruction (Manduca et al., 2017). Encouragingly, many undergraduate students do experience some SMST (Forbes et al., 2018; McNeal, Miller, & Herbert, 2008; Gunn, Mohtar, & Engel, 2002; Williams, Lansey, & Washburne, 2009), but introductory geoscience courses do not tend to incorporate SMST and instead students receive exposure to SMST in other courses (Macdonald, Manduca, Mogk, & Tewksbury, 2005). SMST skills encourage students to think about relationships between interacting components and the ability to demonstrate what those components and interactions look like (Baumfalk et al., in press; Bawden et al., 1984; Danish, et al., 2017; Schwarz et al., 2009; Troy et al., 2015). However, despite these advancements made in faculty preparation and student learning, gaps remain in what we know about effective teaching and learning in undergraduate geoscience courses. More work is needed to identify the highest impact strategies for student learning, how to support faculty to engage in instructional change, and identification of institutional features that foster both (Libarkin & Anderson, 2005; Macdonald, Manduca, Mogk, & Tewksbury, 2005, Zigic & Lemckert, 2007). Results from this study provide important insights into the current use and emphasis on one set of related learning processes and outcomes – scientific modeling and systems thinking -in post-secondary geoscience courses that can optimally meet the needs of the STEM workforce and cultivate scientifically literate citizens.

First, overall, study results provide insight into SMST in undergraduate geoscience courses. The most frequently used SMST elements are the discussions of a change with multiple effects in the system, the complexity of scale and interactions and the description of a system in terms of parts and relationships. These three elements are found in over half of the courses taught by responding instructors to the survey in this study. This implies that over half of the students in these courses are being afforded opportunities to increase their familiarity with the interconnectedness of systems and different ways changes are observed in varying system components. Alternately, the practices of making systems visible through causal maps, system exploration using computer-based models, and the building of predictive models are the least common in courses. Student learning is enhanced with the inclusion of multiple types and opportunities for modeling and systems thinking (Assaraf & Orion, 2005; Baumfalk et al., in press; Arnold & Wade, 2015; Hmelo-Silver, et al., 2017; Scherer, Holder, & Herbert, 2017; Williams, Lansey, & Washburne, 2009). An emphasis on SMST in geoscience courses is a critical way to cultivate a scientifically-literate populous (Mosher et al., 2014) and respond to calls from government agencies and policy documents (U.S. Global Change Research Program, 2009; U.S. Department of Energy, 2012; Earth Science Literacy Initiative, 2010). However, while many argue for the importance of SMST in undergraduate STEM education, including the geosciences, and disciplinary standards for geoscience teaching and learning exist, there is less guidance on targets for the extent to which SMST should specifically be emphasized in particular disciplinary contexts. Without clearly articulated benchmarks for STEM practices, including SMST and particularly at the undergraduate level, it is difficult for both educators and researchers to make judgements about the implementation of SMST in undergraduate geoscience courses. As such, more work is needed to provide an empirical basis for both defining objective outcomes and measuring progress towards SMST-related goals for undergraduate teaching and learning.

Second, differences were observed in reported SMST practices between instructors in the geoscience sub-disciplines. Faculty associated with meteorology, climate science, environmental science, and ‘other’ sub-disciplines reported the highest rates of SMST practices, while geology instructors reported the fewest SMST practices. One interpretation of this finding is that meteorology and climate science lend themselves more readily to SMST than other sub-disciplines in the geosciences. Modeling in these courses is critical because the phenomena under study may be difficult to observe in real life, necessitating modeling so that the unseen can become seen. Another possible explanation is the temporal foci of these disciplines. While traditional geology is largely concerned with views into the Earth’s past, much of contemporary meteorology, climate science, and environmental science is concerned with evidence-based predictions of the future, which involves the use of big data and complex models. As such, faculty in various sub-disciplines may vary in the ways they are prepared to teach and in the opportunities afforded to tenure-track faculty who are new to supporting student learning about SMST (Libarkin, 2006). However, these differences in the particulars of SMST inclusion and practice are not necessarily negative; the added diversity might be beneficial for student learning. More research would help illuminate the ways in which particular SMST practices are implemented in undergraduate geoscience courses spanning these sub-disciplines.

Third, results illustrate how SMST practices are being emphasized to varying degrees by different groups of geoscience faculty. Education- and research-focused faculty report both implementing more SMST practices than teaching-focused faculty. Conventional wisdom might suggest that these two groups would not overlap in their teaching strategies. Surprisingly, there is a fair amount of relatability between them, with research faculty reporting using SMST practices at a similar level as the education-focused faculty within the geosciences. Despite roadblocks such as lack of knowledge of professional development opportunities, the number of faculty in the U.S. incorporating SMST is on the rise (Mosher et al., 2014). Even though research and education faculty appear distinct, they likely share important similarities. For example, these two groups are likely teaching similar populations of undergraduate students and teaching similar types and quantities of courses (Manduca et al., 2017). Even though some groups within the geosciences are using SMST and are providing students similar types of student-centered experiences, this is not the case across all instructors. Not all types of geoscience faculty reported employing SMST practices to the same extent. Disaggregating faculty by groups - teaching faculty, research focused, and education-focused - revealed the clear trend that the teaching-focused instructors are emphasizing SMST practices the least. Teaching focused instructors may avoid SMST because they may teach too many courses, have little or no access to resources to help them incorporate SMST practices, and their courses may be more challenging from an instructional standpoint, so they use lecture most often as supported by the results.

Fourth, in addition to faculty type, instructional profiles of respondents also illuminate differences in reported SMST practices in geoscience classrooms. The instructors reporting the use of more active learning strategies in their courses also report more SMST practices. Lecture is still used in a number of classes and is an important teaching strategy. However, lecture does have drawbacks, including limited student involvement and opportunities for critical thinking (Macdonald, Manduca, Mogk, & Tewksbury, 2005). Active learning is integral to incorporate in geoscience classrooms, often taking the form of SMST, consistent with broader calls for undergraduate education in STEM (NRC, 2002). SMST practices encompass active learning components including group discussions, evaluation of understanding, and actively engage the student in doing the associated activities. The educators reporting increased active learning in their classroom are incorporating best –practice strategies. Based upon study results, we would also observe that courses with less active learning would necessarily exhibit less SMST, resultantly. As recently as the 2012 implementation of the National Geoscience Faculty Survey, 49% of instructors were implementing lecture for 80% of course time (Manduca et al., 2017). The accomplishment of converting time from lecture to SMST and other student-centered teaching strategies is a worthwhile investment in terms of student participation and learning (McNeal, Miller, & Herbert, 2008; Mosher, et al., 2014). Making the shift from lecture to student-centered instruction is important to meeting the goal of high quality teaching and meaningful learning (Manduca, et al., 2017), including SMST.

Finally, results from the regression model highlight the predictive capabilities of these variables. While variables measured in the survey and discussed in this paper have the ability to predict nearly 20% of the overall variability in reported SMST practices in undergraduate geoscience classrooms, this leaves over 80% of the variability unexplained. The remaining variability may be related to SMST through factors that were not captured by the survey. Variables such as perceived student benefits, the difficulty of grading SMST assignments, priorities of individual institutions, and available instructional technology and support could all affect the implementation of SMST in undergraduate geoscience courses. Instructors who do not understand the benefits of SMST to student learning might not include these practices as often in their courses. SMST assignments can be lengthy and difficult to grade because of the individualized interpretations and solutions presented by students. The amount of time it takes to grade such assessments in large enrollment courses may be cost-prohibitive. Support of interdisciplinary course components may not be available within all disciplines. Instructors that do not feel supported in these efforts may not feel compelled to include content outside of their area of expertise. Many of these variables could be impacted and influenced by other processes and components. More research is needed to explore other factors that may predict how and to what extend SMST practices are implemented in undergraduate geoscience courses.

LIMITATIONS

Limitations inherent to this study may affect the unexplained variability found in the type of SMST practices reported by instructors in geoscience classrooms. For example, the GER survey is self-report. There are no additional interviews or other qualitative data to clarify responses or provide examples. As a result, conclusions drawn from analysis of survey data are uncorroborated. Correspondingly, the response rate for the survey was low. Out of 10, 910 individuals contacted for survey completion, only 2,615 responses meeting required criteria for inclusion were returned. Criteria for inclusion included current instructor and submission of a valid email address. The response rate of 27.3% indicates that the SMST practices of nearly 2/3 of geoscience instructors are not included in the data. Another limitation unrelated to the survey is the reality that there may be more than nine elements of SMST. This survey captured data on the nine items that are known to contribute to SMST, but there could be others, which are missing. This would result in an incomplete picture of SMST practices in post-secondary geoscience classrooms.

IMPLICATIONS AND CONCLUSION

The emphasis on SMST practices in undergraduate geoscience courses is important to the overarching goal of enhancing undergraduate STEM teaching and learning. Opportunities for SMST are needed to support undergraduate students' learning about Earth systems. However, this type of change does not happen in a vacuum. Sustained support from administration and constant evaluation of teaching efforts by individual faculty are critical to the incorporation of more SMST practices within the geosciences (Mosher et al., 2014). When the fewest opportunities are afforded in the most common courses, such as introductory geology, then this is a point of concern. This constitutes both the largest group of students and instructors and the lowest frequency of reported SMST practices. We must continue to identify and advocate ways to incorporate SMST into these high enrollment introductory courses, which reach many students and arguably have the greatest impact on fostering scientific literacy.

Financial and pedagogical support for teaching, research focused, and education focused faculty, as well as graduate students and 2-year college faculty, is needed to enable the systemic changes needed in SMST instruction (Mosher, et al., 2014). Different approaches for different types of instructors is appropriate given the resources available to them. Not only are differences and similarities between instructor type important to consider; differences between geoscience sub-disciplines also factor into the implementation of SMST practices. SMST occurs less in traditional, instructor centered, lecture style classrooms, than in student-centered classrooms in which active learning strategies are employed. As such, more attention is needed to developing strategies to address SMST teaching and learning practices in these types of settings. Providing opportunities to faculty to learn course specific SMST strategies would be beneficial for students and instructors.

There are also relationships between variables reflecting individual faculty involvement in pedagogy focused professional development. As shown in the study findings, the more involved an instructor is in an array of professional development activities, the more SMST they report. This points to the possibility that the more involvement in and the more discourse about teaching an instructor has, the more likely SMST will be incorporated into their classes. Different types of faculty, both in terms of content area and faculty type, need to work together to enhance student learning because each group brings a different skillset to the classroom (Kastens et al., 2009; NRC, 2012,). Future research is needed, including observational studies, to validate and examine the relationship between teaching focused professional development and SMST incorporation. Regardless of the direct cause, it is beneficial for faculty to participate in these types of pedagogical activities (Manduca, et al., 2017; National Research Council, 2012). Active participation in the overarching geoscience education discussion, science-based teaching methods, and SMST, a leading component of geoscience education, will help hasten the pace of necessary course changes including content and teaching approaches.

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APPENDIX 2.A

Demographics

Respondent Institution Types	N	%
Research/Doctoral	1466	59.5%
Master's	440	17.9%
Baccalaureate	232	9.4%
Associate's	316	12.8%
Special Focus/Other	8	0.3%
Total (N)	2462	100.0%
Missing	153	

Response Rate

Institution Type	Respondents	Total sampled	Response rate
Research and/or Doctoral	1466	6512	22.5%
Master's, Baccalaureate, Associate's, or other institution types	996	3566	27.9%

*Level of Education**	N	%
Master's	284	11%
Ph.D.	2285	89%

Years in Position

Years	N	%
0-5	436	17.1%
6-10	444	17.4%
11-15	398	15.6%
16-20	374	14.6%
21-25	283	11.1%
26-30	245	9.6%
31-35	178	7%
36-40	123	4.9%
41-45	66	2.6%

Disciplinary Focus	N	%
Oceanography	241	9.3%
Atmospheric Science	247	9.5%
Geology/Other	2,112	81.2%

Total	2,600	100.0%

APPENDIX 2.B

Correlation Matrix for Multiple Linear Regression Model (N = 2056)

	Mean	SD	20_COMP	S16_1	S16_25_COMP	S16_27_COMP	PRESENTRESEARCHR	NUMPUBLISHR	TALKCONTENT	ATTENDTEACHTALKSR_2	ATTENDWRKSHPR	PRESENTTEACH	NUMARTICLES	TRADLECb	LECDEMOb	INDIVQUESTb	ALLQUESTb	SMALLGRPDISb	WHOLEGRPDISb
20_COMP	3.61	2.222	1.000		***														
S16_1	2.03	1.499	.130*	1.000	***														
S16_25_COMP	4.3558	1.89711	.277	.037	1.000***														
S16_27_COMP	4.7128	1.82064	.158	.005	.306***	1.000													
PRESENTRESEARCHR	2.84	2.128	.113	.026	.047*	-.018	1.000												
NUMPUBLISHR	2.81	2.544	.093	.021	.030	-.048*	.676***	1.000											
TALKCONTENT	2.58	.843	.133	-.032	.138	.083***	-.044*	-.083***	1.000										
ATTENDTEACHTALKSR_2	2.01	1.773	.101	-.020	.086**	.113***	-.039*	-.2168***	.241***	1.000									
ATTENDWRKSHPR	1.25	1.403	.095***	.086	.116***	.154***	-.125***	-.240***	.175***	.558***	1.000								
PRESENTTEACH	1.76	.418	-.120	-.032	-.068**	-.042***	-.039*	.114***	-.117***	-.408***	-.273***	1.000							
NUMARTICLES	.18	.597	.067***	.084	.059*	.032**	.068**	.027	.060***	.236**	.203***	-.359***	1.000						
TRADLECb	.77	.405	-.069	-.026	-.053*	-.125	.010	.037*	-.089***	-.162***	-.168***	.141	-.119***	1.000					
LECDEMOb	.40	.466	.060	-.035	.056**	.079	-.036	-.050*	.066***	.043*	.061**	-.041	-.011	.089***	1.000				
INDIVQUESTb	.60	.477	.090	-.015	.014	.083*	.026	.019	.047*	.043*	.058**	-.024**	-.022	.142***	.188***	1.000			
ALLQUESTb	.26	.424	-.002	-.023	.002	-.014	-.004	-.015	.038*	.102***	.128***	-.063***	.063**	.037*	.041*	.065**	1.000		
SMALLGRPDISb	.34	.458	.141	.021	.063**	.159***	.009	-.044*	.155***	.237***	.234***	-.143***	.088***	-.208***	.027	.146***	.200***	1.000	
WHOLEGRPDISb	.32	.454	.169	.034	.093***	.146***	.023	.001	.080***	.116***	.109***	-.083***	.038*	-.148***	.082***	.138***	.008	.367***	1.000

INCLASSb	.43	.487	.099	.028	.048**	.165***	-.038*	-.088***	.090***	.212***	.214***	-.150***	.073***	-.184***	.172***	.100***	.100***	.446***	.284***

* p < 0.05; **, p < 0.01; ***, p < 0.001.

CHAPTER 3

UNDERGRADUATE EDUCATION ABOUT WATER AND CLIMATE CHANGE: STUDENTS' USE OF A WATER BALANCE MODEL

Global climate change is a critical issue affecting both Earth's climate and water as inextricably paired systems. One of these linkages is found in dwindling groundwater resources. Worldwide, over half of the largest aquifers are over-withdrawn; these areas often overlap with locations of significant surface water stress (United Nations Educational, Scientific and Cultural Organization [UNESCO], 2016). It has been hypothesized that for an increase in global warming of one degree, water availability will be decreased by 20% for nearly 38 million people (UNESCO, 2016). Climate change will exacerbate the unpredictability of weather, which heightens the unreliability of seasonal precipitation for the recharge of freshwater resources (Food and Agriculture Organization of the United Nations & World Water Council, 2015). The complexities of global climate change underscore the importance of fostering individuals' reasoning about water resources and climate, through formal K-16 classroom settings.

Teaching and Learning about Climate and Water

Climate change and all of its impacts require students to possess accurate conceptions of both Earth's climate and water systems. Students need opportunities to develop climate literacy (Climate and Energy Awareness Network [CLEAN], 2019), or understanding and abilities to reason and make informed decisions about weather, climate, and its functions and impacts in relation to their environment. Standards for science teaching and learning foreground Earth's climate, GCC, and water systems as core concepts spanning K-16 learning environments (CLEAN, 2019; USGS et al., 2009), including at the undergraduate level. However, the geosciences are progressively de-emphasized across the K-12 science curriculum (Banilower et al., 2018). Water and climate are topics with which students may engage in a distributed manner in many different course contexts. Water education is critical because of expected changing water availability and profound weather changes in the coming years (Seibert, Uhlenbrook, & Wagener, 2013). At the undergraduate level, most opportunities for students to encounter curriculum surrounding climate change is within the broad discipline of natural resources followed by mathematics and social science (Aubrecht, 2018). This would be adequate if all students at least pursued a minor in one of these fields, however, many students do not take coursework in these content areas during their time in college. Course descriptions feature climate change in as little as 10% of core curriculum courses (general education courses) while students have a 17% chance of enrolling in a minimum of one climate change focused coursed throughout their core curriculum (Hess & Collins, 2018).

Perhaps as a result, undergraduate students possess scientifically inaccurate ideas about water (Halvorson & Westcoat, 2002) and climate (Libarkin et al., 2015), with these alternative understandings persisting into adult, post-educational life (Abbott et al., 2019; Duda et al., 2005). Students specifically struggle with water related concepts such as evaporation and latent heat (Cardak, 2009) and climate related concepts such as the impact of climate change on the ozone layer (Libarkin et al., 2015). These types of inaccurate ideas reflect a rudimentary understanding to which, linear mono-causal thinking contributes. This type of thinking is difficult to overcome because it implies a direct cause and effect relationship for processes that are in reality much more complex

(Raia, 2008). Students need to be able to conceptualize the water cycle, but they must also know how resources and living things interact through various cycles (NGSS Lead States, 2013). In light of the persistent learning gaps, students need more and more effective opportunities to encounter climate change and water curriculum in order to learn to reason about climate and its related components (Abbott et al., 2019).

Scientific Models and Modeling in Undergraduate Education

Models are a tool that instructors can use to help students learn to reason more effectively about climate and water systems. Computer-based models can be used to provide a visual representation of what students would otherwise perceive as invisible, such as climate, its change over time, or groundwater movement. Models, when used in parallel with a suite of other active-learning strategies, can contribute to student learning surrounding climate and water through hypothesis experimentation (Lally & Forbes, 2019) and the ability to visualize system patterns (Carey & Gougis, 2017). Computer based-water models rely on the user to input accurate information in order to receive an output from which they can make a decision. Students must know most or all of the interacting components and how the data presented from a model will affect or be affected by such interactions and components. Models are only useful in decision making if the learner can make use of the graphic output and apply it to a situation with the inclusion of the most recent theories and data as well as current interactions between components. There have been calls for increased implementation of climate and water model use in undergraduate courses, including practices such as science-based teaching strategies and computational modeling (CUAHSI, 2018; Mosher et al., 2014).

Unfortunately, neither climate models nor water models are frequently used in introductory undergraduate coursework (Merwade & Ruddell, 2012; Tasquier et al., 2016), reinforcing a limited emphasis on modeling in undergraduate geoscience courses (Lally et al., 2019).

Regardless of the disciplinary focus of students' investigation, modeling involves a set of core modeling practices including model development, prediction, questioning, explanation, evaluation, revision, and support of ideas (Forbes et al., 2015) and the epistemic dimensions of representation, evidence, and explanation (Lally & Forbes, 2019). Of these modeling practices and epistemic dimensions, model use and evaluation are just two of the skill sets students learn using models in the course. Model use in this context includes the students' participation in modeling habits consisting of using the model to make a hypothesis, determine relationships between variables, and citing the model as evidence to substantiate claims (Lally & Forbes, 2019). Evaluation of a model comprises skills including modification, contrasting, validating the accuracy and precision (Coll et al., 2005; Gouvea & Passmore, 2017) and suitability for a context (Pluta, Chinn, & Duncan, 2011). The ability to evaluate a model contributes to enhanced model-based reasoning (Gobert & Buckley, 2000). Model organization and power can fluctuate from model to model; students require opportunities to interact with different models to practice the skills of use and evaluation in different contexts.

All models, including computer-based models of water systems, are limited in their scale and scope (Habib, Ma, Williams, Sharif, & Hossain, 2012) and range in accuracy and contextual fit (Lally & Forbes, 2019). Therefore, students need opportunities to practice using several different types of models in order to evaluate them successfully (Lally & Forbes, 2019). Yet, more opportunities for simulation modeling, interaction with authentic data, and the application of other active learning opportunities are needed to support hydrologic courses and learning (CUAHSI, 2010; Merwade & Ruddell, 2012; Ruddell & Wagener, 2014). To begin to address this need, we developed and studied the implementation of a computer-based water simulation model in an undergraduate water course.

Supporting Students' Model-Based Learning about the Water Balance: A Case Study

Here, we report on the use of a computer-based water modeling tool developed for an interdisciplinary, introductory-level course, *Water in Society* (Forbes et al., 2018), which serves both STEM and non-STEM majors. After learning to use the model, students completed a decision making task which was justified using model outputs as evidence. In a previous study, we found students' evaluation of the WBM improved from year 1 to year 2 surrounding themes of model complexity, generalizability, and specificity (Lally & Forbes, 2019). Here, we investigate quantitative results surrounding gender, year, and year of a computer-based simulation water model assignment and qualitative findings of student reasoning on the effect of precipitation and potential evapotranspiration on the water table. This work is part of our team's broader research program focused on teaching and learning about water across the K-16 continuum (Forbes et al., 2018; 2015; Lally & Forbes, 2019; Owens et al., under review; Petitt & Forbes, 2019; Sabel et al., 2017).

Course Context

Students were enrolled in an introductory, interdisciplinary, water course, SCIL 109: *Water in Society* at a large Midwestern University. The course, offered every spring beginning in 2017, meets twice as a whole class and once for a one-hour, small-group lab weekly, for a total of 3-credit-hours (Forbes et al., 2018). Contributing to the interdisciplinary nature of the course, three faculty members from different disciplines- agricultural economics, a hydrogeophysicist, and science education, along with two graduate students, were part of the developmental and instructional team for the course. The course incorporates increasing interconnectivity of the FEW-Nexus and projects to support course content spanning multiple weeks (Lally & Forbes, 2019). Integrated within the course are both the human and natural aspects of systems (i.e. socio-hydrologic systems). Students represented a variety of STEM and non-STEM majors due to the course fulfillment of several general education requirements for the University (Table 3.1). Students were evenly distributed between genders and included a large proportion of study-abroad students from Africa and Asia. Instructors, course goals, and assessments were the same in each iteration of the course (Lally & Forbes, 2019).

Table 3.1

Student Demographics from 2017, 2018, 2019

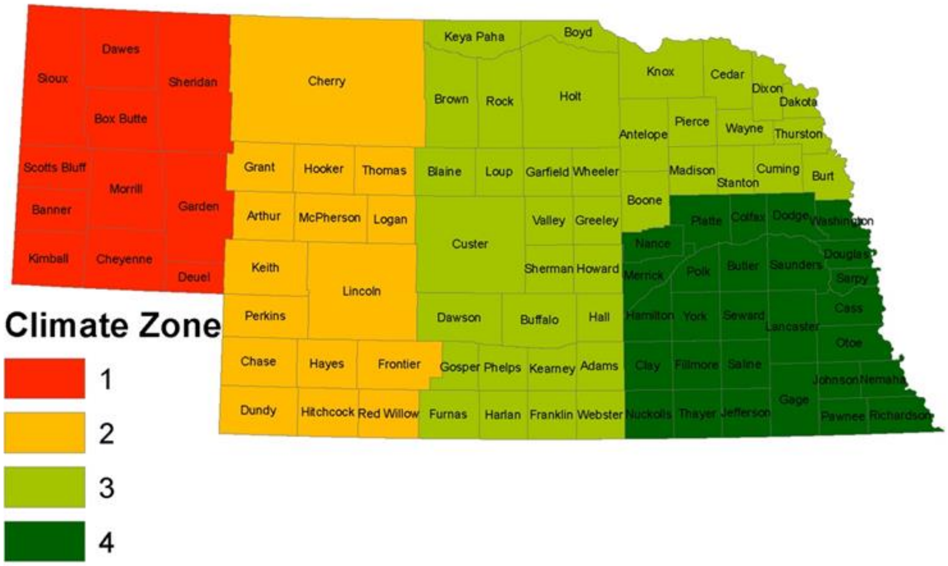
	Female	Male	Freshmen	Sophomore	Junior	Senior/+	STEM Major	Non-STEM Major
2017	15	20	9	10	9	7	26	9
2018	27	21	2	24	13	9	44	4
2019	19	27	5	16	16	9	42	4

Outside of class, students were responsible for learning content through readings, videos, simulations, and worksheets. During class, students practiced and refined their ideas about content through large and small group discussions, small group activities, worksheets, and group decision making. Throughout the course, students created and revised an infographic about a water-related issue, completed summative assignments surrounding two computer-based water models, and explored a regionally relevant sociohydrologic issue through systems thinking as a capstone assessment.

Water Balance Model (WBM)

The Water Balance Model (WBM) is an online modeling tool that allows the student to simulate realistic future scenarios investigating the tradeoffs between land use (i.e. irrigation intensity) and water table decline across four climate zones within the state of Nebraska (Fig 1). Because of the coupled nature of surface and groundwater, this problem is particularly challenging for both policy making as well as developing realistic water balance simulation tools.

Figure 3.1. *Four climate zones for Nebraska grouped by increasing rainfall and decreasing potential evapotranspiration from zone 1 to 4 (1 being the driest).*



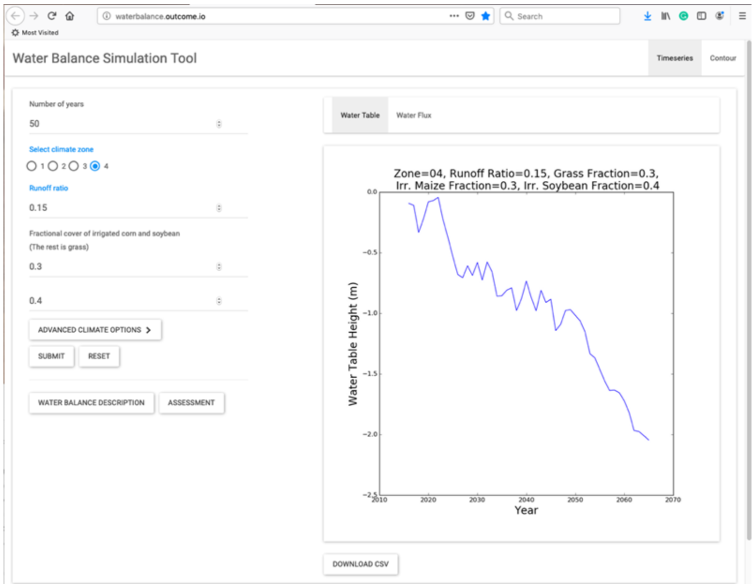
The WBM simulates a 1-dimensional bucket type water balance using:

$$P + I = ET + Q + \frac{\Delta S}{\Delta t} \qquad \text{(Eq. 1).}$$

Where P is the yearly precipitation (mm/yr), I is the yearly irrigation (mm/yr), ET is the yearly evapotranspiration (mm/yr), Q is the streamflow (mm/yr), S is the change in unconfined aquifer storage (mm), and t is time (yr). In order to simulate the future streamflow and water table change the student specifies a number of inputs in the Graphical User Interface (Fig. 2). These include: the number of years to simulate (range 5-125), the climate zone (1-4), the runoff ratio (fraction of rainfall that is assumed to directly turn into streamflow, 0-1), fractional cover of irrigated corn and irrigated soybean (remainder is natural grassland vegetation and all three terms must sum to 1). Following the scenario selection, P and potential ET (PET) are generated stochastically for each month using the long-term historical data (Sharma & Irmak, 2012 a;b; Wang & Zlotnik, 2012). The monthly totals are then summed to determine both growing season

(May through September) and annual totals. Next Q is calculated directly from the runoff ratio input set by the user. Note this runoff ratio and the fraction of irrigated area are the key “knobs” to tune the model output to meet the criteria of the scenario and justify the policy decision. Using the simulated PET and P, ET and I for the corn, soybean, and native grassland (I = 0) areas can now be calculated. Finally Eq. (1) and the estimates of the individual fluxes by land use (e.g. P, I, ET, Q), the change in aquifer storage and thus water table decline can be calculated (see Fig. 2 for example solution). Advanced climate options allow the student to change the future pattern of rainfall and potential ET (e.g. inflation and deflation factors of historical annual averages) such that scenarios can mimic output and predictions from General Circulation Models (Pachauri et al., 2014).

Figure 3.2. *Graphical user interface the student uses to simulate water balance scenarios.*



Number of years
50

Select climate zone
○ 1 ○ 2 ○ 3 ● 4

Runoff ratio
0.15

Fractional cover of irrigated corn and soybean
(The rest is grass)
0.3

0.4

Zone=04, Runoff Ratio=0.15, Grass Fraction=0.3, Irr. Maize Fraction=0.3, Irr. Soybean Fraction=0.4

Here a scenario was selected and the graphical results are displayed.

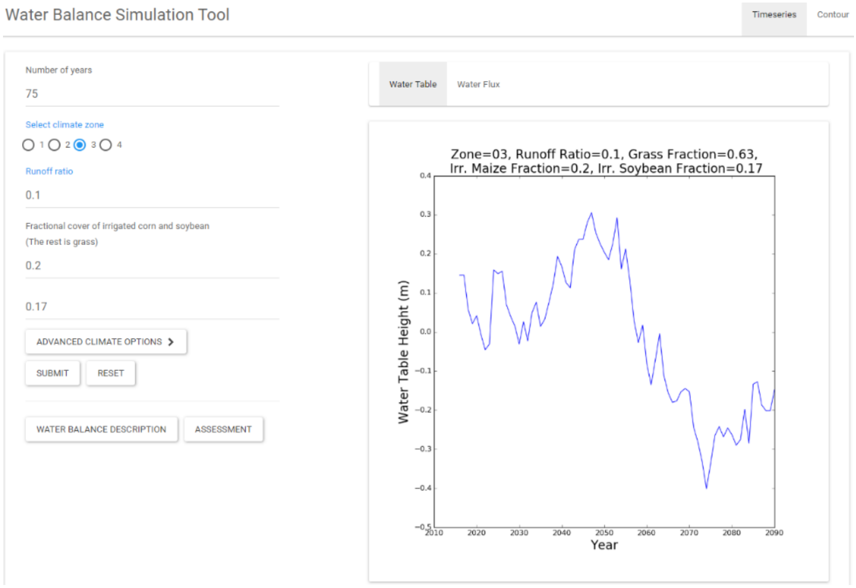
The Water Balance Model allowed students to model the effects of a changing climate and land use on groundwater resources in Nebraska. Students then used this scenario data to make a decision about groundwater use in the face of an unpredictable climate. In the context of the course, students used the WBM to explore climate and hydrologic scenarios that would be otherwise impossible without the use of a model. For example, students use the WBM to test different advanced climate options including P or PET annual mean inflation/deflation, variance inflation/deflation, and net irrigation requirement reduction for either corn or soybeans. Using the resulting graphical outputs, in small groups, students practice making decisions surrounding the quantity of irrigated acres that would result in a stable water table (defined in the class as a change of less than +/- 1m over 100 years). Students can also use the WBM to investigate runoff ratio ramification for both change in water table height and annual water table decline. This information allows students to test the predicted severity of changes in farming and climate on groundwater availability and concomitant changes in streamflow. We note that in climate zone 1 land economic assessments between irrigated and rainfed areas differ by a factor of ~4, with center pivot irrigated crop being assessed at $2700/acre and rainfed being evaluated at $700/acre in 2018 for Northwest Nebraska (Jansen & Stokes, 2018) directly affecting the rural economy and livelihood of stakeholders. As an advanced climate option, the students are able to change how rainfall and temperature/PET may be affected in the future (compared to the historical average) and how that might affect the sustainability of the system. Outputs from the model are both a graphical solution (Fig. 2) and CSV of the yearly simulations for further analysis.

The WBM Project

Students completed a summative assignment surrounding the WBM in which they answered a series of questions and completed exercises that looked at the sustainability of the overall agricultural production, groundwater, and surface water systems. Here the sustainability of the system is impacted by the tradeoffs between reduced streamflow, water table decline, and fractional area used for irrigation agriculture (i.e. economic livelihood of local stakeholders). The students imagined themselves as a water manager of a Natural Resources District in Nebraska and make justifiable decisions about fractional land use that balanced the needs of various stakeholders including environmentalists and producers. Additionally, students learned to evaluate the WBM through explicit discussions about its limitations, utility for decision making despite its limitations, and potential WBM improvements. The WBM contains climate and groundwater components to evaluate, giving students the opportunity to compare two types of information between and within models.

Part I. In Part 1 of the assignment, students selected a climate zone (Figure 3.1) and identified the runoff ratio resulting in a stable water table over the next 100 years with 100% grass cover. Next, they answered set of questions building off their initial runoff ratio finding. Students were asked to find the runoff ratio resulting in a stable water table for the following scenarios: 10% irrigated corn, 10% irrigated soybean, 25% irrigated corn, 25% irrigated soybean, 50% irrigated corn, and 50% irrigated soybean. Responses were accompanied by a brief description of each graph in terms of production and water table maintenance (Figure 3.3).

Figure 3.3. *Graphical user interface example of predicted water table height change for a 75 years period in Zone 3 of Nebraska with 10% runoff ratio and fractional land cover of 20% irrigated corn, 17% irrigated soybean, and 63% grass cover.*



Water Balance Simulation Tool

Number of years
75

Select climate zone
○ 1 ○ 2 ● 3 ○ 4

Runoff ratio
0.1

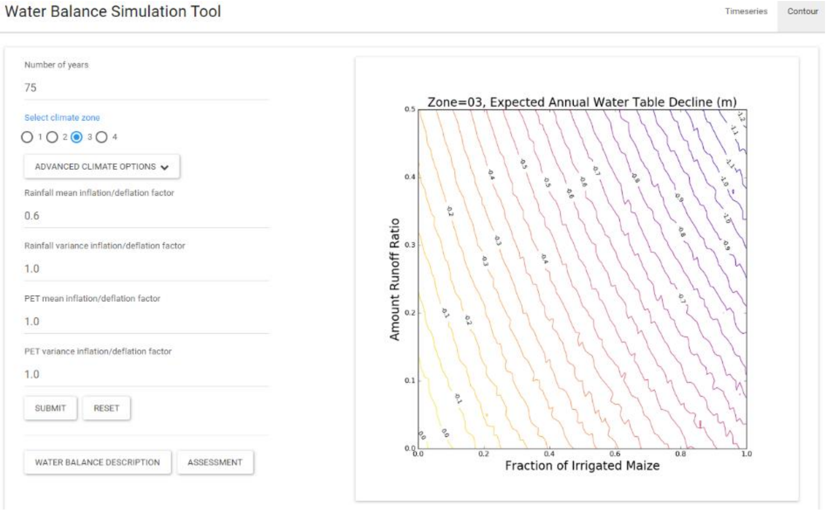
Fractional cover of irrigated corn and soybean
(The rest is grass)
0.2
0.17

Zone=03, Runoff Ratio=0.1, Grass Fraction=0.63,
Irr. Maize Fraction=0.2, Irr. Soybean Fraction=0.17

Using the graphical outputs and descriptions, students then made a decision concerning the number of acres they would allocate for corn and soybean production in their Natural Resource District, described the impact of their decision on runoff ratio and streamflow, and justified their decision to the Natural Resources District Board of directors including multiple stakeholders. In this way, students demonstrated their ability to operate the model, interpret the outputs, and apply the predicted outcomes to real-world problems.

Part 2. Part 2 of the WBM assignment required students to use the same Zone as Part 1, but in the context of advanced climate options following hypothetical outputs from general circulation model emission scenarios affecting changes in precipitation and air temperature/PET (Figure 3.4). Students used the model to make contour graphs and identify, for 100% grass cover, what runoff ratio gives a stable water table for rainfall mean inflation/deflation factors: 0.6, 0.8, 1.2, and 1.4. A graphical solution was required for the answer with a label for the runoff ratio of each. Students wrote a summary of their graphical and runoff ratio findings including ideas such as the effect of rainfall on production and the water table.

Figure 3.4. *Graphical user interface example of expected annual water table decline for a 75-year period in Zone 3 of Nebraska with a rainfall mean inflation/deflation factor of 60%.*



Number of years
75

Select climate zone
○ 1 ○ 2 ● 3 ○ 4

Rainfall mean inflation/deflation factor
0.6

Rainfall variance inflation/deflation factor
1.0

PET mean inflation/deflation factor
1.0

PET variance inflation/deflation factor
1.0

For the second question set of Part 2, students used the contour tab to find, for 100% grass cover, the runoff ratio that gives a stable water table for the PET mean inflation/deflation factors of: 0.6, 0.8, 1.2, 1.4. A complete response included a graphical solution with the runoff ratio labelled. This information was used to generate a paragraph summary of their findings from this set of graphs including ideas such as the effect of PET on production and the water table.

As a synthesis question, students were asked, “What has a larger effect on the water table for the same magnitude of change, a change in mean precipitation or mean PET?”

In the last question of Part 2, students also revisited the decision they made in Part 1 about the fraction of irrigated acres they would permit in their Natural Resources District. They are instructed to think about the effects of climate change on water resources in the future in reference to their decision. Answers from Part 1 and 2 could be used to defend their decision or to change their decision based on anticipated climate effects. For reference, three key figures on GCM output were provided to help guide their decision and provide justification to the board on the level of climate risk they were willing to consider. Some students changed their percentage of irrigated acres while others did not, each response was defended using graphical output from the model to predict future effects of climate change on production, streamflow, and runoff ratio.

Part 3 of the assignment was a reflection on the Water Balance Model. Students reflected on the overall strengths and weaknesses of the WBM, any information they needed to help make decisions as an NRD manager, and the general benefits of modeling.

Results

Findings from the data analysis of student work reveal consistencies across student demographics from multiple years of the course. Qualitative results reveal encouraging comparative trends overall in student reasoning surrounding the WBM. Overall, exploring climate and water relationships through the WBM presents students with an opportunity to revise their thinking about water resources and the Food-Energy-Water-Nexus. Through analysis of the WBM summative assessment, we were able to determine that there is no difference between gender, academic year, or major (STEM or non-STEM) in students' ability reason about the WBM model (Table 3.2 and 3.3). These findings suggest that because of the active learning methods employed in the course, students of all backgrounds, years in college, and genders can effectively engage with the WBM to explore groundwater and climate variables.

Table 3.2

t-test Results of WBM Scores by Gender, and Major

	n	*Mean*	*SD*	*df*	*t*	*p*	*d*
Male	73	0.73	0.16	136	0.56	>.05	0.06
Female	65	0.74	0.18				
STEM	123	0.74	0.17	36	1.79	>.05	0.32
Non-STEM	15	0.68	0.2				

Table 3.3

One-Way Analysis of WBM Scores by Year

	df	*SS*	*MS*	*F*	*p*
Between groups	3	0.02	0.008	2.67	>.05
Within groups	134	3.92	0.03		
Total	137	3.94			

However, results of qualitative analysis show that students struggled with the ability to discern the difference between the effect of precipitation and PET on the water table. Specifically, they struggled to identify which variable, precipitation or PET, had a larger effect on water table height for the same magnitude of change; compounded by the difficulty students had in reading contour graphs. This obstacle was consistent across course iterations, regardless of whether WBM reasoning improvement increased. For example, one student wrote, "I don't see a significant difference between the two when looking at runoff ratios. At the same values for deflation and inflation you get roughly the same runoff." 219_WBM. This student did not describe the difference observed between PET and rainfall on the water table. This may be a product of the lack of specificity in model outputs as well. For example, the outputs do not have a finer grain than 10% for runoff ratio. This makes comparing runoff ratios between scenarios difficult because the values look similar on the graphs, but could be larger if the runoff ratio scale were finer. Another student responded to the question about water table effect by writing, "I think that both are equally important, depending on the area, year, etc." 158_WBM. This student identified that year and area are important variable when considering the impact of PET and rainfall inflation/deflation on water table height, but did not identify which had a greater effect on the assignment outputs. The ability to effectively read contour plots has a significant impact on a student's ability to determine quantitative differences between variables.

Course Outcomes and Next Steps

Conducting research in iterative offerings of the same course has allowed the instructional team to make changes between years based on student feedback and statistical analysis of student work (Forbes et al., 2018; Lally & Forbes, 2019). Overall, we have moved towards a flipped-style course structure increasingly over time to afford students better ways of working with the WBM. A flipped course context offers students time to think about content outside of class, distributing their learning (Gross et al., 2015), while in class time is devoted to practicing the content through discussions, questioning, and evaluating (Jones et al., 2019; Zainuddin & Perera, 2019). In the *Water* *in Society* course, course content related to the WBM is now presented fully online so that students can begin to practice using the model on their own, then come to class ready to start working in groups and answering questions. Class meetings are designed to be student-centered, utilizing an array of active learning strategies. For example, carefully selecting activities and discussion questions surrounding modeling has shown to help increase learning gain in model use and evaluation (Lally & Forbes, 2019). Findings presented here suggest that because of the active learning methods employed in the course, students of all backgrounds, years in college, and genders can effectively engage with the WBM to explore groundwater and climate variables.

Moving forward, due to the interdisciplinary nature of the course and the variety of content, more focus needs to be placed on the connection between the energy, water, and economic components of the course. Students are exposed to the connection between food and water several times throughout the course through models, guest speakers, and even their own personal experiences using water to grow food. Yet, the link between economy and sustainability needs to be more explicit. This could take the form of incorporating an economic component to the WBM to make it more robust. For example, adding in the costs for yield differences between irrigated and rainfed acres, as well as costs for the pumping of water depth below the surface increases. Another factor to include could be the difference in land valuations of irrigated versus rainfed acres as a direct impact on the tax base for the state. This would have huge ramifications on school funding and infrastructure, which could further exasperate the urban and rural conflict (i.e. sociohydrolgoy). The increasingly unpredictable nature of climate events directly relates to choices made over the past decades. Therefore, it is critical that students experience models such as the WBM, which allow them to evaluate water needs for a variety of users in the context of a rapidly changing climate. Fully supporting students in learning the interrelated facets of sociohydrologic and climate issues is at the heart of this course. In the future, a premium will continue to be placed on students' use of models to explore the ways human and natural systems interact.

Data availability

The WBM online simulation tool is freely available at: http://waterbalance.outcome.io/. Model code, description, and assessment are available upon request.

CHAPTER 4

MODELING WATER SYSTEMS IN AN INTRODUCTORY UNDERGRADUATE COURSE: STUDENTS' USE AND EVALUATION OF DATA-DRIVEN, COMPUTER-BASED MODELS

The ability to apply scientific information to daily life is one of the most important skills a student must develop and a core component of scientific literacy. This requires an a) understanding of science concepts and b) science-informed reasoning and decision-making skills, including in the geosciences (Tewksbury, Manduca, Mogk, Macdonald, & Bickford, 2013). The application of scientific knowledge and practices to real world issues reflects the three interwoven strands of scientific literacy: the nature of science, interaction of science with society, and scientific concepts (Murcia, 2009). Introductory science courses, in particular, provide an opportunity to emphasize application of disciplinary ideas and practices to real-world issues (Sundberg & Dini, 1993). One critical topic for which students must develop scientific literacy is water, including its natural and human dimensions (i.e., socio-hydrologic systems). However, research has shown that students, including undergraduate students, may not possess scientifically accurate ideas about water (Author, 2015a, b; Cardak, 2009; Gunckel, Covitt, Salinas, & Anderson, 2012; Halvorson & Westcoat, 2002), including components and processes associated with the global water cycle. Some evidence suggests these misconceptions carry over into adulthood (American Museum of Natural History [AMNH], 2005)

Models are an important tool with which to support students' learning about complex systems, including water. Modeling helps students engage with otherwise inaccessible phenomena and develop skills, including explaining ideas, making connections between the real world and scientific content, evaluation of models and ideas, metacognitive processes, and modify alternative conceptions surrounding a phenomenon (Author, 2015a,b). While scientific models can take a variety of forms (visual representations, physical models, computer simulations, analogies, etc.; Bybee, 2011; Coll, France, & Taylor, 2005), here we focus on data-driven, computer-based computational models for water systems.

Computer-based models allow students to both learn to hypothesize based on evidence and demonstrate their understanding of a process (Sins, Savelsbergh, van Joolingen, & van Hout-Wolters, 2009; Calvani, Cartelli, Fini, & Ranieri, 2008). This is particularly the case with hydrologic phenomena and socio-hydrologic systems, where students can explore multiple hypotheses, develop policies, and quickly run multiple scenarios (Gunn, Mohtar, & Engel, 2002; Williams, Lansey, & Washburne, 2009; Zigic & Lemckert, 2007). Thus, students incorporate the nature of science as they test ideas while simultaneously applying knowledge of hydrological concepts.

Despite the potential of benefits to teaching and learning, introductory geoscience courses generally do not offer students the opportunity to use computer-based water models. As a result, gaps exist in our understanding of how to support undergraduate students’ model-based reasoning about water systems. In our own introductory water course, we have designed learning experiences for students, including both STEM majors and non-majors, that foreground use of data-driven, computer-based models to explore real-world hydrologic challenges (Author, 2018). In an effort to continue to refine the course, we hypothesized that a flipped classroom model and enhanced active learning opportunities surrounding water systems simulation modeling can better support students' use of computer-based models to learn about socio-hydrological systems. To test our hypothesis, we conducted a study in which we collect and analyze student data from two consecutive years of the course to address the following research questions:

1. To what extent do students' a) model-based reasoning and b) conceptual understanding of hydrology differ between Years 1 and 2?
2. How does students' model-based reasoning differ between Years 1 and 2?

Undergraduate Model-Based Teaching and Learning about Water

Prior research has shown that students across the K-16 continuum have limited knowledge of water (Author, 2015b; Gunckel et al., 2012), including undergraduate students (Author, 2017a; Cardak, 2009; Halvorson & Westcoat, 2002; Raia, 2005; Sherchan et al., 2016; Sibley et al., 2007). Alternative conceptions exist surrounding such fundamental concepts as the relationship between water vapor and air, the fluidity and form of groundwater, and the flow of substances between humans and the natural environment (Raia, 2008). More specifically, undergraduate misconceptions such as: a) evaporation occurs only from seas/oceans and b) soil moisture is only found in areas that receive rain, among others, resist change in students (Cardak, 2009). More broadly, students conceptualize these and other water-related phenomena, such as glaciation, as occurring due to linear, mono-causal chains of events. Conceptions such as these are resistant to change because learners tend to think about events as direct, demonstrating a specific effect for a specific cause (Raia, 2008). Students are also likely to omit ‘invisible’ components of the water cycle such as water vapor, condensation and groundwater movement (Author, 2017a; Sibley et al., 2007). Components which students cannot visualize or are the result of dynamic processes are areas in need of epistemic improvement.

To confront their alternate conceptions about hydrologic processes, students can use computational, simulation-based models in formal learning environments which, when combined with other teaching strategies, can support undergraduate learners to develop a more comprehensive understanding of hydrology (AghaKouchak, Nakhjiri, & Habib, 2013; Habib, Ma, Williams, Sharif, & Hossain, 2012; Merwade & Ruddell, 2012). Enhancing undergraduate hydrology curriculum through simulation models harnesses the benefits of active learning to interaction with authentic data for complex analysis and decision-making (AghaKouchak et al., 2013). Computer-based models can help students engage with hydrologic phenomena that are difficult to access directly (Singha & Loheide II, 2011), allow them to distribute their learning over time with the simulation serving as a responsive, on-demand tool (Zigic & Lemckert, 2007), and facilitate peer collaboration of problems and concepts.

However, undergraduate students’ access to such tools is limited. Data-driven, computational water models are primarily used in upper-level coursework but, even then, simpler tools, such as Microsoft Excel, are still most common (Merwade & Ruddell, 2012). In the instances where introductory hydrology courses exist, they lack opportunities for computer-based modeling and use of data (Merwade & Ruddell, 2012). Calls for change in hydrology course content include the use of simulation modeling, authentic data, videos, development of strategies and resources for use in all levels of hydrology education, and the incorporation active learning techniques (Consortium of Universities for the Advancement of Hydrologic Science [CUAHSI], Inc., 2018; Merwade & Ruddell, 2012; Ruddell & Wagener, 2013). Broadly, the changes needed to reform hydrology education emphasize the push and pull of systems components and processes, including human interventions, through a transdisciplinary lens (CUAHSI, 2018). Specific areas of improvement include opportunities to engage in authentic applications of hydrology practices and the inclusion of variability in both systems and simulation models, (Ruddell & Wagener, 2013) all at a level which is accessible to students with little modeling experience (Erturk, 2010).

Model-Based Teaching: Flipped Classroom Model

While models can be a powerful tool to support student learning about water, their implementation through research-based curriculum and instruction is critical. Effective, model-centric instructional strategies align with best practices in undergraduate STEM instruction, including active learning (Handelsman et al., 2004) and innovative teaching strategies to positively affect student outcomes (Gunn et al., 2002). A ‘flipped’ approach to course design is one such strategy in which other ‘best practices’ in undergraduate STEM education can be used. In a flipped approach, students use class time to work in small groups and practice applying content; outside of class, students watch videos and complete other tasks related to learning content (Abeysekera & Dawson, 2015). There is indication that flipped classroom strategies are effective at enhancing student learning and engagement (Abeysekera & Dawson, 2015; Barral, Ardi-Pastores, & Simmons, 2018;

Jones, McConnell, Wiggen, & Bedward, 2019; Zainuddin & Perera, 2019). Students can spend more time thinking about content outside of class, which is beneficial from a learning psychology standpoint as learning is distributed instead of squeezed into a short time period (Gross, Pietri, Anderson, Moyano-Camihort, & Graham, 2015). Flipped classrooms also offer students opportunities to use varying strategies and work in different settings where they are more likely to find an effective strategy, thus enhancing learning for diverse populations of students (Gross et al., 2015).

Flipped classrooms foreground interactive, collaborative group work and position the instructor as an orchestrator of scaffolds in a real-time, on demand setting. Shifting the responsibility of learning content to students, as an out-of-class exercise is worthwhile because in-class time can then be spent discussing, asking questions, and evaluating (Jones et al., 2019; Zainuddin & Perera, 2019); which are all better suited to a group environment. Flipped classroom techniques are specifically beneficial for learning to use simulation models because after learning the initial model content out of class, they are prepared to work on higher order thinking problems in groups and use the model in ways that are more sophisticated. Thus, flipped techniques, when applied to simulation models can enable group problem solving to increase the understanding of water's complexity (Singha & Loheide, 2011; Gunn et al., 2002).

Theoretical Framework for Modeling

To engage effectively with simulation models in formal classroom settings, students must attend to both the practices of modeling and their epistemic dimensions (Author, 2015a). In order to achieve this goal and consistent with constructivist theory, students need opportunities to engage directly with models in an iterative manner to construct and revise their ideas (Nersessian, 1999; Schwarz et al., 2009). Epistemic dimensions such as representation, evidence, and explanation are components of modeling practices. Awareness of models as proxy for the phenomenon under investigation is important because it allows students more accurately to interact with phenomena (Krajcik & Merritt, 2012). Explaining the constraints of a model is a way of expressing the evidence of fit. The ability to explain outputs and the reasons for model validity under certain circumstances are important and further improved with the incorporation of multiple models and evidence to confirm its validity (Krajcik & Merritt, 2012). These three educational dimensions are interwoven concepts, lend support to modeling practices, and contribute to both more understanding of scientific concepts and conceptual change (Nersessian, 1999). Conceptual change serves as evidence that students have shifted in how they interact with a model and how they generalize overall modeling skills (Schwarz et al., 2009). Students need support to develop skills in these practices and increase their overall generalizability through conceptual change.

To serve this role, individuals must interact with computer-based models. We foreground specific modeling practices, including a) the *use* of models and b) the *evaluation* of models, as part of a more comprehensive framework developed as a component of our broader research and development work spanning K-12 and postsecondary contexts (e.g., Author, 2017b, 2015a,b). The *use* and *evaluation* of a model are two types skills associated with model-based reasoning (Gobert & Buckley, 2000). The *use* of models involves skills and tasks such as visualization of otherwise invisible phenomena, streamlining information, learning novel ideas, and hypothesizing (Gilbert, 2004; Gouvea & Passmore, 2017). In this study, model *use* also includes skills such as identifying relationships between model components, referencing the model in hypothesis making, and explaining ideas using the model as evidence. *Use*, in this study, encompasses all of the ways in which students interact with the model, identify relationships between model components, and cite the model as confirmation of claims. The *evaluation* of models involves revision, comparison, verification of accuracy, precision (Coll et al., 2005; Gouvea & Passmore, 2017), and contextual fit (Pluta, Chinn, & Duncan, 2011). In this study, students *evaluate* the computer-based model's ability to predict, overall complexity, organization, and explanation of groundwater. Models vary in strength, students need to see and use different types of models and evaluate each model within its own context to use them in testing a hypothesis.

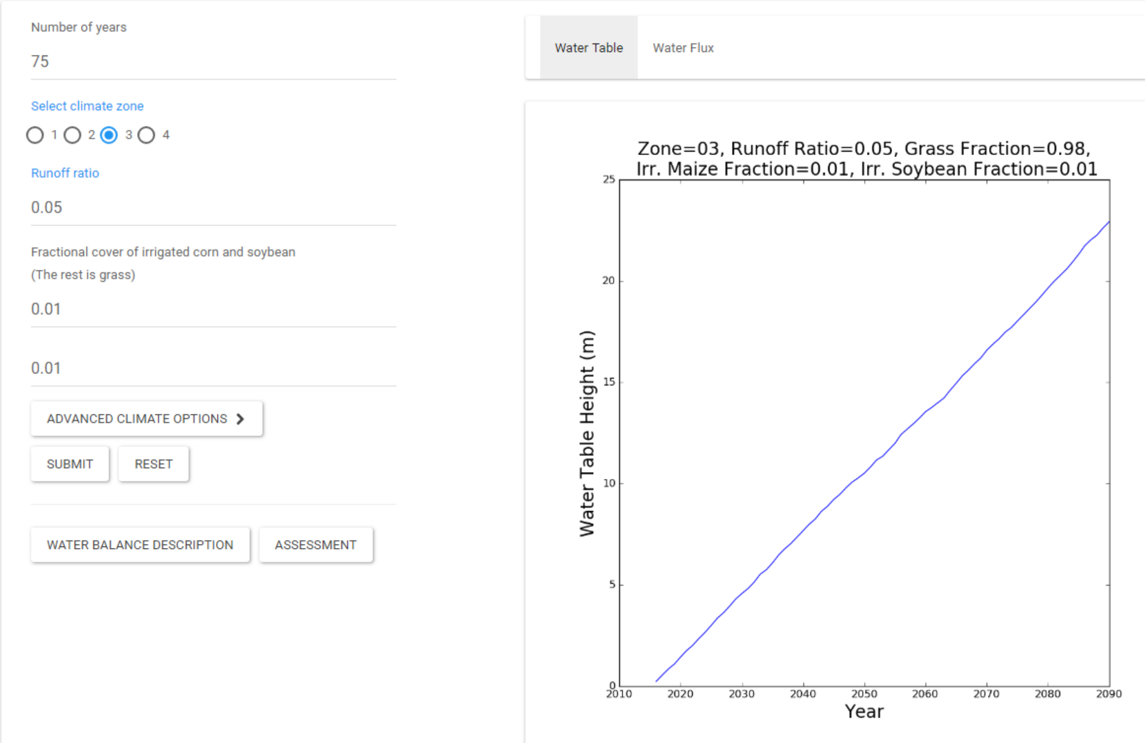
Methods

SCIL109: Water in Society

Course overview. This independent convergent mixed methods study (Plano Clark & Ivankova, 2015), was conducted in the context of SCIL109 (Forbes et al., 2018), a medium-sized, interdisciplinary, elective, introductory water course at the [institution name]. The course includes a) classes of increasing interconnectivity surrounding the FEW-Nexus, and b) multi-week projects supporting course content. During the course, students learn to use two computer-based, data-driven water models, contribute to large and small group discussions, and complete a summative systems thinking assessment incorporating course themes and goals. The course, taught annually in the spring semester, serves an average of 55 students per semester in its first three offerings. The present study focuses on two consecutive course offerings in spring, 2017 (Year 1) and 2018 (Year 2), for which, the course goals, organization, instructors, and major assessments were the same.

SCIL 109, Water Balance Model, and course revision. For both Year 1 and 2, students used a data-driven, computer-based groundwater modeling tool called [model name withheld for blind review] (Figure 4.1). This model is grounded in authentic historical hydrologic data from [US state] and region.

Figure 4.1. *Screenshot of the model interface.*



Number of years
75
Select climate zone
○ 1 ○ 2 ● 3 ○ 4
Runoff ratio
0.05
Fractional cover of irrigated corn and soybean
(The rest is grass)
0.01
0.01

In Year 1, students learned all of the content and use skills surrounding the model during one class period (50 minutes) and had two lab periods (50 minutes each) of practice with the model prior to submitting the summative project. Direct instruction was primarily used to teach the model, students discussed the model intermittently throughout the class lecture, and approximately ten minutes was spent independently using the model at the end of class. The lecture focused on the theory behind the model and the spatial variation of precipitation across the geographic area. Prior to lab, students worked on model homework, and then during lab worked in groups to solve problems based on the model. During the second lab period focused on the model, students were introduced to the model project and began working on the assignment.

Between Year 1 and Year 2, changes were made to course reflecting a flipped course model (Table 4.1). The project team produced videos of background and model tutorials, which prior to class; students viewed independently, practiced using the model, and identified model components. Students then came to class ready to discuss in large and small groups, ideas including the conservation of mass as related to the water balance, potential inputs, outputs, dimensions, and storages affecting the water balance, the relationship between a stable water table, runoff, and streamflow. During class, students practiced using the model and interpreting contour and time series maps in small groups. The second week, students were reminded how to use the model, worked together in jigsaw groups to discuss themes from the four climate zones within the model, summarize outputs, and make decisions about the allocation of irrigated acres all in small and large group settings. Overall, students in Year 2 spent more time with the model than in Year 1. These two weeks of scaffolded practice led up to the culminating model project.

Table 4.1
Instructional Course Elements from 2017 and 2018

2017

Activities:

Basic hydrologic content pre-/post-test
Assigned readings
Direct instruction
Personal reflection
Small discussion groups
Large group discussions
Content quizzes (3)
Computer-based water model projects (2)
Guest speaker: Extension engineer: water management
Guest speaker: hydrogeology challenge computer-simulation model
Guest speaker: historical perspectives
Field trip: local water management
Infographic development (2)
Small to large group jigsaw of water issues
Systems thinking project
Computer-based model independent practice
Graph interpretation
Water use calculation

Modeling:

Global water cycle
Groundwater movement
Groundwater recharge
Water molecule

Topics:

Molecular properties of water
Human relationships with water
Historical, present, future uses of water
Distribution of water on earth and the global water cycle
Water resource management decisions making framework
Watersheds and aquatic systems

2018

Activities:

Basic hydrologic content pre-/post-test
Assigned readings
Direct instruction
Personal reflection
Small discussion groups
Large group discussions
Content quizzes (3)
Computer-based water model projects (2)
Guest speaker: Extension engineer: water management
Guest speaker: historical perspectives
Field trip: local water management
Infographic development (2)
Small to large group jigsaw of water issues
Water use calculation
Systems thinking project
Graph interpretation
Water on Earth calculations
Model evaluation and comparison
Computer-based model independent practice
Computer-based model group practice
Course content videos and associated questions
Tree water balance calculations
Simulation model specific key terms worksheet
Groundwater management toolkit
Rationale method for estimating urban runoff

Modeling:

Global water cycle
Water molecule
Groundwater movement
Groundwater recharge
Contour lines

Groundwater
History of irrigation to today
Interactions between climate, weather, and water, general circulation models
Water balance concept
Water law and policy challenges and misconceptions: local, state, federal
Historical cases and development of municipal water
Water entrepreneurship
Graph interpretation
Temporal and spatial scales
Climate change
Development and use of models in social ecological systems to make policy recommendations
Kenyan water balance examples
Water balance formula
Flint, MI and Des Moines, IA water crises
Sewers and epidemiology
Urban water cycle and systems
Municipal water
Systems thinking

Microhabitat

Topics:

Molecular properties of water
Human relationships with water
Historical, present, future uses of water
Distribution of water on earth and the global water cycle
Water resource management decisions making framework
Watersheds and aquatic systems
Groundwater
History of irrigation to today
Interactions between climate, weather, and water, general circulation models
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sewers and epidemiology
urban water cycle and systems
municipal water
systems thinking

Participants

Participants in Year 1 (*n*=38) and Year 2 (*n*=53) were undergraduate students enrolled in the course. Participants for both years represented a diverse population including a large proportion of international students. Student demographics are presented in Table 4.2.

Table 4.2
Student Demographics from 2017 and 2018

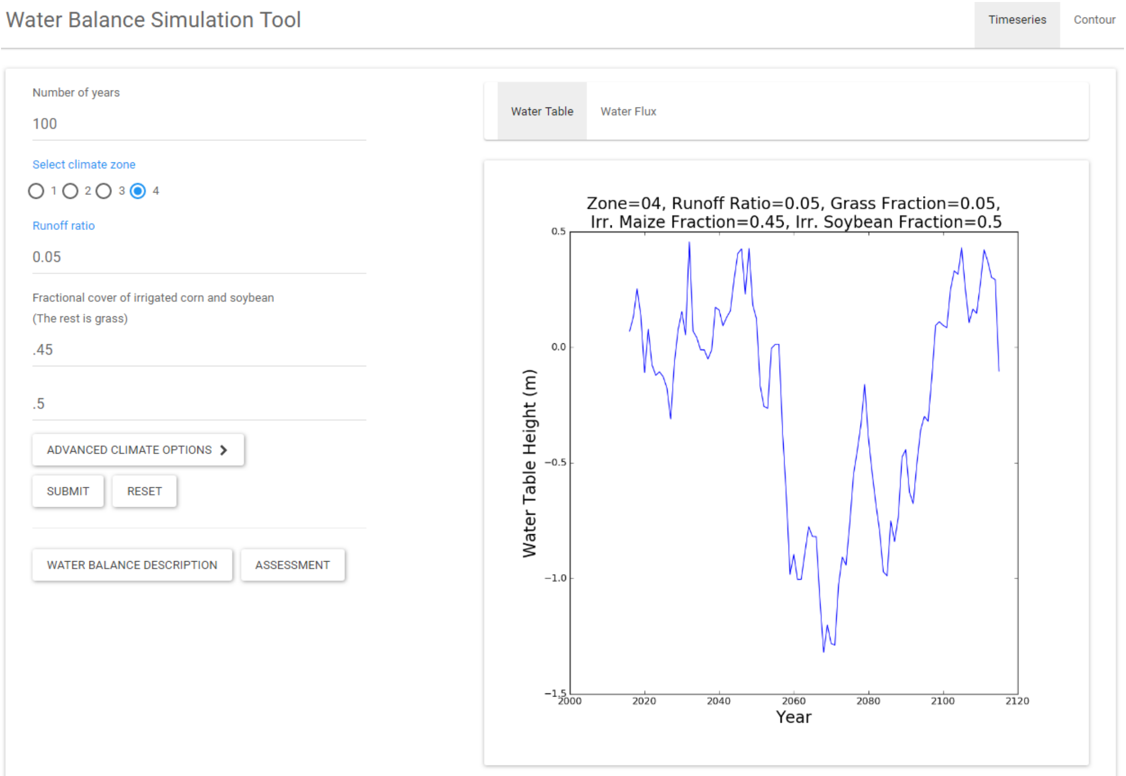
	Female	Male	Freshmen	Sophomore	Junior	Senior/+	STEM Major	Non-STEM Major
2017	16	22	10	11	9	8	34	4
2018	30	23	1	28	17	7	51	2

Data Collection

Pre-/Post-course concept inventory. The assessment used in this study is based on existing instruments tested and validated with postsecondary students (Petcovic & Ruhf, 2008). Questions selected for the pre-/post-assessment focus on water-related concepts addressed in the course and include a mixture of multiple choice and short answer items. Concepts evaluated included: phase change, greenhouse gases and their relative quantities, the water cycle, sea ice, relative quantities of types of water and their locations on Earth, clouds, latent heat, contour maps, direction of water flow, watershed boundaries, runoff, and plant-water relations. The assessment contained 41 questions, for a total possible score range of 0-41. Each question was scored as incorrect, 0 points, or correct, 1 point. The assessment was administered at the beginning and end of the semester.

Computer-based model assignment. Students were provided with a scenario in which they must make a decision regarding the allocation of the acres of irrigated corn and soybeans. They must use the model outputs to make a decision that balances irrigation needs with a stable water table. For Part I, students select a climate zone within the model, then using the timeseries function, identify the runoff ratio that gives a stable water table for varying acres of grass cover, irrigated corn, and irrigated soybeans (Figure 4.2). In the context of this model and assignment, a stable water table is defined as maintaining +/- 1-meter change in height over the selected period. For each graphical solution, students describe the effect on production and water table maintenance in a written response. Next, students use their findings to make a decision about the number of irrigated corn and soybean acres they would allocate, describe the impact on runoff and stream flow compared to historic levels, and address the concerns of various stakeholders such as producers, naturalists, and local business owners.

Figure 4.2. *A stable water table output for Climate zone 4 over a 100-year period with 45% of the area covered in irrigated corn and 50% of the area covered in irrigated soybeans, remaining area is grass.*



Water Balance Simulation Tool

Number of years: 100

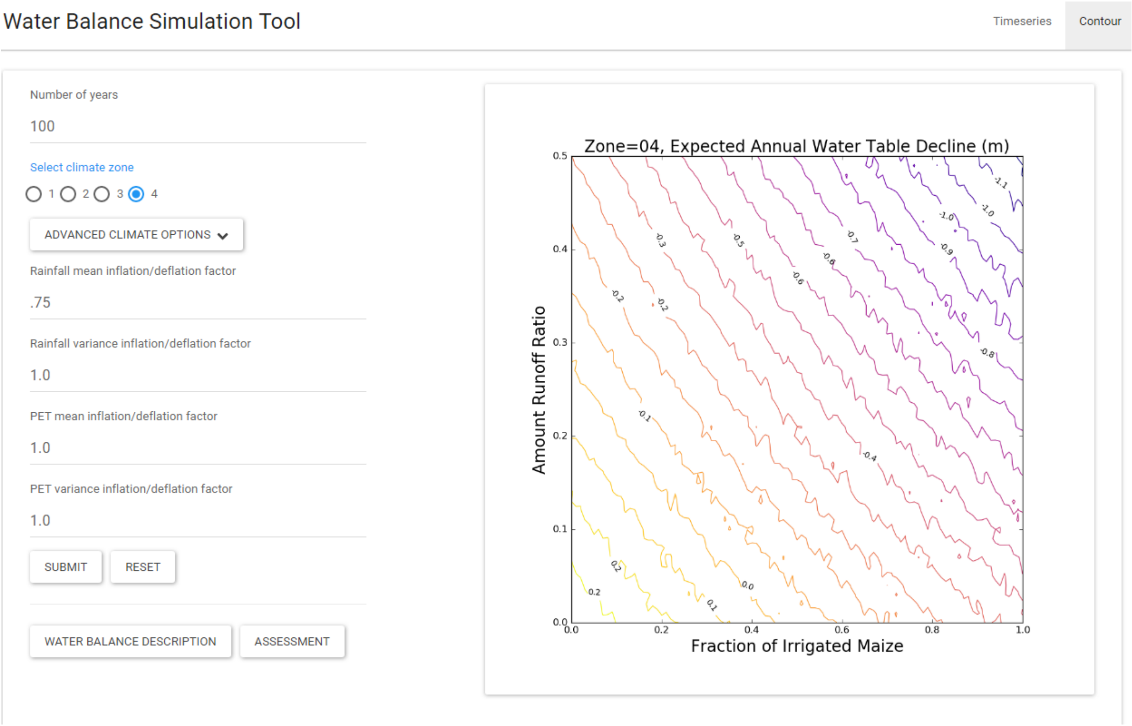
Select climate zone: ○ 1 ○ 2 ○ 3 ● 4

Runoff ratio: 0.05

Fractional cover of irrigated corn and soybean (The rest is grass): .45, .5

For Part II, students use the same climate zone as Part I, but use the contour function of the model (Figure 4.3, 4.4). The students generate contour graphs by manipulating the inflation and deflation factor for rainfall and potential evapotranspiration, labelling the runoff ratio for each graph. Summaries of the findings for both the effect of rainfall on production and the water table and the effect of potential evapotranspiration on production and the water table are written using the graphs as evidence. Students then revisit the initial decision from Part I regarding the allocation of irrigated crop acres and stakeholders who are concerned about climate change effects on future water resources. Students defend or change their decision based on graphs of anticipated climate effects.

Figure 4.3. *A contour graph output for climate zone 4 over a 100-year period with the rainfall mean inflation/deflation factor set at 75%.*



Water Balance Simulation Tool

Number of years

100

Select climate zone

○ 1 ○ 2 ○ 3 ● 4

Rainfall mean inflation/deflation factor

.75

Rainfall variance inflation/deflation factor

1.0

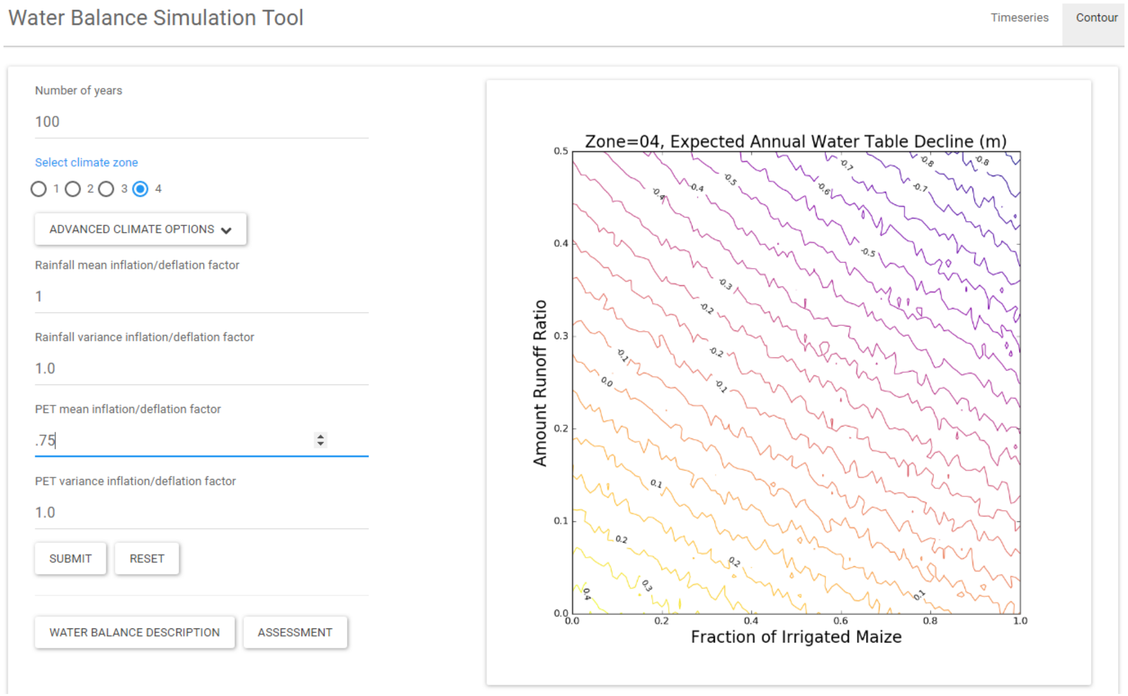
PET mean inflation/deflation factor

1.0

PET variance inflation/deflation factor

1.0

Figure 4.4. *A contour graph output for climate zone 4 over a 100-year period with the PET mean inflation/deflation factor set at 75%.*



Water Balance Simulation Tool

Number of years
100

Select climate zone
○ 1 ○ 2 ○ 3 ● 4

Rainfall mean inflation/deflation factor
1

Rainfall variance inflation/deflation factor
1.0

PET mean inflation/deflation factor
.75

PET variance inflation/deflation factor
1.0

In Part III of the assignment students reflect on the model's characteristics, specifically the strengths and what the model helped them accomplish. Next, they address the model weaknesses and what the model did not help them fulfill. Students consider if there is additional information they would want to help make a decision reflect on the general benefits of modelling.

Student interviews. Semi-structured interviews (Merriam, 2009) were also conducted in Year 1 (n=18) and Year 2 (n=17). All students registered in the course were invited to participate in the interviews; those that voluntarily participated in the interviews received a $20 Amazon gift card for their cooperation. Interviews ranged from 15-30 minutes and were audio-recorded and transcribed. We interviewed students about the computer-based model and questions focused their responses to ideas about the model, decision-making, opinions about water and water related issues, and the utility of the computer based model.

Data Analysis

Quantitative analyses. Data for this component of the student came from both the pre-/post-test results and the student model assignments. Based upon our ongoing research efforts around the course (Author, 2018) and broader work promoting and studying teaching and learning about water systems across the K-16 continuum (e.g., Author, 2017b, 2015a, b), we developed and used a scoring rubric to provide a measure of students' use and *evaluation* of the model. The scoring rubric is explicitly aligned with our theoretical framework for scientific modeling and was adapted for use in a post-secondary classroom with computer-based water models. The rubric assesses student responses based on two sub-scores: a) the extent to which they describe what a model is and how it is *used* and b) how they *evaluate* what a model is and how it is used. *Use* scores range from 0, 2, 4 and *evaluation* scores range from 0 to 1 (Figure 4.5). Each cumulative score is based on seven model use categories, scored from 0-4, for a total of 28 as well as seven model evaluation categories, scored from 0.-1, totaling 7, the maximum score possible from the rubric is 35 points (Figure 4.5). Inter-rater reliability was established between two coders each of year of the study, using the rubric. The initial round of coding included 10% of the data sample and included a review of discrepancies between coders. This continued until percent agreement reached 1.0; Cohen's Kappa was calculated after the final round of coding for 2017 (*k*=1.00) and 2018 (*k*=1.00) (Lombard, Snyder-Duch, & Bracken, 2002). Pre- and post-course change scores on the concept inventory were also analyzed quantitatively in comparison to *rubric* scores from the modeling project to explore relationships between students' model and conceptual understanding of hydrogeology concepts. Students' scores on the model project were normalized as a percentage, giving each a total score between 0 and 1.

Figure 4.5. *Model project scoring rubric.*

A Model Is	Use	0	2	4	Evaluate	Yes/No
Evidence-based	Learner uses a model to incorporate new evidence about a phenomena	Not present	Uses a model with vague or few components and relationships.	Uses a model with specific and varied components and relationships.	Learner evaluates a model based on the evidence provided about the phenomena	Yes = 1 No = 0
Appropriately detailed/complex	Learner uses a model that is appropriately detailed/complex to describe a phenomena	Not present	Non-detailed descriptions of output	Detailed output descriptions	Learner evaluates the appropriateness of the complexity of a model pertaining to a phenomena	
Generalizable	Learner uses a model to make a generalization about a specific phenomena	Not present	No relation between similar processes or how components can affect movement of water.	Does generalize to other areas. Shows understanding of how components can affect movement of water.	Learner evaluates the generalizability of a model of a phenomena	
A Model Is Used For						
Predict/Hypothesize	Learner uses a model to predict and hypothesize about a phenomena	Not present	Partially explains prediction. Provides non-detailed answers with minor reference to findings generated by the model	Uses specific evidence the model generates to make a prediction.	Learner evaluates a models ability to predict and hypothesize about a phenomena	
Explain (whole/ part)	Learner uses a model to explain some or all of a phenomena	Not present	Partially explains problem and solution based on the model, but provides non-detailed answers	Thoroughly explains concepts based on the model.	Learner evaluates a models explanation of a phenomena	
Organize	Learner uses a model to organize their ideas about a phenomena	Not present	Learner references the model and provides partial explanations.	Thoroughly explains with evidence from the model.	Learner evaluates a models organization of a phenomena	
Generate	Learner uses a model to generate new information/ideas about a phenomena	Not present	Student uses the model to make a decision.	Students uses the model to make a decision, references specific information from the model, and provides detailed response.	Learner evaluates a model to generate new information/ideas about a phenomena	

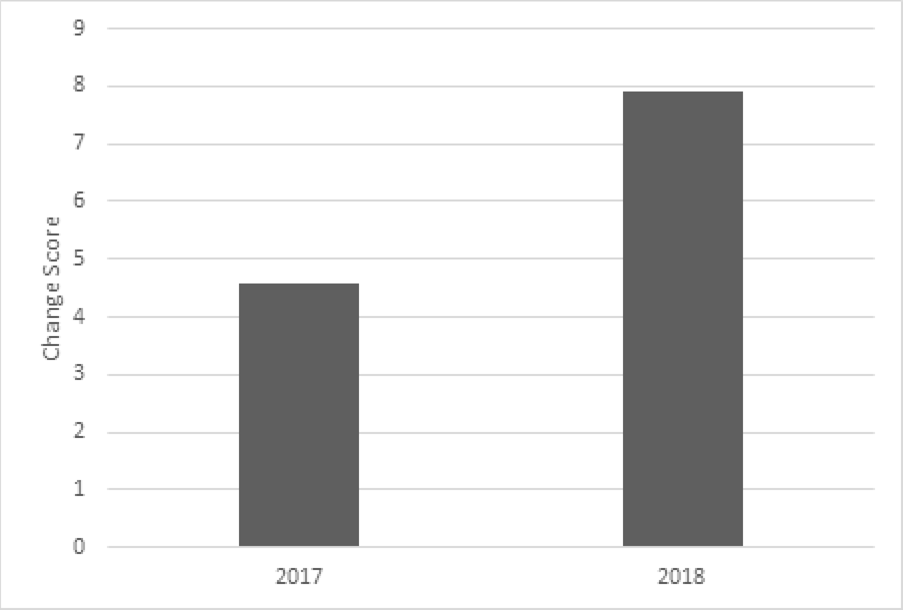
Because of our robust sample size and normal distribution of data, parametric statistical tests (t-tests, ANOVA, etc.) were used for analysis.

Qualitative analyses. For this component of the study, data sources included student model assignments and interviews, which were coded, based on the evaluation and use practices reflected in the theoretical framework and scoring rubric. Responses were coded for themes including generalizability, specificity, and complexity, as identified in rubric. Generalizability in this study refers to those comments which reflect an ability to think about or use model outputs or components in real-life scenarios or in other hydrologic content areas. Specificity, as defined in this instance, includes those comments that deal with the model's outputs or components as they relate to the *specific* area and content for which it was designed. Complexity, in this study, encompasses the comments relating to appropriateness of the model's variables both in quantity and quality and the level of detail demonstrated by outputs. Inter-rater reliability was established between two coders using the interview transcripts and the rubric. The initial round of coding included 10% of the samples. Each round of coding included a review of discrepancies between coders and continued until percent agreement reached .86; Cohen's Kappa was calculated after the final round of coding (*k*=0.59) (Lombard et al., 2002). Identification of themes allowed for comparison between years and patterns distinguished among students. The coded interview data serves to confirm and augment the results from the quantitative analyses.

Results

In research question 1, we asked, "*To what extent do students' a) model-based reasoning and b) conceptual understanding of hydrology differ between Years 1 and 2?*" Statistical analyses were conducted using students' pre- and post-course assessment normalized scores. For students' pre-test scores, results show a significant difference between Year 1 (n=38) (*M*=74.9, *SD*=8.61) and Year 2 (*M*=58.7, *SD*=14.9), *t*(88)=5.98, *p*<0.05, *d*=1.33. This suggests that there is a statistically significant difference between the two populations' understanding of basic hydrology concepts at the beginning of the course. We also observed from change scores that students in Year 2 (n=53) (*M*=7.92, *SD*=3.90) developed greater understanding of core hydrology concepts than did students in Year 1 (*M*=4.58, *SD*=2.64), *t*(88)=-4.57, *p*<0.05, *d*=1.00 (Figure 4.6). These findings suggest while the 2017 students began the course with greater levels of conceptual understanding of course-related hydrological concepts, students in Year 2 showed increased gains in their conceptual understanding over the course of the semester. On the pre-test, students in both years frequently provided incorrect answers to questions related to contour interpretation, phase change, greenhouse gases, volume of water on Earth, and how trees affect the water cycle. Students improved on each of the most commonly missed pre-test questions as evidenced by an increased percentage of correct answers on the corresponding post-test (Appendix 4.A).

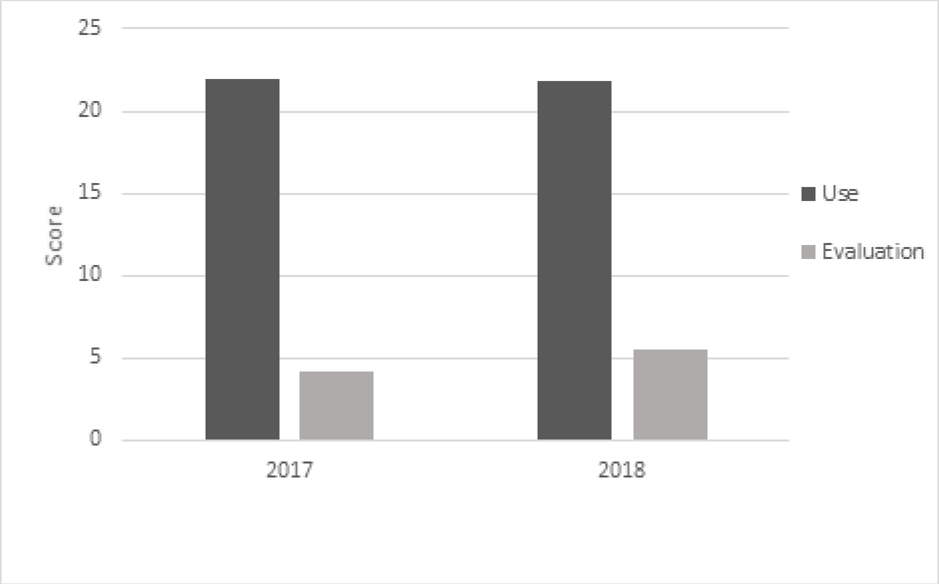
Figure 4.6. *Mean 2017 and 2018 pre- and post-test change scores.*



At the end of the course, there was a significant difference between post-test scores for Year 1 (M=92.5, SD=7.43) and Year 2 (M=89.1, SD=10.8), $t(88)$=1.67, p>0.05, d=0.37. This suggests that students in Year 1 reached a slightly higher level of understanding of core hydrology concepts by the end of the course. Students' scores on the model project were analyzed and mean model project scores do not differ significantly by year. Results show that students in Year 2 (M=78, SD=15.3) scored similarly to students in Year 1 (M=75, SD=17.2), $t(89)$-0.95, p>0.05, d=0.18. This suggests that students in Years 1 and 2 were overall reaching similar levels of model proficiency.

In research question 2, we asked, "*How does students' model-based reasoning differ between Years 1 and 2?*" Mean model *use* sub-scores did not vary significantly within either year: students performed the same in both Year 1 (M=21.95) and Year 2 (M=21.85) on their *use* of the model, $t(89)$=0.09, p>0.05, d=0.02. Scores for model *use* ranged from 10 to a maximum score of 28. These results indicate that students in both years used model information and understood the model outputs in similar ways. However, model *evaluation* scores do differ significantly by year. Students in Year 2 (M=5.49) scored higher than those in Year 1 (M=4.18), $t(89)$=4.24, p<0.05, d=0.36 (Figure 4.7). Scores for model *evaluation* ranged from 0 to a maximum score of 7. Overall, these results indicate that between years, there is no difference in a student's use of the model, but students in Year 2 scored higher on model project evaluation tasks than students in Year 1. These analyses suggest differences in students' model-based reasoning about groundwater is due primarily to their evaluation of the model, not their use of the model.

Figure 4.7. *Mean 2017 and 2018 model evaluation and use scores.*



Qualitative analyses of students' written assignments and interviews provide additional insight into these findings. Overall, there was consistency and similarities in how students used the simulation model in both Year 1 and Year 2. Students used the model outputs to identify patterns, make a decision about groundwater use, lend support to their decision, and make hypotheses about how future water use will affect aquifer stability. Students interpreted the patterns to understand the types of variables that would lead to a stable aquifer, such as potential evapotranspiration, runoff, and climate change. For example, in Year 2, one student, when asked about the general effect observed between runoff and percent cultivated crops on the water table, responded, "Well, it seemed like the runoff was tied to how few crops there were. So if there were less crops that were taking up all the water, then there was more runoff" (WBM_CC). Students responded with relationships between several different factors identified as patterns from model outputs. Model outputs were also used to make decisions and hypotheses about groundwater use and as specific evidence in support of their ideas. Students who used model outputs to support their ideas often did so by looking at multiple outputs. For example, one such student in Year 1 described how they justified their decision, saying, “I just looked at how the different scenarios affected the runoff ratio and the water table and then I chose the situation but it was best for the scenario” (WBM_XX). Using the computer-based model to support a decision based on multiple outputs is an example of using patterns alongside outputs to provide evidence for a hypothesis about groundwater use.

However, there were also important differences in how students engaged in model evaluation in Year 1 and 2. Analyses revealed three themes related to model evaluation: *complexity*, *generalizability*, and *specificity*.

Complexity. First, analyses revealed an increasing emphasis on students’ attunement to model *complexity* in Year 2 compared to Year 1. Coded qualitative data demonstrated that eight of the seventeen students interviewed in Year 2 and nine of the eighteen students in Year 1 all commented on model *complexity*. Despite the similarities in the number of students commenting on complexity during their interviews, the real difference lies in their content. In Year 1, students noted that the model is fun and could be helpful in making a decision, but the majority of the students described problems understanding model outputs and features of the model interface itself. For example, one student, in Year 1, when asked about drawbacks or limitations of the model, responded, “I think some supplemental information or explanations might be useful. Just like little boxes that have a little clips or facts about what you’re doing, what you’re working with” (WBM_XX). Students responding that they needed more help learning to use the model mentioned several options for addressing this shortfall, indicating that the model may have been too complex for them to understand fully. Another student from Year 1 suggested, “…I would reduce the size of the range, for someone can try with less values to get the needed depth” (WBM__ZZ). This response infers a perceived need among students for a range of values to work with, instead of all possible values. One student appreciated the struggle in working with the model, saying:

> When I first looked at the contour one, I was a little bit lost until I actually looked at what I was typing in in accordance to what the graph was giving me and how it was labelling things…It actually made you work, which honestly it probably is more of a strength than weakness. (WBM_WW)

Students such as this implied that with more work, they were able to understand the model components and outputs. Overall, evaluation of model *complexity* themes from Year 1 indicate students needed more support to understand the model as they had few critiques about its *complexity*.

In contrast, analyses of data from Year 2 surrounding *complexity* revealed that students thought the model was easy to use and allowed them to make a prediction. However, unlike in Year 1, the majority of students thought the model was not complex enough and did not provide enough options or detail to make a sound decision. For example, one student when asked about drawbacks or limitations of the model, responded,

> One drawback was that it was very broad, and so it focused on the entire climate region, which I’m sure varies greatly between if you’re in the

> southern part of climate zone one, versus way up north where it's almost the badlands… (WBM_CC)

Students responding that they wanted more depth and options within the model addressed this shortfall with suggestions. One student asked, "What about the other crops, what if it's an integrated system or have a crop rotation" (WBM_DD)? This response indicates that students have moved past a basic evaluation of the model and are looking for more *complexity* to make the output more reliable.

Other types of *complexity* critiques were more specific, including considerations for topography and soil type differences. For example, one student suggested, "…I think that elevation is the same throughout the model and sometimes elevation changes depending on what is underground and things like that" (WBM_QQ). This response infers that the student knows elevation above ground and below could affect the accuracy of the model for a given location. Another suggested the inclusion of soil type to increase model complexity,

> If I could edit the model, I would make sure that I put, I was talking about the types of soils and how they all have different way they hold water and so I would make sure that if I have to say this is a sandy soil and specify it. (WBM_EE)

This response suggests that the type of soil should be included as a way to make the model more reflective of the *complexity* found in nature. Observed Year 2 growth in model evaluation resulted in the transition from a basic level of understanding of how to appraise a model to an understanding inclusive of model limitations as evidenced by an increased desire for model *complexity*, matched by enhanced output generalizability evaluation.

Generalizability. Second, evaluation of the model output's *generalizability* increased in Year 2 from Year 1. In Year 1, only three out of the 18 students interviewed commented on model *generalizability* during their interview. While in Year 2, seven out of the seventeen students commented on model generalizability in their interview. More student interviews from Year 2 contained ideas about the evaluation of the model's *generalizability* overall. Students in Year 1 focused on the ability of the model to provide outputs for a 100-year time span and a lack of trust in climate change forecast data, demonstrating a low evaluation of *generalizability* of the model data. For example, when asked about model benefits and drawbacks, a student from Year 1 replied,

> A benefit I would say is that it's good to be able to look at a hundred year span and that way you can kind of see how things play out more than just 10 years or 20 years, because there a lot of long term impacts in everything especially when you're talking about irrigation…A downside would be you can look at climate models, but sometimes climate models can change. Especially with climate change and the way it is, we don't necessarily know… (WBM_BB)

This type of response demonstrates that the evaluation of the *generalizability* of the model was limited to time scale and lack of trust in climate data projections. Students from Year 1 also reported a lack of *generalizability* within the written assignment for the model. For example, one student, when prompted to consider what the model did not help the user to do, responded, "The model did not help me visualize future changes in precipitation and temperature" (WBM_01). This student exhibited a lack of *generalizability,* the movement of water did not contribute to their understanding of the interrelated nature of the model's precipitation components with future climate change. Other students struggled to *generalize* the components of the model to the reliability of the output. One student, when prompted to consider what the model did not help the user to do, responded, "There is no exact way to alter precip or PET values. It only gives it as an inflation or deflation factor which is helpful in a general sense" (WBM_06). This student's response reflected overall ideas from the Year 1 model written project responses, which demonstrate a lack of *generalizability* between model components, processes, and outputs.

However, in Year 2, students evaluated the simulation model outputs based on the *generalizability* between processes and their effect on water movement. When asked about the benefits and drawbacks of the model, one student responded, "It gives a general idea about the relationship of water use, irrigation, and how the water table is affected. The relationship is really clear and really understandable" (WBM_DD). Mirroring this thought, another student replied, "…a person can easily figure out the water stability and instability. It has a scale, a time interval, it makes calculations of the graph, and it is very easy to use…" (WBM_HH). These students demonstrated the ability to evaluate the model output's *generalizability* through the clarity of process relationships. One student, took the idea of generalizability a step forward and applied it to their own life experiences with water and irrigation,

> Positives, that it's as close as real life decision making. The data search and models that you could find as a student. I've never been on a farm. I've never dealt with water table, do you have enough water to irrigate your crops or not. So this is as close as I could get. (WBM_RR)

This type of response shows that the model's overall generalizability to students and their previous interactions with and knowledge about groundwater and irrigation was helpful.

When asked about how they might edit the simulation model, one student responded, "…I was talking about the types of soils and how they all have different way (*sic*) they hold water and so I would make sure that if I have to say this is a sandy soil and specify it" (WBM_EE). This student described how soil type affects other hydrologic processes, demonstrating their evaluation of the model's *generalizability*. Overall, students in 2018 included stronger evaluation of the *generalizability* of model components than students in 2017.

Specificity. The third theme that emerged from the student interviews and written model assignment work focused on the model's *specificity*. Year 2 interview data included four out of seventeen interviewed students commenting on the model's *specificity*, while three of the eighteen students interviewed in Year 1 evaluated the model's *specificity* during their interview. Year 1 themes surrounding *specificity* were related to model components, such as ease of use and the breakdown of model factors. For example, one student when asked to identify the weaknesses of the model, responded, "It did not explain how to adjust the factors and what it means when you change one. The graphs were hard to read unless previously explained" (WBM_23). This student's thoughts related to the theme of *specificity*, as they did not understand the factors or graphs within the model or in reference to the assignment content and context. Other students in Year 1 felt that the model's specificity was sufficient and were able to understand the meaning of components and outputs of the model. A student with this opinion, when asked about the benefits or drawbacks of the model, responded,

> The positives, I think, being able to visualize something like this. All the graphs and the charts and everything made it easier for me to understand

> exactly what was going on. Also, being able to manipulate the visualize as easily as we did. Just being able to type in, for instance, inflation, deflation factor of one point two, and then typing in your percent or irrigated maize and just hitting enter and having that graph pop up, I thought, was really, really nice. It made it easy. (WBM_ZZ).

This student's response indicated that the level of specificity was appropriate for their use and understanding of the model. Other students combined these two sentiments. Some felt that the model was easy, but that *specific* components of the model were cumbersome. Another student, when asked about the benefits or drawbacks of the model, responded,

> It was a little clunky maybe, with actually putting in the numbers but I think that it was really organized in the way that the subjects, the different factors were broken down. And with having a different list for the advanced climate options, I liked that. (WBM_EE).

This response reveals that while the *specificity* of the model in relation to the factors and components was sufficient for the content and context of the assignment, the user/interface interaction was lacking. Overall, in Year 1, student evaluation of the model's *specificity* were limited to its usability and the utility of the components/outputs. However, in Year 2, student responses surrounding the *specificity* focused on the precision of the model and less on the ease of its use or the physical utility of model features. For example, one student, when asked about the model drawbacks, responded, "I was not specific because you can't have certain point, this is ... you have to imagine maybe it's on 44% or 15% and sometimes you need specific number" (WBM_EE). Another student echoed this sentiment when asked about the model limitations, "Finding the specific measurements of the amount of runoff ratio that was predicted. Umm, yeah, mainly prediction" (WBM_HH). Both of these responses indicate that the *specificity* of the model's outputs were not precise enough and they wanted values that are more specific.

When asked about the ways they would change the model, one student suggested, "I think I can include a space where we can enter some data, like create data. Maybe measuring soil moisture…" (WBM_SS). This response demonstrates the thought that by potentially adding real-time, site-specific data, the *specificity* of the model, would overall increase. A parallel idea is the interest in more *specific* contextual information within the model. When asked to consider additional information needed to help make a decision within the context of the model assignment, one student responded, "One piece of additional information that would help is looking at a groundwater map of my specific district in order to determine which areas are in most need of aquifer replenishment" (WBM_13.2). This response reflects a desire for increased *specificity*, to reflect more accurately and precisely, the groundwater depth in a selected zone within the model. Overall, the theme of specificity revealed a desire for more accuracy and precision both within the model and its outputs in Year 2.

Discussion

Students across the K-16 continuum exhibit an array of alternative ideas about water systems (Author, 2015b; Gunckel et al., 2012; Author, 2017a; Cardak, 2009; Halvorson & Westcoat, 2002; Raia, 2005; Sherchan et al., 2016; Sibley et al., 2007) which can linger into adulthood (AMNH, 2005). Specifically, alternative conceptions such as those surrounding the movement of groundwater are resistant to change (Raia, 2008). As such, there is an ongoing, critical need for effective teaching and learning about water in formal classroom settings, including undergraduate classrooms (CUAHSI, 2018; Merwade & Ruddell, 2012; Ruddell & Wagener, 2013; Raia, 2005; Sherchan et al., 2016; Sibley et al., 2007). Introductory-level undergraduate courses offer unique opportunities to reach broad audiences of students (Sundberg & Dini, 1993). In these courses, students can learn to apply scientific knowledge to the most pressing Earth systems challenges of our age (Tewksbury et al., 2013), including those related to water. The application of the knowledge and practices of science to real world issues is a core component of scientific literacy in which students engage with the nature of science, interaction of science with society, and scientific terms and concepts (Murcia, 2009). Engaging students in the use of computational, data-driven water modeling tools can be an effective means to address this need (Gunn et al., 2002; Habib et al., 2012; Williams et al., 2009). This study provides important insights into students' abilities to interpret and use computer-based models to reason about real-world water-related issues.

First, study findings show that students' model-based evaluation skills and gains in basic hydrologic knowledge were greater in Year 2 than Year 1. Alternate conceptions, which were held at the beginning of the semester, were altered as evidenced by post-test responses. Phenomenon such as phase changes of water, which are difficult to visualize, are often an area with which students struggle (Cardak, 2009). Students enhanced their understanding of such ideas as phase changes, contour maps, plant-water relations, and overall diagram interpretation throughout the year. We hypothesize that these observed differences are attributable to the inclusion of active learning opportunities surrounding model instruction, a flipped classroom approach, group work, and increased sophistication of modeling practice in their performance on assignments.

The literature indicates that flipped classroom techniques are capable of increasing student learning and engagement (Abeysekera & Dawson, 2015; Barral et al., 2018; Jones et al., 2019; Zainuddin & Perera, 2019). Additionally, flipped classrooms offer diverse populations of learners varied opportunities to interact with content, making them more likely to encounter an effective strategy for learning (Gross et al., 2015). These pedagogical changes may have enabled students to not only increase their basic understanding of hydrologic concepts, but also better unpack the model outputs in order to understand their meaning more thoroughly and apply it to questions related to the use of groundwater flow and aquifer use in the Midwest.

However, we observed no clear relationship between students' understanding of core hydrological concepts and their model-based reasoning about water. A core assumption of undergraduate STEM education, including in the geosciences, is that students should develop multi-faceted understanding of core disciplinary concepts to be able to reason effectively about natural systems and their human dimension (Tewksbury et al., 2013). These findings contribute to the understanding of how to help students develop understanding of hydrologic concepts in the context of an innovative, interdisciplinary course, and present questions that merit further study.

Second, study findings illustrate finer-grain trends in students' model-based reasoning. Students exhibited higher levels of model-based evaluation reasoning in Year 2 as compared to Year 1. These improvements to students' evaluation of the model revolved around the three themes of complexity, generalizability, and specificity. Giving students the tools and power to evaluate a model helps them to build their own learning about model content (Gouvea & Passmore, 2017) as well as the ability to identify the practical constraints of models (Coll et al., 2005). Knowing when the application of a specific model is contextually appropriate (Pluta et al., 2011) is developed through the process of model evaluation, of which, learning to compare, revise, and verify are all components (Bybee, 2011; Coll et al., 2005; Gouvea & Passmore, 2017). Learning to evaluate a model's characteristics, then, is similar to learning to think scientifically. Making comparisons, revisions, and checking veracity are all components of scientific thinking that must be developed. These are key findings that contribute to a broader body of work on model-based teaching and learning in science across the K-16 continuum (Author, 2017a, b; 2015a, b).

Implications

Using models requires students to develop skills and proficiencies surrounding both their *use* and *evaluation* (Gobert & Buckley, 2000) and including the visualization of phenomena, explanation of information, innovation, and hypothesizing (Gilbert, 2004; Gouvea & Passmore, 2017). A key element in undergraduate students' productive use of models is the model itself. It is vital that the simulation model provided is substantive enough for meaningful student use while preserving a practical interface for introductory students (Erturk, 2010). The model used in this study meets these needs. It offers a clean and simple interface, based on scientific data, fulfilling criteria for an effective simulation model for introductory students and includes in-model assistance with definitions and pop-up graphs, which are helpful to students navigating the input options (Erturk, 2010). Nevertheless, students can still evaluate this model in the context of the course and assignment based on key epistemic dimensions.

Yet, study findings suggest that simply making computer-based models available and accessible to students is only part of the challenge. Specific curriculum and teaching in support of desired modeling practices and outcomes is needed. Students need opportunities to practice evaluating models for their ambiguity, as well as other model features such as reliability and limitations. Computer-based models supported by instruction and curriculum are needed to highlight the unpredictability of water in relationship to other equally chaotic processes such as climate and the economy so that students are prepared to meet the challenges of the future (CUAHSI, 2018). As shown in Year 1, merely providing students with a user-friendly model does not necessarily result in its effective use and evaluation. Purposefully designing curriculum to support learning to evaluate a model, as indicated by Year 2 data, does help to increase these types of learning gains. Learning to use a model can benefit students through the advancement of the habits of mind and an increase in the ability to appraise model components (Krajcik & Merritt, 2012; Nersessian, 1999; Schwarz et al., 2009). Pairing the right model to content at the right time in a student's developmental trajectory is a critical part of effective model-based instruction.

Limitations

While several insights can be gained from this study, limitations exist. This study is limited by the sample size of students as constrained by the maximum number of students thought by the research team to be optimal for enrollment in the course and course activities. Future work surrounding larger numbers of students would aid in evaluating both the model itself and the teaching strategies described. Additionally, because the questions on the model project were open-ended some students may not have demonstrated evaluation or use skills they actually possessed. The rubric was aligned with our scientific modeling theoretical framework, but was adapted for use in this study. While the rubric is useful, the project was not written for the rubric and may have needed more explicit instructions in order for students to achieve the highest possible rubric score.

Conclusion

This study illustrates undergraduate students' model-based reasoning about water systems, advances research focused on students' use of computer-based models to reason about water systems (Author, 2018, 2017a, b; Singha & Loheide, 2011; Sins et al., 2009; Williams et al., 2009; Zigic & Lemckert, 2007) and students' ability to critically evaluate models (Calvani et al., 2008). Students likely differ between years based on increased emphasis of model evaluation in Year 2 over Year 1. Epistemic dimensions including evidence, representation, and explanation are useful in underpinning specific student instruction surrounding model evaluation and use and may have contributed to overall increased model evaluation reasoning skills in Year 2. To help students make these types of gains, increasingly student-centric instructional strategies can be used to assist students in developing scientific habits (Handelsman et al., 2004). The incorporation of active learning approaches, such as modeling, can enhance learning about hydrologic processes and hydrologic course content (AghaKouchak et al., 2013), supporting overall student learning. Specifically, best practice strategies including active learning opportunities within a flipped classroom can contribute to learning gains surrounding the evaluation of a model. Curriculum that supports these components and students is valuable.

Appendix 4.A

Most Commonly Missed Pre-test Questions and Percentage of Correct Post-test Answers from 2017 and 2018

2017				2018		
Most Commonly Missed Pre-test Questions	Pre-test % of correct answers	Post-test % of correct answers		Most Commonly Missed Pre-test Questions	Pre-test % of correct answers	Post-test % of correct answers
Using the diagram below, please write a sentence describing each of the following: 1) The most likely location of a stream, 2) The watershed boundary of that stream, 3) At least 4 arrows that represent the directions of the surface runoff in this area after a high rainfall event.	11	29		On a beautiful morning in late November, you go outside and all of the windows on your car are covered with frost. Why did this frost form?	12	85
Latent heating of the atmosphere refers to heat transferring through the process of:	18	84		Using the diagram below, please write a sentence describing each of the following: 1) The most likely location of a stream, 2) The watershed boundary of that stream, 3) At least 4 arrows that represent the directions of the surface runoff in this area after a high rainfall event.	23	87
A large tree can pull in 200 gallons of water a day. Describe what happens to the 200 gallons of water that the tree pulls in. List one place that the water the tree pulls in could go. Explain how it gets there and why it goes there. How much of the water that the tree uses would go there?Â All, most, half, or a little?	39	50		Can pollution in the river water at Town B get to Town C? Why or why not?	25	90
What is the most prevalent greenhouse gas found in the atmosphere?	39	92		Latent heating of the atmosphere refers to heat transferring through the process of:	27	87
Which of the following greenhouse gases can cause an increase in the temperature of the atmosphere?	50	92		Describe the direction water is flowing away from Town F. How do you know the water is flowing this direction?	35	60
On a beautiful morning in late November, you go outside and all of the windows on your car are covered with frost. Why did this frost form?	55	82		What is the most prevalent greenhouse gas found in the atmosphere?	35	88
What is needed for clouds to develop?	55	95		The total volume of water on earth is: increasing, decreasing, varies over time	44	94
Can pollution in the river water at Town B get to Town C? Why or why not?	55	97		Ice is placed in a container which is heated steadily and continuously. The ice is initially below its freezing point, and during the heating process it turns to water and finally the water boils. The graph below shows how the temperature varies with time during the heating process. Four distinct portions of the graph are labeled 1, 2, 3, and 4. Which portions represent phase changes?	44	96
Ice is placed in a container which is heated steadily and continuously. The ice is initially below its freezing point, and during the heating process it turns to water and finally the water boils. The graph below shows how the temperature varies with time during the heating process. Four distinct portions of the graph are labeled 1, 2, 3, and 4. Which portions represent phase changes?	58	79		Which of the following greenhouse gases can cause an increase in the temperature of the atmosphere?	44	87
The total volume of water on earth is: increasing, decreasing, varies over time	63	95		If the playing fields were treated with fertilizer, do you think that some of the fertilizer could get into the river? If you think yes, explain how and why the fertilizer could get into the river. If you think no, explain why fertilizer would not get into the river.	48	92

CHAPTER 5

SOCIO-HYDROLOGIC SYSTEMS THINKING: AN ANALYSIS OF UNDERGRADUATE STUDENTS’ OPERATIONALIZATION AND MODELING OF COUPLED HUMAN-WATER SYSTEMS

A hallmark of environmental problem solving is the complicated interweaving of components with varying rates and magnitudes of response to change (Richmond, 1993). Exacerbating the challenging nature of these contemporary problems is the interconnectivity of human and natural components of a system, such as the effect of human activity on water systems. One way of addressing these types of problems is through systems thinking, which is a key component of science and environmental literacy (Hmelo-Silver et al., 2017; Yoon & Hmelo-Silver, 2017). Learning how to think about interactions between systems, the far-reaching effects of a system, intended and unintended human interactions with system processes, and the dynamic nature of systems, are all important systems thinking skills. Yet, requiring students to solve problems that either do not exist or have low impact is not engaging, does not contribute to active learning for students, and can minimize the benefits of systems thinking. It is therefore critical to systems thinking skill development to engage students in authentic learning opportunities grounded in real-world scenarios where students can gain experience thinking about, explaining, and making decisions about complex coupled human-natural systems.

An integrated sociohydrologic system is an ideal context through which students could develop systems thinking skills. Sociohydrologic systems (SHS), are water systems that include both human and natural dimensions. However, research has shown students are challenged by reasoning about both natural and human dimensions of SHS (e.g., Assaraf & Orion, 2005; Covitt et al., 2009; Gunckel et al., 2012; Petitt & Forbes, 2019; Sabel et al., 2017; Sibley et al., 2007). To support students' systems thinking about SHS, we developed and implemented a new interdisciplinary undergraduate course. The course, Water in Society, engages students in systems thinking through the lens of water. In the course, students engage in reasoning and decision-making about real-world sociohydrologic issues, an important component of water literacy (Shepardson et al., 2009), interpreted as a subcomponent of scientific literacy. However, although systems thinking-based problem-solving has the potential to benefit student learning, gaps exist in our understanding of students' use of systems thinking to operationalize and model SHS, as well as their metacognitive evaluation of systems thinking.

Studying student use of systems thinking through operationalization, modeling, and metacognitive evaluation of an SHS is valuable because the way students learn about hydrologic systems can directly impact their conception of such systems (Shepardson et al., 2009). Learning how students use systems thinking is also important from an informed populace standpoint; decision making and implementing changes in human actions to benefit the hydrologic system is critical to the overall earth system (Batzri et al., 2015). How can we identify the ways in which students, in the context of an interdisciplinary sociohydrologic issue, (1) use systems thinking to operationalize a problem, (2) communicate the system through a robust systems thinking model, and (3) evaluate the limitations of their work? We hypothesize that systems thinking-based explanation and modeling are correlated skills that can help students reason about a SHS.

To test this hypothesis, we collected and analyzed data from three consecutive years of SCIL109 to respond to the following study questions:

1. How do students perform on a sociohydrologic issue systems thinking modeling and writing assignment?
2. To what extent is the systems thinking model score predictive of the writing assignment score on a sociohydrologic issue?
3. How do students evaluate their own systems thinking models of a real-world sociohydrologic issue?

Teaching and Learning about Water

Students' experiences of, formal education about, and resulting ideas concerning hydrologic systems change over time. Transitioning from spontaneous experiences with water to more nuanced ideas about water systems and the role that humans play in them requires students to connect concepts such as conservation of matter with fundamental hydrologic concepts (Covitt et al., 2009). Formal education from kindergarten through to grade 12 (K-12) helps students build basic knowledge about water and, for many, may be their last experiences with water-related content in formal classroom settings. Misconceptions that are not addressed in the K-12 grades may continue to be expressed as scientifically inaccurate ideas surrounding water in undergraduate students (Cardak, 2009; Gunckel et al., 2012; Halvorson & Westcoat, 2002; Vo et al., 2015) and potentially in adult life (Duda et al., 2005).

Undergraduate students' understanding of water systems should develop as students learn more about related systems, processes, and phenomenon. However, not all students are required to take classes where they are exposed to water-related concepts and, therefore, may not develop robust conceptual understanding of water. As a result, misconceptions surrounding evaporation, atmospheric water, and conservation of matter relating to water through the hydrologic cycle may persist (Cardak, 2009). Students also illustrate varying levels in their ability to think about the unseen components of the hydrologic systems and associated repercussions such as hydrogeochemical processes or the interactions of groundwater (Sibley et al., 2007). Those parts of the cycle, which are invisible or difficult to observe directly, such as hydrologic cycle phase changes, often represent an obstacle to undergraduates when considering the water cycle (Sibley et al., 2007). For example, students have been found to demonstrate misconceptions of as many as seven different aspects of just one phase change—evaporation (Coştu et al., 2010). On the other hand, others compartmentalize the water cycle as separate from the carbon and rock cycles, despite the explicit linkages between them (Batzri et al., 2015), or compartmentalize parts of the water cycle such as atmospheric water cycling as separate from geosphere water cycling (Cardak, 2009). Compounding their misconceptions is the difficulty in applying content to students' everyday lives and the often-theoretical nature of models used to teach hydrologic content (Canpolat, 2006). In response to these challenges of needing more formal hydrologic cycle instruction, the invisible nature of some hydrologic cycle components, and the difficulty in applying theory to practice in life, students may turn to their previous experiences with the hydrologic cycle to fill in the gaps (Shepardson et al., 2009). Experiences in the form of education, social structures, and other cultural factors could all work to shape student systems thinking

(Shepardson et al., 2009). In order to be able to reason effectively about water-related issues in the future, students need more opportunities and support to develop skills related to water literacy.

Theoretical Framework for Systems Thinking

Systems thinking is the study of the interplay between the subsystems comprising an overall system (Bawden et al., 1984). Effective systems thinking requires both the application of scientific knowledge and its associated epistemic dimensions. These epistemic dimensions take the form of contextualization and integration of human actions (Bawden, 2007). Systems thinking requires the learner to contextualize a multifaceted issue by interweaving varying levels of the problem with different earth system components. Students must integrate themselves, or, at the very least, humans and their actions, as inherent catalysts of change within a system. Taking the dimension of integration a step further, the perspective of the learners must be reconciled with the context and content of the system if a decision or hypothesis is a desired outcome (Bawden, 2007). Learning to connect content, context, interactions, and human integration into systems thinking requires directed learning surrounding the related skills.

Here, we draw upon two conceptual frameworks for systems thinking. First, within the context of a systems thinking model, students explore the interlocking phenomenon/patterns, mechanisms, and components through a visual representation (Jordan et al., 2014b) (Table 5.1). Second, five components of systems thinking are expressed through a framework reflecting the inherent features of systems (Grohs et al., 2018) (Table 5.2). Both the systems thinking modeling and written dimensions contribute to the overall theoretical framework as one amplifies the other (Figure 5.1). These two linked skills help students by serving as a placeholder for ideas, thereby helping alleviate some of the mental load of systems thinking.

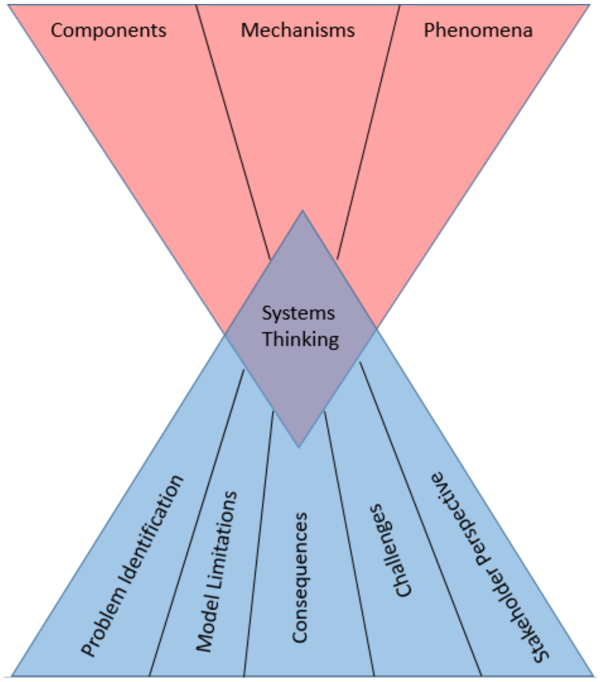
Table 5.1. *Elements of a systems thinking model (Jordan et al., 2014b).*

Element	Definition	Example
(P)henomenon or Pattern	Final product(s) or process(es) resulting from the system	Eutrophication, unsafe water
(M)echanism	Processes involved with the system	Leaching, increasing taxes, lobbying
(C)omponent	Things and organizations involved with the system	Nitrogen, taxpayers, farm, government

Table 5.2. *Components of systems thinking (Grohs et al., 2018).*

Component	Description
Problem identification	The mechanics and the circumstances of the problem.
Stakeholder awareness	The different people and roles they play in the system and potential solutions.
Unintended consequences	Unintended and intentional consequence exploration in both immediate and delayed temporal scales.
Implementation challenges	Including the non-negotiable processes and components, both mechanical and circumstantial in nature, accompanied by the exchanges that occur when trying to problem solve for multiple layers and players in a system.
Model limitations	The product of self-evaluating the comprehensiveness of one's systems thinking model.

Figure 5.1. *Theoretical framework of systems thinking skills.*



As modeling is a key component of systems thinking, model evaluation is then also a necessary practice. Specifically, model evaluation is a component of a more comprehensive schema stemming from our K-12 and undergraduate research and development (e.g., Lally & Forbes, 2019b; Zangori et al., 2017). Model evaluation includes all of the ways in which students compare, confirm accuracy, revise (Coll et al., 2005; Gouvea & Passmore, 2017), and identify fit (Pluta et al., 2011).

Supporting Students' Systems Thinking

Students need opportunities to develop systems thinking in formal classroom contexts. However, although systems thinking is a critical outcome for students, research has shown that it is arguably underemphasized in undergraduate geoscience courses (Lally et al., 2019) and, even when it is emphasized, students often struggle to engage in this practice productively (Batzri et al., 2015; Jordan et al., 2014a; Kastens et al., 2009;

Rates et al., 2016). However, there are many ways in which formal learning environments can be designed to support students' developing systems thinking abilities. For example, first, instructors can help students learn systems thinking skills through explicit instruction and practice with the requisite cognitive skills. When the development of systems thinking is broken down into specific cognitive skills, it becomes apparent that students must be taught each of these skills (Vo et al., 2015), how to link them, and be given opportunities to practice using all seven of these faculties at one time. Due to the interlinking nature of systems thinking, it is helpful to teach students to systems think with increasingly difficult systems, or by increasing the complexity of a single system.

Second, models students generate by hand or digitally can be used as scaffolds to student learning and thinking about systems (Cardak, 2009; Danish et al., 2017). The ability to see the system helps students by alleviating some of the mental burden of simultaneously thinking about and visualizing the components of a system. One reason for the difficulty of systems thinking is that many different thought processes must all occur simultaneously, including finding patterns, visualization, quantification, operationalization, and hypothesizing (Vo et al., 2015). Multiple layers, players, and systems have to be considered when using systems thinking to evaluate a problem or test a hypothesis. It can be challenging to overcome the difficulty of keeping many chains of thought moving all at the same time.

Another way to enhance systems thinking fluency is by spending time discussing the mechanisms and patterns surrounding components to help students make system connections (Cardak, 2009). Sometimes it is difficult for students to conceptualize how all of the seemingly disparate components of a system might be connected. The more students engage in discussion about areas of difficulty, the more detail they may be able to include in their systems thinking models. Transfer is the ability to use information from one scenario in a seemingly disparate way in another scenario, and can be useful to consider for students in the systems thinking process (Cardak, 2009). Students who are engaged in active learning surrounding systems thinking can demonstrate a more robust understanding of the system, as demonstrated by a more detailed and inclusive systems thinking model product (Assaraf & Orion, 2005). Development of a robust systems thinking model is enhanced when theories, ideas, and content from other areas merge in one cohesive model.

Materials and Methods

Water in Society

Participants and data for this study came from the course, Water in Society (Forbes et al., 2018), an elective, interdisciplinary, three-credit introductory water course at the University of Nebraska. Students learn about the increasingly linked components of the Food–Energy–Water nexus (FEW-Nexus) and complete several projects related to course material. Throughout the course, students learn to use and complete assignments surrounding two computer-based water models, participate in large and small group discussions, and complete a capstone systems thinking assignment that integrates course goals and content. Averaging 55 students per year, the course has been offered annually in the spring semester for each of the past 3 years. This study focuses on three consecutive course offerings of spring 2017 (Year 1), 2018 (Year 2), and 2019 (Year 3), each including the same instructional team, goals, organization, and assessments.

During the systems thinking unit, students completed a worksheet in which they learned the basic process and associated terms of systems thinking. They listened to a short recording about climate and wrote down everything they identified as relevant to or influencing climate. These terms were then sorted into the categories of flux, storage, and feedback. Next, students evaluated a systems thinking model of the climate recording, and revised it as needed in accordance with their notes and through small group discussions. During the following class period, students formed small groups and made a systems thinking model of a recreational lake of their choosing. They were instructed to include the components, mechanisms, and overall processes contributing or resulting from the systems. Upon completion, students participated in a gallery-walk, in which the models were hung on the walls of the classroom for all students to view. This provided an opportunity for students to evaluate one another's systems thinking models and provide and receive feedback. Finally, students developed a list of all of the processes, components, and reservoirs of the Raccoon River water crisis as a warmup for the systems thinking assignment they would complete.

Participants

Participants in Year 1 (*n* = 35), Year 2 (*n* = 48), and Year 3 (*n* = 46), were undergraduate students enrolled in the course. Approximately equal numbers of male and female students enrolled in the course, with science, technology, engineering, and mathematics (STEM) majors comprising the majority of students across the three study years. A large proportion of the learners were international students, contributing to the diverse populations of learners represented by the participants. Student demographics are presented in Table 5.3.

Table 5.3. *Student demographics from 2017, 2018, and 2019.*

	Female	**Male**	**Freshmen**	**Sophomore**	**Junior**	**Senior/ +**	**STEM Major**	**Non-STEM Major**
2017	15	20	9	10	9	7	26	9
2018	27	21	2	24	13	9	44	4
2019	19	27	5	16	16	9	42	4

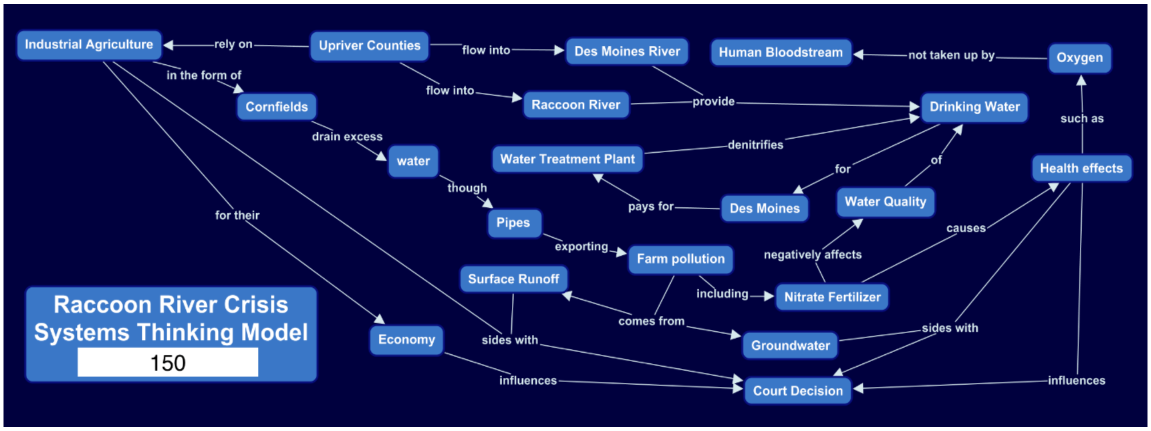
Data Collection

Systems thinking assignment. In the course, students completed a systems thinking assignment in which they were provided with information about a contemporary sociohydrological issue grounded in the Raccoon River near Des Moines, Iowa (IA). The river scenario affecting the city of Des Moines in the state of Iowa (IA) was selected because it is a regionally relevant sociohydrologic issue (SHI). Broadly, the Des Moines, IA, water crises is the result of a tangled web of competing interests. The Raccoon and Des Moines Rivers provide much of the city’s water, from which nitrates and phosphates are removed prior to human use. Some feel that farmers upstream are benefiting from a Clean Water Act loophole that identifies farm runoff as non-point source pollution. However, farming is one of the primary economic drivers of the state and any future water quality regulations probably would be difficult to implement and enforce (Rodgers

& Eller, 2017). A lawsuit was filed by the Des Moines Water Works board against upstream counties of northern Iowa (Rodgers & Eller, 2017) and the state has passed the Water Quality Bill containing a two-pronged approach directing money at projects related to helping (1) farmers problem-solve to reduce fertilizer runoff and (2) municipal water facility improvements (Pfannenstiel & Eller, 2018). On a national scale, the Raccoon River is in the Mississippi River watershed and contributes to the Gulf of Mexico dead zone (Royte, 2017). This reduced water quality is also detrimental to local water resources, contributing to increased algal blooms in Iowa lakes.

As part of the assignment, students were to generate a systems thinking model (box-and-arrow diagram) (Figure 5.2) and write an accompanying newspaper article-style description. Students' goal for the assignment was to describe the system in a way that enabled the citizens of Des Moines to understand the problem and associated processes. For the systems thinking model, students were to identify components of the water crisis within boxes, then demonstrate interconnectedness between the components through a series of arrows or lines. Labelling each arrow or line with a process demonstrates the relationship between connected components. Students were encouraged to include as many details, including processes and components, as they could find that were relevant to the system and helpful in describing it to a potential reader (Table 5.1).

Figure 5.2. *Students' most often included system components in their model.*



For the newspaper article description of the Des Moines, IA, water crisis, students were to explain their model to readers and supply additional information not captured within their model. The article was required to include an overview of the system including major components, feedback, and processes with their interconnectivity described for readers (Table 5.2). A discussion of non-negotiable systems components and processes was to be included, along with a description of what could happen within the system if nothing is done to alleviate the problem. To further demonstrate understanding of the human component, students needed to address how various stakeholder groups would benefit or not benefit from various interacting components and processes. Finally, students were to include a description of the limits of the model including ideas that it did not contain or show. Discussing the limits of their model is important because it can be used as a way to qualitatively measure student self-evaluation.

Data Analysis

Quantitative analyses. A scoring rubric, modified from Grohs and colleagues (2018), was applied to the written article component of the systems thinking assignment. Written systems thinking articles were scored according to the depth of discussion surrounding five key categories: problem identification, stakeholder awareness, unintended consequences, implementation challenges, and model limitations, ranging from 0 to 3 (see Appendix A). The modeling component of the systems thinking assignment was scored using the rubric from Jordan, Sorensen, and Hmelo-Silver (2014b) (Table 1). Models were scored according to a simple count of the number of occurrences of *phenomenon*, *mechanisms,* or *components* found in each. Numeric scores were calculated for each article and model.

Inter-rater reliability was established between two coders for all of the data from each year of the study for both models and written components. Rounds of coding for both the models and written components included 10% of the data sample and a review of discrepancies between coders, continuing until percent agreement reached 0.9 for the models and 0.85 for the written component, with discussion following each round of coding, resulting in percent agreement of 1.0 for both the written and components and models. Cohen's kappa was calculated after the final round of coding for the models (k = 0.79) and the written assignments (k = 0.81) (Lombard et al., 2002). Model scores were analyzed quantitatively in comparison to article scores to explore relationships between students' written systems thinking understanding and modular representation.

Qualitative analyses. For this component of the study, student self-evaluation identified as model limitations in the written article scoring rubric were grouped by emergent theme. Identification of self-evaluation themes allowed for comparison between rubric score levels and pattern identification among students. For this study, students' written articles were analyzed for the described limitations of their systems thinking model. Limitations were categorized on the basis of the type of limitation: scope/scale; temporal; or a specific component, mechanism, or pattern that was excluded from the model. Only one round of coding was needed to reach a percent agreement of 0.93 with 10% of the data coded and discussion following coding until agreement reached 1. Cohen's kappa was calculated after this first and final round of coding for the model limitations (k = 0.89) (Lombard et al., 2002). The coded self-evaluation data supports and helps explain the results from the qualitative analyses.

Results

In research question 1, we asked, "How do students perform on an SHI systems thinking modeling and writing assignment?" Statistical analyses were conducted using mean scores on students' drawn models and newspaper articles across all 3 years. For students' drawn model scores, there was a significant effect of model category on overall model score at the $p < 0.05$ level ($F(2, 384) = 91.67$, $p < 0.05$). Post hoc comparisons using Tukey's honestly significant difference (HSD) test indicated that the mean score for components was significantly higher than the mean score for mechanisms, which was also higher than the mean score for phenomenon/patterns (Table 5.4) (see Appendix 5.B). These results suggest that students included more components than mechanisms or patterns in their drawn models of the system. The model category, mechanisms, correlates with, components ($r(127) = 0.24$, $p < 0.05$), but not phenomenon/patterns. This observation indicates that as students included more mechanisms in their models, the quantity of components increased in their drawn models as well.

Statistical analyses were also conducted using the written systems thinking newspaper article scores. There was a significant effect of article category on overall model score ($F(5, 768) = 401.6$, $p < 0.05$). Results show that students scored the highest on problem identification from their written newspaper article and scored the lowest on their description of unintended consequences. Post hoc comparisons using Tukey's HSD test indicated that the mean score for problem identification was significantly higher than all of the other categories (Table 5.5) (see Appendix 5.B). Although the category of implementation challenges is not significantly different from limitations or stakeholder awareness, students scored higher on it than on unintended consequences, indicating that students were best at articulating the problem within the system and least proficient in describing the unintended consequences of the system. Although stakeholder awareness and model limitations also represented areas of improvement for students, model limitations was distinct because it was correlated with all of the categories (stakeholder awareness, $r(127) = 0.178$, $p < 0.05$; unintended consequences, $r(127) = 0.422$, $p < 0.05$; implementation challenges, $r(127) = 0.0543$, $p < 0.05$) except problem identification. Overall, these findings indicated that as students incorporate more ideas about model limitations, their overall article score increases.

Table 5.4. *Tukey's honestly significant difference (HSD) comparisons for article and model components.*

				Tukey's HSD Comparisons		
Model Component	***n***	**Mean**	**SD**	**Components**	**Mechanisms**	**Phenomenon/ Patterns**
Components	129	13.54	7.15			

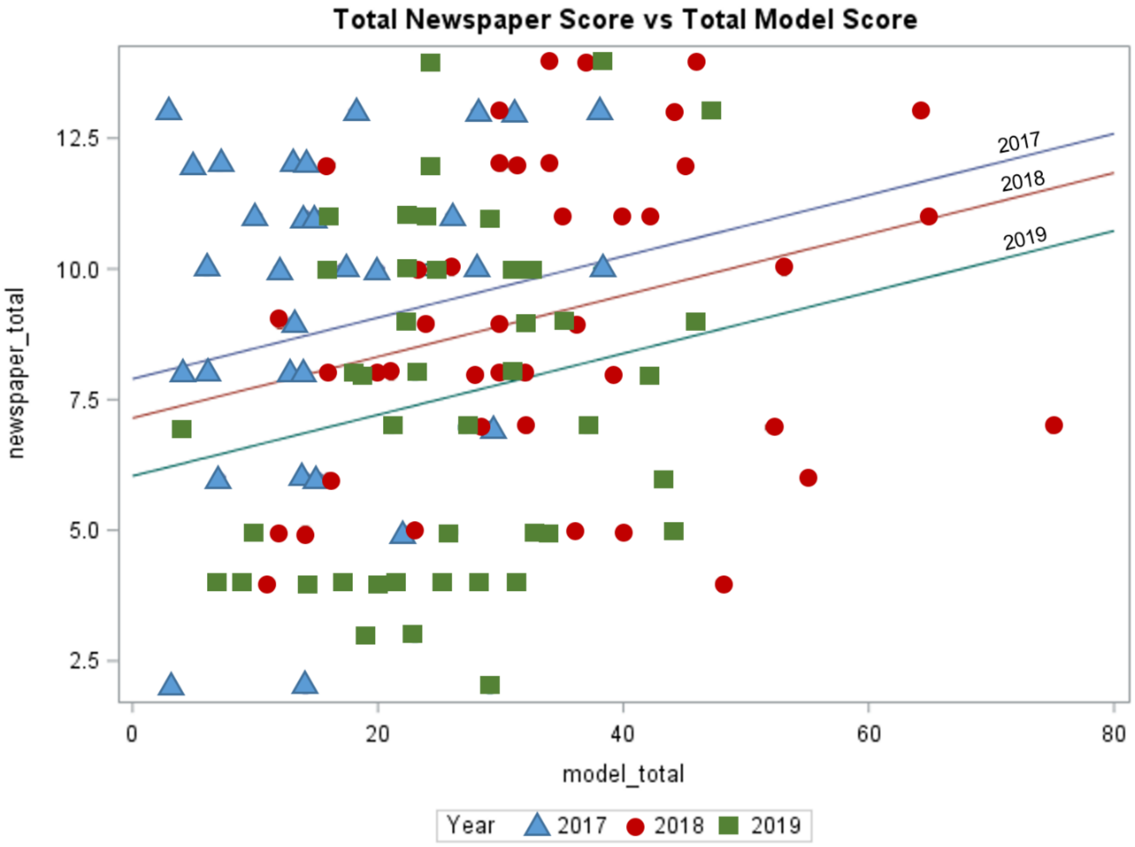
Mechanisms	129	9.34	7.86	<0.0001	
Phenomenon / pattern	129	3.01	2.39	<0.0001	<0.0001

Table 5. *Tukey's HSD comparisons for article and model components.*

				Tukey's HSD Comparisons				
Article Component	***n***	**Mean**	**SD**	**Problem Identification**	**Stakeholder Awareness**	**Unintended Consequences**	**Implementation Challenges**	**Model Limitations**
Problem identification	129	2.22	0.73					
Stakeholder awareness	129	1.5	0.82	<0.0001				
Unintended consequences	129	1.43	1.1	<0.0001	0.9883			
Implementation challenges	129	1.79	1.21	0.0058	0.1379	0.04		
Model limitations	129	1.53	1.14	<0.0001	0.9992	0.9484	0.2294	

For research question 2, we asked, “To what extent is the systems thinking model score predictive of the writing assignment score on a sociohydrologic issue?” Written article, model scores, and cumulative systems thinking assignment scores for each year were also compared to one another to gain further insight into the relationships between the two systems thinking tasks. A regression analysis and analysis of variance (ANOVA) were performed, results of which suggest that students who score better on the drawn model also perform better on the written article ($t(125) = 6.60$, $p= 0.01$, $\eta^2 = 0.88$) (Figure 5.3). We also analyzed the effect of year on total systems thinking score, which is the drawn model and written article combined, through a regression and an ANOVA analysis ($r(125) = 3.19$, $p = 0.04$, $\eta^2 = 0.57$; $F(2, 126) = 19.8$, $p < 0.001$). Both analyses indicate that there were statistical differences between total systems thinking scores for each year of the course (see Appendix 5.C). An ANOVA of the effect of year on the total systems thinking score revealed that regression lines of expected scores overlain with observed scores for each year demonstrate the slope remaining constant for varying intercepts for each year (*β* = 0.058). The way we approached the year was taking this as a blocking effect. This allows us to assume and model that the years are acting differently.

Figure 5.3. *Observed values by year with associated regression lines.*



The systems thinking scores across years were significantly different from each other. The higher total model and total article scores were all from 2019, whereas the lower total model and total article scores were from both 2017 and 2018. These outstanding points could have resulted from changes made to other course components and overall differences between student populations from year to year. However, the overall regression for model effect was greater than that for year effect on the systems thinking score. This allowed us to end up with a model including a year effect. Where the intercept starts was different because some years were naturally more variable, and the slope remained the same for the total systems thinking score for each year. Overall scores differed between years, but the relationship between the drawn model and written article scores did not. The fundamental relationship was the same no matter where they started or ended.

For research question 3, we asked, “How do students evaluate their own systems thinking models of a real-world sociohydrologic issue?” This qualitative data served to augment the quantitative results from research questions 1 and 2. A positive correlation existed between the limitations score and the overall written assignment score ($r(127) = 0.71$, $p < 0.001$; $F(1, 128) = 7.51$, $p < 0.05$). Correlations were neither found between the limitations written assignment score and overall model score, nor the individual scores for mechanisms, components, and phenomenon/patterns. Students who included a more robust discussion of limitations also performed better on the overall written assignment. Out of the 129 students who completed the systems thinking assignment, 22% failed to include a discussion of any limitations of their drawn model. Of the students who did discuss a drawn model limitation, following analyses, three themes emerged: *scope/scale limitations; temporal limitations; and specific components, mechanisms, or phenomena excluded*.

Scope and scale limitations. First, analyses revealed responses categorized as those having to do with the limitations of the capacity to deal with concepts such the limits to the assignment itself, limited available information, or a limited level of specificity. Students commented on the limitations inherent within the assignment itself, including ideas such as the physical space the assignment uses, the quantity of factors, and the ability to effectively communicate their ideas about a “wicked problem”. For example, one student responded about these types of limitations, writing, “Part of the issue of showing all data is that there can never be enough space to show connections without it becoming incredibly confusing to understand and intricate” (ST_55). Other students echoed this message of *scope and sale limitations* by writing, “It does not show all aspects of this issue, it only shows the ones that are easy to portray” (ST_9). Similarly, a student wrote that, “The model would have to be expanded tenfold to be able to incorporate all of the human interactions in this system” (ST_6). Students felt that they were not able to effectively discuss all of the influences and aspects of the Raccoon River Water Crisis without compromising the intelligibility of their drawn models. Sometimes students combined multiple ideas into one response such as, “The limit of the model is that there are so many components involved and the model does not clearly explain the how much each party contribute” (ST_129). This response demonstrates both the concepts of scope and scale—the idea of scope as a nearly infinite quantity of components that they would need to include in their model for it to be accurate. The idea of scale is also alluded to; some components had larger impacts than others within the system, which this student noted was not defined within the model. For the model, students were not specifically asked to prioritize components, mechanisms, or phenomena. Similarly, some components of the system remained unmeasured or undocumented (e.g., microplastics), further limiting the overall scope and scale of the model.

However, some felt that they did not have all of the information they needed to effectively convey the scope and scale of the Raccoon River Water Crisis system. For example, one student responded to model limitations by stating, “I think the systems thinking model is limited just because of all the ‘hidden’ things that haven’t been in the news articles” (ST_130). This acknowledges that there are components that are missing from their available information sources, which could have contributed to their model’s accuracy. Another student described a lack of quantitative data as a limiting factor of their model, “I was limited due the fact that there are no numbers that shows how one component affect the other” (ST_124). This response indicates that the level of precision of their model was hampered by the lack of quantitative data available. This level of specificity as a scope and scale limitation was less common in student responses. However, several students commented on scope and scale specificity limitations in reference to names and overall dynamics.

Some students explored the idea of scope and scale specificity through their discussion of limitations related to grain size. One student listed a generalized statement of limited scope and scale by writing, “Broadly, farmers, wildlife, government and environmental groups are not specific. They are listed as large groups although there are probably many different opinions and perspectives within these groups” (ST_96). This type of limitation demonstrates that although the student chose not to break down groups into subgroups, they acknowledged that in doing so, their model may be misleading. A student spoke to this idea as using the model for approximating the scenario without including every specific detail available. They wrote,

> The model we use to estimate what is going on is likely to be limited to not putting into consideration every little factor that is involved in this process and it is likely to make assumptions about some processes involved but it is going to help us with estimating what is going on with the river and its system. (ST_61).

This type of response indicates that even though the models were limited in scope and scale, as well as the fact that some of the details were glossed over, the models were still valuable as proxies for the scenario overall.

Temporal limitations. Temporal limitations were primarily described as those having to do with not knowing what will happen in the future with the system. In a written response containing a temporal limitation, one student said,

> I think that the system model gives more of a past and present description instead of the future description and although that's good, I think it would be even better if the future was also deeply analyzed because it would help in determining the rate at which the problem needs solved. (ST_63)

This response indicated that students were aware of the past, present, and future dimensions of a system and acknowledge that their models are limited without the future possibilities. A few students spoke to future possibilities as limiting factors within their models. A student with this type of response wrote, "It may take years of research to learn what species got affected by the algae in the river, and what health effects it had on people" (ST_45). Responses like this one demonstrate that without the ability to either know or predict future effects of the Raccoon River water crisis on different parts of the system, models will be limited to past and present data, which may not encompass all of the system changes, including specific components, mechanisms, or phenomena.

Specific components, mechanisms, or phenomena excluded. Most often, in their discussion of model limitations, students listed a specific component/mechanism/phenomenon that was missing from their drawn model. The most common of these three categories was specific components that were excluded from the model. For example, one student wrote, “I find limitation with the way that there is not shown part of the city population in contaminating the rivers, it seems like all blame is for the farmers who use fertilizers on their farms” (ST_139). Student responses such as this indicate that they realized their models were limited in the specific perspectives included. Other students shared similar sentiments, stating that their models were limited in the lack of farmer perspectives included. Another specific component students cited as missing from their interpretation was monetary values. A student responded to the model limitations by writing, “My model does not show economic struggles of the area and how the money in this city is currently being used” (ST_8). This student demonstrated awareness of the importance of money in finding a solution, but also the effect that lack of money can have on different stakeholders. Similarly, a student wrote that, “It doesn’t include all the possible solutions, or the specific amount of money that’s been put towards fixing the crisis” (ST_90). Responses such as this indicate that students were aware of prior solutions and expenses and that there could be other solutions that have not been tried. Often, student responses had a dimension of more than one type of limitation.

Overall, students described fewer mechanisms as missing from their systems thinking models. The students that did include a mechanism as missing from their model largely focused on two processes—economics and environmental processes. One student writing about economic processes missing from their model wrote,

> It also doesn’t show the complex economic processes. Companies in Des Moines help farmers with tractors and agribusiness and sales and this causes a growth in the population of Des Moines. People work on large farms that contribute to the Des Moines economy and grows Des Moines further. This kind of large scale economic and industrial feedback is very intricate… (ST_6)

Students writing about detailed processes such as this exhibited a robust understanding of the problem’s social and scientific components. Students who wrote about environmental processes as a limitation of their model also included ideas about socioscientific components, “The graph also doesn’t specify how the water may flow, even through the ground, reaching other areas that aren’t polluting or receiving benefits from the state” (ST_113). Students incorporating knowledge from across the semester of hydrologic and human interactions demonstrated their depth of learning and attainment of course learning goals.

Phenomena or patterns were also identified as specific model limitations that were discussed in the written newspaper articles. The majority of responses in this category of limitation surrounded the idea of polluted water flowing from the Raccoon River to the dead zone in the Gulf of Mexico and harming wildlife. One student wrote about all of these ideas in summary by stating,

> The model is missing the dead zone and the environmental portion of the issue. To make the model better, it would have to include these environmental effects. Including the animal species and the systems that function in that environment. Another way to make this model stronger, would be to add the communities that would also be affected in the Gulf. (ST_121)

Students demonstrate their ability to view the contribution of one geographic area to the degradation of another. Another student wrote, “… but it does little to show the far-reaching effects of this problem as a whole. Nitrates from these and other fields around the United States pollute the Gulf of Mexico, and countless other waterways" (ST_25). This response took the idea of phenomena generalizability to a higher level by describing how the model was limited by leaving out this aspect and including the idea that this is happening in other parts of the country and affecting other waterways.

Discussion

In the context of water systems, students express a variety of levels of understanding and often alternative conceptions across the continuum of K-12 and undergraduate formal education (Coştu et al., 2010; Halvorson & Westcoat, 2005; Sibley et al., 2007) and beyond (Duda et al., 2005). Systems thinking is a way to help students utilize water systems concepts to engage in problem solving, which is a critical part of science and environmental literacy (Hmelo-Silver et al., 2017; Yoon & Hmelo-Silver, 2017). Students need opportunities to develop the epistemic dimensions of contextualizing the system and integrating themselves into the system (Bawden, 2007). Learning to consider how seemingly separate systems interact to cause a phenomenon, as well as the integration of human actions into such systems, is important when using systems thinking. Yet, this important skill is often difficult for students to learn effectively (Coştu et al., 2010; Jordan et al., 2014a; Kastens et al., 2009; Rates et al., 2016). Providing students with the specific instruction in this skill (Richmond, 1993) and opportunities to practice systems thinking with increasingly challenging scenarios can be an effective way to address this need. Engaging students in generating models of a system is a method to scaffold learning about complex issues (Danish et al., 2017; Hmelo-Silver et al., 2017), including sociohydrologic issues. This study provides valuable insights into students' use of models, written descriptions, and evaluations of a real-world water-related issue using systems thinking.

First, study findings showed that the students who drew a more robust diagrammatic model were also better able to operationalize the system through writing. This trend and empirically supported relationship was consistent across the 3 years of the course, though at varying levels. We hypothesize that this was due to explicit instruction surrounding the development of a systems thinking model and the benefits gained from thinking about the system in both visual and descriptive contexts. The literature indicates that specific instruction in systems thinking is helpful in increasing student systems reasoning (Hmelo-Silver et al., 2017; Yoon & Hmelo-Silver, 2017), whereas diagrammatic models also serve as a scaffold (Jordan et al., 2014b). Students can hold ideas in the drawn model, freeing up cognitive space for more nuanced connections between systems in their written article. Additionally, affording students opportunities to practice these skills in successively more interwoven and ill-defined systems can be an effective strategy for learning this skill (Assaraf & Orion, 2005; Vo et al., 2015). Pedagogical practices such as these may have enabled students to better clarify the components, mechanisms, and phenomena involved in the Raccoon River crisis in order to describe it more thoroughly in a written format. These findings contribute to the understanding of how to help students develop understanding of sociohydrologic systems through the context of a systems thinking modeling and writing assignment.

Second, results provided finer-grain insights into elements of systems thinking that students emphasize in relation to SHS. Students emphasized components more strongly in their diagrammatic models than mechanisms or phenomenon/patterns (Figure 2). When students reason about an SHS, their values and experiences inform their ideas and decisions (Petitt & Forbes, 2019). Student experiences with water frame, particularly their firsthand experiences, may have directly contributed to the emphasis of components in diagrammatic models. System components are tangible and easy to visualize, making them more readily transferrable to diagrams than mechanisms or phenomenon/patterns. Providing students with a specific system can help them productively constrain their model to the most salient parts (Gouvea & Passmore, 2017), in this case through an emphasis on the tangible parts of the SHS.

In the context of the written article, students emphasized problem identification most and unintended consequences least. Similar to components in a diagrammatic model, students more thoroughly identified the problem within the SHS. Problem identification includes the mechanics and circumstances of the problem (Grohs et al., 2018). In identifying the problem, students expressed more robust descriptions of the overall issue; doing so likely requires less context and nuance than probing the unintended consequences and implementation challenges of potential solutions. This pattern of more fully exploring the problem in the article and the components of the diagrammatic model could be a product of these being more concrete and therefore easier to analyze.

Third, study findings illustrated trends in one of the elements of modeling and systems thinking—students' model evaluation. The majority of students included some form of model limitation in their article, and these limitations fell into three categories of temporal, scope/scale, and specific component/mechanism/phenomena. Additionally, findings indicated that as students provided more thorough descriptions of the ways in which their model was limited, their overall written assignment score increased. These findings surrounding evaluation contributed to a wider body of teaching and learning work in water education across the K-16 continuum (Pluta et al., 2011; Sabel et al., 2017; Vo et al., 2015; Zangori et al., 2017). The ability to critique one's work highlights the following constraints: mental, physical, and temporal, all of which contribute to the final product (Grohs et al., 2018). Model evaluation can take place during or after the development of a systems thinking model. The repeated process of revising one's work and thinking of an idea as malleable are ways that students can harness the benefits of metacognition to systems thinking (Grohs et al., 2018). Evaluating a model for its constraints is one of the types of critical thinking that students need in order to develop scientific literacy (Coll et al., 2005; Lally & Forbes, 2019b). All physical models are incomplete renderings of the natural world. Models are useful comparisons to the real-world, and their effect is maximized when students evaluate their own and others' models in comparison to experts' models (Coll et al., 2005). Students need opportunities to think about model constraints and their effect when using models to solve real-world problems.

Conclusion

"…All things are *not* knowable and that the whole *is* indeed greater than the sum of its parts" (Bawden et al., 1984). Systems thinking is complicated, and demanding students to be able to consider all of the possibilities and pieces that are potentially related to a system is unrealistic. However, it is important for students to know and experience that it is neither the case that any one part of a system is greater than the whole system, nor does a model require inclusion of every potential component or process within a systems thinking model in order for it to be useful. Models are inherently simplified versions of complex systems and valued for their applicability to particular problems. However, models do give students the opportunity to hypothesize and experiment with varying outcomes of a model in the pursuit of a suite of potential solutions.

This study highlights (1) undergraduate students' systems thinking-based reasoning about water systems (Danish et al., 2017), (2) advances in research focused on students' use of systems thinking to reason about water systems (Hmelo-Silver et al., 2017), and (3) students' ability to critically evaluate drawn systems thinking models (Jordan et al., 2014a; Jordan et al., 2014b). The study findings suggest that teaching students to use systems thinking to reason about an SHS is only one part of the challenge. Students need encouragement to include as many details surrounding the components, mechanisms, and phenomena as possible in their models so they have more to discuss when they write about them. Linking this need with the use of systems thinking, students can develop experience and techniques in areas such as problem identification, stakeholder awareness, unintended consequences, implementation challenges, and model limitations surrounding an SHS (Grohs et al., 2018). Explicitly defining each of these categories and allowing students to explore interconnectivity between them in small and large group settings using primary and secondary sources can be beneficial to students of all backgrounds and levels of proficiency. Combining the skills of diagramming a system and writing a description of the system could be powerful in increasing student systems thinking skills overall.

Misconceptions surrounding water, particularly the components and processes—which are more inaccessible and hard to visualize—persist (Cardak, 2009), and these processes are often thought of as discreet from other, related geoscience processes (Batzri et al., 2015; Shepardson et al., 2009). Students may have relied on experiences to identify components of the system, and they may have had fewer experiences with the mechanisms and phenomena of the system; thus leading to fewer mechanisms and phenomena in their drawn models. Study findings also suggest that students need more practice both drawing and describing systems thinking models, opportunities that may not be commonplace in undergraduate geoscience courses (Lally et al., 2019). Specific curriculum and instruction to support growth in reasoning about the complexities and interactions between water systems are needed to help students develop ideas about their application to daily lives (Canpolat, 2006; Covitt et al., 2009; Gunckel et al., 2012). Purposefully designing undergraduate learning experiences to support systems thinking can help to increase the quality of systems thinking models and thereby student understanding of them. Focusing on specific concepts such as feedback loops is helpful to students in developing these linkages (Kastens et al., 2009). Using systems thinking also helps students learn about their individual responsibility to use water wisely given the uncontrollable nature of cycles (Rates et al., 2016). Learning gains in systems thinking are developed through the use of best practice strategies including active learning opportunities in group settings and through iterative practice with increasingly more complex scenarios. Providing space for students to consider the role of humans in SHSs is valuable because they move forward as future decision makers and change agents.

Appendix 5.A *Systems thinking writing rubric (Grohs et al., 2018).*

Component	**0**	**1**	**2**	**3**
Problem identification	No response provided or respondent was unable to identify a relevant problem.	The problem statement identified was only technical or only contextual (economic, political, environmental, social, time, etc.) in scope.	The problem statement (A) defined both technical and contextual aspects but did not acknowledge interaction and complexity between issues, (B) identified technical aspect or contextual aspect only, and acknowledged interactions and complexities between issues.	The problem statement identified both technical and contextual aspects and acknowledged interactions and complexity between issues
Stakeholder awareness	No response was provided or respondent only provided a list of stakeholders but no discussion on the role that the stakeholders will play in identifying and implementing possible solutions.	The response included a list of stakeholders; discussion of role of stakeholders was limited only to one group of stakeholders (community, power/politics, experts) providing input in discussions to identify possible solutions.	The response listed an array of various stakeholders (community, power/politics, experts). Discussion of the role of stakeholders included (1) one group of stakeholders being engaged in activities to identify and implement possible solutions, or (2) more than one group of stakeholders providing input in discussions to	The response listed an array of various stakeholders (community, power/politics, experts). Discussion of the role of stakeholders included all stakeholders iteratively giving input and engaging with each other to identify and implement possible solutions. The discussion explicitly included

			identify possible solutions.	listening to the community voice and getting buy-in from the community.
Unintended consequences	No response was provided, or response did not show potential unintended consequences	The response identified potential unintended consequences that covered one or more aspects: technical and/or contextual (economic, political, environmental, social, time, etc.), but did not consider interaction of different aspects and issues.	The response identified several potential unintended consequences. Response considered/implied issue interaction of several aspects, but there was notable focus on a single aspect.	The response identified several potential unintended consequences. Responses considered and discussed issue interaction between aspects and considered both short- and long-term consequences.
Implementation challenges	No response was provided or response did not identify any potential implementation challenges	The response identified potential simple, short-term implementation challenges focused on one aspect: technical or contextual (economic, political, environmental, social, time, etc.).	The response identified potential implementation challenges that were (1) focused on one aspect long-term, (2) focused on one aspect and considered both short- and long-term challenges, or (3) considered both technical and contextual aspects and short-term challenges.	The response identified several potential challenges that considered both technical and contextual aspects and the possible interaction between aspects; response recognized possible barriers due to

				trade-offs between short- and long-term plans.
Model limitations	No response was provided or response did not identify any potential limitations of the model.	The response identified potential model limitations focused on one aspect: technical or contextual (economic, political, environmental, social, time, etc.).	The response identified several potential model limitations. Response considered/implied several reasons for limitations, but there was notable focus on a single aspect.	The response identified several potential model limitations. Responses considered and discussed model limitations and their potential model impacts.

Appendix 5.B *Model and article rubric components ANOVA analysis.*

		df	**SS**	**MS**	***F***	***P***
Model Components						
Components	Between groups	2	1122.98	561.49	12.99	<0.05
	Within groups	125	5404.99	43.24		
	Total	127	6527.97			
Mechanisms	Between groups	2	1746.59	873.29	17.88	<0.05
	Within groups	126	6154.41	48.84		
	Total	128	7900.99			
Phenomenon/patterns	Between groups	2	107.93	53.97	10.86	<0.05
	Within groups	126	626.04	4.97		
	Total	128	733.97			
Article Components						
Problem identification	Between groups	2	8.22	4.11	8.6	<0.05
	Within groups	126	60.26	0.48		
	Total	128	68.48			

Stakeholder awareness	Between groups	2	4.06	2.03	3.1	<0.05
	Within groups	125	81.93	0.66		
	Total	127	85.99			
Unintended consequences	Between Groups	2	7.74	3.87	3.37	<0.05
	Within Groups	123	141.25	1.15		
	Total	125	148.99			
Implementation challenges	Between Groups	2	8.53	4.26	3.04	>0.05
	Within Groups	123	172.69	1.4		
	Total	125	181.21			
Limitations	Between Groups	2	0.36	0.18	0.14	>0.05
	Within Groups	123	159.11	1.29		
	Total	125	159.47			

Appendix 5.C *Model and article rubric component mean, standard deviation, and Tukey's HSD for 2017, 2018, and 2019.*

Model Components		***n***	**Mean**	**SD**	**Tukey's HSD Comparisons**		
					2017	2018	2019
Components	2017	35	9.8	6.19			
	2018	48	17.06	6.96	<0.0001		
	2019	46	12.72	6.41	0.1207	0.0048	
Mechanisms	2017	35	3.83	3.98			
	2018	48	13.1	9.56	<0.0001		
	2019	46	9.61	5.42	0.001	0.044	
Phenomenon/ patterns	2017	35	1.8	1.69			
	2018	48	2.85	1.77	0.5514		
	2019	46	4.12	2.91	0.0002	0.0613	
Article Components		**n**	**Mean**	**SD**	**Tukey's HSD Comparisons**		
					2017	2018	2019
Problem identification	2017	35	1.94	0.87			
	2018	48	2.54	0.5	0.0005		
	2019	46	2.11	0.71	0.535	0.0082	
Stakeholder awareness	2017	35	1.26	0.74			
	2018	48	1.71	0.77	0.0348		
	2019	46	1.46	0.89	0.5148	0.2884	
Unintended consequences	2017	35	1.86	1.03			
	2018	48	1.38	1.16	0.1097		
	2019	46	1.17	1	0.0141	0.6343	
Implementation challenges	2017	35	2.14	0.91			
	2018	48	1.88	1.16			
	2019	46	1.43	1.38			
Limitations	2017	35	1.6	0.95			
	2018	48	1.58	1.18			
	2019	46	1.41	1.24			

CHAPTER 6

SYNOPSIS AND CONCLUSION

Significance of Study

The Anthropocene has not been gentle toward water resources. Nearly every large river in the world has been dammed (Nilsson, Reidy, Dynesius, & Revenga, 2005), Northern India has the highest rate of aquifer loss of similar sized areas in the world (Tiwari, Wahr, & Swenson, 2009), and the yearly cost of amending the water in Des Moines, IA is figured to be over 300 million dollars (Secchi et al., 2007). Disruptive damming, water extraction, and water pollution are but three of the ways in which humans have altered the hydraulic landscape. Students need to learn about the pressures imposed on water systems and how to quantify measurements in order to be able to make decisions about water related issues, moving forward. Students who do not have the essential understanding of water and its importance for humans and ecosystem services will be at a disadvantage in the coming years. Humans require water for transportation, electricity, food, and a variety of other uses. If decisions are not made in the interest of protecting water resources, meeting these needs with diminished clean and convenient water resources will be more difficult. However, learning about water while in school can aid students through informed decision-making about water related issues.

Of the many important socioscientific issues, water related issues are becoming increasingly more urgent for governments and individuals alike. It is not enough to understand water as a stand-alone resource. Students are required to conceptualize the water cycle, but they also need to know how resources and living things interact through various cycles (NGSS Lead States, 2013). No longer is it sufficient for learners to be able, for example, label the parts of the water cycle (Covitt, Gunckel, & Anderson, 2009). Students should also be able to account for the movement of unseen water and how humans interact with water in various, sometimes inadvertent ways (Covitt, Gunckel, & Anderson, 2009). Taking the next step after learning the various roles water plays on our planet requires students to be able to apply their knowledge in new ways. The complexities of global climate change in relation to water underscore the importance of relating what is known about water and enhancing it with new information found in media articles and primary sources. This is the goal of developing a scientifically literate public.

Scientific literacy not only involves knowing factual scientific information, but it also involves the ability to apply those facts to everyday decision-making (Rudolph, 2014). Our dynamic world requires not only science professionals, but also the general population to be able to read, inform decisions, and determine the trustworthiness of scientific information (DeBoer, 2000). To prepare for the future as a decision maker, students need the skills of interpreting, evaluating, and applying scientific data as presented in the *Next Generation Science Standards* (NGSS Lead States, 2013), for which gaps have been exposed by research (Norris & Phillips, 1994; Hoskins, Loppato & Stevens, 2011).

To help undergraduate students move past their misconceptions surrounding water and incorporate a systems approach to hydrologic understanding, support is needed from instructors. For example, supporting the development of scientific and hydrologic literacy through practices such as modeling and systems thinking in the classroom can benefit students (Assaraf & Orion, 2005; Baumfalk et al., 2019; Arnold & Wade, 2015; Hmelo-Silver et al., 2017 Scherer, Holder, & Herbert, 2017; Williams, Lansey, & Washburne, 2009). The focus of this quartet of studies, broadly, is on the current use and trends surrounding science modeling and systems thinking among geoscience faculty and undergraduate students. More work is needed to understand the implementation of science modeling and systems thinking in undergraduate courses by faculty and the most productive ways to support students' model-based reasoning and systems thinking about water systems. From these recognized needs, two questions guided the overarching dissertation:

1. How does the implementation of science modeling and systems thinking increase student understanding of basic hydrologic content?
2. How does the implementation of science modeling and systems thinking help students grow in their critical evaluation of models?

Conceptual and Theoretical Frame Synopsis

Each of these studies was framed by the conceptual need to increase student literacy surrounding systems thinking and science modeling within the context of a geoscience course. Effectively learning the related scientific content and theoretical skills of use, evaluation, and modeling can contribute to student reasoning about Earth systems including hydrologic systems. The incorporation of the human element into these skills and theories is critical for students to be able to interpret the ways hydrologic systems are affected by humans and how this affects seemingly tangential system components, mechanisms, and patterns. Students need iterative, constructive experiences with models (Schwarz et al., 2009) and systems thinking (Bawden, 2007) in order to experiment with both types of representation to allow their ideas surrounding them to mature (Nersessian, 1999). The epistemic dimensions of context and integration (Bawden, 2007) are components of systems thinking and contribute to student modeling ability; so too are the modeling epistemic dimensions of representation, evidence, and explanation (Schwarz et al., 2009) components of systems thinking. The push and pull of these factors as they develop supports both student systems thinking and model reasoning.

The evaluation of both models and systems thinking outcomes also supports model reasoning and systems thinking. Evaluating takes the form of revision, comparison, precision, accuracy (Coll et al., 2005; Gouvea & Passmore, 2017), and suitability (Pluta, Chinn, & Duncan, 2011) within a student. As students become more proficient at each of these skills, their overall ability to reason about a model or use systems thinking could also become more refined.

Research Approach and Synopsis

The four studies I conducted respond to the overarching research questions, each containing its own questions, data, and analyses (Table 6.1). Chapter 2 focused on the current trends and supports reported by postsecondary geoscience educators as related to science modeling and systems thinking (SMST). I analyzed self-reported surveys from the 2016 National Geoscience Faculty Survey for characteristics including demographic information, teaching and learning practices, and a set of nine SMST practices items. The survey, consisting of 209 questions, was administered and designed by research teams from the National Association of Geoscience Teachers, On the Cutting Edge, InTeGrate, and SAGE 2YC.

This quantitative study included 2056 participants who both met the criteria for inclusion and returned the completed electronic survey. The majority of respondents were from research/doctoral and master's granting institutions representing disciplines including geology/other, atmospheric science, and oceanography. I explored the relationships between the nine SMST practices found in the survey and other variables including course changes made, scientific meeting presentations, publications, professional development, and active learning strategies used. The survey responses for SMST practices were limited to "yes" and "no" while the responses to other variable included open response, selection from a list, and Likert style number grouping.

Data for the two scientific modeling studies and the systems thinking study came from SCIL109: Water in Society. This course was taught in spring 2017, 2018, and 2019 as part of an NSF grant. Scientific modeling use and evaluation skills are explored through a computer-based water model assignment and recorded interviews. The scientific modeling studies use a comparative, concurrent, mixed methods design to addresses the need to better understand students' abilities to interpret and use computer-based models to reason about real-world water-related issues. All students regardless of gender, year in college or major can effectively engage with the Water Balance Model. Student scores differ between years of the study because of the inclusion of active learning opportunities surrounding model instruction, group work, and increased modeling practice as evidenced by their performance on the Water Balance Model assignment. This has implications for the study of post-secondary student development of hydrologic knowledge and computer-based water modeling and model evaluation and illustrates ways post-secondary students use computer-based water models and can increase their basic water knowledge.

Systems thinking is explored through multiple, regional, sociohydrologic issues. This study focused on systems thinking model evaluation results surrounding the quantity of relationships between a given process or component, student operationalization of the system, and the ways students think about their own ability to model a system. Students who scored higher on the systems thinking assessment have more numerous components and processes. Students who are able to think objectively about their model will be able to demonstrate understanding about the limitations of models in general and their overall utility in understanding phenomena.

Water education is important because of expected changing water availability and profound weather changes in the coming years (Seibert, Uhlenbrook, & Wagener, 2013). If students will be expected to make decisions about water related issues later in their lives, it is important they have had practice evaluating and making such decisions. Water science education should not occur within a vacuum. Water and life are interconnected. Water is connected in an interdisciplinary way to all other content areas. Water science needs to be taught in a three pronged fashion including fieldwork, lab work, and classroom learning (Gleeson, Allen, & Ferguson, 2012). Taking this idea a step further, not only are these three components critical to student learning, but they also need to be integrated in an active learning environment. (Hakoun, Mazzilli, Pistre, & Jourde, 2013).

Table 6.1

Research Studies Synopsis

Chapter	Population	Topic	Research Questions	Data Sources
2	Post-secondary geoscience instructors	Survey analysis of the factors influencing the prevalence of systems thinking and science modeling components in geoscience classes.	1. To what extent do geoscience instructors report engaging in scientific modeling and systems thinking? 2. What instructor- and course-level factors help predict and explain the extent to which geoscience instructors report engaging students in in scientific modeling and systems thinking?	·2016 National Geoscience Faculty Survey
3	Undergraduate introductory water students	The use of the Water Balance Model and active learning strategies demonstrate how all students can learn to effectively engage with models.	1. What differences exist between gender, major, and year in college and Water Balance Model project score? 2. How are students reasoning about precipitation, PET, and contour lines using the Water Balance Model?	·Water Balance Model project ·Semi-structured interviews
4	Undergraduate introductory water students	A between years comparative study of student use and evaluation of the Water Balance Model.	1. To what extent do students' a) model-based reasoning and b) conceptual understanding of hydrology differ between Years 1 and 2? 2. How does students' model-based reasoning differ between Years 1 and 2?	·Pre- and post-course hydrologic concept inventory ·Water Balance Model project ·Semi-structured interviews

5	Undergraduate introductory water students	Systems thinking operationalization, model analysis of a water related issue, and evaluation of model limitations.	1. What systems thinking modeling components, processes, and mechanisms do students emphasize in drawing a model of a real-world scientific issue? 2. What do students operationalize surrounding a real-world socio-hydrologic issue? 3. How do students evaluate their own systems thinking models of real-world socio-hydrologic issue?	·Systems thinking project

Overall Implications and Future Work

Science literacy can be increased and influenced in a variety of ways, each complimentary of the others. Each method shares the common thread of information evaluation and use to make a decision. Students need to learn to ask questions about scientific information they encounter and learn to evaluate the claims stemming from it (Allchin, 2014). Questioning and curiosity can lead to engagement with information a student may have otherwise dismissed or passively accepted as true. Science literacy encompasses the idea of excitement leading to action, not simply the acceptance of things the way they are (Wheland, et al., 2013).

The frontier of scientific inquiry and global interconnectedness merge at the point where new problems are discovered and discussed (McFarlane, 2013) and reflects the potential for collaboration to occur to solve global problems through the expansion of scientific literacy. When thinking about science, it should be considered in a way which maximizes its potential for use by all people in their everyday lives and decision making as well (McFarlane, 2013).

It is the everyday encounters with science, which make up the vast majority of the public's scientific experience. These experiences and interactions are valuable. Activation of prior knowledge depends on learners having experienced scientific phenomenon in informal education settings and everyday events (McFarlane, 2013). The connections and revisions students can learn to make between their lived experiences resulting in prior knowledge and new information are what lead to science literacy. Organic, everyday settings where students can experience science are important, but the connection students make between these everyday occurrences and scientific information is critical.

It is exciting to think about the ways in which increased focus on science literacy skills, active learning, and decision-making will influence student learning in the years to come. Understanding the when and where of scientific modeling and systems thinking within geoscience instruction will enhance student access to innovative scientific research and primary data. Increased ability to understand and use this information will be critical to student success in academic, innovation, and decision-making areas.

The inclusion of modeling and systems thinking practices in geoscience courses is beneficial to students. However, gaps exist in the how, when, who, and where of SMST use undergraduate education. Knowing more about the use of these practices is critical to developing faculty education, support, course content, and ultimately preparing students to make life decisions based on scientific information. SMST practices are often linked in the classroom because they employ many of the same skills: developing a model, thinking about cause/effect, and understanding the dynamic nature of environments. However, there are distinctions between scientific modeling and systems thinking which are important to consider as their own areas of study.

Systems thinking requires students to think about all of the connections, which are possible between different components in a system and how they interact with one another. This information can be used to make a decision and is improved by knowing more about the background processes, which support the primary interactions affecting components of a problem. The skills of systems thinking can then be forwarded and applied when considering the results of computer-based water models.

Computer based-water models rely on the user to input accurate information in order to receive an output from which they can make a decision. Students must know most or all of the interacting components and how the data presented from a model will affect or be affected by such interactions and components. Models are only useful in decision making if the learner can make use of the graphic output and apply it to a situation with the inclusion of the most recent theories and data as well as current interactions between components. Increasing scientific literacy in students through these three strategies will not only be complimentary, but vertically aligned for student success in science. The skills of interpretation, evaluation and application of scientific data are a critical area of study of a scientifically literate population (Norris & Phillips, 1994; Hoskins, Loppato & Stevens, 2011).

Directions of Future Work

Future dimensions of this work will broaden the scope of the studies presented in this dissertation. First, I would like to continue to the study of faculty professional development through either participating in research with the 2020 National Geoscience Faculty Survey or collaborative department based education research aimed at faculty development improvement. Knowing the who, when, where, and how of faculty characteristic and classroom pedagogy characteristics will help inform future faculty development and simultaneously highlight areas for further research in student science literacy gains. Second, as an extension of the science literacy skills of systems thinking and science modeling studied, I am interested in learning more about how students learn to read and use scientific journal articles. Students are often required to perform this task within their first year of study without having prior experience with the necessary skills to comprehend effectively what they are reading. Studying the development of these skills could be a way to help students increase their science literacy overall. This mixed methods study would include quantitative data from assignments and qualitative data from student surveys and help demonstrate gaps in achievement or gains in a skill area.

REFERENCES

Abbott, B. W., Bishop, K., Zarnetske, J. P., Minaudo, C., Chapin, F. S., Krause, S., ... & Plont, S. (2019). Human domination of the global water cycle absent from depictions and perceptions. *Nature Geoscience*, 1.

Abeysekera, L., & Dawson, P. (2015). Motivation and cognitive load in the flipped classroom: Definition, rationale and a call for research. *Higher Education Research & Development*, *34*(1), 1-14.

AghaKouchak, A., Nakhjiri, N., & Habib, E. (2013). An educational model for ensemble streamflow simulation and uncertainty analysis. *Hydrology and Earth System Sciences*, *17*(2), 445-452.

Allchin, D., Andersen, H. M., & Nielsen, K. (2014). Complementary approaches to teaching nature of science: Integrating student inquiry, historical cases, and contemporary cases in classroom practice. *Science Education*, *98*(3), 461-486.

Arnold, R. D., & Wade, J. P. (2015). A definition of systems thinking: A systems approach. *Procedia Computer Science*, *44*, 669-678.

Assaraf, O.B.Z., & Orion, N. (2005). Development of systems thinking skills in the context of earth system education. *Journal of Research in Science Teaching*, *42*(5), 518-560.

Aubrecht, K. B. (2018). Teaching relevant climate change topics in undergraduate chemistry courses: Motivations, student misconceptions, and resources. *Current Opinion in Green and Sustainable Chemistry*, *13*, 44-49.

Banilower, E. R., Smith, P. S., Malzahn, K. A., Plumley, C. L., Gordon, E. M., & Hayes, M. L. (2018). Report of the 2018 NSSME+.

Barral, A. M., Ardi-Pastores, V. C., & Simmons, R. E. (2018). Student learning in an accelerated introductory biology course is significantly enhanced by a flipped-learning environment. *CBE—Life Sciences Education, 17*(3), ar38.

Batzri, O., Assaraf, O. B. Z., Cohen, C., & Orion, N. (2015). Understanding the earth systems: Expressions of dynamic and cyclic thinking among university students. *Journal of Science Education and Technology*, *24*(6), 761-775.

Baumfalk, B., Bhattacharya, D., Vo, T., Forbes, C., Zangori, L., & Schwarz, C. (2019). Impact of model-based science curriculum and instruction on elementary students' explanations for the hydrosphere. *Journal of Research in Science Teaching*, *56*(5), 570-597.

Bawden, R. (2007). Knowing systems and the environment. *The SAGE Handbook of Environment and Society,* 224-234.

Bawden, R. J., Macadam, R. D., Packham, R. J., & Valentine, I. (1984). Systems thinking and practices in the education of agriculturalists. *Agricultural Systems*, *13*(4), 205-225.

Bybee, R. W. (2011). Scientific and engineering practices in K-12 classrooms: Understanding a framework for K-12 science education. *Science and Children*, *49*(4), 10.

Bybee, R., McCrae, B., Laurie, R. (2009). PISA 2006: An assessment of scientific literacy. *Journal of Research in Science Teaching*, *46*(8), 865-883.

Calvani, A., Cartelli, A., Fini, A., & Ranieri, M. (2008). Models and instruments for assessing digital competence at school. *Journal of E-learning and Knowledge Society, 4*(3), 183-193.

Canpolat, N. (2006). Turkish undergraduates' misconceptions of evaporation, evaporation rate, and vapour pressure. *International Journal of Science Education*, *28*(15), 1757-1770.

Cardak, O. (2009). Science students' misconceptions of the water cycle according to their drawings. *Journal of Applied Sciences, 9*(5), 865-873.

Carey, C. C., & Gougis, R. D. (2017). Simulation modeling of lakes in undergraduate and graduate classrooms increases comprehension of climate change concepts and experience with computational tools. *Journal of Science Education and Technology*, *26*(1), 1-11.

Climate and Energy Awareness Network (CLEAN). 2019. Available at http://cleanet.org/ (accessed 20 November 2019).

Coll, R. K., France, B., & Taylor, I. (2005). The role of models/and analogies in science education: Implications from research. *International Journal of Science Education*, *27*(2), 183-198.

Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI) (2018). *Water in a dynamic planet: A five-year strategic plan for water science,* CUAHSI, Washington, D.C.

Coştu, B., Ayas, A., & Niaz, M. (2010). Promoting conceptual change in first year students' understanding of evaporation. *Chemistry Education Research and Practice*, *11*(1), 5-16.

Covitt, B. A., Gunckel, K. L., & Anderson, C. W. (2009). Students' developing understanding of water in environmental systems. *The Journal of Environmental Education*, 40(3), 37-51.

CUAHSI. (2018) *Water in a dynamic planet: A five-year strategic plan for water science,* CUAHSI, Washington, D.C

Danish, J., Saleh, A., Andrade, A., & Bryan, B. (2017). Observing complex systems thinking in the zone of proximal development. *Instructional Science*, *45*(1), 5-24.

Dauer, J.M., Lute, M., Straka, O. 2017. Indicators of informal and formal decision-making about a socioscientific issue. *International Journal of Education in Mathematics, Science and Technology*. *5*(2):124-138.

Dauer, J.T., Dauer, J.M. (2016). A framework for understanding the characteristics of complexity in biology. *International Journal of STEM Education. 3*(13).

DeBoer, G. E. (2000). Scientific literacy: Another look at its historical and contemporary meanings and its relationship to science education reform. *Journal of Research in Science Teaching, 37*(6), 582-601.

Dickerson, D.L., Penick, J.E., Dawkins, K.R., & Van Sickle, M. (2007). Groundwater in science education, *Journal of Science Teacher Education*, 18(1), 45-61.

Duda, M.D., De Michele, P.E., Jones, M., Criscione, A., Craun, C., Winegord, T….Herrick, J.B. (2005) *Americans' knowledge of and attitudes toward water and water-related issues.* Harrisonburg, VA: Responsive Management.

Durant, J. R. (1993). What is scientific literacy? In J. R. Durant & J. Gregory (Eds.), *Science and Culture in Europe.* (pp. 129–137) London: Science Museum.

Earth Science Literacy Initiative. (2010). Earth science literacy principles: The big ideas and supporting concepts of Earth science. *Arlington, VA: National Science Foundation.*

Eaton, T. (2009). Engaging students in evaluating learning process using collaborative exams in introductory courses. *Journal of Geoscience Education, 57*(2), 113-120.

Edelson, D. (2002). Design research: What we learn when we engage in design. *The Journal of the Learning Sciences, 11*(1), 105-121.

Erturk, A. (2010). A simple stream water quality modelling software for educational and training purposes. *Turkish Journal of Fisheries and Aquatic Sciences*, *10*(1), 61-70.

Ewing, M. S., & Mills, T. J. (1994). Water literacy in college freshmen: Could a cognitive imagery strategy improve understanding? *The Journal of Environmental Education*, *25*(4), 36-40.

Feinstein, N. (2010). Salvaging science literacy. *Science Education*, *95*(1), 168-185.

Flavell, J. H. (1979). Metacognition and cognitive monitoring: A new area of cognitive–developmental inquiry. *American Psychologist, 34*(10), 906.

Food and Agriculture Organization of the United Nations & World Water Council. (2015). Towards a water and food secure future. Critical perspectives for policy-makers.

Forbes, C.T., Brozovic, N., Franz, T., Lally, D., & Petitt, D. (2018). Water in Society: An interdisciplinary course to support undergraduate students' water literacy. *Journal of College Science Teaching, 48*(1), 36-42.

Forbes, C.T., Vo, T., Zangori, L., & Schwarz, C. (2015). Supporting students' scientific modeling when learning about the water cycle, *Science and Children, 53*(2), 42-49.

Forbes, C.T., Zangori, L., Schwarz, C.V. (2015). Empirical validation of integrated learning performances for hydrologic phenomena: 3rd-grade students' model-driven explanation-construction. *Journal of Research in Science Teaching, 52*(7), 895-921.

Fosnot, C. T., & Perry, R. S. (1996). Constructivism: A psychological theory of learning. *Constructivism: Theory, Perspectives, and Practice, 2,* 8-33.

Gilbert, J. K. (2004). Models and modelling: Routes to more authentic science education. *International Journal of Science and Mathematics Education, (2)*2, 115-130.

Gleeson, T., Allen, D. M., & Ferguson, G. (2012). Teaching hydrogeology: a review of current practice. *Hydrology and Earth System Sciences, 16*(7), 2159-2168.

Gobert, J. D., & Buckley, B. C. (2000). Introduction to model-based teaching and learning in science education. *International Journal of Science Education*, *22*(9), 891-894.

Golick, D., Dauer, J., Lynch, L., & Ingram, E. (2017). A framework for pollination systems thinking and conservation. *Environmental Education Research*, 1-16.

Gouvea, J., & Passmore, C. (2017). Models of 'versus' models for. *Science & Education, 26*(1-2), 49-63.

Grace, M. (2009). Developing high quality decision-making discussions about biological conservation in a normal classroom setting. *International Journal of Science Education, 31,* 551–570.

Grohs, J. R., Kirk, G. R., Soledad, M. M., & Knight, D. B. (2018). Assessing systems thinking: A tool to measure complex reasoning through ill-structured problems. *Thinking Skills and Creativity*, *28*, 110-130.

Gross, D., Pietri, E. S., Anderson, G., Moyano-Camihort, K., & Graham, M. J. (2015). Increased preclass preparation underlies student outcome improvement in the flipped classroom. *CBE—Life Sciences Education*, *14*(4), ar36.

Gunckel, K. L., Covitt, B. A., Salinas, I., & Anderson, C. W. (2012). A learning progression for water in socio-ecological systems. *Journal of Research in Science Teaching, 49*(7), 843-868.

Gunn, R. L., Mohtar, R. H., & Engel, B. A. (2002). World-Wide-Web-based soil and water quality modeling in undergraduate education. *Journal of Natural Resources and Life Sciences Education, 31*, 141-147.

Habib, E., Ma, Y., Williams, D., Sharif, H. O., & Hossain, F. (2012). HydroViz: Design and evaluation of a Web-based tool for improving hydrology education. *Hydrology and Earth System Sciences*, *16*(10), 3767-3781.

Hakoun, V., Mazzilli, N., Pistre, S., & Jourde, H. (2013). Teaching groundwater flow processes: connecting lecture to practical and field classes. *Hydrology and Earth System Sciences, 17*(5), 1975-1984.

Halverson, K.L., Siegel, M.A., Freyermuth, S.K. (2009). Lenses for framing decisions: Undergraduates' decision making about stem cell research. *International Journal of Science Education, 31*, 1249– 1268.

Halvorson, S. J., & Wescoat J. L., Jr. (2002). Problem-based inquiry on world water problems in large undergraduate classes. *Journal of Geography*, *101*(3), 91-102.

Handelsman, J., Ebert-May, D., Beichner, R., Bruns, P., Chang, A., DeHann, R., Gentile, J., Lauffer, S., Stewart, J., Tilghman, S., & Wood, W. (2004). Scientific teaching. *Science, 304*(5670), 521-522.

Hess, D. J., & Collins, B. M. (2018). Climate change and higher education: Assessing factors that affect curriculum requirements. *Journal of Cleaner Production, 170,* 1451-1458.

Hmelo-Silver, C. E., Jordan, R., Eberbach, C., & Sinha, S. (2017). Systems learning with a conceptual representation: A quasi-experimental study. *Instructional Science*, *45(1),* 53-72.

Hoskins, S. G., Lopatto, D., & Stevens, L. M. (2011). The CREATE Approach to Primary Literature Shifts Undergraduates' Self-Assessed Ability to Read and

Analyze Journal Articles, Attitudes about Science, and Epistemological Beliefs. *CBE—Life Sciences Education*, *10*, 368-378.

Jansen, J., & Stokes, J. (2018). Nebraska farm real estate market highlights 2017-2018. *Nebraska Farm Real Estate Reports, 45*, 1-56

Jones, J. P., McConnell, D. A., Wiggen, J. L., & Bedward, J. (2019). Effects of classroom "flipping" on content mastery and student confidence in an introductory physical geology course. *Journal of Geoscience Education*, 1-16.

Jordan, R. C., Brooks, W. R., Hmelo-Silver, C., Eberbach, C., & Sinha, S. (2014a). Balancing broad ideas with context: An evaluation of student accuracy in describing ecosystem processes after a system-level intervention. *Journal of Biological Education*, *48*(2), 57-62.

Jordan, R. C., Sorensen, A. E., & Hmelo-Silver, C. (2014b). A conceptual representation to support ecological systems learning. *Natural Sciences Education*, *43*(1), 141-146.

Kastens, K. A., Manduca, C. A., Cervato, C., Frodeman, R., Goodwin, C., Liben, L. S., ... & Titus, S. (2009). How geoscientists think and learn. *Eos, Transactions American Geophysical Union*, *90*(31), 265-266.

Krajcik, J., & Merritt, J. (2012). Engaging students in scientific practices: What does constructing and revising models look like in the science classroom?. *The Science Teacher*, *79*(3), 38.

Krajcik, J., McNeill, K. L., & Reiser, B. (2007). Learning-goals-driven design model: Developing curriculum materials that align with national standards and incorporate project-based pedagogy. *Science Education*, *92*(1), 1-32.

Lally, D. & Forbes, C.T. (2019a) Modelling water systems in an introductory undergraduate course: Students' use and evaluation of data-driven, computer based models, *International Journal of Science Education, 41*:14, 1999-2023.

Lally, D., Forbes, C. T., McNeal, K. S., & Soltis, N. A. (2019b). National Geoscience Faculty Survey 2016: Prevalence of systems thinking and scientific modeling learning opportunities. *Journal of Geoscience Education*, *67*(2), 174-191.

Li, S. & Liu, Q. (2003). Interactive groundwater (IGW): An innovative digital laboratory for groundwater education and research. *Computer applications in Engineering Education, 11*, 179-202.

Libarkin, J. C. (2006). Geoscience education in the United States. *Planet*, *17*(1), 60-63.

Libarkin, J. C., & Anderson, S. W. (2005). Assessment of learning in entry-level geoscience courses: Results from the Geoscience Concept Inventory. *Journal of Geoscience Education*, *53*(4), 394-401.

Libarkin, J. C., Thomas, S. R., & Ording, G. (2015). Factor analysis of drawings: Application to college student models of the greenhouse effect. *International Journal of Science Education*, *37*(13), 2214-2236.

Lombard, M., Snyder-Duch, J., & Bracken, C. C. (2002). Content analysis in mass communication: Assessment and reporting of intercoder reliability. *Human Communication Research*, *28*(4), 587-604.

Macdonald, H.R., Manduca, C.A., Mogk, D.W., and Tewksbury, B.J. (2005) Teaching methods in undergraduate geoscience courses: Results of the 2004 On the Cutting Edge Survey of U.S. faculty. *Journal of Geoscience Education*, *53*(3), 237-252.

Manduca, C. A., Iverson, E. R., Luxenberg, M., Macdonald, R. H., McConnell, D. A., Mogk, D. W., & Tewksbury, B. J. (2017). Improving undergraduate STEM education: The efficacy of discipline-based professional development. *Science Advances*, *3*(2), e1600193.

McCabe, M. F., Rodell, M., Alsdorf, D. E., Gonzalez Miralles, D., Uijlenhoet, R., Wagner, W.,… & Shi, J. (2017). The future of Earth observation in hydrology. *Hydrology and Earth System Sciences*, *21*(7), 3879-3914.

McFarlane, D. A. (2013). Understanding the challenges of science education in the 21st century: New opportunities for scientific literacy. *International Letters of Social and Humanistic Sciences*, (04), 35-44.

McNeal, K. S., Miller, H. R., & Herbert, B. E. (2008). The effect of using inquiry and multiple representations on introductory geology students' conceptual model development of coastal eutrophication. *Journal of Geoscience Education*, *56*(3), 201-211.

Merriam, S. B. (2009). *Qualitative research: A guide to design and implementation* (3rd ed). San Francisco, CA: Jossey-Bass.

Merwade, V., & Ruddell, B. L. (2012). Moving university hydrology education forward with geoinformatics, data and modeling approaches. *Hydrology & Earth System Sciences Discussions*, *9*(2). 2601-2628.

Millar, R. (2006). Twenty first century science: Insights from the design and implementation of a scientific literacy approach in school science. *International Journal of Science Education, 28*(13), 1499-1521.

Mislevy, R. & Haertel, G. (2006). Implications of evidence-centered design for educational testing. *Educational Measurement: Issues and Practice*, *25*(4), 6-20.

Moll, L. C. (Ed.). (1992). *Vygotsky and education: Instructional implications and applications of sociohistorical psychology*. Cambridge University Press.

Mosher, S., Bralower, T., Huntoon, J., Lea, P., McConnell, D., Miller, K., Ryan, J., Summa, L., Villalobos, J., & White, L. (2014). *Future of undergraduate geoscience education: Summary report for summit on future of undergraduate geoscience education*.

Murcia, K. (2009). Re-thinking the development of scientific literacy through a rope metaphor. *Research in Science Education, 39*(2), 215-229.

National Research Council. (1996). *National science education standards*. Washington, D.C.: The National Academies Press.

National Research Council. (2012). *Discipline-based education research: Understanding and improving learning in undergraduate science and engineering*. Washington, DC: The National Academies Press.

National Science Foundation (2005). *Complex environmental systems: Pathways to the future*. Advisory Committee for Environmental Research and Education (AC-ERE). Washington, DC.

Nersessian, N. J. (1999). Model-based reasoning in conceptual change. *Model-based Reasoning in Scientific Discovery*. Springer, Boston, MA. 5-22.

NGSS Lead States (2013). *Next generation science standards. For states, by states*. Washington, DC: The National Academies Press.

Nilsson, C., Reidy, C. A., Dynesius, M., & Revenga, C. (2005). Fragmentation and flow regulation of the world's large river systems. *Science, 308*(5720), 405-408.

Norris, S. P., & Phillips, L. M. (1994). Interpreting pragmatic meaning when reading popular reports of science. *Journal of Research in Science Teaching, 31*(9), 947-967.

Ødegaard, M., Haug, B., Mork, S. M., & Sørvik, G. O. (2014). Challenges and support when teaching science through an integrated inquiry and literacy approach. *International Journal of Science Education, 36*(18), 2997-3020.

Owens, D., Pettit, D. Lally, D., & Forbes, C.T. (under review). Undergraduate students' reasoning about socio-hydrologic challenges: Scientific literacy and informed decision-making in interdisciplinary STEM. In *Research in Science Education*.

Pachauri, R. K., Allen, M. R., Barros, V. R., Broome, J., Cramer, W., Christ, R., ... & Dubash, N. K. (2014). *Climate change 2014: Synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change* (p. 151). IPCC.

Pea, R. D. (2004). The social and technological dimensions of scaffolding and related theoretical concepts for learning, education, and human activity. *The Journal of the Learning Sciences, 13*(3), 423-451.

Pennington, K. L., & Cech, T. V. (2009). *Introduction to Water Resources and Environmental Issues*. Cambridge University Press.

Petcovic, H. L., & Ruhf, R. J. (2008). Geoscience conceptual knowledge of preservice elementary teachers: Results from the Geoscience Concept Inventory. *Journal of Geoscience Education*, *56*(3), 251-260.

Petitt, D. N., & Forbes, C. T. (2019). Values use in undergraduate students' socio-hydrological reasoning: A comparative study. *Natural Sciences Education, 48*(1).

Pfannenstiel, B. & Eller, D. (2018, January 28). Key achievement or drop in the bucket? What $282 million water quality bill means for Iowans. *Des Moines Register.* Retrieved from https://www.desmoinesregister.com/

Plano Clark, V. L., & Ivankova, N. V. (2015). *Mixed methods research: A guide to the field* (Vol. 3). Sage Publications.

Pluta, W. J., Chinn, C. A., & Duncan, R. G. (2011). Learners' epistemic criteria for good scientific models. *Journal of Research in Science Teaching*, *48*(5), 486-511.

Raia, F. (2005). Students' understanding of complex dynamic systems. *Journal of Geoscience Education*, *53*(3), 297-308

Raia, F. (2008). Causality in complex dynamic systems: A challenge in earth systems science education. *Journal of Geoscience Education*, *56*(1), 81-94.

Rates, C. A., Mulvey, B. K., & Feldon, D. F. (2016). Promoting conceptual change for complex systems understanding: Outcomes of an agent-based participatory simulation. *Journal of Science Education and Technology*, *25*(4), 610-627.

Richmond, B. (1993). Systems thinking: Critical thinking skills for the 1990s and beyond. *System Dynamics Review, 9*(2), 113-133.

Rodgers, G. & Eller, D. (2017, January 27). Environmentalists say ruling could slow water quality efforts. *Des Moines Register*. Retrieved from https://www.desmoinesregister.com/

Royte, E. (2017, December 7). The simple river-cleaning tactics that big farms ignore. *National Geographic*. Retrieved from https://news.nationalgeographic.com/

Ruddell, B. L., & Wagener, T. (2013). Grand challenges for hydrology education in the 21st century. *Journal of Hydrologic Engineering*, *20*(1), A4014001-1-8.

Rudolph, J. L. (2014). Dewey's "Science as Method" a century later: Revising science education for civic ends. *American Educational Research Journal*, *51*(6), 1056-1083.

Sabel, J.L., Vo, T., Alred, A., Dauer, J.M., & Forbes, C.T. (2017). Undergraduate students' scientifically-informed decision-making about socio-hydrological issues. *Journal of College Science Teaching, 46*(6), 64-72.

Sadler, P. M., Coyle, H., Miller, J. L., Cook-Smith, N., Dussault, M., & Gould, R. R. (2010). The astronomy and space science concept inventory: Development and validation of assessment instruments aligns with the K-12 National Science Standards. *Astronomy Education Review*, 8.

Sadler, T. & Zeidler, D. (2004). The significance of content knowledge for informal reasoning regarding socioscientific issues: Applying genetics knowledge to genetic engineering issues. *Science Education*, *89*, 71-93.

Sadler, T.D. & Zeidler, D.L. (2009). Scientific literacy, PISA, PISA, and socioscientific discourse: Assessment for progressive aims of science education. *Journal of Research in Science Teaching*, *46*, 909–921.

Schaffer, D. (2013). *The development and validation of a three-tier diagnostic test measuring pre-service elementary education and secondary science teachers' understanding of the water cycle* (unpublished doctoral dissertation). University of Missouri, Columbia.

Scherer, H.H., Holder, L., & Herbert, B.E. (2017) Student learning of complex Earth systems: Conceptual frameworks of Earth systems and instructional design. *Journal of Geoscience Education*, *65*(4), 473-489.

Schwarz, C. V., Reiser, B. J., Davis, E. A., Kenyon, L., Achér, A., Fortus, D., ... & Krajcik, J. (2009). Developing a learning progression for scientific modeling: Making scientific modeling accessible and meaningful for learners. *Journal of research in science teaching*, *46*(6), 632-654.

Secchi, S., Gassman, P. W., Jha, M., Kurkalova, L., Feng, H. H., Campbell, T., & Kling, C. L. (2007). The cost of cleaner water: Assessing agricultural pollution reduction at the watershed scale. *Journal of Soil and Water Conservation*, *62*(1), 10-21.

Seibert, J., Uhlenbrook, S., & Wagener, T. (2013). Preface. Hydrology education in a changing world. Hydrol*ogy and Earth Systems Sciences*, *17*(4), 1393-1399.

Sharma, V., & Irmak, S. (2012 a). Mapping spatially interpolated precipitation, reference evapotranspiration, actual crop evapotranspiration, and net irrigation requirements in Nebraska: Part I. Precipitation and reference evapotranspiration. *Transactions of the ASABE, 55*(3), 907-921.

Sharma, V., & Irmak, S. (2012 b). Mapping spatially interpolated precipitation, reference evapotranspiration, actual crop evapotranspiration, and net irrigation requirements in Nebraska: Part II. Actual crop evapotranspiration and net irrigation requirements. *Transactions of the ASABE, 55*(3), 923-936.

Shepardson, D.P., Wee, B., Priddy, M., Schellenberger, L., & Harbor, J. (2009) Water Transformation and storage in the mountains and at the coast: Midwest students' disconnected conceptions of the hydrologic cycle. *International Journal of Science Education, 31*(11), 1447-1471.

Sherchan, S., Pasha, F., Weinman, B., Nelson, F. L., Sharma, F. C., Therkelsen, J., & Drexler, D. (2016). Seven faculties in search of a mission: A proposed interdisciplinary course on water literacy. *Applied Environmental Education & Communication*, *15*(2), 171-183.

Shin, N., Stevens, S. Y., & Krajcik, J. (2010). Tracking student learning over time using construct-centered design. In S. Rodrigues (Ed.), *Using analytical frameworks for classroom research: Collecting data and analyzing narrative* (pp. 38-58). London; Taylor & Francis.

Sibley, D. F., Anderson, C. W., Heidemann, M, Merrill, J. E., Parker, J. M., & Szymanski, D. W. (2007) Box diagrams to assess students' systems thinking about the rock, water and carbon cycles. *Journal of Geoscience Education, 55*(2), 138-146.

Singha, K., & Loheide II, S. P. (2011). Linking physical and numerical modelling in hydrogeology using sand tank experiments and COMSOL Multiphysics. *International Journal of Science Education*, *33*(4), 547-571.

Sins, P. H., Savelsbergh, E. R., van Joolingen, W. R., & van Hout-Wolters, B. H. (2009). The relation between students' epistemological understanding of computer models and their cognitive processing on a modelling task. *International Journal of Science Education*, *31*(9), 1205-1229.

Sivapalan, M., Savenije, H., & Blöschl, G. (2012). Socio-hydrology: A new science of people and water. *Hydrological Processes, 26*, 1270–1276.

Smith, J.M., Edwards, P, & Raschke, J. (2006). Using technology and inquiry to improve student understanding of watershed concepts. *Journal of Geography, 105*(6), 249-257.

Somerville, R., & Bishop, W. (1997). Geoscience education: A recommended strategy. *National Science Foundation, NSF,* 97-171.

Sundberg, M. D., & Dini, M. L. (1993). Science majors vs. nonmajors: Is there a difference?. *Journal of College Science Teaching, 22*, 299-304.

Tasquier, G., Levrini, O., & Dillon, J. (2016). Exploring students' epistemological knowledge of models and modelling in science: Results from a teaching/learning experience on climate change. *International Journal of Science Education, 38*(4), 539-563.

Tewksbury, B. J., Manduca, C. A., Mogk, D. W., Macdonald, R. H., & Bickford, M. E. (2013). Geoscience education for the Anthropocene. *Geological Society of America Special Papers*, *501*, 189-201.

Thompson, S.E., Ngambeki, I., Troch, P.A., Sivapalan, M., & Evangelou, D. (2012). Incorporating student-centered approaches into catchment hydrology teaching: A review and synthesis. *Hydrology and Earth System Sciences, 16*, 3263–3278.

Tiwari, V. M., Wahr, J., & Swenson, S. (2009). Dwindling groundwater resources in northern India, from satellite gravity observations. *Geophysical Research Letters*, *36*(18).

Troy, T. J., Konar, M., Srinivasan, V., & Thompson, S. (2015). Moving sociohydrology forward: a synthesis across studies. *Hydrology and Earth System Sciences, 19*(8), 3667-3679.

U.S. Department of Education. (2013). *Common guidelines for education research and development*. Washington, DC.

U.S. Department of Energy. (2012). Essential principles and fundamental concepts for energy education.

U.S. Global Change Research Program. (2009). Climate literacy: The essential principles of climate science.

United Nations Educational, Scientific and Cultural Organization. (2016). The United Nations world water development report 2016 “water and jobs”.

USGS, U. Army Corps of Engineers, US Department of the Interior, and NOAA. 2009. *Climate change and water resources management: a federal perspective. Reston, Va*.

Vygotsky, L. S. (1978). *Mind in society: The development of higher psychological processes*. Harvard University Press.

Wagener, T., Kelleher, C., McGlynn, B., Gooseff, M., Marshall, L. Meixner, T., McGuire, K., Gregg, S., Sharma, P., & Zappe, S. (2012). It takes a community to raise a hydrologist: The Modular Curriculum for Hydrologic Advancement (MOCHA). *Hydrology and Earth System Sciences, 16,* 3405–3418.

Wang, T. J., & Zlotnik, V. A. (2012). A complementary relationship between actual and potential evapotranspiration and soil effects. *Journal of Hydrology*, *456*, 146-150.

Wheland, E. R., Donovan, W. J., Dukes, J. T., Qammar, H. K., Smith, G. A., & Williams, B. L. (2013). Green action through education: A model for fostering positive attitudes about STEM. *Journal of College Science Teaching*, *42*(3), 46-51.

White, B. Y., & Frederiksen, J. R. (1998). Inquiry, modeling, and metacognition: Making science accessible to all students. *Cognition and Instruction, 16*(1), 3-118.

Willerment, C., Mueller, A., Juris, S.J., Drake, E., Upadhaya, S., & Chhetri, P. (2013). Water as life, death, and power: Building an integrated interdisciplinary course combining perspectives from anthropology, biology, and chemistry. *Journal of the Scholarship of Teaching and Learning, 13*(5), 106 – 124.

Williams, A., Lansey, K., & Washburne, J. (2009). A dynamic simulation based water resources education tool. *Journal of Environmental Management, 90,* 471-482.

Wilson, K., & Devereux, L. (2014). Scaffolding theory: High challenge, high support in Academic Language and Learning (ALL) contexts. *Journal of Academic Language and Learning, 8*(3), A91-A100.

Wilson, M. (2005). Constructing measures: *An item response modeling approach*. Mahway, NJ: Erlbaum.

Wood, D., Bruner, J. S., & Ross, G. (1976). The role of tutoring in problem solving. *Journal of Child Psychology and Psychiatry*, *17*(2), 89-100.

Yoon, S. A., & Hmelo-Silver, C. (2017). Introduction to special issue: Models and tools for systems learning and instruction. *Instructional Science, 45*(1), 1-4.

Yore, L. D., & Treagust, D. F. (2006). Current realities and future possibilities: Language and science literacy-empowering research and informing instruction. *International Journal of Science Education*, *28*(2-3), 291-314.

Zainuddin, Z., & Perera, C. J. (2019). Exploring students' competence, autonomy and relatedness in the flipped classroom pedagogical model. *Journal of Further and Higher Education*, *43*(1), 115-126.

Zangori, L. & Forbes, C. T. (2015). Exploring 3rd-grade students' model-based explanations about plant relationships within an ecosystem. *International Journal of Science Education, 37*(18), 2942-2964.

Zangori, L., Vo, T., Forbes, C.T., & Schwarz, C. (2017). Supporting 3rd-grade students' model-based explanations about groundwater: A quasi-experimental study of a curricular intervention. In *International Journal of Science Education*, *39*(11), 1421-1442.

Zigic, S., & Lemckert, C. J. (2007). Development of an interactive computer-based learning strategy to assist in teaching water quality modelling. *Computers & Education*, *49*(4), 1246-1257.