Intertwining Three Dimensions: Levels of Performance for Computational Thinking While Using Models of Hydrologic Systems

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Prepared for the Annual International Meeting of NARST
March, 2020

This material is based upon work supported by the National Science Foundation DRL – 1543228 Comp Hydro: Integrating data computation and visualization to build model-based water literacy. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

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Abstract

Computational thinking is integral to explaining and predicting abstract phenomena, modeling complex systems, and solving challenging problems. In the context of three-dimensional learning, insight is needed into how students engage in computational thinking while interacting with system models. To address this problem, we designed an embedded assessment to elicit students' computational thinking while using models to trace water through hydrologic systems. We collected, from groups of high school students at three sites across the United States, written responses to prompts embedded in a task that incorporated a computational model of either a groundwater or surface water system. We identified three levels of performance on the task. Groups at the lower level could manipulate the model to accomplish the task but viewed the model as isolated from a physical system. At the middle level, groups were able to use the model as a tool and identify parameters relevant to the system. The upper level groups connected hydrologic principles to computational thinking by describing algorithms for tracing water. These findings show that computational thinking develops as students become more proficient at using models and that more sophisticated computational thinking is necessary to use system models to explain and predict phenomena.

As a science and engineering practice, computational thinking is integral to explaining and predicting abstract phenomena, modeling complex systems, and solving challenging problems (Grover & Pea, 2018; National Research Council, 2010; Wing, 2006). As a goal for science education, computational thinking is a relatively new focus, not receiving widespread recognition until the release of the *Framework for K-12 Science Education* (National Research Council, 2012). Since that time, research related to computational thinking has focused on defining computational thinking and developing frameworks for what students should know and be able to do with respect to computational thinking (e.g., Sengupta, Kinnebrew, Basu, Biswas, & Clark, 2013; Weintrop et al., 2016) and developing projects to teach students how to code and model (e.g., Leonard et al., 2016; Puttick & Tucker-Raymond, 2018). The next step is to better understand student computational thinking as students participate in instructional activities designed to engage them in this practice.

In the context of three-dimensional learning, in which science and engineering practices are intertwined with crosscutting concepts and disciplinary core ideas, the development of computational thinking does not occur in isolation. Computational thinking is deeply intertwined with modeling (Sengupta et al., 2013; Wilkerson & Fenwick, 2017). As such, engagement in computational thinking incorporates understandings of systems and system models, a crosscutting concept in the *Framework for K-12 Science Education*. Furthermore, understanding systems relies on principles grounded in various disciplinary core ideas within life science, physical science, and Earth and space science. Therefore, understanding how students engage in and develop competence in computational thinking requires examination of their participation in instruction that intertwines science and engineering practices, crosscutting concepts, and disciplinary core ideas.

Our work investigated the development of students' computational thinking while learning about hydrologic systems. Principles of water movement through groundwater and surface water systems are integral to disciplinary core ideas in Earth's Systems (ESS2) and Earth and Human Activity (ESS3) (National Research Council, 2012). We developed several high school-level units of instruction that engage students in using computational models of hydrologic systems to learn about groundwater contamination or watershed runoff and urban flooding. Included in this instruction were embedded assessment tasks that prompted students to express their computational thinking while working with a model of either a groundwater or surface water system.

Our research questions were:

> RQ 1: In what ways do students approach and interact with models of hydrologic systems? (Systems & System Models)
>
> RQ 2: In what ways do students engage in computational thinking when using models of hydrologic systems? (Computational Thinking)
>
> RQ 3: What does student use of models of hydrologic systems indicate about their understanding of hydrologic systems? (Disciplinary Core Ideas)

Frameworks

The *Framework for K-12 Science Education* outlines a vision for science learning and teaching that intertwines three dimensions of science learning: science and engineering practices, crosscutting concepts, and disciplinary core ideas. This vision promotes the idea that these three strands work together to build more integrated and robust understandings of science concepts while engaging students in building and using scientific knowledge. The *Framework* makes explicit eight *science and engineering practices* that scientists and engineers use when building and using science knowledge. These practices define what it means to do science and think like scientists. The *crosscutting concepts* are organizational ideas that span discipline areas. These concepts can be viewed as lenses with which to make sense of phenomena from different perspectives, as bridges to make connections between concepts, as tools for constructing deeper understandings, and as epistemic rules for building scientific knowledge across domains (Rivet, Weiser, Lyu, Li, & Rojas-Perilla, 2016). *Disciplinary core ideas* are the big ideas that have broad importance in science. They are organized under four domains: life science; physical science; Earth and space science; and engineering, technology and applications of science. The Next Generation Science Standards and science standards from various states combine practices, crosscutting concepts, and disciplinary core ideas to identify performance expectations for students at each grade level.

Our work on computational thinking recognizes that computational thinking is intertwined with crosscutting concepts and disciplinary core ideas. We do not focus on a particular performance expectation, but are more interested broadly in how computational thinking develops with respect to systems thinking about water in environmental systems. Below we describe these three dimensions in more detail.

Computational Thinking

Computational thinking is an analytical approach to investigating problems that relies on abstracting the essential elements of systems in order to define problems, identify relationships, and search for solutions (Grover & Pea, 2018; National Research Council, 2010; Sengupta et al., 2013; Wing, 2006, 2014). Wing describes computational thinking as the thinking necessary to break problems into parts in such a way that a computer would be able to solve them. It relies of abstracting the essential elements of systems. This type of thinking is necessary to code computer models, but is also useful for understanding how computer models work, and for interpreting, evaluating, and critiquing computer models and their output (Wilensky & Reisman, 2006). Examples of computational thinking practices include discretization, parameterization, interpolation, and writing rules or algorithms. *Discretization* is the process of dividing a problem space into discrete chunks that can be represented and analyzed in a computer model. *Parameterization* is the process of assigning values to the cells based on characteristics of the system being modeled. In the case of groundwater flow, parameters that define the system include the type of substrate (e.g., sandstone, unconsolidated gravel) and the gravitational potential energy within any given cell in the model. These values may be assigned based on actual data or estimated based on *interpolation* from nearby data points. Another aspect of computational thinking is developing *rules*, also known as *algorithms*, which define for the computer model how to make decisions when solving a problem. These rules reflect principles based on relationships between variables. For water flow, either above or below ground, a foundational rule is that water moves from areas of high potential energy to low potential energy. These computational thinking practices allow scientists and students to break down, explain, and predict complex systems and problems such as the flow of water and contaminants through hydrologic systems.

Systems and System Models

A model is an abstract representation of a system that hides some elements and highlights others to help scientists better understand a phenomenon (Schwarz et al., 2009; Wing, 2014). Systems are defined by structures and limited by boundaries that isolate the interacting elements to be studied. Modeling the system involves articulating the scientific, principle-based relationships that govern how the system works and identifying the emergent properties that arise when the system's parts are functioning together (Hmelo-Silver, Marathe, & Liu, 2007). In water systems, boundaries may be defined by topography, such as in the case of a watershed, or stratigraphy, in the case of groundwater flow. Stratigraphy and geology also define the structure of a system. The principles that are used to define algorithms in computational models are grounded in the relationships that govern the flow of water through systems, including the driving forces, such as pressure and gravity, and constraining variable, such as topography or permeability, that create the pathways of least resistance through which water flows.

Knowledge of systems and system models functions as an epistemic tool for engaging in scientific practices. Understanding models of systems requires identifying the parts and the boundaries of the system, how those parts interact, and how relationships are represented in a model (Ben-Zvi Assaraf & Orion, 2005; Hmelo-Silver et al., 2007). Using knowledge of systems for computational thinking requires recognizing the relationships between the model and the system that it represents, including what the model highlights and hides and its affordances and constraints for explaining and predicting phenomena and testing ideas.

Water in Socio-ecological Systems

Within the *Framework*, a disciplinary core idea in Earth and space science is that water continually moves among and through various reservoirs within the Earth's hydrosphere (ESS2.C). Understanding these movements requires unpacking the components and processes that operate within groundwater and surface water systems. These systems, however, do not operate separately from human actions (ESS3.A and ESS3.C). Environmental systems, such as groundwater and surface water systems, include both natural and connected human-engineered components and are inextricably linked to human social and economic systems (Gunckel, Covitt, Salinas, & Anderson, 2012). Groundwater and surface water systems provide fresh water necessary for living systems, including the global human population. Human actions impact the structure and function of hydrologic systems, which in turn has implications for human socio-political systems.

Model-based explanations and predictions of water moving through surface water and groundwater include detailed descriptions, at various scales from atomic-molecular through landscape, of multiple pathways through systems. These explanations and predictions account for scientific principles (e.g., driving forces such as gravity and pressure and constraining factors such as permeability and topography), interpret constraining factors such as permeability and topography from representations of the physical world, such as maps or cross-section, connect representations to the physical world. They also recognize human dependence on environmental systems, the impacts of human activity as a part of these systems, and the dependence of humans on hydrologic systems for survival (Gunckel et al., 2012).

Methods

Research Design

This research is part of a design-based research project (Design-Based Research Collective, 2003) focused on integrating computational thinking into instruction about hydrologic systems at three sites across the United States. Each site developed a 3-week unit of instruction for high school (9th-12th grades) focused on a local groundwater (Sites 1 and 2) or surface water (Site 3) issue. Each unit included Net Logo computational models (Wilensky & Reisman, 2006) and "unplugged" models that did not require computer technologies but nevertheless incorporated computational thinking about such processes as discretization and parameterization.

Embedded Assessment Instrument

In this iteration of the project, we designed an assessment embedded into a lesson or lessons at each site. The embedded assessment was formulated as a task that required students to use hydrologic principles (e.g., groundwater flows from high potential energy to low potential energy), computational thinking (e.g., parameterization), and systems modeling concepts (e.g., defining systems and system boundaries) to trace water through a hydrologic system. At Sites 1 and 2, the assessment was embedded into Net Logo models that traced contaminated water through groundwater systems. At site 3, the assessment was embedded various unplugged activities throughout the unit that traced water through watersheds. Prompts were embedded in the task(s) that required students to explain their interpretation of the model and their reasoning behind the decisions they made in manipulating the model. Although the prompts were worded differently at each site, all sites included prompts that addressed hydrologic principles, computational thinking, and systems models. Figure 1 shows an example of an assessment prompt embedded in a Net Logo Model. Table 1 shows the prompts across sites.

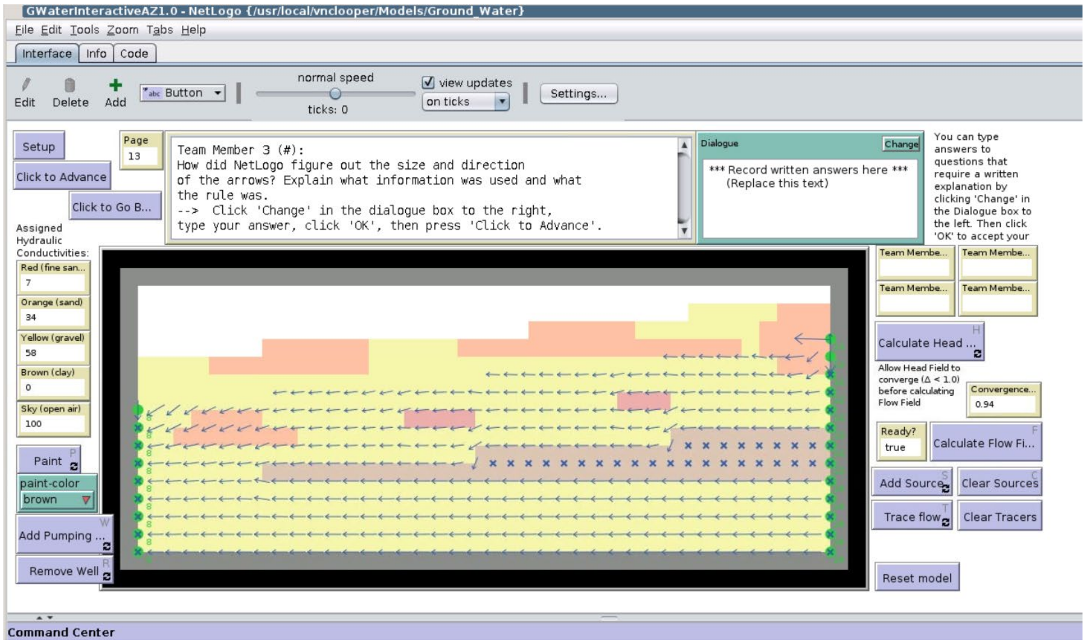

Figure 1: Example assessment prompt embedded into a Net Logo computational model.

Table 1: Example Embedded Assessment Prompts

Concepts Assessed	Site 1 (Groundwater)	Site 2 (Groundwater)	Site 3 (Surface Water)
System models	What type of sediments does red represent? What color represents gravel?	Imagine you were using the NetLogo Groundwater computer model to represent a real world groundwater system. Describe a situation in which you would want to set the right model boundary as open (allows water to pass through) instead of closed (water cannot pass through).	Identify the large watershed in the simulation. What information in the computer model causes this boundary to form?
Hydrologic principles	Which direction do you think water will flow through this model? Why?	Now use the pushpin cursor to identify the area in the model where groundwater flow will be upwards (move from deeper underground toward the surface).	Which direction do you think water will flow through this model? Why?
Using computational thinking: Rules	How did Net Logo figure out the size and direction of the arrows? Explain what information was used and what the rule was.	What rules do you think were written into the computer model code to tell the model to draw the flow field arrows?	What features or variables of the surface in the computational model determine how water will flow over the landscape? Explain your reasoning for each variable you list.

Sample

The student demographics of the sites ranged from predominantly white-rural classrooms (Site 1) to urban classrooms with >90% students-of-color (Sites 2 and 3). At each site, students worked in groups of two to four to complete the embedded assessment tasks. We analyzed1658 groups from Site 1, 78 groups from Site 2, and 53 groups from Site 3 for a total of 296 groups across the sites.

Analysis

Responses from each group to each prompt were collected and compiled. Working with examples of responses from prompts from all three sites, we developed a coding document to categorize student performance on the embedded assessment tasks. Specifically, we looked at how student responses in each category indicated that students made connections between the models and the physical world and made connections across hydrologic principles, models, and computational thinking. We used this coding document to code the category of performance on the assessment task for each group at each site. Interrater reliability was calculated for each site's data using a Weighted Cohen's Kappa and ranged from .86 to .92. We then looked for patterns in responses within each category to characterize student understanding of systems and use of system models (RQ1), which computational thinking practices students engaged in (RQ2), and how they were connecting hydrologic principles to their work with the models (RQ3). We also calculated the percentage of groups whose performance fit within each category (RQ3).

Findings

Based on student interactions with the models in the embedded assessments, we identified three categories of student performance based on their conceptions of system models and approaches to using the models: Literal Interface Users, Model Technicians, and Principle-based Model Users. Literal Interface Users used the models to solve the problem presented on the graphical computer interface or the unplugged version of the model. Problem-solving Technicians used the computer model as a tool for solving a real-world problem, but demonstrated little understanding of how the computer model produced the results. Principle-based Model Users provided evidence that they understood not only what the computer model produced, but could also use principles of computational thinking, systems modeling, and hydrology to explain and critique the models. Below we describe the characteristics of each group's approach to interacting with computational models, their engagement in computational thinking, and their understanding of hydrologic systems.

Students' Approaches to Using Models of Hydrologic Systems

Our first question looked at how students' approach to using the models provide evidence for how they think about the purpose of computational models. Literal Interface Users approached the use of the computational model as if it were a video game in which they worked to manipulate the model interface to complete the given task. For example, the embedded assessment task at one of the sites asked students to determine where to place wells to clean up contaminated groundwater. Groups in this category sometimes placed the well at the source of the contamination. An example student explanation for this placement was, "It was like putting a bandaid on another spot rather than the wound, you put it on the source." This type of response suggested that students viewed the model as a simulation where they could manipulate the image on the screen to achieve the goal, in this case, making the dots on the screen representing contamination stop flowing. Their solution was effective because the model interface no longer showed the groundwater contamination, but their written response did not indicate an understanding of how groundwater contamination resides in and moves through aquifers. Similarly, when asked what rules the model used to produce the results, groups gave responses such as “We used the “add source tool” to add the contamination [to the model interface] which caused the flow going.” To these groups, the rules were procedures for interacting with the model interface. Although the groups could successfully achieve the goal of the task (i.e., clean up the contamination), there is little evidence that they were recognizing that the model on the screen represented a physical system in the world beyond the model.

In contrast, responses from groups in the Model Technicians category made connections between the models and physical systems. When asked how they used the model to complete the task, students made comments such as, “By looking at the model to see where a well can help with the problem.” These groups recognized the model was helping them see something about a physical system that they might not otherwise be able to see, such as where water might flow underground. In response to prompts asking about the rules that the model used to represent the system, students named relevant parameters, such as permeability of layers of sediment, although they did not explain how the model used these parameters. These responses indicated that Model Technicians recognized that the models were abstract representations of hydrologic systems and could be used as a tool to figure out solutions to problems, such as to help them see where contamination is coming from or going to, or to make calculations to figure out how much water is moving through a watershed.

The third category of students, Model-based Users, were able to express how the model used information from the physical world to represent the flow of water in the system. For example, when asked when one would set the boundary of a groundwater model as “open,” a group coded at this level responded, “When if this were a real world situation a boundary that would allow water to pass through could be a spring or a lake or something of that sort.” These students went beyond Model Technicians by articulating how the model might handle data at the boundaries and considering whether the model accurately reflects the real system. They were able to not only use the model as a tool, but could also interpret the implications of the model design to evaluate possible solutions.

Students Computational Thinking When Using Models of Hydrologic Systems

Each of the three categories of groups also engaged in computational thinking in fundamentally different ways as they used the models to explain and predict the flow of water in hydrologic systems.

The Literal Interface Users paid primary attention to the visible aspects of the models. For example, one of the groundwater models tasked asked students to place a contamination source on the model and then ran the model to see where the contamination flowed. An embedded assessment question asked why the contamination flowed in the direction they observed. Groups in this category provided responses such as, “The water will flow north from the airport,” “It would go in that direction because the water is moving along with the contamination,” and “The water flow is going down ward and is easier for the contamination to move downwards.” These responses all described what was happening to the water and contamination that they observed in the model interface.

Groups in the Model Technicians category began to identify hydrologic parameters relevant to the system represented in the model. For example, when asked why the contamination would flow that direction, groups provided responses such as, “It would flow in that pathway shown because the clay is preventing it from going farther down while the elevation of the ground is making the contamination go to the left." These groups described how the computer used this information by making statements such as, "The computer model uses the permeability of the rock as well as the energy to see where the contamination goes through." In the watersheds embedded assessment, groups were asked why water followed certain pathways over the landscape. They responded with answers such as, "Slope- helps determine water flow speed Elevation- helps determine watershed boundaries." These answers all name relevant parameters, such as permeability of the aquifer or the potential energy of the system, but they do not yet connect these variables to model-based principles about how and why water moves through systems.

In the Principle-based Model Users category, groups went beyond naming parameters to unpacking the algorithmic rule that the model followed to trace the flow of water through a system. They made statements such as, "The computer model uses its knowledge of the materials (color and permiability [sic]) to determine the flow of the contaminent [sic] and water. Example, red is fine sand so water and the contaminent [sic] flow slower than in normal gravel," "That water in areas with a higher potential energy will flow to an area with lower potential energy," and "Water is going to flow from high elevation to low elevation on the steepest line." These students were not just repeating a rule; they were applying the rule to explain how the computer program would trace water through a model of a system.

Student Understanding of Hydrologic Systems

Within each group, student understanding of how water moves through hydrologic systems is intertwined with their computational thinking and understanding and use of system models. Literal Interface Users describe where water flows on the model interface; their descriptions do not provide mechanisms for how or why water moves. There is little evidence that they connect the depiction of water flowing on the screen with water flowing through real-world systems. Furthermore, their manipulations of the model interface to achieve a goal requires little reason to explain how or why the water moves. However, Model Technicians demonstrate not only more awareness of the connection between models and real-world systems, they also identify characteristics of those systems, such as permeability or potential energy, that influence the flow of water through those systems. Furthermore, they can use this information to help them solve a problem, such as figuring out where water and contamination in a real world system might go. Principle-based Model Users can connect principles of water flow to how the computer model traces that flow in hydrologic systems.

We arranged the three categories hierarchically, showing an increase in sophistication, from Literal Users to Model Technicians to Principle-Based Model Users, in how students approached models, engaged in computational thinking, and used principles of model-based understandings of hydrologic systems. We calculated the percentage of groups from all three project sites across these three categories. Table 2 shows that the majority of the student groups interacted with the models and engaged in computational thinking as Model Technicians. These are the students who recognize models as representations of physical systems useful for providing answers or solving problems but who do not yet connect principles of computational thinking and hydrologic systems to explain or critique the model's function or output.

Table 2: Characteristics of Groups based on Performance on the Embedded Assessment

	Approach to interacting with the model	**Engagement in computational thinking**	**Percentage of Groups**
Principle-based Model Users	Model represents a system in the physical world; explains how the model produces a solution or answer.	Connects hydrologic principles to computational thinking by identifying parameters relevant to the hydrologic system and describing computational rules (algorithms) for tracing water.	20%
Model Technicians	Model represents a system in the physical world; uses the model to solve a problem or answer a question.	Identifies hydrologic information relevant to the system (e.g., describes permeability or potential energy)	56%
Literal Interface Users	Model is a simulation isolated from specific physical world system; focuses on manipulating the model interface.	Describes where water flows on the model interface.	25%

Across the three categories of student performance, students' computational thinking was linked to their understanding and use of systems and system models and their understanding of hydrologic principles for water moving through hydrologic systems. At the lowest level, Literal Interface Users focused on using the computer model as a simulation of an isolated world did not require them to engage in computational thinking or use hydrologic principles to interact with the computer model. In contrast, Model Technicians, who recognized the connections between the model and physical systems, were able to also use hydrologic principles to define the system represented by the model. However, it was only the Principle-based Model Users who were able to engage in computational thinking to understand how the model traced water through hydrologic systems. This pattern suggests that students' understanding of systems and system models is foundational to developing more sophisticated understandings of hydrologic principles and computational thinking practices. As students' understanding of systems and system models moves from seeing computer models as games with objectives to be achieved towards being representations of systems that can be used to explain and predict phenomena, students are able to recognize how hydrologic principles operate within the models, engage in computational thinking such as parameterization and assigning rules, and how the models function to trace water and contamination through systems.

Discussion

In this project, the highest-level student performances on the embedded assessment performances required the use of computational thinking to explain and predict phenomena within hydrologic systems. However, our findings show that using a computational model (either plugged or unplugged) of a hydrologic system does not automatically result in computational thinking. Computational thinking is a practice that develops as students become more sophisticated at using models. This finding suggests that while in science and engineering the practice of computational thinking is intertwined with understanding of system and system models as well as disciplinary, model-based principles (Schwarz et al., 2009; Sengupta et al., 2013; Wilkerson & Fenwick, 2017), learning to achieve performances that intertwine all three dimensions may begin with developing proficiency one strand at a time. By looking at how students interacted with models while learning to engage in computational thinking, we submit that learning to engage in computational thinking to understand and use models is a sophisticated practice that may first require developing an understanding of what a model is and how it represents physical systems. Making the shift from seeing models as simulations to be manipulated in order to achieve objectives established for interacting with the model to recognizing that models are tools that can be used to explain and predict phenomena in the physical world is a significant shift in how one interacts with models of complex systems. Our data suggest that this shift may be necessary in order for students to begin intertwining disciplinary core ideas about models and then computational thinking into their work with models. The cross-cutting concept of understanding systems and system models might be the foundational strand to which disciplinary core ideas and then computational thinking are gradually interwoven.

Importantly, we do not argue, however, that our findings suggest that each strand should be taught in isolation. Indeed, the instructional units in which these assessment tasks were embedded were designed to specifically integrate computational thinking into learning about hydrologic systems. Three-dimensional learning still requires instruction that engages students in all three dimensions (National Research Council, 2012). Rather, we are arguing that our findings could inform how researchers and teachers interpret student progress towards achieving performances that intertwine along three dimensions, especially with respect to performance expectations that include computational thinking. For example, recognizing that students may initially interact with models in the ways that the Literal Interface Users interacted may help researchers and teachers design learning experiences that support these students in making progress towards Model Technicians and then Principle-based Model Users.

The category of Model Technicians is an important category for teachers and researchers to consider. Groups that were categorized as Model Technicians seemed considerably more sophisticated than Literal Interface Users and had made important shifts in their thinking about models and systems by recognizing the connections between models and physical systems. Their responses to the embedded assessment prompts showed that they were making progress towards becoming more proficient principle-based users of these systems (Covitt et al., March, 2020). That this category included the greatest number of groups also aligns with previous research on students' development of model-based accounts of water, where the majority of students learn to provide school-science based accounts of water in environmental systems but have not yet progressed to model-based accounts (Gunckel et al., 2012).

Our work also demonstrates an approach to understanding how students learn to engage in three dimensional learning, especially with respect to computational thinking. Our previous research (Gunckel et al., March, 2018) on computational thinking has relied on pre- and post-instructional assessments and post-instructional interviews with students, which provides only the final product of student thinking and does not offer insight into how students engage in computational thinking while using computational models of hydrologic systems or become more sophisticated in the practice. We found the use of embedded assessments was helpful for getting a glimpse of how students engage in computational thinking while working on instructional tasks – in the moments of learning. This approach may be useful for developing more nuanced approaches to researching how students progress as they engage in three dimensional learning tasks.

Conclusion

Assessing three-dimensional learning, especially when it involves sophisticated science and engineering practices, such as computational thinking, is in its infancy. Yet, figuring out how to better understand how students engage in computational thinking as they participate in instructional activities designed to integrate all three dimensions is necessary to learn how to support students in achieving the performance standards set out in the Next Generation Science Standards and other similar state standards. The next step for this research is to establish whether the hierarchy of groups identified in this project represents a rigorously-defined learning progression for computational thinking in the context of working with models of hydrologic systems.

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