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Using Students' Conceptual Models to Represent Understanding of Crosscutting Concepts in an NGSS-Aligned Curriculum Unit About Urban Water Runoff

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Abstract

Recent science education reforms, as described in the *Framework for K-12 Science Education* (NRC, 2012), call for three-dimensional learning that engages students in scientific practices and the use of scientific lenses to learn science content. However, relatively little research at any grade level has focused on how students develop this kind of three-dimensional knowledge that includes crosscutting concepts. This paper aims to contribute to a growing knowledge base that describes how to engage students in three-dimensional learning by exploring to what extent elementary students represent the crosscutting concept systems and system models when engaged in the practice developing and using models as part of an NGSS-aligned curriculum unit. This paper answers the questions: How do students represent elements of crosscutting concepts in conceptual models of water systems? How do students' representations of crosscutting concepts change related to different task-based scaffolds? To analyze students' models, we developed and applied a descriptive coding scheme to describe how the students illustrated the flow of water. The results show important differences in how students represented system elements across models. Findings provide insight for the kinds of support that students might need in order to move towards the development of three-dimensional understandings of science content.

Keywords Water runoff · Models · Crosscutting concepts · Systems

Introduction

Recent science education reforms, as described in the *Framework for K-12 Science and Education* (NRC, 2012), represent a fundamental shift in the approach to teaching and learning of science and engineering in the USA. The *Framework* describes three dimensions of science and engineering learning: disciplinary core ideas (DCIs), crosscutting concepts (CCCs), and science and engineering practices (SEPs). The move towards three dimensions of science and engineering education represents a shift from science as participation in activities focused on science content towards a focus on developing an understanding of the big ideas of science (DCIs) through engaging with SEPs and CCCs to explain phenomena and solve problems. Cutting across the disciplinary core ideas and in support of the SEPs are the crosscutting concepts (CCCs), which are a part of developing a deeper understanding of science content (e.g., Jin & Anderson, 2012), and supporting students to develop understandings across disciplines (e.g., Opitz et al., 2019).

While disciplinary core ideas and science practices have been integrated in a variety of lines of research (e.g., Duschl & Osborne, 2002; Krajcik et al., 2008; Lehrer & Schauble, 2006; Sampson & Clark, 2009), fewer studies document student learning across all three dimensions, with explicit attention to the crosscutting concepts (Fick, 2018). Some prior research assumes that if

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all three dimensions are integrated within a curriculum, then students will automatically develop a facility with all three dimensions, including use of the CCCs (Carlson et al., 2013). However, relatively little research at any grade level has focused on how students' use of the three dimensions develops which explicitly includes CCCs. This paper aims to contribute to a growing knowledge base of how to engage students in three-dimensional learning by exploring to what extent elementary students represent targeted DCIs and CCCs when engaging in the SEP of developing conceptual models as part of an NGSS-aligned curriculum unit.

Background

The *Framework* proposes that science and engineering learning is three-dimensional in nature. As a part of this process, students start with authentic science questions and engineering problems and engage in realistic science and engineering practices to make sense of the content and practices using CCCs. However, the role that the CCCs play in this work has been underspecified (Fick & Arias, 2019), and the *Framework* describes the articulated learning progression as hypothetical because of the lack of research on some of the crosscutting concepts. For most DCIs, using many if not all SEPs will help a student to unpack how the processes work in the context of natural phenomena. However, how a CCC interacts with particular DCIs is not well described, though examples of the interaction exist (National Research Council, 2012). For example, with the DCI of water on Earth's surface processes, one could take a systems approach to understand inputs and outputs, or a conservation approach to understand that matter cannot disappear. Hypothetically, any CCC could be used with any DCI to illuminate different aspects of the phenomenon under study; however, some of these combinations may have more explanatory power (Fick et al., 2019). For example, structure and function or cause and effect could help explain why water collects in lakes and streams, but those CCCs may not help students understand the phenomenon as well as energy and matter with systems and system models. For every phenomenon, some CCCs may have more power to explain particular scientific processes. Therefore, both students and teachers alike need support to understand which CCCs will help them make sense of a particular phenomenon, how to apply those CCCs, and for what purpose are they doing so. However, little research explicates what CCCs are best suited for what concepts (National Research Council, 2012). This paper aims to address this gap by looking specifically at how a specific SEP (modeling) may be synergistic with a specific CCC (systems).

Developing Models to Provide Insight into the CCC of Systems

This study focuses on the SEP of developing and using models and the CCC of systems and system models. Developing and using models involve students in creating representations of how they believe a phenomenon works. Sometimes, this process involves the development of physical, computational, or conceptual representations that include underlying relationships and processes, which helps students to develop understanding of the underlying phenomenon (Schwarz et al., 2009). In addition, modeling can also support students to knowingly revise their understanding of science concepts (e.g., Lehrer & Schauble, 2006; Zangori et al., 2015). For example, developing and revising conceptual models can involve students creating an initial model that shows their prior knowledge and ideas for how something works, engaging in activities that support their development of new ideas and understandings, then changing their model to represent their revised understanding of the concept.

As such, conceptual models can be used to capture both students' understanding of DCIs at particular time points as well as capture students' engagement in the practice of modeling. Research examining students' evolving understanding of the practice of modeling shows that students often start by focusing on representing what they see at the expense of being able to authentically represent the processes and relationships that they are observing (Lehrer & Schauble, 2006). For example, with water systems, students tend to represent water flowing from left to right and include familiar objects such as trees or houses. Students tend to use the sun and bodies of water to represent water processes instead of important system elements for water movement, and understandably reason from visible processes such as rain falling to the ground and flowing in rivers. However, they also often neglect non-visible aspects of water such as subsurface flow and assume subsurface flow as similar to surface flow (Covitt et al., 2009). With support, students at both the elementary and middle school levels have been found to be able to revise models to reflect deeper understanding of both DCIs and the practice of modeling (Fick, 2018; Manz, 2012). These findings have been particularly well represented in the area of how water moves in Earth's surface processes (e.g., Ben-Zvi Assaraf & Orion, 2010; Forbes et al., 2015).

We view engaging in modeling as distinct from the CCC of systems and system models. According to the NGSS, systems are operationalized to have the following components: boundary, inputs, outputs, interactions, and how they are nested within larger systems (NGSS Lead States, 2013, Appendix G). The CCC of systems and system models is a lens one can use to understand scientific phenomena and design engineering solutions. For example, when thinking about water systems, one can apply a systems lens to think about where to apply boundaries to the system, describe the interactions that occur within the system, and to define the inputs and the outputs to understand water movement. Fully understanding the CCC involves being able to apply a systems lens intentionally to different phenomena, as well as generalized understanding of systems concepts such as boundaries, inputs, and outputs that can be transferred across phenomena (Goldstone & Wilensky, 2008).

We see the SEP of modeling as supporting the development of a systems lens for understanding scientific phenomena and designing engineering solutions. Students can learn about important systems concepts by developing models of phenomena. However, the modeling practice itself does not inherently involve using the systems CCC. Students can engage in modeling a phenomenon but have little to no consideration of important systems concepts. For example, students can engage in the practice of modeling by drawing and revising conceptual models of water focused on familiar objects without representing or including explicit discussion of boundaries, inputs, or outputs, or interactions among elements within the water system.

Examining students' models using a systems thinking lens can reveal implicit information about the nature of the students' understanding of the system under study (Ben-Zvi Assaraf & Orion, 2010). Students' models can reveal what aspects of a system or systems concept they may not understand. For example, if students do not represent input components, they may not understand the concept of inputs to a system. If students represent input components that equal the amount of output components in a system, the student may hold and have applied an understanding of conservation of matter. If the student represents unequal amounts of inputs and outputs, the student may not understand or apply a conservation of matter lens. Thus, supporting students to help represent their knowledge through modeling tasks can provide insight into students' understanding of CCCs.

Understanding and applying systems to make sense of phenomena and solve problems includes the implicit use of other CCCs, as was seen in the example above. In that example, ensuring consistent inputs and outputs required applying an energy and matter lens to attend to the conservation of matter. This example shows how simple systems can be accessed using other CCCs as well. Some have even argued that there is a hierarchy to the CCCs with systems being the most prominent and other CCCs playing supporting roles in sense-making (Rehmat et al., 2019). In their research developing a learning progression about carbon cycling, Jin and Anderson (2012) found that those participants with the deepest levels of understanding used a conservation of matter lens for making sense of the system.

Scaffolding Elementary Students to Develop Models

Several studies have investigated how to support students' engagement in modeling practices (e.g., Forbes et al., 2015; Lehrer & Schauble, 2006; Manz, 2015; Schwarz et al., 2009). Based in research of other practices, this kind of support, or scaffolding, can take many forms, including framing the activities (e.g., González-Howard & McNeill, 2019), teachers' use of questions to support students' knowledge construction (e.g., Chin, 2007), or curricular supports that break down the science practice into manageable chunks for students (e.g., McNeill & Krajcik, 2008).

However, relatively little research has addressed supporting elementary students in modeling (Baek et al., 2011). In studies that do focus on elementary students, research points to the importance of helping students develop conceptual models (Baumfalk et al., 2019). For example, Zangori et al. (2015) investigated how providing background context and the task prompt can affect the development of elementary students' models. In the unscaffolded condition, students were given an empty box and a very general prompt to "draw a model of what you think happens to rain after it hits the ground." In the scaffolded condition, the students started with a background of trees, clouds, a house, and a lake and were prompted more specifically to "draw the most important things that happen to rain." Students in the scaffolded condition represented and connected more processes than those in the unscaffolded condition; however, students in the unscaffolded condition were able to identify causal mechanisms in later model-based explanations. The study highlights the importance for task scaffolds and prompts for elementary students to engage in developing models.

Supporting Elementary Students to Understand Systems

Research has investigated helping students understand complex systems in elementary settings. Studies suggest that students need support and framing of systems concepts (Yoon et al., 2018). For example, many studies use a structure-behavior-function framework to help elementary students understand components and processes of biological systems (Hmelo et al., 2000). Other studies consider a system a collection of parts that make up a whole that has a larger function of its own where the interactions between the parts and their feedback loops define the function of the system (Ben-Zvi Assaraf & Orion, 2005). These two approaches are different from the description in the NGSS which focuses on inputs, outputs, the boundary, interactions with the system and the nesting of systems within one another (NGSS Lead

States, 2013). However, few studies have explored how to concurrently support elementary students' understanding of the systems CCC and the SEP of modeling (Zangori & Forbes, 2015).

Research Questions

Because of the potential for the under researched relationship between the systems CCC and SEP of modeling to support student learning, this study focuses on how elementary students represent CCC concepts during the development of conceptual models in an online learning environment. Due to studies demonstrating the importance of task-based scaffolds in elementary settings (Zangori et al., 2015), we also explore how students' representations of key CCC concepts change as a result of different scaffolding contexts. In particular, this paper addresses the following research questions:

1. How do students' technology-enhanced conceptual models of water systems indicate understanding of the system and conservation of matter within that system?
2. How do students' representations of the CCC elements and concepts change related to different technology-enhanced task-based scaffolds?

Methods

Curricular Context

We examined student work within a 5-week curricular unit that engaged students to design a playground to withstand flooding facilitated through an online learning environment. The curricular unit was developed over a 6-month period through a collaboration of researchers, a district STEM coordinator, and one upper elementary teacher to align with a set of NGSS performance expectations (5-ESS3-1, 3-5ETS1-1, 3-5ETS1-2). Students were challenged to design a playground to reduce the amount of accumulated water after heavy rainfall, focusing on supporting students to engineer solutions to human impacts on earth systems. The project specifically targeted the SEP of developing models in the context of both science inquiry and engineering design while applying the CCC of systems thinking (for more information on curriculum design, see Chui, 2019). The project used the Web-based Inquiry Science Environment (WISE; Slotta & Linn, 2009) to support and facilitate student inquiry throughout the project and the Collaborative, Computational STEM (C2STEM) environment (Hutchins et al., 2020) to test design solutions based on their conceptual models.

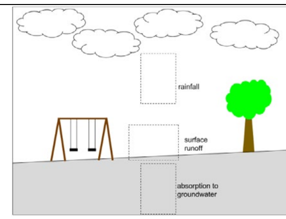
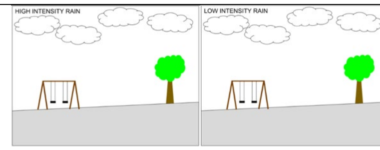
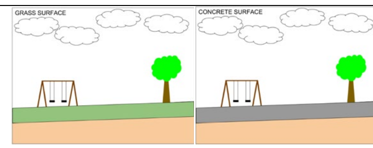
Students were given criteria for the design of their playground, which included choosing surfaces for particular purposes including a playground, a basketball court, and a field; making the playground accessible for physically disabled students; accumulating less than 0.5 inches of rain in a 1.2 inch rainfall storm; and an overall maximum budget of $200,000. Throughout the unit students engaged in activities to support their understanding, including physical experiments where students investigated the interactions of water with different surface materials. Physical experiments aimed to help students examine what happens to water after it hits the Earth's surface, what happens to water with various intensities of rainfall, and how different surface materials absorb different amounts of water. After they engaged in each of these three activities, students were asked to develop conceptual models showing their understanding of how the water flows. These conceptual modeling activities at three distinct timepoints were intended to support students to synthesize their understandings to support and inform their design solutions.

Three types of electronic task-based scaffolds were used in the modeling activities (Table 1): (1) in the first modeling activity, students were given three dashed line boxes labeled as "rainfall," "runoff," and "absorption," that they were instructed to add arrows to in order to show where the water was flowing. Within the learning environment, students were provided with digital stamps that represented arrows of various sizes that they could use to show the flow of water. The dashed line boxes with their labels were intended to illustrate where students could place arrows to represent rainfall, surface runoff, and absorption to groundwater. These boxes were not included in the second and third modeling activities so that students would need to intentionally include appropriate arrows, rather than feeling compelled to place an arrow in every box. As such, students' responses to the second and third modeling activities capture students' own ideas about which arrows are necessary to model each phenomenon. (2) In the second and third modeling activities, students were supported to attend to differences in the amount of rainfall and differences in the surface material, respectively. These differences in framing of the activity were intended to support students to represent how the system would be affected by changing inputs, and how the system would be affected by changing surface interactions. Finally, (3) the third modeling activity changed the appearance of the surface material in the background of the model, scaffolding students to realize that one was grass (green) and concrete (gray) which were also labeled.

Participants

One 5th grade teacher ($N = 123$ students) and two 6th grade teachers ($N = 274$ students) implemented the unit over a 5-week period. The 5th grade teacher worked together with the research team to develop the curricular materials, and all three teachers worked together to plan the implementation of the curriculum materials. The online interface was developed to provide all information necessary for students to

Table 1 The model prompt and model background for each modeling activity

Activity	Prompt	Model Background(s)
Activity 1	**Create a water runoff model** Using what you have read, create a water runoff model that shows the flow of water on a playground when it rains. Use the stamp tool to add arrows showing different amounts of water flow--**big arrows show a lot of flow, small arrows show a little flow**. Include arrows for • Rainfall • Surface runoff (above the surface) • Water absorption (below the surface) When you have finished, be sure to click the button to add your diagram to your notebook.	
Activity 2	**Create a runoff model: HIGH intensity vs. LOW intensity** Create 2 runoff models below. One should show water flow in **HIGH INTENSITY RAIN**. The other should show water flow in **LOW INTENSITY RAIN**. For each model, use the stamp tool to add arrows showing **rainfall, surface water runoff, and absorption to ground water**. Use **bigger arrows** to show **high flow rates** and **smaller arrows** to show **low flow rates**. Use the text tool to **label your arrows**.	
Activity 3	**Create a runoff model: GRASS vs. CONCRETE** Develop 2 runoff models below. One should show water flow on **GRASS.** The other should show water flow on **CONCRETE.** For each model, use the stamp tool to add arrows to show **rainfall, surface water runoff, and absorption to ground water.** Use **bigger arrows** to show **high flow rates and smaller arrows** to show **low flow rates.** Use the text tool to **label your arrows.**	

Bolding and underlining were in original prompts.

complete the curriculum within the WISE learning environment, and teachers largely adhered to the unit as designed in WISE. Therefore, all three teachers implemented the same project in WISE. Each day, the teachers led an opening class discussion, set daily goals for learning activities, and provided targeted whole-class instruction as needed. The teachers supported the students during the project by checking in with individual students or student groups, helping students to work through activities or discuss content. Teachers also facilitated hands-on investigations with surface materials and runoff that occurred during the unit.

This paper includes the data from the 381 user accounts in WISE across all three teachers. The upper elementary school where the curriculum was implemented is in a district where 42% of students were white, 31% Black, and 13% Latinx; 44% of students received free or reduced lunch; and 14% of students were emerging bilinguals with 51 languages spoken. Some students worked individually in the WISE learning environment, while some worked in pairs, but each student had their own device and groups worked at their own pace on the project. All activities were completed during class time.

Data Sources

All of the students' work was collected within the online environment. Three assignments that were part of the unit included the development of conceptual models in WISE. Each model provided students with a simple landscape image to use as a background. Students then added arrows to represent the flow of water. For each of the models, the prompt supported students to create representations of the amount of water in different scenarios. Because students worked at their own pace, some students did not complete all of the models. Approximately half ($n = 179$) of the students completed all 5 models, while 18 students did not complete any of the 5 models.

Analysis Methods

Since students were not explicitly prompted to attend to the relationship between the quantities of rainfall, runoff, and absorption represented in the modeling activities (Table 1), we applied a post hoc analytical lens to see how students used the crosscutting concepts in their models (Ben-Zvi Assaraf & Orion, 2010). As a part of this analysis, we looked for evidence of students' use of systems and their attention to the conservation of matter within the system. Both of these concepts were important foundations for developing engineering design solutions to the water runoff problem that framed the unit.

To understand student representations of the water system, both a systems and a conservation of matter lens were used. The system was considered to be rainfall within a given area and what happened to that rain after it fell. Since the unit was focused on short-term runoff and flooding problems, the time frame of analysis was immediately after the rainfall, and students were focused on describing where the inputs (rainfall) went immediately after the rain fell (absorption and/or runoff). Another important component of this explanation is that the total amount of water is conserved (conservation of matter), so there should not be more runoff or water absorbed than the total amount of rainfall.

A descriptive coding scheme was generated to describe how the students used arrows in the conceptual model to illustrate the flow of water in the system. The codes captured the presence of each component (rainfall, runoff, and absorption), the direction of each water flow represented and the relative amounts of water flowing. Which component (rainfall, runoff, or absorption) an arrow represented was determined by the location and direction of the arrow. Arrows above the surface aimed down were considered rainfall, arrows below the surface aimed primarily downward were considered absorption, and arrows aimed along the surface were considered runoff. Some models included arrows that did not fit any of these categories (for example, an arrow above the surface that aims toward the sky, likely indicating evaporation) and were not included as one of the three components. Models were also coded for how much water the students showed flowing into the system as rain (inputs) as compared with out of the system as runoff or absorption (outputs). The codes that were used are listed in Table 2. Blank models were counted as "no water represented."

In general, coders considered two small arrows to be equal to one medium arrow and two medium arrows to be equal to one large arrow (Fig. 1). This formula was applied to models in order to compare amounts of water when different sized arrows were used. Three researchers coded the models (coders A, B, and C). Twenty percent of the models were coded by all three, with a percent agreement of 92% between A and B and 95% between A and C and Cohen's kappa of 0.76 for A and B and 0.88 for A and C, which are considered acceptable. The remaining 80% of the models were coded by B and C, with most of the coding being done by coder C.

Table 2 Codebook used to analyze student models

Which models were coded	Codes applied	Descriptive codes
All 5 models	Intensity Represented	# of arrows
		Thickness/size
		No intensity
	Amount of Runoff vs Rainfall	More Runoff
		More Rainfall
		Approx. Equal
	Amount of Absorption vs Rainfall	More Absorption
		More Rainfall
		Approx. Equal
	Amount of Absorption vs Runoff	More Absorption
		More Runoff
		Approx. Equal
	Amount of Rainfall vs. Absorb + Runoff	Rainfall More than Absorb + Runoff
		Rainfall Less than Absorb + Runoff
		Rainfall Equals Absorb + Runoff
High/low intensity models	Differences in Intensity	High Low Equal Rainfall
		Low More Rainfall
		High More Rainfall
Grass/concrete surface models	Differences in Surface	Grass More Rainfall
		Concrete More Rainfall
		Grass Concrete Equal Rainfall
		Grass More Runoff
		Concrete More Runoff
		Grass Concrete Equal Runoff
		Grass More Absorb
		Concrete More Absorb
		Grass Concrete Equal Absorb

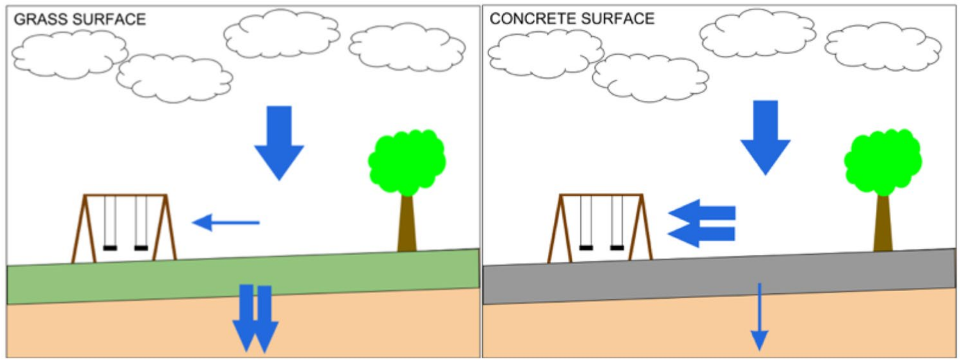


Fig. 1 Comparison of the movement of water on grass (**a**) with concrete (**b**) by student A

For each model, the descriptive codes from Table 2 were applied to capture the presence and location of the arrows within the model and the proportion of the arrows that were representing each of the components of the water flow (rainfall, runoff, and absorption). Each of these codes was converted into a number representative of the categorical code in order to be able to calculate the proportion of students who represented different patterns of relationships within their models.

This analysis of the representativeness and patterns illustrated by the codes was conducted using SPSS. Frequencies were calculated for inclusion of different combinations of elements (rainfall, runoff, and absorption) in the models, for the representation of different proportions of different elements in the models, and for the completion of different combinations of the five models. The analysis was not intended to show changes in individual students' understanding since the conceptual modeling activities had different prompts throughout the unit. Instead, the analysis aimed to reveal patterns in how students represented CCC inputs and outputs in their conceptual models and how text-based scaffolds might affect what students represent.

Findings

Research Question 1: How Do Students' Technology-Enhanced Conceptual Models of Water Systems Indicate Understanding of the System and Conservation of Matter Within that System?

Description of the Components of Models

Overall, of the 179 students who completed all five models, only 18 students represented all three of the components necessary to explain the problem (rainfall, absorption, and runoff) in all 5 models (Fig. 2). Figure 2 also shows the differences in which components students represented across the five models that made up the three modeling activities. In the activity 1 model, students were most likely to represent all three components (rainfall, runoff, and absorption). Students were provided with specific scaffolding in Activity 1 in the form of boxes for all three components (Table 1). In activities 2 and 3, students were much less likely to represent all three components, and more likely to represent two of the three components, which two varied corresponding to the situation presented. Examples of student work from activity 2 are included in Fig. 3. Students' models frequently included only a comparison of rainfall (student L) or only rainfall and runoff (student M). Activity 2 prompted students to compare the amount of absorption and runoff in high and low rain intensity situations (Table 2). In activity 3, when students were comparing concrete to grass, students were more likely to represent all three components in the grass surface model than in the concrete surface model (examples to follow). In the concrete surface, students were more likely to represent rainfall and runoff and leave out absorption.

Description of the Relationships Between the Components of the Models

Student models inconsistently represented the components of the system (inputs and outputs) when they showed the movement of water. Figure 4 shows the relationship of inputs to outputs represented in the students' models, the amount of rainfall (inputs) as compared with absorption and runoff (outputs) in their models over time. In each model, some students seemed to represent the conservation of matter in their models by indicating an approximately equal amount of water flowing into the system (rainfall) as water flowing through the system (combined absorption and runoff; activity 1 = 44; activity 2 high = 41, low = 52; activity 3 grass = 32, concrete = 39). How students represented conservation varied, with some students representing a few arrows and others representing many arrows, but in each case, an approximately equivalent amount of water as inputs and outputs.

A larger proportion of students did not represent conservation in their models, with the amount of rainfall

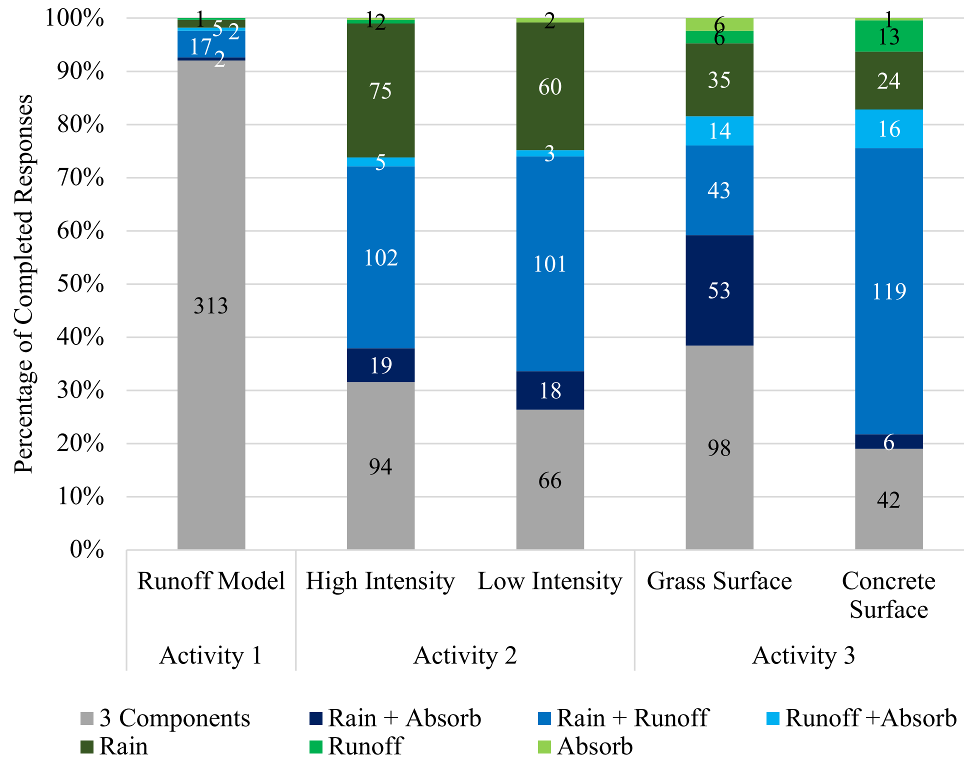


Fig. 2 Students' inclusion of rainfall, absorption, and runoff in their models over time. Models that included two components are represented by shades of blue, models with one component are represented in shades of green

being either greater than or less than the combined amount absorbed and runoff. Across the models, only one student maintained a consistent amount of water as inputs and outputs in all five of the models. A total of 241 students did not represent conservation of matter in any models.

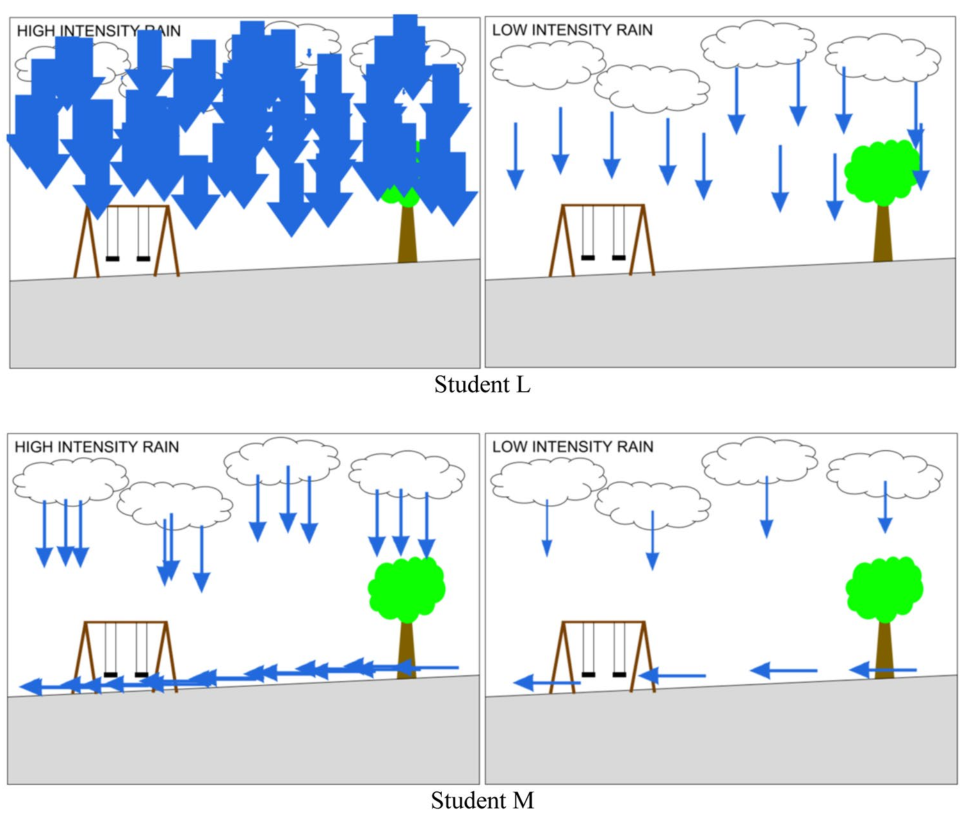


Fig. 3 Examples of high intensity rain (left) and low intensity rain (right) student models in activity 2

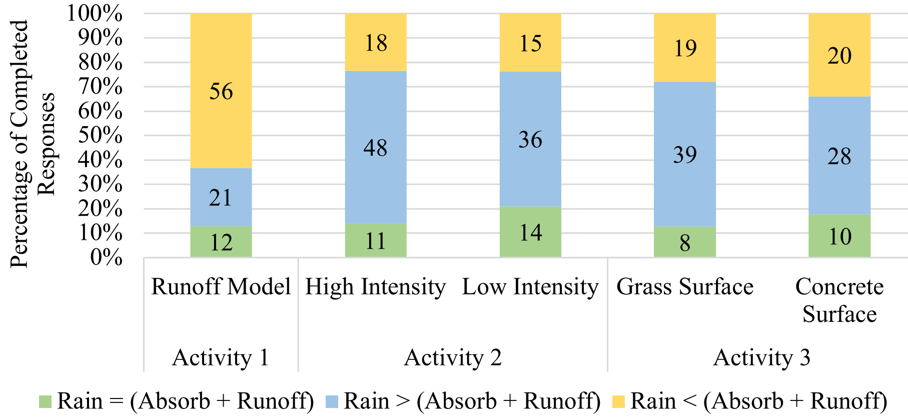


Fig. 4 Students' representation of the proportions of water as rainfall (inputs) as compared with absorption and runoff (outputs) in their models over time

Research Question 2: How Do Students' Representations of CCC Elements and Concepts Change Related to Different Technology-Enhanced Task-Based Scaffolds?

Most students showed rainfall, runoff, and absorption in the first modeling task which had the most scaffolding, but that number dropped off for the other tasks which had less scaffolding. Students' inclusion of all three elements in activity 1 is not surprising, given the heavily scaffolded representation of where to place the arrows showing the movement of water (Fig. 5). Following the initial model, students were not provided with the dashed lines showing where to put the arrows, or the labels for what the arrows represented.

Comparison in the Amount of Rainfall

For activity 2, many students did seem to show a comparison between the high intensity and low intensity rainfall models.

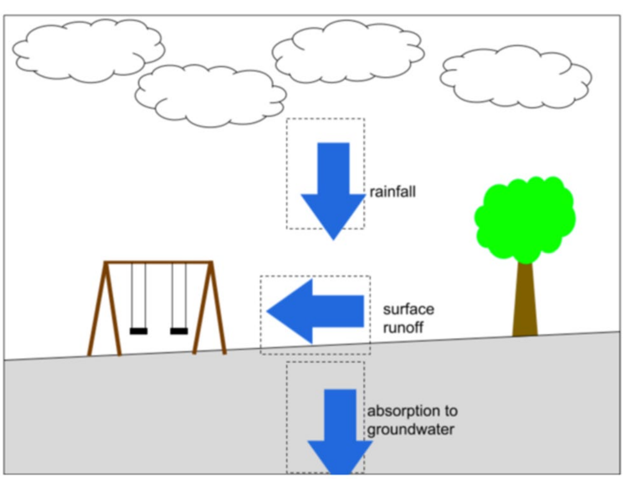


Fig. 5 Representation of water in the initial model by student K

Students generally showed more water in the high intensity rainfall scenario than in the low intensity rainfall scenario ($n = 230$), though some students did show an equal amount of water ($n = 16$), or less water in the high intensity rainfall ($n = 14$). The most common patterns (all rainfall; rain and runoff; rain, runoff, and absorption) are represented in Fig. 6.

For activity 3, students were comparing surface materials. An explanatory system model should show an equal amount of rainfall on both the grass and the concrete surfaces in order to explain that runoff differences are a result of different surface materials. However, students did not always represent equal amounts of rainfall. Some students ($n = 79$) represented an equal amount of rain on both the concrete and grass models (Fig. 1). More often, students represented more rainfall on one model than the other ($n = 128$). Approximately half of these students represented the grass model with more rainfall ($n = 65$), while the other half showed the concrete model with more rainfall ($n = 63$) (Fig. 7). This result suggests that while students may not actually believe more rain falls on either grass or concrete, they may not have been thinking of the importance of having equal amounts of inputs to create models that can be meaningfully compared.

Absorption and Runoff with Different Surfaces

Most students ($n = 175$) who represented runoff in their activity 3 models showed the concrete model having more runoff than the grass model (e.g., Fig. 7). This feature reflects students' understanding of the impact of the permeability of a concrete surface relative to a grass surface. More students omitted absorption into concrete ($n = 119$) than omitted absorption into grass ($n = 43$). This difference suggests that students either did not know concrete absorbs water or believed the absorption to be negligible. Many students made the analogous modeling decision to omit runoff on the grass surface ($n = 53$) more frequently than on the concrete surface ($n = 6$). However, most students ($n = 142$)

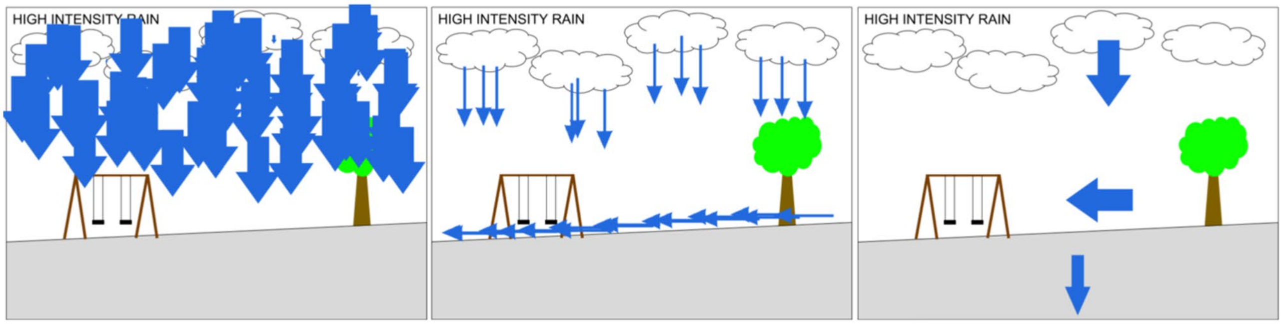


Fig. 6 Differences in elements represented in high intensity rain model (left = rain, student L; middle = rain and runoff, student M; right = rain, runoff, and absorption, student K)

who represented absorption in their models showed the grass model having more absorption than the concrete model, including students who neglected to represent any absorption at all in their concrete model (Fig. 8).

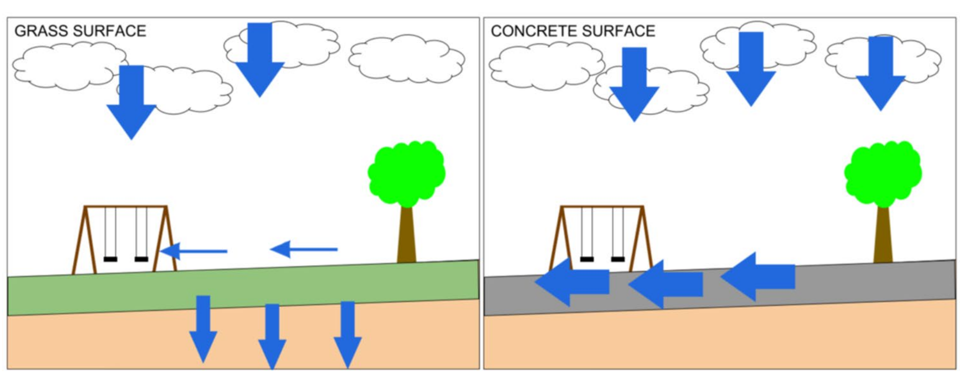
Discussion

Representation of CCCs in Students' Models

The findings illustrate that elementary students were able to represent elements of the CCC systems, such as inputs and outputs, in their development of conceptual models of water systems. Some elementary students were also able to represent conservation of matter within their models, without explicit prompting to do so. Results suggest that students engaged in conceptual modeling within instruction that places a strong emphasis on understanding the underlying relationships and phenomenon can result in students displaying understanding of the systems CCC. However, results also demonstrate that students were largely inconsistent in their use of inputs and outputs or conservation across the three activity contexts. Only one student consistently conserved matter across all models.

The findings revealed which CCCs students seemed to attend to when use of the CCCs of systems or conservation of matter were required for a complete representation of understanding. Most students appeared to include attention to inputs and outputs, though the students in this study were not explicitly taught how or why to use the crosscutting concept for representing their thinking. However, students in the curriculum unit did engage in reading science briefs that discussed inputs and outputs in terms of rainfall, absorption, and runoff; students engaged in hands-on investigations where they varied the amount of rainfall and explored differences in absorption and runoff for different materials; and students used computational models to compare their experimental results to simulated results. Despite the curriculum unit not explicitly teaching about systems terms of inputs and outputs, students included these ideas in their models as there was ample focus on the scientific ideas and concepts throughout the unit. That some students were able to represent these systems components reveals that students at this level are capable of making these connections, but that additional scaffolding is needed to support all students to attend to the systems inputs and outputs when representing science concepts.

Fig. 7 Comparison of the movement of water on grass (left) with concrete (right) by student N



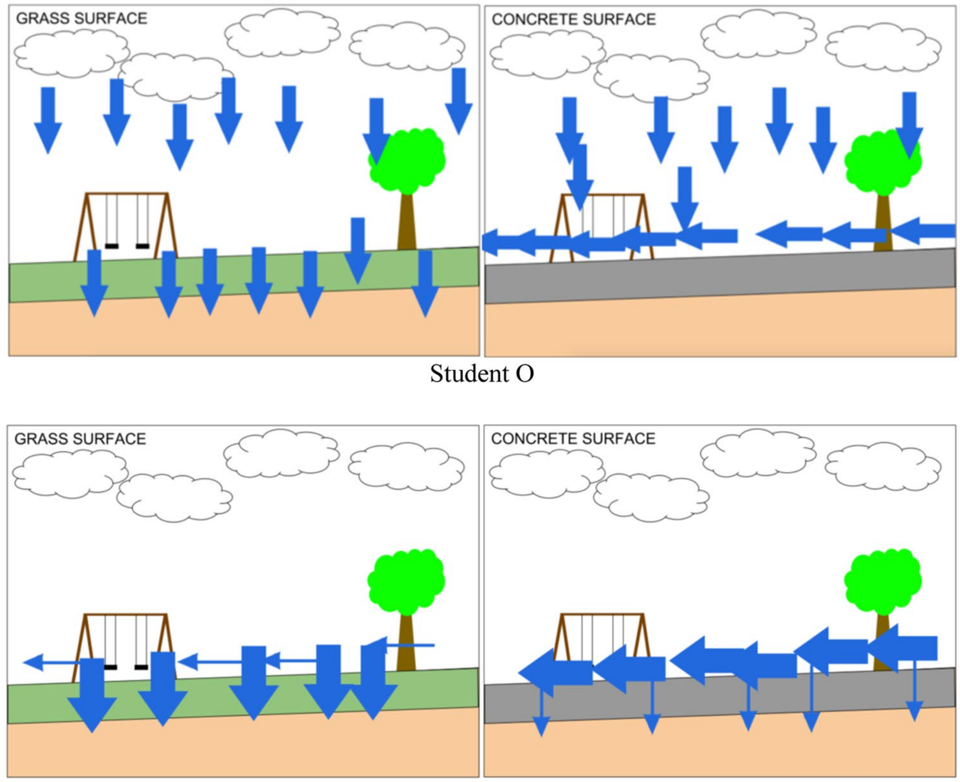


Fig. 8 Example student models of the relative amounts of runoff and absorption in grass and concrete surfaces

Some student models seemed to conserve the amount of water coming into and leaving the system. Only one student appeared to consistently do so, making it a component of the deepest level of understanding about the system. Within the curricular unit, there was not any explicit discussion of conservation of matter. However, students conducted physical investigations where they could observe that the total amount of water was conserved. For example, in the first hands-on investigation, students recorded the total amount of water for low intensity rainfall versus high intensity rainfall across a certain time duration. Although it was not explicitly supported within the instructional materials, students could observe that the total amount of rainfall was conserved. Findings illustrate that there is naturally a strong connection among systems thinking of inputs and outputs, and the need to conserve matter going into and out of the system, consistent with Jin and Anderson's (2012) situation of conservation of matter with the deepest level of understanding of carbon cycles. These findings suggest that students need explicit support to attend to the conservation of equal inputs and outputs in a system. In both cases, integrating the CCCs of conservation of matter and systems with the SEP of developing models seems to be a fruitful starting point towards three-dimensional learning. Supporting students to attend to what is going into and what is coming out of the models could be one simple scaffold to productively build students' attention to both conservation of matter and systems thinking in this context and for other related concepts.

Task-Based Model Scaffolds and Representation of CCCs

The findings indicate that the task-based scaffolds played a large role to support students to represent CCC elements. Within the context of these computer-facilitated tasks, the scaffolds included a background image which provides a surface and context, the representation of specific surface materials (grass and concrete) in certain activities, the presence of dashed boxes in which to represent arrows in activity 1, and the inclusion of different sized arrow stamps colored blue to use to represent different amounts of water flow. Some of these scaffolds were included to simplify the amount of time required to represent water flow (the arrow stamps), while others were intended to support students to show water flowing through different areas (the surface and surface materials). The findings indicate that some of the scaffolds might have helped students, while others may have hindered their representations.

Across all the activities, students largely attended to the most salient aspects of the specific prompt. The labeled boxes in the activity 1 prompt scaffolded students to include all three parts of the runoff process (rainfall, runoff, and absorption), which resulted in a high number of students representing all three elements. However, once the scaffolds were removed, only around a third of the students represented all three elements in their models. Across the high and low intensity rainfall model and the grass and concrete surface models, many students only represented the aspects that were referenced in the title of the model. When considering the high vs low intensity rainfall, students were more likely to leave out the outputs of the model, and only represent the differences in inputs. Similarly, students were likely to leave off absorption in the concrete surface model, and runoff in the grass surface model. These trends suggest that students might have been more likely to attend to what they saw to be the most relevant components and leave out the other factors of the system. These modeling decisions could reflect some students' efforts to be parsimonious by omitting factors that are negligible or that do not explain differences in the scenarios presented.

Although the emphasis in the curricular activities supported students to understand the relationship among rainfall intensity and duration on water runoff, as well as the effect of different surface materials on water runoff with clear numerical values of outputs, students still largely focused on the salient differences among the inputs in their conceptual models. Students also appeared to prioritize these differences over the concept of conservation. Across all three activities the prompts to develop their models changed, which was intended to spur attention to the comparisons being highlighted, but the patterns in students' responses reveal that scaffolds for attending to those comparisons may not have been sufficient to help students generalize their understanding to a subsequent model. While the arrow stamps might have facilitated students' modeling of the water flow, it is possible that use of the same size arrow across types of water was one of the reasons that students did not represent the conservation of matter. In order to represent different amounts of water, students had to pick different sized stamps or resize their arrows to show less water. It is unclear whether students would have been more likely to attend to this factor if required to represent the arrows themselves.

The scaffolds provided for the modeling activity were intended to help students develop understanding of the Earth Science DCI while engaging in the practice of developing models, building on studies such as Zangori and colleagues (2015). However, similar to Zangori and colleagues' finding that students' reasoning may have been impacted by their scaffolding, the scaffolds in this study may have narrowed students' focus within the models to respond to the specific prompts, causing them to prioritize material behavior over conservation. For some students, the condition prompted by the task and the background seemed to be what they focused on in the model, failing to include other relevant information such as where the rain goes after it falls in the rain intensity question, or multiple destinations for the water in the surface material prompt. Future work can investigate the effect of general versus specific prompts (e.g., Davis & Linn, 2000) or different ways of fading (e.g., McNeill et al., 2006) to help students develop understanding of CCCs within modeling contexts.

Limitations

The models that students developed during the unit did not have the same prompt throughout, so the findings cannot be interpreted as changing understanding or student learning during the unit. They only represent what students chose to represent in their models at particular time points. Additionally, the students did not write or orally describe what they were representing in their models, so the coding that was conducted was based on consistent application of rules for interpreting what the students were likely to represent, with a focus on the main ideas developed during the unit. We had to do some interpretation of what the students were most likely to have meant and what they did and did not intend to show. We did not have a way of triangulating (Patton, 2002) to ensure an accurate interpretation of the students' ideas. However, results provide insight into the kinds of CCCs that students may or may not use when engaged in modeling (e.g., Zangori et al., 2015).

Implications

What Does Scaffolding for Systems and Conservation CCCs Look Like?

These findings reveal some promising areas for scaffolding to support students' understanding and use of CCCs in their modeling. First, students were well supported by the dashed boxes to include absorption, runoff, and rainfall in the first model. These scaffolds helped students include both the inputs and outputs that were the subject of the curricular unit, representing a very simple system. The results indicate that this scaffold may have been faded too early, and that students would have benefited from a version of this scaffold and additional scaffolds throughout the unit. Thus, results suggest explicit scaffolding of the CCCs is important for students to understand and use systems CCCs. Another implicit part of this work is ensuring that the simple system has equivalent inputs and outputs (conservation of matter). This was an area of inconsistent success for most students in the study. The struggles that students had representing conservation of matter through having equivalent amounts of inputs and outputs seems to be another area that needs to be explicitly supported as a part of the classroom instruction. Students in this unit were not taught to explicitly attend to the amount of water that serves as an input as compared with outputs, meaning that they were unlikely to be able to represent the proportion of the rain that they expected to travel to particular locations. These findings argue against a common assumption that simply supporting students to use the CCCs will help them understand the CCCs (e.g., Krajcik et al., 2014). A similar shift has taken place in the field's thinking about the use of science practices, moving away from simply having students do science towards understating how and why they are employing the practices (González-Howard & McNeill, 2019; McNeill, 2009). Similarly, scaffolding is needed to support students to learn both how and why to use the CCCs to make sense of the science ideas.

These findings have implications for curriculum development and instruction that supports students to develop three-dimensional science understandings. Explicit supports and scaffolds need to be incorporated into these materials to help students understand how and why to use the CCCs. Only a small proportion of students seem to inherently attend to these aspects of the science understanding, where more students possibly could be supported to integrate these lenses into both their interpretation and representation of science concepts and practices.

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Data Availability Deidentified data is available upon request.

Declarations

Ethics Approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the IRB Office of the [University].

Informed Consent All participants in the study received the approved IRB forms and were explained the study procedures. Participation in the study was part of normal classroom activities.

Conflicts of Interest The authors declare that they have no conflict of interest.

References

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

Baek, H., Schwarz, C., Chen, J., Hokayem, H., & Zhan, L. (2011). Engaging elementary students in scientific modeling: The MoDeLS fifth-grade approach and findings. In Models and modeling (pp. 195–218). Springer, Dordrecht.

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.

Ben-Zvi Assaraf, O. Z., & Orion, N. (2010). System thinking skills at the elementary school level. *Journal of Research in Science Teaching, 47*(5), 540–563.

Carlson, J., Davis, E. A., & Buxton, C. (2013). Supporting the implementation of the Next Generation Science Standards (NGSS) through research: Curriculum materials. https://www.narst.org/blog/ngss-curriculum

Chin, C. (2007). Teacher questioning in science classrooms: Approaches that stimulate productive thinking. *Journal of Research in Science Teaching, 44*(6), 815–843.

Chiu, J. C., McElhaney, K. W., Zhang, N., Biswas, G., Fried, R., Basu, S., & Alozie, N. (2019). A principled approach to NGSS-aligned curriculum development integrating science, engineering, and computation: A pilot study. Paper presented at the NARST Annual International Conference

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.

Davis, E. A., & Linn, M. C. (2000). Scaffolding students' knowledge integration: Prompts for reflection in KIE. *International Journal of Science Education, 22*(8), 819–837.

Duschl, R. A., & Osborne, J. (2002). Supporting and promoting argumentation discourse in science education. *Studies in Science Education, 38*(1), 39–72.

Fick, S. J. (2018). What does three-dimensional teaching and learning look like?: Examining the potential for crosscutting concepts to support the development of science knowledge. *Science Education*, *102*(1), 5–35. https://doi.org/10.1002/sce.21313

Fick, S. J. & Arias, A. M. (2019, March). Examination of the Role(s) of Crosscutting Concepts in Research Articles 2012- June 2018. Paper presented at NARST Annual International Conference, Baltimore, MD.

Fick, S. J., Nordine, J., & McElhaney, K. W. (Eds.). (2019). Conference Proceedings of the Summit for Examining the Potential for Crosscutting Concepts to Support Three-Dimensional Learning. Charlottesville: University of Virginia. Retrieved from: http://education.virginia.edu/CCC-Summit

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.

Goldstone, R. L., & Wilensky, U. (2008). Promoting transfer by grounding complex systems principles. *Journal of the Learning Sciences, 17*(4), 465–516.

González-Howard, M., & McNeill, K. L. (2019). Teachers' framing of argumentation goals: Working together to develop individual versus communal understanding. *Journal of Research in Science Teaching.*

Hmelo, C. E., Holton, D. L., & Kolodner, J. L. (2000). Designing to learn about complex systems. *The Journal of the Learning Sciences, 9*(3), 247–298.

Hutchins, N. M., Biswas, G., Maróti, M., Lédeczi, Á., Grover, S., Wolf, R., Blair, K. P., Chin, D., Conlin, L., Basu, S., and McElhaney, K. (2020). C2stem: a system for synergistic learning of physics and computational thinking. *Journal of Science Education and Technology,* pages 83–100.

Jin, H., & Anderson, C. W. (2012). A learning progression for energy in socio-ecological systems. *Journal of Research in Science Teaching, 49*(9), 1149–1180.

Krajcik, J., McNeill, K. L., & Reiser, B. J. (2008). Learning-goals-driven design model: Developing curriculum materials that align with national standards and incorporate project-based pedagogy. *Science Education*, *92*(1), 1–32. https://doi.org/10.1002/sce.20240

Krajcik, J., Codere, S., Dahsah, C., Bayer, R., & Mun, K. (2014). Planning instruction to meet the intent of the next generation science standards. *Journal of Science Teacher Education, 25*(2), 157–175.

Lehrer, R., & Schauble, L. (2006). Cultivating model-based reasoning in science education. In R. K. Sawyer (Ed.), *Cambridge Handbook of the Learning Sciences*. Cambridge University Press.

Manz, E. (2012). Understanding the co-development of modeling practice and ecological knowledge. *Science Education, 96*(6), 1071–1105.

Manz, E. (2015). Representing student argumentation as functionally emergent from scientific activity. *Review of Educational Research, 85*(4), 553–590. https://doi.org/10.3102/0034654314558490

McNeill, K. L. (2009). Teachers' use of curriculum to support students in writing scientific arguments to explain phenomena. *Science Education*, *93*(2), 233–268. psyh.

McNeill, K. L., & Krajcik, J. (2008). Scientific explanations: Characterizing and evaluating the effects of teachers' instructional practices on student learning. *Journal of Research in Science Teaching, 45*(1), 53–78.

McNeill, K., Lizotte, D., Krajcik, J., & Marx, R. (2006). Supporting students' construction of scientific explanations by fading scaffolds in instructional materials. *Journal of the Learning Sciences, 15*(2), 153–191.

National Research Council. (2012). A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas. The National Academies Press.

NGSS Lead States. (2013). Next generation science standards: For states. By States: The National Academies Press.

Opitz, S. T., Neumann, K., Bernholt, S., & Harms, U. (2019). Students' energy understanding across biology, chemistry, and physics contexts. *Research in Science Education, 49*(2), 521–541.

Patton, M. Q. (2002). Qualitative Research & Evaluation Methods (3rd ed.). Sage Publications.

Rehmat, A. P., Lee, O., Nordine, J., Novak, A. M., Osborne, J., & Willard, T. (2019). Modeling the Role of Crosscutting Concepts for Strengthening Science Learning of All Students. In S. J. Fick, J. Nordine, & K. W. McElhaney (Eds.), Proceedings of the Summit for Examining the Potential for Crosscutting Concepts to Support Three-Dimensional Learning (pp. 66–73). University of Virginia. https://www.curry.virginia.edu/ccc-summit

Sampson, V., & Clark, D. (2009). The impact of collaboration on the outcomes of scientific argumentation. *Science education, 93*(3), 448–484.

Schwarz, C. V., Reiser, B. J., Davis, E. A., Kenyon, L., Achér, A., Fortus, D., Shwartz, Y., Hug, B., & 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.

Slotta, J. D., & Linn, M. C. (2009). WISE science: Web-based inquiry in the classroom. Technology, Education-Connections: Teachers College Press, New York, NY.

Yoon, S. A., Goh, S. E., & Park, M. (2018). Teaching and Learning About Complex Systems in K–12 Science Education: A Review of Empirical Studies 1995–2015. *Review of Educational Research*, *88*(2), 285–325. https://doi.org/10.3102/0034654317746090

Zangori, L., & Forbes, C. T. (2015). Exploring third-grade student model-based explanations about plant relationships within an ecosystem. *International Journal of Science Education, 37*(18), 2942–2964.

Zangori, L., Forbes, C. T., & Schwarz, C. V. (2015). Exploring the effect of embedded scaffolding within curricular tasks on third-grade students' model-based explanations about hydrologic cycling. *Science & Education, 24*(7–8), 957–981.