6-5-2017

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Published in *International Journal of Science Education,* 2017, Vol. 39, no. 11, pp. 1421–1442.
doi 10.1080/09500693.2017.1336683

Submitted 23 December 2016; accepted 27 May 2017; published 5 June 2017.

Supporting 3rd-grade students' model-based explanations about groundwater: A quasi-experimental study of a curricular intervention

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Abstract

Scientific modelling is a key practice in which K-12 students should engage to begin developing robust conceptual understanding of natural systems, including water. However, little past research has explored primary students' learning about groundwater, engagement in scientific modelling, and/or the ways in which teachers conceptualize and cultivate model-based science learning environments. We are engaged in a multi-year project designed to support 3rd-grade students' formulation of model-based explanations (MBE) for hydrologic phenomenon, including groundwater, through curricular and instructional support. In this quasi-experimental comparative study of five 3rd-grade classrooms, we present findings from analysis of students' MBE generated as part of experiencing a baseline curricular intervention (Year 1) and a modelling-enhanced curricular intervention (Year 2). Findings show that students experiencing the latter version of the unit made significant gains in both conceptual understanding and reasoning about groundwater, but that these gains varied by classroom. Overall, student gains from Year 1 to Year 2 were attributed to changes in two of the five classrooms in which students were provided additional instructional supports and scaffolds to enhance their MBE for groundwater. Within these two classrooms, the teachers enacted the Year 2 curriculum in unique ways that reflected their deeper understanding about the practices of modelling. Their enactments played a critical role in supporting students' MBE about groundwater. Study findings contribute to research on scientific modelling in elementary science learning environments and have important implications for teachers and curriculum developers.

Keywords: Primary science, modelling, water, scientific explanations

Developing scientific literacy about water systems is critical to making informed decisions about water-related global issues and challenges (ESLI, 2009). All students, including primary students, should build knowledge about the hydrosphere and its interactions with Earth materials, or groundwater (NGSS Lead States, 2013). Providing these opportunities in the primary grades anchors development of disciplinary knowledge that will serve as the foundation for more complex understanding about Earth systems developed through subsequent learning experiences (NRC, 2007). Yet, learning about groundwater presents challenges for learners across the K-16 spectrum because it is a large-scale phenomenon comprised by less-easily observed components driven by interconnected causal mechanisms spanning the geosphere and hydrosphere (Covitt, Gunckel, & Anderson, 2009; Dickerson, Penick, Dawkins, & Van Sickle, 2007; Dove, Everett, & Preece, 1999; Forbes, Zangori, & Schwarz, 2015; Vo, Forbes, Zangori, & Schwarz, 2015).

To address this challenge, we are engaged in a five-year research and development project in the United States, *Modelling Hydrologic Systems in Elementary Science* (MoHSES), to support 3rd-grade teachers in model-based teaching and for their 3rdgrade students to generate model-based explanations (MBE) about the hydrologic cycle through curriculum enhancement and adaptation (Forbes et al., 2015; Vo et al., 2015; Zangori, Forbes, & Schwarz, 2015). In the first two project years, we engaged in design-based research in five 3rd-grade classrooms to modify the Full Option Science System (FOSS) *Water* (2009) curricular unit to better support students in scientific modelling of the water cycle. Here, we report on the comparison between the enactment of baseline (Year 1) and modelling-enhanced (Year 2) versions of the *Water* unit. Our research examines comparative gains in students' MBE from their pre- to post-unit models in Year 1 (Y1) and Year 2 (Y2). We use this data to examine differences across gain scores by classroom and explore teacher-level factors that may help explain how and why this variation may occur. Our research questions are:

1. How does a modelling-enhanced curricular unit support 3rd-grade students' MBE about groundwater over the standard version of the unit?

2. To what extent do changes in students' MBE about groundwater vary by classroom?
3. How do teachers enact a modelling-enhanced unit to support their students' MBE for groundwater?

Students' reasoning about water and the geosphere

For primary students to learn about the interactions between the hydrosphere and geosphere (i.e. groundwater) and the importance of water systems in everyday life, they require opportunities to visualize and make sense of how water penetrates and flows through earth materials (Dickerson & Dawkins, 2004; Forbes et al., 2015; NGSS Lead States, 2013; Vo et al., 2015). Yet visualizing these interactions is challenging because these processes are largely 'hidden' from direct observations (Covitt et al., 2009; Dickerson et al., 2007). In addition, opportunities to investigate, reason, and build knowledge about how and why water interacts with and influences earth materials is rare in K-12 science learning environments (Dickerson & Dawkins, 2004; Zangori et al., 2015). Without classroom experiences to make sense of these unobserved processes, students must depend on their prior experiences and observations to make sense of groundwater, which can result in substitution of observed processes to unobserved phenomena (Covitt et al., 2009; Dove et al., 1999). To support students' learning about critical water processes, they should develop their own representations of subsurface water flow to use in sense-making about processes underlying the functioning of groundwater systems. These experiences should include developing and interacting with representations in multiple forms such as concrete physical representations that may occur through observing water flow, as well as abstract illustrations such as developing illustrations that make all relevant elements of the process visible and explicit to reify both theory and experience. We identify these representational forms as scientific models (Forbes et al., 2015; NGSS Lead States, 2013; Schwarz et al., 2009; Vo et al., 2015; Zangori et al., 2015).

Theoretical framework: MBE

The conceptual framework underlying our work for MBE is grounded in a *mechanism-based perspective* on scientific explanation generation through iterative cycles of the practices of modelling (Clement, 2000; Forbes et al., 2015; Gilbert, 2004; Halloun, 2007; Schwarz et al., 2009; Vo et al., 2015; Zangori et al., 2015). The practices of modelling include students *developing* an initial model with their prior knowledge. They *use* this model to make predictions and generate scientific explanations of how and why the hydrologic cycle behaves. As they build new understanding about the water and earth material interactions through investigations and observations, they *evaluate* the initial model for its explanatory power and, based on their evaluation, they *revise* the initial model to align with their new understanding. Scientific explanations generation from the practices of modelling as MBE.

We highlight five core features of mechanism-based explanations — *components*, *sequences*, *explanatory process*, *mapping*, and *scientific principle* — to examine students' MBE about groundwater. Each feature represents a subcomponent of sense-making about the functioning of system processes (Forbes et al., 2015; Schwarz et al., 2009). The *components* of mechanism are elements of the system students choose to illustrate, such as clouds and the ground, that they identify as essential to process function. The *sequences* are the relationships they articulate and illustrate occurring between various components. *Explanatory process* foregrounds the connections students articulate between cause and effect for system processes. Both *mapping* and *scientific principle* identify the ways in which students understand their models as a bridge between theory and observation. *Mapping* examines how students understand and relate their representation to the physical world, while *scientific principle* reflects the connection they make to underlying theory.

We previously developed an empirically grounded learning performance for 3rd-grade students' MBE about water and geosphere interactions (see Forbes et al., 2015) that identify patterns in primary students' understanding of hydrologic phenomena, including interactions between water and the geosphere. Higher-level performances align with U.S. science education standards (AAAS, 2007; NGSS Lead States, 2013) to define the MBE that elementary students should generate about how and why water affects the Earth. Lower level performances were identified based on empirical data for students' MBE and represent entry points for students' learning about this concept through the practices of scientific modelling (Forbes et al., 2015). An overview of the learning performances is presented in **Table 1**.

Supporting students to engage in scientific modelling

While primary students can and should use models to reason about natural phenomena (Forbes et al., 2015; NGSS Lead States, 2013; NRC, 2007; Schwarz et al., 2009; Vo et al., 2015), these experiences must be supported through curriculum and instruction. Effective cultivation of model-based science learning environments requires teachers hold robust, pedagogically relevant knowledge of both scientific modelling and disciplinary concepts. This is necessary for them to 'mediate, transform, reorder, organize, group, and frame' (Halloun, 2007, p. 681) students' scientific reasoning

Table 1. Learning performance continuum for 3rd-grade students' MBE about groundwater (Forbes et al., 2015).

Water/geosphere interaction continuum

	Lower	*Upper*
Component	Only visible water movement with no interaction with earth materials	Visible and non-visible interactions between water and earth materials
Sequence	Single direction sequence indicating that water falls to the earth without indicating material impact	Dynamic bi-directional process sequences of how water impacts the earth and how earth materials respond
Explanatory process	Explicating what is occurring on their model, not how or why it is occurring	Articulating how water effects and shapes the geosphere (e.g. erosion) and why it shapes the geosphere (e.g. gravity)
Mapping	Does not recognize a connection between their representation and the physical world	Articulates an evidence-based rationale between their representation and the physical world
Principle	Does not recognize an underlying scientific principle	Articulates all elements of the scientific principle that accounts for interactions between water and the geosphere

about phenomena as it develops through modelling practices. For model-based teaching to be effective, teachers should (a) ask how and why questions about experiences and representations (models) to support students in connecting observation to theory; (b) provide feedback on models, and help students clarify how their thinking has changed when revising and evaluating models; (c) provide student opportunities to share their models and work together to develop consensus models; and (d) provide challenges to expressed alternate conceptions, and support students sense-making about how and why the phenomenon behaves as it does (Gilbert, 2004; Halloun, 2007; Oh & Oh, 2011; Zangori et al., 2015).

However, in-service and preservice teachers' knowledge of, orientations about, and pedagogical practices for model-based teaching and learning vary widely (Crawford & Cullin, 2004; Danusso, Testa, & Vicentini, 2010; Justi & van Driel, 2005; Windschitl & Thompson, 2006; Zangori et al., 2015). These variations occur, in part, because they have typically had limited or no prior experiences with model-based teaching and learning. While some may experience model-based approaches to instruction as part of teacher education (e.g. Windschitl, Thompson, & Braaten, 2008), more typically their prior engagement in modelling is to “learn science concepts” rather than the value of modelling in “learning about science” (Windschitl & Thompson, 2006, p. 788). These prior experiences with modelling may affect if and how they enact model-based curriculum and their support of students’ model-based reasoning (Halloun, 2007; Justi & Gilbert, 2002). As a result, diverse student outcomes related to model-based learning may occur even when teachers use the same curriculum materials.

However, when teachers are supported to consider models as reasoning tools, this understanding can translate to their teaching practice (Crawford & Cullin, 2004; Danusso et al., 2010; Justi & van Driel, 2005; Oh & Oh, 2011). For this to occur, teachers require support in building their knowledge for model-based teaching and learning. Such professional learning experiences should foreground engagement in scientific modelling to build understanding about the ways in which modelling supports their own learning about complex processes, such as groundwater. They also require experiences as teachers to build knowledge about how to support their own students’ learning when using this practice (Crawford & Cullin, 2004; Danusso et al., 2010; Justi & van Driel, 2005; Windschitl & Thompson, 2006). As teachers reason and engage with modelling as learners, extending their knowledge about scientific practice and gaining perspective on how science is performed, they develop an enhanced pedagogical skillset through which to support their students’ model-based explanation.

Methods

In this pretest–posttest quasi-experimental study (Reichardt, 2009), we report findings from the first two years of a five-year project in the United States grounded in design-based empirical research to (a) promote 3rd-grade students’ formulation of MBEs for hydrologic cycling through enhancement of curriculum materials and instruction, and (b) investigate associated instructional, curricular, and student learning outcomes. The study presented here extends prior project research reporting on both student and teacher outcomes (Forbes et al., 2015; Vo et al., 2015; Zangori et al., 2015).

Participants

Study participants, presented in **Table 2**, are teachers and students from five 3rd-grade classrooms from a single U.S. Midwestern state. The teachers were purposefully sampled (Patton, 2001) for their wide range of teaching experience, their use of the *Water* (FOSS, 2009) module, interest in model-based teaching and learning, and school profiles. Their schools represent a

Table 2. Classroom demographics.

Characteristic	*Classroom 1*	*Classroom 2*	*Classroom 3*	*Classroom 4*	*Classroom 5*
Teacher years of experience	0	21	16	13	22
Class size	18	22	26	23	21
Free/reduced lunch	59%	20.9%	5.7%	52%	20.9%

range of demographics that reflect the population of the state as a whole, including widely variant socioeconomic profiles.

Prior to this project, the teachers had not experienced professional development or other professional learning experience focused on model-based teaching and learning. During the summer between Y1 and Y2, as part of the project, they participated in a week-long workshop facilitated by the authors. During the first part of the workshop, teachers were provided opportunities to engage with the practices of modelling as learners, conducting *Water* unit investigations and developing models using the supplemental lessons they enacted in Y1. The authors supported the teachers in generating MBE and considering the nature and purpose of models (i.e. developing epistemic understanding about the practice of modelling) and the iterative nature of modelling in developing, using, evaluating, and revising their models. In the second part of the workshop, the teachers worked with the study authors to co-develop the modified lessons and supplemental activities in the *Water* unit that constituted the Y2 intervention.

A small number of students from each classroom in Y1 and Y2 were selected to participate in clinical interviews in collaboration with project teachers. The students were selected to represent a range of academic performance and interest in science. The student sampling approach was an attempt to balance between maximum variation sampling and typical case sampling (Patton, 2001). The teachers determined the maximum variation participants as high-achieving and low-achieving students.

Curricular context

The *Water* (FOSS, 2009) unit involves a series of four investigations about water. Investigations are broken into multiple lessons, or parts, where students are introduced to the key concept, such as the properties of water, with a short discussion and introduction of new vocabulary terms (e.g. *properties*). Within each investigation, students engage in hands-on water investigations where they classify, organize, look for patterns and relationships within their data and observations, and describe the results of their analysis. Investigations focused on properties of water, including porosity and viscosity, states of matter and temperature, and water through earth materials.

The intervention

Minimal intervention in Y1

We embedded pre-/post-unit supplemental lessons and associated student-modelling tasks within the *Water* unit. The tasks provided students explicit opportunities to develop and revise models of the water cycle and engage in sense-making to connect cause, effect, and mechanism. The supplemental lesson plans provided teachers with background information on how modelling supports student learning, the practices of modelling (*developing, using, evaluating*, and *revising* models), elements of MBE (*component, sequence, explanatory process, mapping*, and *scientific principle*), and rationales for lesson elements including a consensus modelling prior to the final student task. The student task, which was identical at the beginning and end of the unit, involved developing a 2-D diagrammatic model of the water cycle in response to the driving question 'where does the rain go when it reaches the ground?' See Forbes et al. (2015) and Vo et al. (2015) for more information about the Y1 curricular intervention.

Enhanced intervention in Y2

In addition to the pre-/post-unit student-modelling tasks developed in Y1, each unit investigation was modified to integrate consistent, coherent, theoretically aligned opportunities for students to engage in scientific modelling practices in Y2 (**Table 3**). For each FOSS investigation, students used their pre-unit model and embedded prompts to make a prediction about what they thought would happen and why. Then they performed the investigation and recorded their observations and data within their modelling notebooks. They drew a 2-D diagrammatic process model illustrating the water-related phenomena they observed and answered embedded reflection prompts to consider the cause, effect, and underlying mechanism for the investigation. After completion of each investigation, students returned to their original pre-unit model and self-evaluated for accuracy and understanding. They engaged in peer-to-peer discussions where they shared their findings and explanations with each other. Finally, they revised their original model to show how and why their investigation connected to the larger hydrologic cycle. After the completion of all four investigations and modelling tasks, teachers guided students through the development of a consensus model. As part of the consensus-modelling process, students discussed as a whole class what

Table 3. Y2 modelling-enhanced unit investigations and modelling tasks.

Investigation	*2-D diagrammatic model*	*Target explanation*
Water on a slope	Draw a model showing how and why water flows down a slope	Water moves downhill due to gravity at varying speeds depending on surface material
Evaporation	Draw a model showing how and why water evaporates over time	Liquid water changes to water vapor when warmed
Condensation	Draw arrows on the condensation chamber model showing how and why water moves in different temperatures	Water vapor changes to liquid water when cooled.
Water in earth materials	Draw a model showing how and why water moves through earth materials	Water moves downward through earth materials at different rates due to gravity and the composition of the earth materials

elements from their individual models should be included on a consensus model the teachers' drew in front of the class. The students had to reach a consensus before the teachers included the proposed ideas on the consensus model. Finally, students developed their post-unit model as a final artefact reflecting their knowledge of the water cycle. As in Y1, the Y2 post-unit supplemental modelling task was identical to the pre-unit modelling task.

Data collection

Student models

All pre-/post-unit modelling tasks with associated reflective writing samples were collected in Y1 (n_{y1pre} = 88, n_{y1post} = 88) and Y2 (n_{y2pre} = 96, n_{y2post} = 96). Each pre- and post-unit modelling task was assigned a unique identification number that associated it with the student, classroom, and year. The collected data were, therefore, hierarchical (by year) and nested (students per classroom per year).

Student interviews

We conducted clinical interviews with five students from each classroom in both Y1 and Y2 after completion of the pre-unit modelling task (n_{y1pre} = 25, n_{y2pre} = 25) and the post-unit modelling task (n_{y1post} = 25, n_{y2post} = 25). We used a clinical interview protocol designed to elicit student reflections around each of the epistemic features of MBE about groundwater for their pre- and post-unit models. The same students were interviewed after both the pre- and post-unit modelling tasks in both years. All interviews were audio-recorded and transcribed.

Classroom observations

To examine the ways in which the teachers enacted the Y1 and Y2 versions of the *Water* unit, we conducted classroom observations of unit lessons. First, we observed and videorecorded each teacher in both years enacting the pre- and post-unit supplemental modelling lessons (5 teachers × 2 lessons = 10 observations per year). These observations ranged from 60 to 90 minutes. Second, in both Y1 and Y2, we observed and video-recorded each teacher at least four additional times enacting other *Water* unit lessons. This resulted in 38 observations across all teachers in Y1 and 36 observations across all teachers in Y2. All video-recordings were given unique identification numbers and were catalogued for reference.

Teacher interviews

We conducted 53 teacher interviews across the two study years ($n_{Y1} = 30$, $n_{Y2} = 23$). An initial interview occurred at least a week prior to beginning the *Water* unit and the post interview within a week of finishing the unit. Teachers were interviewed at least four times while enacting the *Water* unit. We used a semi-structured protocol (Patton, 2001) to document their thinking about the curriculum materials and the practices of modelling. In Y1, the interviews focused on how the unit may be augmented with the practices of modelling; in Y2, the interviews included the teachers' ideas about the embedded modelling lessons and how the practices of modelling supported their students in connecting observations to MBE.

Data analysis

This study uses a varied dataset and both quantitative and qualitative data analyses. First, we quantitatively analyzed the scores from students' Y1 and Y2 pre- and post-unit models for the presence of MBE. Second, we qualitatively analyzed student interviews and their models to elucidate the quantitative findings. Finally, third, we analyzed the teacher interviews and classroom observations to explore differences in quantitative results across classrooms.

Quantitative analysis

To score students' models, we used an empirically grounded set of learning performances for students' MBE for hydrologic cycling grounded in the mechanism-based perspective (*components, sequences, mapping, explanatory process*, and *scientific principle*) for MBE of water and geosphere interactions (see Forbes et al., 2015). The learning performance levels provided a scaled measure of students' MBE of water/earth material interactions. Students' pre-unit and post-unit modelling tasks were scored using the rubric. An example of the rubric for the *components* feature is shown in **Table 4**.

We used a mixed model ANOVA for the statistical analysis because the data is both hierarchical and nested (Littell, Milliken, Stroup, Wolfinger, & Schabenberger, 2006). The independent variables are (1) the gain score for the aggregate epistemic features from pre- to post-unit model scores in Y1 versus Y2, (2) the gain score for each of the individual five epistemic features (*component, sequence, explanatory process, scientific principle*, and *mapping*) from pre- to post-unit model scores, (3) the overall epistemic feature gain score for each classroom for Y1 versus Y2, and (4) each individual epistemic feature gain score for each classroom for Y1 versus Y2. The dependent variables are the students' model scores nested within their classrooms.

The linear formula for the mixed model ANOVA is $\pi_{0j} = \beta_{00} + \lambda_{0j} + r_{0j}$, where π_{0j} denote students for individual 0 (teacher) in group j (pre/post; Y1/Y2); β_{00} is the mean for the epistemic dimensions (total gain, individual gain for *component, mapping, sequence, scientific principle, explanatory process*); and λ_{0j} is the effects for treatment (pre/post; Y1/Y2). The errors are represented both with variance and with covariance as r_{0j}. Within the initial run of the ANOVA, we included an interaction of teachers *by* year to examine if significant variation existed within the different classrooms for modelling task scores over each year or if the modelling task scores within each classroom were consistent (i.e. if one or two classrooms had a few students that were performing at a substantially higher or lower level on the modelling task causing the classroom to be significantly different from the other classrooms). This interaction was not statistically significant which indicates that

Table 4. Sample scoring rubric for 'components' epistemic feature.

Level	*Description*
0	No components of water in motion represented on model or in associated writings.
1	Includes at least one representation of visible water in motion (example: rain) that does NOT include interaction with the geosphere (example: does not identify that water penetrates the ground). Does not include representation/distribution of non-visible components such as water underground or water evaporating.
2	Includes two or more representations of visible water and one non-visible form of water in motion. Non-visible water in motion form may be liquid water under the surface or water evaporating
3	Includes representations and distribution of water in visible and non-visible water in motion including interactions with the geosphere and water evaporating.

the effects of the modelling task were consistent within the classrooms and any statistical differences between pre- and post-unit model gains between classrooms were due to differences in the teachers' enactments.

Qualitative analysis

Qualitative analysis included student artefacts, student interviews, teacher interviews, and classroom observations. All student data were coded for the epistemic features for mechanism- based perspective (*components, sequences, mapping, explanatory process*, and *scientific principle)*. Teacher data were coded for both the epistemic features and modelling practices (*develop, use, evaluate revise)*. Twenty percent of both the student and teacher data sources were co-coded by the first authors. Inter-rater reliability among the texts averaged at 80% and, after discussion between the authors, 100% agreement was reached for each data set. Source triangulation occurred through multiple data sources (interviews, modelling artefacts, and classroom observations) used in the analysis.

The initial coding round for students and teachers was then queried from the larger data sample to isolate data specific to the research question. We examined patterns and themes (Miles & Huberman, 1994) that elucidated the ways in which the students and teachers understood MBE about water and geosphere interactions. Once themes within the student and teacher interviews were established, we used pattern-matching (Patton, 2001) across Y1 and Y2 student data and teacher data to look for similarities and differences. Qualitative analysis involved an iterative process of data coding, displaying, and verification (Patton, 2001) to identify themes that provided insight into the students' articulation of mechanisms generated from their modelled water cycle sequences and the ways in which teachers' enacted the unit in Y1 and Y2.

Results

Overall, we observed statistically significant increased gains in students' MBE (scores on pre- and post-unit modelling tasks) for interactions between water and Earth materials in Y2 as compared to Y1. However, when examining these trends by individual classroom, only two of the five classrooms demonstrated statistically significant increases in students' gain scores for MBEs across years. Further qualitative investigation indicated the teachers in these two classrooms leveraged specific modelling practices and epistemic consideration differently than their peers. We examine these findings below by first, presenting the analyses of student models across Y1 and Y2 then, second, examining the links between the students' scores and their teachers' ideas and enactments of the *Water* unit.

Development of students' MBE for groundwater

In research question one, we asked, 'how does a modelling-enhanced curricular unit support 3rd-grade students' MBE about water and geosphere interactions over the standard version of the unit?' This question is examined quantitatively through pre-/post-unit model scores and qualitatively through themes within students' interviews and modelling artefacts.

Results of quantitative analysis of model scores

As shown in **Figure 1**, the aggregate gain scores between students' pre- and post-unit models for groundwater increased from Y1 ($\bar{x}$ = 0.362, σ = 0.0.95) to Y2 ($\bar{x}$ = 0.990, σ = 0.090). These differences are statistically significant, $F(1, 4) = 27.711$, $p < .001$, $\eta^2 = 0.257$ indicating that students' MBE about groundwater grew more substantially in Y2 then in Y1.

The sub-scores for each of the five epistemic features identify how each feature contributed to aggregate gains observed from Y1 to Y2. Statistically significant growth was observed for *components* feature scores in Y2 ($\bar{x}$ = 0.115, σ = 0.599) as compared to Y1 ($\bar{x}$ = 0.023, σ = 0.151), F (1, 175), = 73.4, $p = .000$, $\eta^2 = 0.324$. Students' Y2 feature gain scores for *explanatory process* ($\bar{x}$ = 0.07, σ = 0.403) was also higher than in Y1, in which the aggregate score for this feature was zero. Overall, these results suggest that differences in aggregate gain scores in students' MBE between Y1 and Y2 are due to *components* and *explanatory process* they represented in the models.

Results of qualitative analysis of student models and interviews

Findings from qualitative analyses of students' models and interviews illustrate key elements associated with epistemic features of *components* and *explanatory processes* within each year that account for these observed differences.

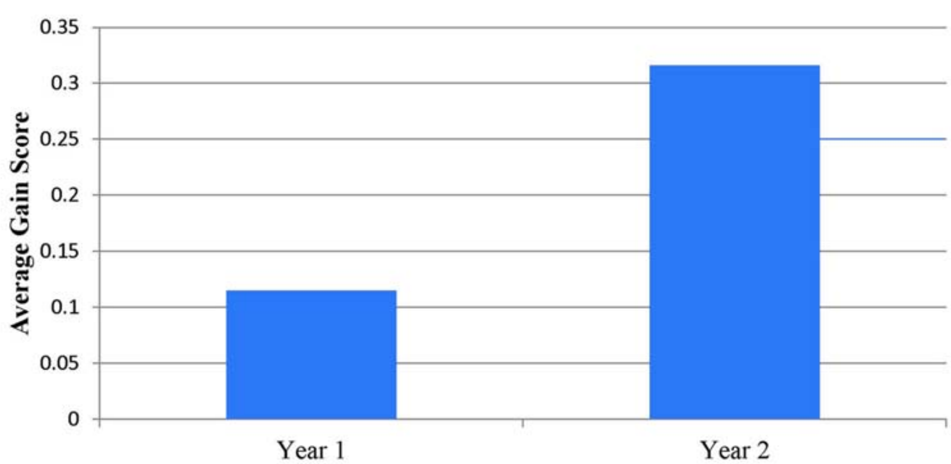

Figure 1. Average gains from pre- to post-unit model scores in Y1 and Y2 for 3rd-grade students' MBE about water and earth material interactions.

Component gains

From Y1 to Y2, students illustrated an increasingly complete set of *components* essential to water movement underground. In Y1, students' models included many above ground elements of the water cycle, such as clouds, water in the form of rain and water vapor, and plant life as essential to the hydrologic cycle. They discussed that water moved from clouds to the ground to plants and returned to the clouds through evaporation from plants or the ground. The majority of students identified plant life as the most important component for water movement. For example, when asked what happened to the water when no plants were present, a male student replied, "I don't know. Uhm, if there aren't any plants I don't know" (P4:51:58) indicating that his understanding of how water moves was connected to plant life. For the small number of students that did consider water underground, water was in the "dirt" or stored in "holes in the dirt" for plants to use. Their models did not consider components below a top soil or 'dirt' layer (**Figure 2**).

In Y2, while students still included plants, clouds, rain, and evaporation they also included earth material layers under the topsoil. They drew and labelled soil, sand, and gravel layers, all materials investigated for water flow in Y2. They also included an additional clay or bedrock layer under the gravel with water moving within the earth material layers. They used arrows and tunnels to show water moving down through the layers

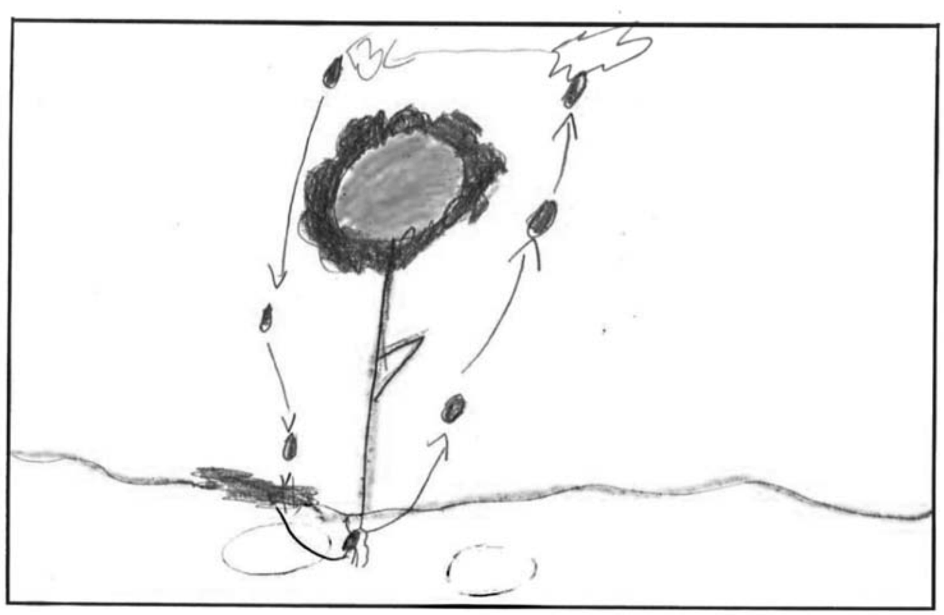

Figure 2. Post-unit Y1 model illustrates the water cycle occurring around a flowering plant. The model shows that water does not travel any further beneath the surface than the roots before cycling back to the clouds.

(**Figure 3**) or they showed water present between the pores within earth materials (**Figure 4**). They also discussed different pore sizes within the components under the ground such as,

Caleb:	It [the water] goes through the dirt really slow, then gets to the rocks. It goes through the small rocks really, really slow ... and it goes through the big rocks kind of fast. And then it goes to clay and sits there.
Interviewer:	Why doesn't it go through clay?
Caleb:	Because the particles are so bind [*sic*] together there is nowhere for it to go.

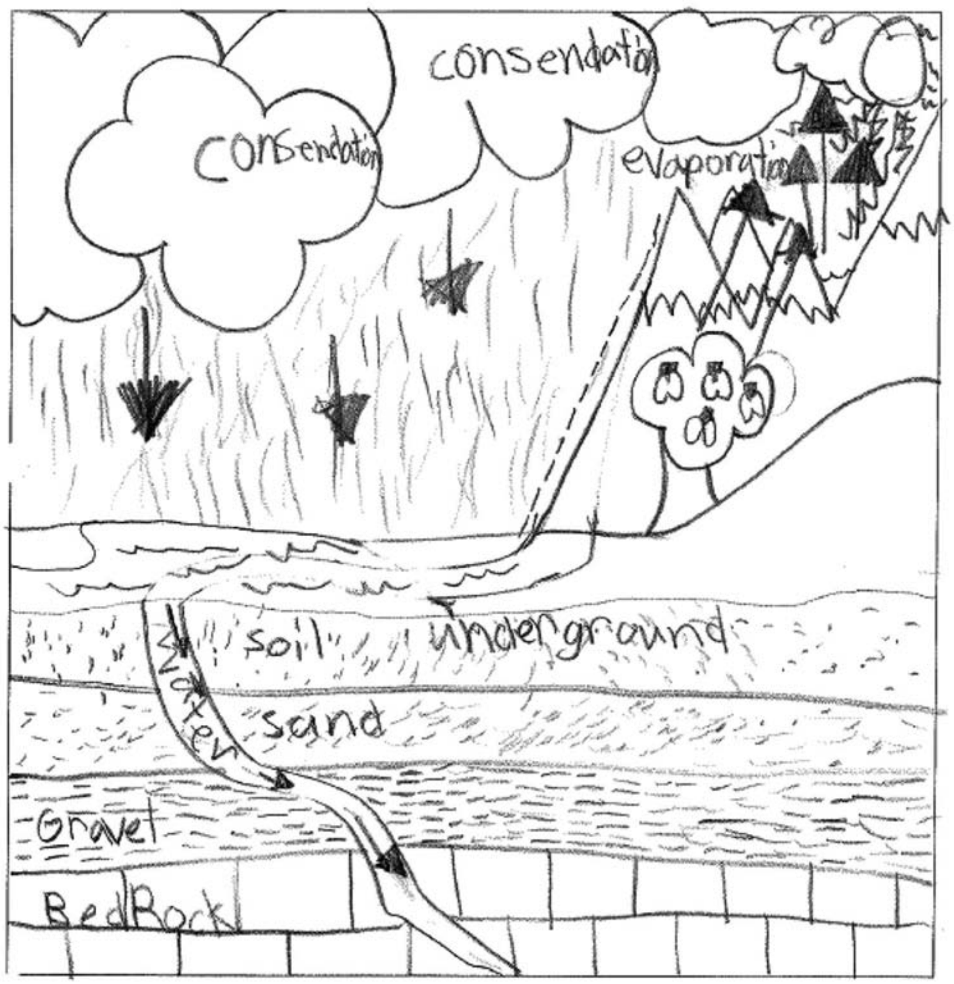

Figure 3. Post-unit Y2 model (T.Sa.M2) where the student has illustrated earth material layers underground and used dots and lines to identify particle sizes within the layers. While plants are included in the model, they are not illustrated as essential elements to subsurface water flow.

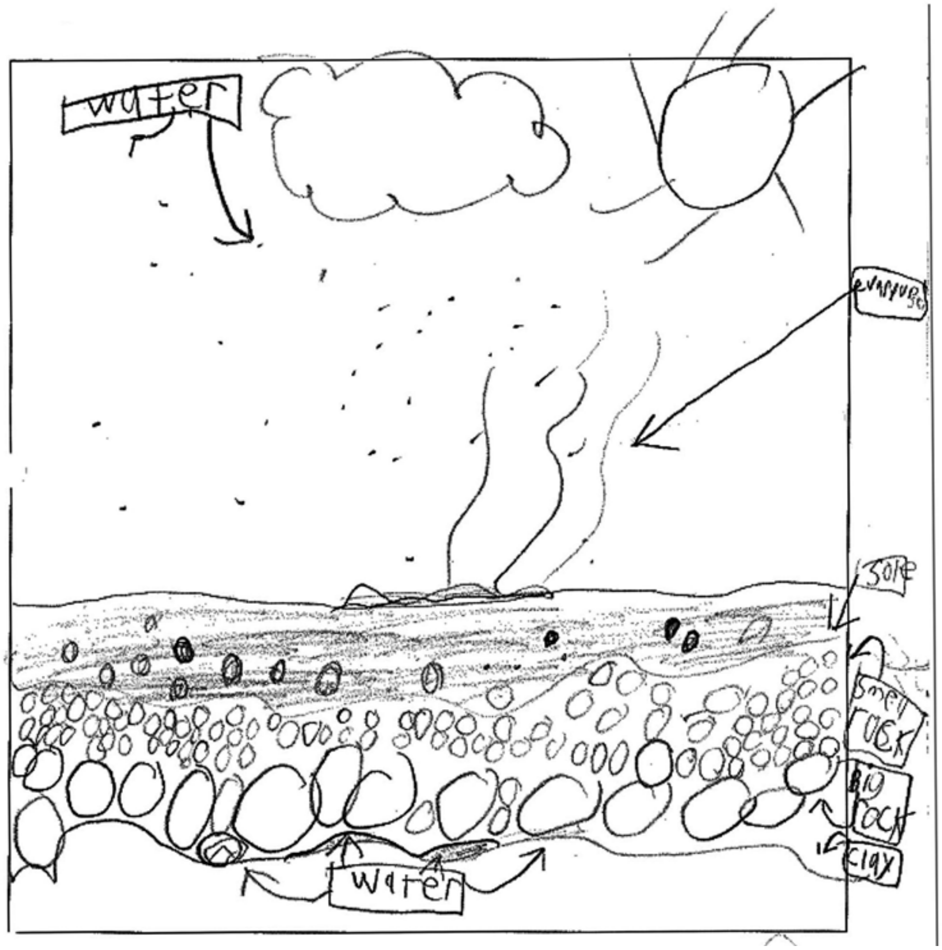

Figure 4. Caleb's post-unit model in Y2 (N.Ca.M2).

While they did discuss water moving through Earth materials, we did not find evidence that they considered water acting on the earth materials to form a tunnel, only that tunnels were present (Figure 3).

Explanatory process gains. From Y1 to Y2, students' models included the necessary *components* to make sense of subsurface water flow, which supported them in generating lesson targeted MBE. In Y1, students did not hold conceptual understanding about water underground, as was seen within their represented *components*. Since underground processes were invisible to them, their *explanatory processes* did not consider ground water and only included what was visible to them, which was plant life as seen in their components. Their cause and effect reasoning included rain falling from clouds (cause) to water plants (effect) because plant roots act "like a magnet, only for water though" (C.JM1). Overall, in Y1, students' sense-making about the water cycle was tightly connected to plant survival, and they conceptualized that any water under the surface only moved towards plant roots.

However, in Y2, as students began to represent hidden *components* underground, their *explanatory processes* also included how and why water moves underground. For example, in the discussion with Caleb about his model (shown in Figure 4):

Interviewer: Okay, so how does the water get down here underground?
Caleb: Gravity … It pulls it down. (N.Ca.11.5)

As Caleb discusses, and was typical in the Y2 student discussions, the students engaged in sense-making about how and why water moved beneath the surface. They connected their represented components showing different particle sizes (cause) to how water flows through earth materials (effect), and down through the ground because of gravity (causal mechanism). Overall, when students included hidden subsurface elements on their models, they used their models as reasoning tools for how and why water flows underground.

Differences in gain scores for students' groundwater MBE between classrooms

In research question two, we asked, 'To what extent do changes in students' MBE about groundwater vary by classroom?' First, we analysed the differences between aggregate pre- and post-unit model scores from Y1 to Y2 across all classrooms. Observed differences in these gain scores for MBEs among the classrooms across the two years is statistically significant, $F(1, 4) = 10.777$, $p < .001$. As shown in **Table 5** and **Figure 5**, Classrooms 3 and 5 show marked increased gains for students' MBE for groundwater from Y1 to Y2 while the remainder of the classrooms do not.

These findings show that overall increased gains between Y1 and Y2 students' MBE for groundwater were because of growth in two of the five study classrooms.

Table 5. Comparative gain scores in Y1 and Y2 models by classroom.

	Y1 Average (standard deviation)	*Y2 Average (standard deviation)*	*F*	*p*
Classroom 1	0.05 (0.51)	0.00 (1.14)	0.031	.860
Classroom 2	0.063 (0.44)	−0.10 (1.02)	0.001	.979
Classroom 3	0.291 (0.91)	0.762 (1.51)	7.69	.008*
Classroom 4	0 (0)	−0.07 (0.99)	0.077	.783
Classroom 5	0.055 (0.99)	0.895 (1.69)	4.76	.032*

* Significant at .05.

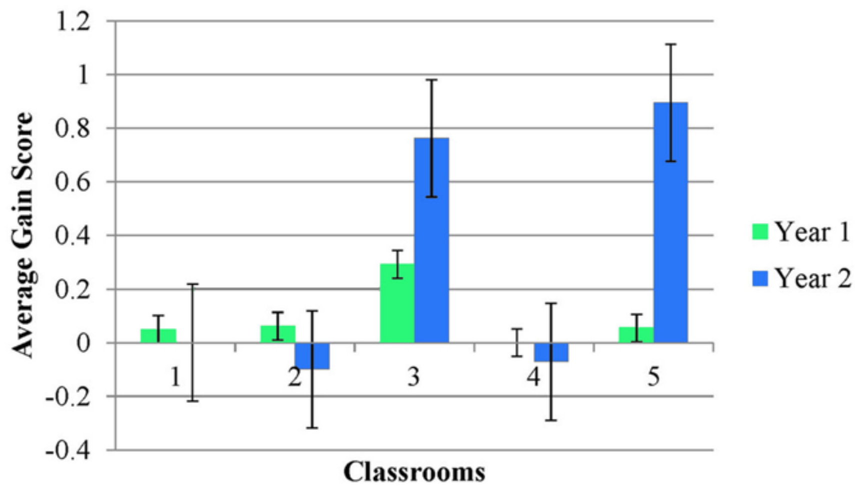

Figure 5. Average overall Y1 to Y2 gain scores for students' models with error bars for individual teachers. Classroom 2 and 4 appear as negative gains in Y2 due to the variability around the mean. The statistical analysis shows that these classrooms did not significantly differ from their aggregate gain scores in Y1 as shown in Table 5.

Qualitative analysis of teachers' pedagogical reasoning about MBE's and unit enactment

In research question three, we asked, 'How do teachers enact a modelling-enhanced unit to support their students' MBE for groundwater?' Evidence shows that in Y1, all five teachers held similar conceptualizations about modelling and similar teaching practices for supporting their students in modelling the water cycle. However, in Y2, two teachers — Clarissa (Classroom 3) and Lenore (Classroom 5) — increased their support for students' formulation of MBE related to *components* and *explanatory processes* associated with the water cycle. Both teachers emphasized components of groundwater and leveraged student discussions to encourage students to place individual water processes within the whole water cycle. We hypothesize that these changes in instructional practice were associated with observed, increased Y2 gains in students' MBEs in these two classrooms.

Changes to support components

From Y1 to Y2, both Clarisse and Lenore began to emphasize the importance of supporting their students to create better models through the inclusion and integration of components. Clarisse said in Y2, for example, ' ... they had to think about the parts and pulling it together to get the [model]. That's not a strong point of third graders. They really have to be taught how to do that' (C_final_Y2). Lenore also reflected on students' modelling practice, saying:

> It's hard … to get all the details in there. It's hard, I think, because in their grade to remember all the different things to get it in there and I don't know if it would be cheating to make a list … to be sure to include the different parts of the water cycle. (L_11_10_Y2)

These concerns for students' inclusion of various components of the water cycle were not observable in Y1. As such, Lenore and Clarisse's emphasis on supporting students' reasoning about model components represents growth in their pedagogical reasoning and decision-making for model-based teaching.

In tandem with these Y2 instructional priorities, both teachers modified their classroom instruction in ways they identified would support students in considering unobservable components of the water cycle associated with groundwater. Clarisse, for example, consistently utilized analogies as a tool to support students' MBE. For example, in one lesson in Clarisse's classroom, students were discussing groundwater. She highlighted to her students that they had not included partial size with water speed in their models, asking:

> What is normally between particles? [a few students answer "space/room"]. Space which is filled by air, kinda [*sic*] like going through a busy mall, it's a little bit easier to navigate when there are less people packed in. That's the same as water going through the layers that we learned about in our earth (C_10_17_Y2, 14:34:).

This analogy occurred after students worked with a physical model of water moving through packed and loose earth materials and soil layers. During this observation, Clarisse tasked pairs of students to consider the 'people in the mall' comparison, and incorporate particle size and water movement into their models, "like the scientists do," emphasizing the need for important elements to be represented in students' models. Throughout Y2, Clarisse used references to students' lived experience to help them conceptualize trends, represent them in their models, and use their models to explain groundwater-related phenomena.

Lenore also accentuated particular components of the water cycle through questioning her students about representational aspects of their models associated with groundwater. For example, during one lesson in which students investigate the movement of water through different substrates, Lenore asked small groups of students to "talk about how the water is moving through the dirt. Slow? Fast?" (L_ 12_5_Y2a) and "why does your group think it, water, would move faster through the gravel?" (L _12_5_Y2b) and include these ideas in their models. This question was asking students to consider particle size as a possible representational component necessary to help explain why groundwater moves through particular earth materials.

While each teacher emphasized components in different ways, each of these examples demonstrates how Clarisse and Lenore supported their students in considering essential groundwater *components* in their models.

This focus on components is attributed to Clarisse and Lenore's desired outcomes when they asked their students to discuss their models with their peers. In Y1, the teachers rarely emphasized peer-to-peer discussions in their lessons, and whole class discussions were focused on idea gathering or on the teachers describing the investigations rather than students sharing their models. However, in Y2, peer-to-peer discussions were included in the enhanced curriculum, and both teachers began to discuss the importance of peer-to-peer discussions during their enactments. After the initial peer-to-peer discussion in the first lesson, both teachers commented that students were not using their models when they spoke to each other, but instead were generally describing how water moves. Clarisse stated "They're not [using their models], they just ... they just don't articulate well ..." (C_9_17_Y2) and Lenore discussed that if they talked through their models with each other "That would make that [the modeling experience] more powerful, I think, as far as explaining their thinking" (L_11_10_Y2).

To better support their students in discussing their models with each other, they purposefully asked students to use their models to describe individual components within individual processes to each other. After this shift, both teachers remarked that students were now using their models during their peer-to-peer discussions. Clarisse noted, "... they were able to talk about their drawings better when it wasn't the whole cycle" (C_9_26_Y2). Lenore stated that when they talked through their models with each other, "it was probably the ... highlight of the whole lesson" (L_11_22_Y2). For both teachers, the desire to have students' use their models in productive ways during peer-to-peer conversations led to increased individual *components* highlighted during student discussions.

Changes to support explanatory process

Explanatory process was another key element of MBE these two teachers began to emphasize more explicitly in Y2. In Y1 both teachers, consistent with the larger group of five teachers, described students' use of scientific models as a recording tool to represent knowledge. Clarisse commented that modelling the water cycle would help students by 'either drawing what they have thought through or drawing what you're talking about and labelling it they get a better understanding about that process' (C_1_11_Y1). In Y1, the teachers identified that the only purpose of constructing a model was so that it 'looks like' the water cycle. However, in Y2, as Clarisse and Lenore increased a focus on *components*, they also more significantly emphasized ways to support students in *explanatory processes* for what they were showing on their models. When each teacher discussed their reasoning about students' development of MBE and *explanatory process*, they stressed the importance of providing support for explaining phenomena. Lenore commented, "They do need, I don't want to say a lot of direction, but they do need some guidance if you're wanting them to get certain concepts, but you still want them to find it on their own" (L 9_24_Y2). Support, in the case of both teachers, focused on leveraging student discussions to connect more water cycle features, associating model *components*, to a degree, unseen in other classrooms. For example, during an Y2 classroom observation focused on water moving through soil (C_10_15_Y2), Clarisse encouraged small groups of students that included layers of soil in their models to discuss with other students why they included that *component* and how and why water moves through different layers. She explicitly stated, "if the how and why aren't there you gotta [*sic*] keep going, talking ..." in order to get students to talk about porosity, layers of substrate, and gravity within their models. One student stated that her model did not include layers underground. Clarisse insisted, "... we can change that, that's why we have erasers, scientists change their thoughts" (C_10_16_Y2), encouraging students to include these new explanatory process.

In another observation, Lenore asked students, "What's that force that causes water to keep going downward?" (L_12_5_Y2c). Students said gravity. Lenore then asked students to discuss in small groups, "What does that tell us about water underground?" This led students to have productive discussions on *explanatory processes* underlying groundwater phenomena. This type of discussion did not occur in Y1 when students did not consider *components* below ground on their models. Finally, in Y2 at the end of the unit, Lenore also had student small group discussions sharing the important *components* in their models. Lenore encouraged peers within the groups to point to out "missing connections" within each other's models (L_12_5_Y2c), an activity that was not seen in other classrooms. These, and other examples, provide evidence that the opportunity to engage in *explanatory processes* was linked to the types of *components* students could identify. Both Clarisse and Lenore placed greater emphasis on *explanatory process* in Y2 than Y1, which links to trends in student MBE gains from Y1 to Y2.

We attribute this change in Y2 to the increased emphasis both Clarisse and Lenore placed on student reflection within their enacted lessons. They each increasingly supported their students to critique their own models. In Y1, both teachers only thought of assessment as how *they* would assess their students. Their thinking about assessment focused on *what* the models included such as "[if I were to assess] I would want to see in there that water vapor, when it's cooled, will turn back into a liquid" (L_12_13_Y1). During Y1, neither teacher considered if the students understood how or why the processes occurred nor did they consider having students self-assess to reflect on their own thinking. However, in Y2, the lessons included opportunities for students to self-assess their models. After both teachers had completed the lesson with the first student self-assessment, they each discussed the importance of these reflections for students to be metacognitive about their model-based thinking. For example, Lenore stated that the self-assessment provided opportunities for students to say to themselves "Look at what I know. How can I change what I know?" (L_11_22_Y2). Over the course of the Y2 curriculum, they expanded the self-assessments to also include a broader array of student reflection prompts, such as "What do we learn from it [the lesson]?" and "How does that help us understand our world better?" (C_1_11_Y2). Their increased attention to the importance of asking students to self-assess and building on these self-assessments for larger reflections supported their students in connecting how and why the processes they represented worked.

Synthesis and discussion

The practices of modelling provides both a visualization and reasoning tool that enables users to build understanding about large complex processes, such as the hydrologic cycle, through developing simplified process representations which make fundamental processes explicit and visible (Clement, 2000; Covitt et al., 2009; Dove et al., 1999; Forbes et al., 2015; Gilbert, 2004; Halloun, 2007; NRC, 2007; Schwarz et al., 2009; Vo et al., 2015). However, both scientific modelling and concepts related to groundwater are underemphasized in elementary science learning environments (Covitt et al., 2009; Forbes et al., 2015; Vo et al., 2015; Zangori et al., 2015). To begin to address these needs, we report here on the first two years of a longitudinal project designed to support both 3rd-grade students and their teachers to engage in the practices of modelling to build understanding about groundwater.

Elementary students' MBE about groundwater

First, our findings suggest that primary students used their models to conceptualize *components* of below ground water movement and above ground water movement and *explanatory processes* to make sense of how and why this occurred. Water scientists and educators alike have called for learning environments that provide middle-, secondary-, and college-level students multiple and varied opportunities to make non-visible processes explicit and visible and identify how these processes underlay system function (Covitt et al., 2009; Dickerson & Dawkins, 2004; Libarkin & Brick, 2002). Our results provide evidence that discipline-specific content embedded within scientific practices in developmentally appropriate ways can also be effective in the primary classroom. This knowledge about the practices of modelling and groundwater was foundational, focusing on identifying the essential elements to discuss what is happening, and then reason about these elements to discuss how and why it is happening. Students will be able to draw upon this knowledge as in future learning opportunities about complex hydrologic interactions (Covitt et al., 2009).

Classroom variation in MBE about groundwater

However, second, while our evidence suggests that the elementary students articulated MBE about groundwater, we observed variation across the five classrooms, with only two demonstrating statistically significant gains from Y1 to Y2. Within these two classrooms, the teachers shifted beyond using models to simply illustrate water movement to include instructional supports to help students make sense of groundwater. We found that these shifts were due to their developing ideas about peer-to-peer discussions and increasing frequency with which they provided students opportunities to self-assess their own learning. While these were each opportunities present in the Y2 curriculum materials, we found that two of the teachers substantially elaborated these opportunities. Past studies have discussed the important role teachers play in students' understanding of models and modelling and suggest more research should be focused on teachers' practice in supporting model-based instruction (Henze, van Driel, & Verloop, 2008; Justi & Gilbert, 2002; Oh & Oh, 2011). Here we find evidence that demonstrates how teachers' model-based teaching influences student outcomes and how small changes to their model-based teaching practice influences gains in students' model-based explanation construction.

As we have discussed elsewhere (i.e. Forbes et al., 2015; Vo et al., 2015; Zangori et al., 2015) in Y1, teachers identified that models should "look like" the water cycle. However, in Y2, we found gains in students' MBE for groundwater in the classrooms where teachers' instructional practices moved beyond 'look like' to asking students to *use* their models to connect *components* to *explanatory processes*. This occurred through their increased focus on *components* in model construction, due to their desire to have students use their models for peer-to-peer interactions to describe processes and asking students to use their *components* in their *explanatory processes*, due to their desire to have students self-asses their own understanding. These results suggest that teachers' attention to features of MBE is critical to using models as sense-making tools and model-based teaching.

Conclusion and implications

This study contributes to a limited body of research on model-based teaching and learning in elementary science learning environments, specifically about hydrologic phenomena (; Dove et al., 1999; Forbes et al., 2015; Vo et al., 2015; Zangori et al., 2015). Results have important implications for curriculum developers, researchers, and science educators in considering the challenges in supporting elementary students to both consider non-observable components and propose underlying mechanisms inherent to large complex processes. First, study implications suggest that primary science learning environments should include model-based curriculum where students *develop, evaluate,* and *revise* their models to make their thinking visible and *use* their models to reason about how and why water moves through unseen elements. Curriculum and instruction should include opportunities for students to work with multiple representations, such as physical models, as well as develop their own illustrations of how and why phenomenon occurred at the process level to use as bridges between observations and the physical world (Gilbert, 2004). They should then be asked to reason about how and why individual key processes occur as well as place these processes at the system level to understand how the process supports system function. In this manner, alternate conceptions may be challenged as students build knowledge about how and why systems behave as they do (Clement, 2000; Dickerson & Callahan, 2006; Dickerson et al., 2007).

Second, implications also suggest that for 3rd-grade students to generate MBE, they require curriculum and instructional support in *using* their models to consider unseen, non-visible mechanisms and elements. Building this expertise should begin in preservice teacher education (Windschitl & Thompson, 2006; Windschitl et al., 2008) and continue within in-service professional development (Henze et al., 2008; Justi & Gilbert, 2002). Experiences should be long-term, providing multiple opportunities for preservice and in-service teachers to use their models to generate MBE at the process and system level. Instruction should also include opportunities for preservice and in-service teachers to teach model-based curriculum.

Finally, third, primary curriculum materials should be more model-based, providing support for students, but also educative for teachers in how to support their students in formulating MBE. Providing teachers with strong rationales behind how and why model-based teaching and learning should be implemented in the primary classroom is only one of many curricular enhancements that could support teachers in successfully implementing science at the elementary level (Halloun, 2007; Oh & Oh, 2011). Embedding these types of educative elements into curricular resources for teachers may provide opportunities and supports for them to engage in and familiarize themselves with scientific practices that are new and unfamiliar. For example, by reading a vignette to explain the process and pratfalls of the implementation of a model-based lesson, teachers might gain insight that would be applicable to their personal situations or provide them instructional resources like when discussion questions could be asked.

Our results begin to shed light on the tentative relationship between student learning gains and teachers practices with scientific modelling at the primary grade band. As this project progresses, we will continue working with these teachers, helping to revise their lesson plans and supporting them in providing engaging and authentic modelling opportunities for their students. We will continue to work with all five teachers in finding leverage points in curriculum and instruction to support their students in building understanding about groundwater (Forbes et al., 2015; Zangori et al., 2015). Primary students have been shown to have a rich understanding of the natural world. By understanding how students and teachers leverage that knowledge through the practice of scientific modelling in particular disciplinary domains, we can provide opportunities for authentic engagement with science.

Acknowledgments — We appreciate the interest and cooperation of Christopher Soldat, Julie Foltz, Sheila Barron, and the students and teachers who made this research possible. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

Disclosures — No potential conflict of interest was reported by the authors.

Funding — This material is based upon work supported by the National Science Foundation (DRL-1443223). Directorate for Education and Human Resources.

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