Teacher Pedagogical Content Knowledge for Using Learning Progressions

Abstract

Over the past decade, research on learning progressions has led to important advances in understanding how student ideas change over time. Yet research into teachers' uses of learning progressions and related curriculum materials in classrooms has demonstrated the challenges of supporting teachers in effectively using learning progressions for instruction. Two important factors that may influence how teachers use learning progressions are teachers' content knowledge and pedagogical content knowledge (PCK). In this paper we explore the relationships among content knowledge, PCK, and a learning progression for model-based reasoning about water in environmental systems. We examined three dimensions of PCK: Knowlege of curriculum (KC-LG), knowledge of students (KS), and knowledge of instruction (KI). We developed assessments to measure teacher content knowledge and PCK in the domain of water moving through environmental systems. Results show that teachers' content knowledge and PCK mostly aligned with knowledge for teaching phenomenological reasoning and not model-based reasoning. Teachers' content knowledge and PCK changed little as a result of using learning progression-based curriculum materials for instruction. The most significant changes were in teachers' KC-LG and KS, but not in KI. Teachers' overall PCK did have a medium-size positive correlation to teacher effect size on student learning, with teachers whose learning goals aligned more closely with the domain of the water learning progression having the most significant effect. Our findings contribute to understanding the role of content knowledge and PCK on teachers' understanding and use of learning progression-based innovations to support students in reaching model-based reasoning.

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Teacher Pedagogical Content Knowledge for Using Learning Progressions

Over the past decade, research on learning progressions has led to important advances in understanding how student ideas change over time. By describing potential learning pathways between learners' initial ideas and more sophisticated understandings about big ideas in science, learning progressions provide a road map for curriculum, measures for assessment, and tools for instruction (Alonzo & Gotwals, 2012; Corcoran, Mosher, & Rogat, 2009; Duncan & Hmelo-Silver, 2009; National Research Council, 2007). Interest has recently shifted to supporting teachers in using learning progressions and learning progression-based curriculum resources in classrooms. Yet teachers' knowledge of and for using learning progressions remains undertheorized (Duschl, Maeng, & Sezen, 2011).

As research-based innovations, learning progressions and learning progression-based curriculum materials are unfamiliar to most teachers. Initial attempts to support teachers in using learning progressions in instruction have had mixed results. For example, in her work with helping teachers use learning progressions for formative assessment, Furtak (2012) found that the teachers often viewed learning progressions as lists of misconceptions that teachers should correct during instruction. Furthermore, teachers did not often leverage the full potential of learning progressions to inform the enactment of instruction that is both rigorous and responsive to students' initial ways of thinking.

Researchers have long known that teachers' uses of innovations are influenced by many factors. Two important factors are teachers' content knowledge and pedagogical content knowledge (e.g., Cohen & Yarden, 2009; Van Driel, Beijaard, & Verloop, 2001). In this paper we explore the relationships among content knowledge, pedagogical content knowledge, and a learning progression for model-based reasoning about water in environmental systems. We hypothesize that in order to use learning progressions and learning progression-based curriculum materials to support students in developing model-based accounts of water (i.e., predictions and explanations), teachers need to demonstrate model-based understandings of water. Furthermore, they need knowledge of curriculum, knowledge of student thinking, and knowledge of instruction that aligns with supporting model-based reasoning. At the same time, there is evidence that teachers' pedagogical content knowledge develops as teachers gain more teaching experience in a particular domain (Van Driel, Verloop, & de Vos, 1998). As such, it is possible that teachers might develop necessary content knowledge and pedagogical content knowledge as they learn to use learning progression-based curriculum materials for instruction.

In this study, we worked with teachers in two related projects who received professional development about the Water Systems Learning Progression (Gunckel, Covitt, Salinas, & Anderson, 2012; Gunckel, Mohan, Covitt, & Anderson, 2012) and used curriculum materials and instructional tools related to this learning progression to teach about water. We developed assessment items to measure teacher content knowledge and pedagogical content knowledge related to teaching about water in environmental systems and administered these assessments prior to teachers' participation in the professional development and again after teaching using the instructional resources. Our overall goal was to investigate a possible link among teachers' content knowledge, pedagogical content knowledge, and the levels of achievement on the Water Systems Learning Progression. Our research questions were

1. Is it possible to differentiate knowledge of curriculum, knowledge of students, and knowledge of instruction dimensions of pedagogical content knowledge?

2. What is the status of teachers' content knowledge and pedagogical content knowledge in relationship to the Water Systems Learning Progression?
3. How did using the learning progression-based curriculum materials in instruction support teachers in developing content knowledge and pedagogical content knowledge relevant for teaching about water in environmental systems?
4. Is there a relationship between teacher content knowledge and pedagogical content knowledge and student learning on the Water Systems Learning Progression?

Our findings will contribute to understanding the role of content knowledge and pedagogical content knowledge in teachers' understanding and use of learning progression-based innovations to support students in reaching model-based reasoning.

Background

In previous work, we developed the Water Systems Learning Progression to map students' ideas about water and substances in water moving through environmental systems (Gunckel, Covitt, et al., 2012; Gunckel, Mohan, et al., 2012). We found that students initially use informal force-dynamic reasoning that explains and predicts water phenomena by assigning natural tendencies to water or actors that move water from one location to another (Pinker, 2007; Talmy, 1988). Later, students develop phenomenological reasoning, telling school science stories that put events in order and name processes that move water. The goal for high school students, the upper level of the learning progression, is for students to use qualitative model-based reasoning to account for water movement (Braaten & Windschitl, 2011). Model-based accounts recognize driving forces (e.g., gravity, pressure) and constraining variables (e.g., permeability, topography) at multiple scales (from atomic-molecular to landscape). Unfortunately, our work has also shown that by the end of high school, the majority of students still provide force-dynamic and phenomenological accounts and few students provide model-based accounts of water in environmental systems (Gunckel, Covitt, et al., 2012).

To address this problem, we designed curriculum units, instructional tools, and formative assessments that aligned with the Water Systems Learning Progression. These materials have shown promise. Teachers who used these resources in instruction achieved greater effect sizes in student learning as measured on the learning progression than teachers who did not (Gunckel, Covitt, & Salinas, 2014). Nevertheless, high school students still provided predominately phenomenological accounts and did not reach model-based reasoning. This led us to explore how teachers used the learning progression-based curriculum resources and instructional tools that we developed. Our investigations showed that teachers' uses of the learning progression-based resources varied widely (Covitt, Syswerda, Caplan, & Cano, 2014; Gunckel et al., 2014). Some teachers assimilated learning progressions into their existing instructional practice to teach typical school science narratives while others used the learning progression-based resources to support students in moving toward model-based reasoning about water in environmental systems. Our motivation in conducting this study was to understand better these results. We began by exploring if and how teachers' content knowledge and pedagogical content knowledge might play a role.

Frameworks

Content Knowledge (CK): Water Systems Learning Progression

We used the Water Systems Learning Progression as a framework for measuring student and teacher content knowledge (CK) of water and substances in water moving through environmental systems (Gunckel, Covitt, et al., 2012; Gunckel, Mohan, et al., 2012). Environmental systems include both natural systems (i.e., surface water, soil and groundwater, atmospheric, and biotic systems) and human-engineered dimensions (i.e., wells, water treatment plants, human-altered landscapes including roads, buildings, parks, canals, etc.). The learning progression describes four levels of sophistication of accounts (i.e., explanations and predictions) of water moving through these systems. Level 1 and level 2 force-dynamic accounts of water frame events as resulting from natural tendencies of water to move by itself or from agents acting on water to move water (e.g., clouds suck up water). These accounts focus mostly on water in visible locations. Level 3 phenomenological accounts trace water along potential pathways by putting events in order, naming processes that move water, and tracing water through hidden (e.g., underground) and invisible (e.g., water vapor) parts of systems. Level 4 accounts explain how and why water and substances in water move through systems. They identify driving forces that move water (e.g., gravity, pressure) and constraining factors that influence the pathways that water takes. These accounts trace water along multiple pathways and at multiple scales (i.e, atomic-molecular through landscape). Level 4 represents the knowledge and reasoning necessary for making evidence-based decisions about environmental issues and meets performance expectations for high school as described in the *Framework for K-12 Science Education* (National Research Council, 2012) and Next Generation Science Standards (Achieve, 2013). Table 1 provides an overview of the characteristics of accounts at each level of achievement.

An important aspect of the Water Systems Learning Progression is that accounts at each level are situated in the ways of talking, thinking, and acting of the community in which one is participating. The ways of talking, thinking, and acting characteristic of a community are referred to as Big "D" Discourse (Gee, 1991). Therefore, progress along the learning progression requires learning the Discourse of a new community (Gunckel, Mohan, et al., 2012).

Table 1
Water Systems Learning Progression Framework

	Level of Achievement	Characteristics of Accounts
Increasing level of sophistication (↑)	4: Model based accounts	Use causal mechanisms to explain how and why events occur. • Identify driving forces that move water (e.g., gravity, pressure) • Identify constraining factors (e.g., permeability, topography, etc.) • Connect multiple scales from atomic-molecular to landscape
	3: Phenomenological accounts	Tell school science stories that trace water along potential pathways but do not attend to model-based principles. • Trace water through multiple connected steps and processes • Span microscopic through landscape scales • Recognize hidden and invisible parts of systems
	2: Force dynamic accounts with mechanisms	Frames events as resulting from natural tendencies of water or agents acting on water. • Identify informal mechanisms that move water • Limited to visible and macroscopic parts of systems
	1: Human-centered force dynamic accounts	Provides human-centric accounts of events. • Identifies humans as movers or changers of water • Describes water as fulfilling the needs of humans • Describes water in isolated, visible locations only (e.g., puddles, bathtubs)

Pedagogical Content Knowledge (PCK) for Teaching about Water

Pedagogical content knowledge (PCK) is the specialized knowledge of curriculum, students, teaching, and assessment necessary to teach about specific topics (Grossman, 1990; Magnusson, Krajcik, & Borko, 1999; Park & Oliver, 2008; Shulman, 1986; Van Driel & Berry, 2010). A common model for PCK includes five dimensions: orientations to science teaching, knowledge of curriculum, knowledge of students' understanding of science, knowledge of assessment, and knowledge of instructional strategies (Magnusson et al., 1999; Park & Chen, 2012; Park & Oliver, 2008). These dimensions are interrelated, with each shaping, constraining, and building the others.

Sztajn et al. (2012) argued that learning progressions can unify these dimensions of specialized knowledge. The knowledge of learning progressions and the knowledge necessary to use learning progressions are situated in each of these PCK dimensions, are interrelated to knowledge in other dimensions, and become part of a teachers' overall, integrated pedagogical knowledge for teaching about specific topics. In our work, we looked specifically at teachers' knowledge of curriculum, knowledge of students, and knowledge of instruction. We argue that knowledge of the Water Systems Learning Progression can bring coherence to these dimensions of teachers' PCK for teaching about water in environmental systems. Figure 1 shows how we conceptualize the learning progression linking these areas of teacher pedagogical content knowledge. Below we describe these three dimensions in more detail.

- *Knowledge of curriculum learning goals (KC-LG)* describes teacher knowledge of learning goals for teaching about water. The Water Systems Learning Progression bounds the curriculum to concepts and practices necessary to provide model-based accounts of water moving through environmental systems. As such, the learning progression has the potential to support teachers in moving beyond articulating learning goals as disconnected facts to identifying challening goals for model-based reasoning and engaging in scientific practices.
- *Knowledge of students (KS)* describes teacher knowledge and understanding of student thinking about water. The Water Systems Learning Progression describes characteristics of student accounts at each level of achievement and how their thinking changes as their ideas become more sophisticated. The learning progression has the potential to support teachers in moving beyond identifying misconceptions to be fixed to assessing and building on student ideas to build more sophisticated understandings about water.
- *Knowledge of instruction (KI)* describes teacher knowledge of appropriate instructional strategies and activities. The Water Systems Learning Progression provides principles for responding to students at various levels of achievement on the learning progression. As such, the learning progression has the potential to support teacher in moving beyond just providing hands-on experiences to engaging students in appropriate experiences with phenomena and scientific practices to build higher levels of understanding.

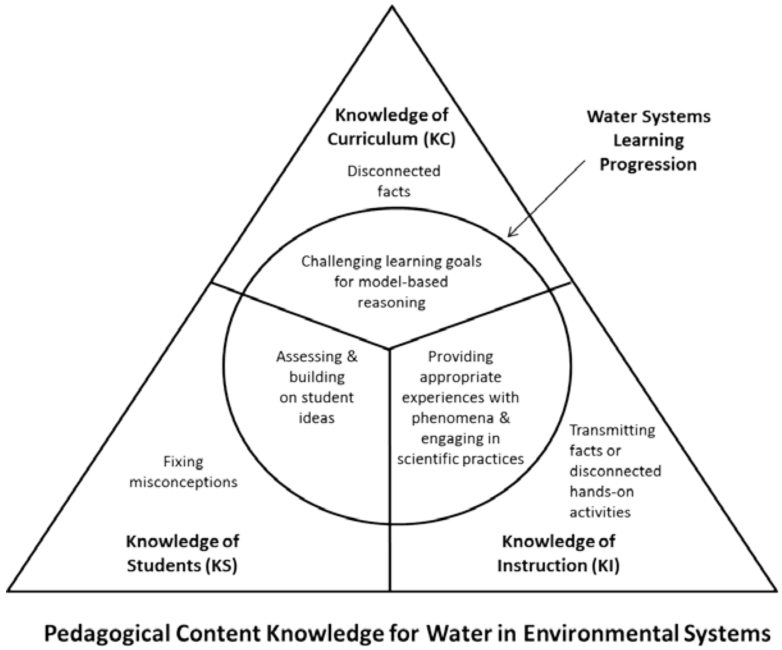

Figure 1
Pedagogical content knowledge for water in environmental systems

Methods

Study Context

The data from this study were taken from two projects related to the development and use of learning progression-based curriculum materials, formative assessments, and instructional tools to support students reasoning about water in environmental systems. The Pathways Project developed curriculum materials that engaged students in collecting data and calculating the water budget for their school yard. The curriculum materials were designed to support students in developing model-based accounts of water systems. This project also included the development of formative assessments that teachers could use to assess their students' progress on the Water Systems Learning Progression. These formative assessments included teacher materials that provided suggested instructional sequences for students at different levels on the learning progression. The Tools Project focused on the development of graphic reasoning tools that teachers could use in conjunction with the formative assessments to support students in tracing water through multiple pathways and identifying driving forces and constraining factors on water movement.

Both projects involved middle and/or high school teachers in professional development related to the Water Systems Learning Progression and use of the associated instructional resources. Teachers then taught about water systems using the curricular resources they had used in their professional development. Teachers' students completed online assessments to measure their performance on the Water Systems Learning Progression prior to and following instruction. Teachers also completed similar assessments that measured both their performance on the Water Systems Learning Progression and their pedagogical content knowledge.

Participants and Sampling

Participants in the study were middle and high school science teachers and their students from project research sites in six states across the country. The six sites represented a diversity of schools from low to middle socio-economic rural, suburban, and urban communities. Racial and ethnic diversity spanned communities that were predominately African American or predominately White to communities with diverse populations. Teachers in the study were predominately White (85%) and female (75%).

176 teachers participated in our combined projects (155 Pathways Project, 21 Tools Project). For this study, we included only teachers who completed both the pre-assessment and the post-assessment. This sampling resulted in 54 teachers (40 Pathways Project, 14 Tools Project). We used this sample to answer research questions one, two, and three. For research question four, about correlations between PCK and effect size, we used data from teachers who had both completed a post-assessment and had at least 30 students who completed pre- and post-assessments. This sampling resulted in 24 teachers (6 Pathways Project, 18 Tools Project). Because some teachers from both projects participated for multiple years, we included their data from each year separately, providing us with a n = 37 for the PCK and effect size correlation.

Assessments

Both students and teachers took assessments associated with the Water Systems Learning Progression (Gunckel, Covitt, et al., 2012). The student version of the assessment included nine or ten items (depending on the project) about water in surface, groundwater, atmospheric, and living systems. Items were open ended and administered through an online assessment system. The teacher version of the assessment included four content knowledge that were the same as the items on the student assessment, one each for the surface water, groundwater, atmospheric, and living systems. This overlap in items between student assessments and teacher assessments allowed us to calibrate the assessments using item response theory.

The teacher assessments also included ten PCK items. There were three types of PCK items. The KC-LG item prompts described the domain (i.e., water moving through surface, groundwater, atmospheric, and living systems) and asked teachers to write example learning goals for instruction in this domain. KS items provided teachers with a student response to an item on the student version of the assessment, then asked teachers to interpret the student's response. KI items asked teachers to describe their next instructional move for the student. Some versions of the KS and KI items were multiple-choice and explain items in which teachers selected their response from a set of possible options and explained their choice. One of each type of item was completely open-ended with no choice options given. Pre-test items and post-test items were the same for both students and teachers.

Analysis

The first step in our analysis was to code responses to all items. For each teacher, we randomly sampled 30 students who had completed at least 50% of the items for at least 50% of the systems (i.e., surface water, groundwater, atmospheric, and living systems) on both the pre and post assessments. For teachers who had fewer than 30 students who matched these criteria, we coded all of the teachers' students' responses who matched these criteria.

For CK items, we used exemplar workbooks created during development of the Water Systems Learning Progression (Gunckel, Covitt, et al., 2012; Gunckel, Mohan, et al., 2012). Exemplar workbooks include indicators of accounts that align with each level of achievement on the learning progression. Coders used these indicators to assign a level of achievement (1 through 4) to each assessment response. When responses included items with indicators from more than 1 level of achievement, coders assigned an in-between code (e.g., 2.5, indicating that the response suggested the student was transitioning from level 2 to level 3). In order to code the large number of responses, multiple coders were used. Interrater reliability was established by having pairs of coders independently code a set of 30 responses. Coders compared their codes, discussed differences and revised the exemplar workbooks to clarify differences in successive rounds until 85% interrater reliability using Cohen's Kappa was established. Coders then continued to coding with 10% overlap of responses for ongoing interreliability checks. All differences in codes were discussed and resolved. Codes were then averaged across all CK items to provide a mean overall score for each student and each teacher. We grouped the CK means into 4 bins according to levels on the Water Systems Learning Progression (L1: 1.0 to <1.5; L2: 1.5 to <2.5; L3: 2.5 to <3.5; L4: >3.5 to 4.0).

Analysis of PCK items required the development of coding examplar workbooks. We used a process similar to the process we used to develop the initial construct maps for the Water Systems Learning Progression (Gunckel et al., 2012). Three coders worked with batches of about 30 reponses at a time for each item to rank and group responses from least to most sophisticated. We identified common characteristics in each group and used those characteristics to independently code another batch of 30 responses. Based on this process, we developed three categories of responses for teach item. Category A represented knowledge that was either aligned with level 2 force-dynamic reasoning or outside the domain of the learning progression. Category B represented knowledge that was aligned with typical school science narratives about teaching and learning about water. Category C represented knowledge that was aligned with model-based reasoning. Table 2 describes these categories for each PCK item type.

Table 2
Coding categories for each PCK item type

	Category A Knowledge aligned with level 2 force-dynamic reasoning OR outside the domain of the learning progression	Category B Knowledge aligned with level 3 phenomenological reasoning	Category C Knowledge aligned with level 4 model-based reasoning
KC-LG	Disconnected facts about water or facts	Emphasis on naming processes and events and defining vocabulary	Challenging learning goals for model-based reasoning
KS	Teacher's content knowledge interferes with assessing student ideas.	Emphasis on fixing misconceptions	Assesses and interprets student ideas and reasoning
KI	Chooses activities that are fun to do or because they are hands-on.	Emphasis on transmitting facts or explanations about water	Provides appropriate experiences with phenomena based on student responses and engages students in scientific practices.

Once the categories were developed, all three coders independently coded all responses to all PCK items. All three coders discussed differences and came to consensus on all response codes. Codes were then assigned a value (A = 1, B = 2, C = 3). These values were averaged to find a mean overall PCK score. Scores for each item type (i.e., KC-LG, KS, and KI) were also averaged. We grouped the PCK means (KC-LG, KS, KI) into 3 bins according to the categories for coding (Category A: 1 to <1.6; Category B: 1.6 to <2.3; Category C: 2.3 to 3.0).

Finally, we used these mean scores for student and teacher CK and teacher PCK to perform the additional statistical tests necessary to answer our research questions. We used Pearson's r to investigate correlations and t-tests to establish significance. Teacher effect sizes were determined using item response theory based on mean differences in students' pre- and post-assessments.

Results

Differentiating Dimensions of PCK

To begin, we wanted to know if our assessment items were measuring different dimensions of pedagogical content knowledge. We averaged teachers' scores on all items in each dimension and then ran Pearson's Correlations among all three dimensions (Table 3). Small or negligible correlations would indicate that the dimensions are distinct. These results gave us confidence that items designed to measure knowledge of curriculum, knowledge of students, and knowledge of instruction were each measuring different dimensions of PCK.

Table 3
Correlations among dimensions of PCK

Correlation	Pearson's r (df)	Size and direction
KC-LG and KS	0.037 (106)	negligible
KC-LG and. KI	0.231 (106)*	Small positive correlation
KS and KI	0.276 (106)*	Small positive correlation

* $p<.05$

Teachers' Content Knowledge and Pedagogical Content Knowledge

Next, we wanted to know the status of teachers' CK and PCK for teaching about water in environmental systems. Figure 2 shows teachers' CK and PCK both before introduction to the Water Systems Learning Progression (pre) and after using the learning progression-based curriculum materials and formative assessments (post). In this section we describe the pre column only (gray column). We use the pre column as a proxy for the status of teachers' CK and PCK prior to professional development. In the next section we will describe the changes from pre to post (gray column to black column).

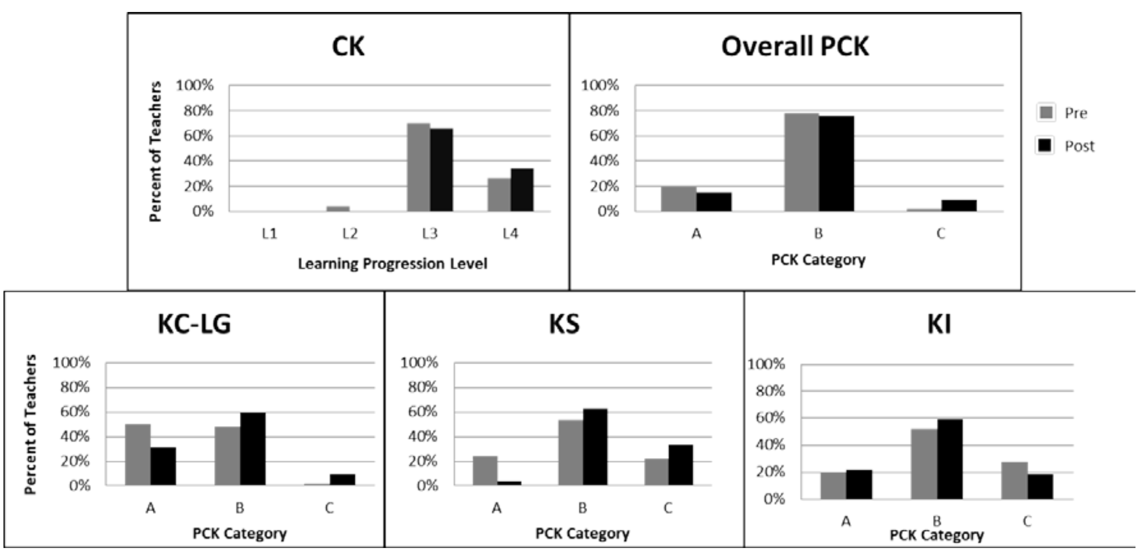

Figure 2
Teachers' Content Knowledge and Pedagogical Content Knowledge

Content knowledge (CK). Content knowledge is measured as teachers' performance on the Water Systems Learning Progression. Before participating in the professional development, the majority of teachers (~70%) provided level 3 phenomenological accounts of water and only about a quarter of teachers provided level 4 model-based accounts (~25%). Phenomenological accounts are representative of typical school science narratives about the processes that move water through the water cycle. School science narratives can trace water along complex pathways, but because they do not include driving forces or constraining variables, phenomenological accounts of water may also include pathways that are not probable or possible given the constraints of specific systems. The content knowledge necessary to provide phenomenological accounts of water falls short of the content knowledge necessary to support students in developing model-based accounts of water in environmental systems.

Pedagogical content knowledge (PCK). Teachers' overall PCK is their mean score across all PCK assessment items. These means were binned into the three PCK categories, as described above. Teachers' overall PCK fell mostly into category B (~77%). Category B reflects knowledge necessary for teaching school science narratives about water. Relatively few teachers' overall PCK was binned into category A (~20%), knowledge for teaching at level 1 or 2, and fewer teachers in category C (~2%), knowledge necessary for teaching model-based reasoning. Below we break out the dimensions of PCK and look at the distribution of teachers mean scores for items in each dimension.

Knowledge of curriculum learning goals (KC-LG). Teachers' efforts to generate relevant learning goals were distributed approximately equally across categories A and B (~ 49% in each). Category A learning goals were too general to be relevant to the specific focus of the Water Systems Learning Progression and/or they demonstrated level 2 force-dynamic reasoning. For example, a learning goal that students should learn about the water cycle is broadly general and does not clearly identify what students should learn about water and substances moving through environmental systems. In addition, the learning goal suggests that the water cycle is an object, not a model of water movements. Referring to the water cycle as an object or a mechanism for moving water aligns with level 2 force-dynamic accounts on the Water Systems Learning Progression.

Category B learning goals aligned with level 3 phenomenological accounts. An example category B learning goal was, "Students will be able to describe the phases that water can go through and explain the process of changing from one phase to another." This learning goal aligns with level 3 accounts that trace water through multiple connected steps and processes. Few teachers provided category C learning goals that would suggest their goal was supporting students in providing level 4 model-based accounts. An example of one learning goal that did fall into category C was, "Water infiltraits [sic] into the ground at different rates due to the permiability of the different surface types." This learning goal focuses on the role of permeability as a constraining factor in the movement of water. Overall, teachers' learning goals tended to align with level 2 force-dynamic accounts and level 3 phenomenological accounts and did not set as a goal students providing level 4 model-based accounts. It could be that teachers were more familiar with thinking about learning goals in terms of topics that their curricula should cover or facts students should repeat rather than in terms of supporting students in reasoning about how and why water moves through the environment.

Knowledge of students (KS). KS items assessed how teachers interpreted student responses to water assessment items. Twenty five percent of teachers provided category A interpretations of students. These responses suggested that the teacher's content understanding of the item was interfering with their interpretation of the students' response. In many cases, it was difficult for us to interpret from category A responses whether the teacher was describing student reasoning or the teachers' own reasoning. The majority of teachers' responses both pre- and post-instruction fell into category B (~53%). These responses focused on identifying what students did and did not know or whether the student response was correct, rather than interpreting how students were reasoning. For example, the River Maps KS item asked teachers to interpret a student's response to an assessment item about the direction of river flow based on a map. On the map, the river flowed from south to north and then east. The example student account given in the PCK item was a level 2 account that traced water flow from south to north and then west along a tributary rather than down the main stem of the river (east). The student did not provide a reason. A typical category B interpretation of this student's account was, "This student does not seem to understand how rivers flow." This teacher response suggests that the teacher interpreted that if the student did not provide a correct answer to the item prompt that the student did not have the knowledge necessary to answer the question correctly. In contrast, fewer teachers' responses fell into category C (~22%). A teacher who provided a category C interpretation stated, "He [the student] believes that water flows toward the lake and may not recognize that D and F are tributaries of E" (D, F, and E were points marked on the map in the assessment item). This teacher response shows familiarity with the characteristics of student accounts at level 2 and makes an interpretation of the students' reasoning behind the account. These results suggest that most teachers were used to interpreting student accounts in terms of whether students provided correct answers rather than considering possible student reasoning for the accounts student gave.

Knowledge of instruction (KI). KI assessed teachers' instructional thinking. Teachers were asked to choose and explain their reasoning for a next instructional move for a student based on the student's response to an assessment item. Here, ~20% of teachers gave category A responses. These responses focused on choosing next instructional moves that the teachers thought would be fun to do or were hands-on activities without giving any other pedagogical reasoning for choosing the activity.

The majority of teachers gave responses that fell into category B (~52%). These responses often focused on explaining concepts to students rather than attending to the students' particular learning needs. For example, a common category B choice based on the River Maps KS item described above was that the teacher should explain that water moves from smaller bodies of water to larger bodies of water because, "I think that the student is confused about the direction of water flow." This response is problematic for four reasons. First, by focusing on explaining ideas to students, the response emphasized that teaching is telling and does not involve students in investigating phenomena in ways that would support students in reasoning about direction of water flow. Second, the chosen response is a typical school science heuristic that does not explain how or why water moves in a particular direction based on elevation and topography. Third, the chosen response did not attend to the challenge that the student was experiencing, which was connecting two-dimensional map representations of watersheds with a three-dimensional vision for what that watershed might look like. Finally, the teacher's response again indicated that the teacher was only thinking that the student response as wrong rather than conjecturing about how the student might be reasoning.

About 28% of teachers provided category C responses that chose appropriate next instructional moves and provided explanations for that choice that suggested the teachers were basing their choice on an interpretation of students' reasoning rather than whether the student was right or wrong. For example, category C responses usally chose the instructional response that described having students pour water on a stream table or tarp model of a watershed and trace water flow. One teacher explained, "This would help them visualize what is going on on the map and give them a way to figure out where the high point on the map actually is." This explanation of the teachers' pedagogical reasoning shows that the teacher was thinking about why the student was having difficulty reading a map and that rather than tell the student how water would flow, the teacher would engage the students with a phenomenon that would then support them in moving from three-dimensional models of watersheds to two-dimensional representations. This response also identifies reading elevation on a map as an important characteristic of model-based reasoning as a goal for instruction. Overall, these results suggest that teachers might rely heavily on traditional school science narratives of learning and teaching that emphasize teaching as telling and are not responsive to students' thinking.

Taken together, these findings suggest that these middle and high school teachers' content knowledge and pedagogical content knowledge reflected knowledge for teaching level 3 phenomenological reasoning and not for level 4 model-based reasoning. Based on these results, we argue that teachers' content knowledge and pedagogical content knowledge may constrain how they use learning progressions and learning progression-based curriculum materials, formative assessments, and other instructional tools. Although these materials are designed to support students reaching the highest levels of the learning progression, teachers' knowledge for using these resources may constrain their teaching to teaching for level 3 phenomenological accounts rather than level 4 model-based accounts.

Change in Content Knowledge and Pedagogical Content Knowledge

In this section we describe changes in content knowledge and pedagogical content knowledge from before the teachers were introduced to the learning progressions (pre results) to after they had used the learning progression-based curriculum materials and formative assessment in their own instruction (post results) (Figure 2). As shown in Figure 2, most of the pre-post shifts for all categories were small.

For content knowledge, a few more teachers provided level 4 model-based accounts on the post assessment than the pre-assessment. A paired one-tailed t-test on the change in mean scores shows that this change was not significant ($t(52) = -2.80$, $p<0.05$) meaning the shift from level 3 to level 4 is not different from chance. We had hoped that participating in the professional development and teaching using the learning progression-based curriculum materials would have supported more teachers in developing their own model-based accounts of water.

Changes for PCK were also small. None of the shifts in categories for Overall PCK were significant. However, the patterns for the individual components were interesting. Two dimensions, KC-LG and KS show a similar pattern of change. For KC-LG, fewer teachers provided category A learning goals on the post assessment and a few more teachers provided category C learning goals than on the pre-assessment. The shift in category A pre to post was significant ($t(106) = 1.959$, $p<0.5$) but the shifts in category B and category C were not. This result suggests that teachers were moving away from establishing learning goals for disconnected facts about water and towards at least aligning their learning goals more with putting events in order and naming processes that move water, but not yet significantly towards developing challenging learning goals that aim for model-based accounts of water moving through systems. The same pattern is evident for KS, with almost no teachers providing category A interpretations on the post assessment and a few more teachers providing category C interpretations. The shift was significant only for category A ($t(106) = 3.061$, $p<.05$). It appears that some teachers, at least, were moving towards interpreting student ideas more in line with the Water Systems Learning Progression, although few teachers used the learning progression to assess and build on student ideas in ways that have the potential to support model-based reasoning. For both KC-LG and KS, the pattern suggests that teachers were moving across the categories in order, from categories A to B and B to C, with teachers initially in Category A making the most progress to category B. Overall, the KC-LG and KS shifts suggest that participating in the professional development on the Water Systems Learning Progression and using the learning progression-based curriculum materials and formative assessments supported some teachers in focusing their learning goals and attending to student thinking, but did not yet support most teachers in developing the knowledge of curriculum and students necessary to teach for model-based reasoning.

The pattern for knowledge of instruction (KI) was different. It appears that more teachers provided category A and B responses and fewer provided category C responses on the post assessment. These shifts, however, were not significant. This situation suggests that the learning progression, which describes characteristics of student accounts, and the associated curriculum materials and formative assessments, supported some teachers in interpreting student ideas, but not in figuring out what to do next in response to student performance. Although the curriculum materials provided suggestions for next instructional moves, it seems that the KI dimension of PCK was more difficult for teachers to develop from using the curriculum materials or that the curriculum materials and formative assessments did not provide adequate guidance and scaffolding for developing this aspect of teachers' PCK.

To further investigate the shifts in teachers PCK, we constructed Wright maps using Item Response Theory (Figure 3). This figure shows item difficulties for each item on the PCK assessments on the right and histograms of the distribution of teacher proficiencies for the pre assessment and post assessment on the left. Graphically, the map shows the relative difficulties of the steps between categories. Although there is some variability in the difficulty of the step between category A and category B for all items, for no item is the step between category A and B more difficult than the step between category B and C. This observation provides evidence that these categories are distinct and represent progressively more sophisticated PCK. The pre and post proficiency maps confirm that there is a small shift from pre-assessment to post-assessment in teachers' PCK from category A to category B, with some teachers providing category C responses for some items. Furthermore, teachers move from category A to B to C in order. Category B, described as traditional school science PCK, seems to be an important stepping stone in how teachers' pedagogical content knowledge becomes more sophisticated.

What this Wright Map adds is that the most difficult items were related to tracing water through trees via transpiration (Items LG-TR, KS-TR, KI-TR). It was more difficult for teachers to write category B learning goals for this domain, more difficult for them to provide category C interpretations of student ideas, and more difficult for teachers to determine next instructional moves in this domain than in the domains of the other items (i.e., surface water, groundwater, and atmospheric systems). The teachers were probably more familiar with teaching about water moving through surface, atmospheric, and groundwater systems than water moving through living components of water systems because school science curricula tend to emphasize evaporation, precipitation, runoff, and infiltration over the process of transpiration. Likely, teachers had less experience writing learning goals, interpreting student thinking, and planning next instructional moves in this area. This result also means that teachers' difficulty in the domain of water moving through living systems may have constrained their overall PCK scores.

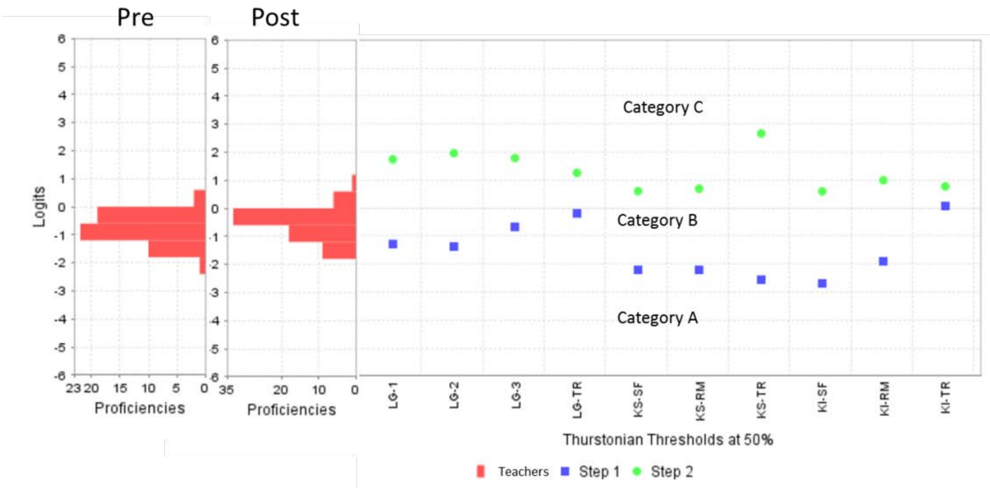

Figure 3
Wright Map of PCK Assessment Items for Pre and Post Assessment

Taken together, teachers' shifts in CK and PCK suggest that participating in the learning progression-based professional development and using the learning progression-based teaching materials had little overall influence on teachers' CK and PCK. Most teachers' CK and PCK were aligned with the knowledge necessary to teach phenomenological school science narratives about water and not model-based reasoning and did not change after one year of professional development and using the curriculum materials.

Relationships among CK, PCK and Effect Size

While we have described teachers' content and pedagogical content knowledge related to teaching about water in environmental systems, we wanted to know whether PCK made a difference in teachers' effect on student learning. Table 4 shows the results of Pearson's Correlations between teachers' effect size on student performance on the Water Systems Learning Progression and content knowledge and overall PCK as well as the individual KC-LG, KS, and KI dimensions of PCK.

Table 4
CK and PCK correlations to effect size

Correlation	Pearson's r (df)
CK and effect size	0.254 (35)
Overall PCK and effect size	0.406 (35)*
KC-LG and effect size	0.399 (35)*
KS and effect size	0.310 (35)
KI and effect size	0.288 (35)

* p<.05

Overall PCK showed a statistically significant correlation to teacher effect size on student learning at the $p < .05$ level, although the size and significance of this correlation is modest. Content knowledge did not seem to have a significant correlation with effect size. One explanation for these results could be that most of teachers had level 3 content knowledge and PCK that fell into category B, knowledge necessary for teaching phenomenological reasoning. Most of the students in these teachers' classes were moving from level 2 force-dynamic reasoning to level 3 phenomenological reasoning. Therefore, teachers with level 3 CK and category B PCK were just as well-prepared to support students in making this shift as teachers who had level 4 CK and category C PCK. In addition, because we had so few teachers with level 4 CK and category C PCK and few students moving to level 4, it would be difficult to find a correlation at the upper end.

In breaking down the PCK correlation results, it appears that for these teachers, only teachers' KC-LG seemed have a significant correlation to effect size. Teachers' whose learning goals were most aligned with the domain of the Water Systems Learning Progression seemed to have the greatest effect on supporting student learning as measured on this learning progression. KS and KI seemed to contribute little to the correlation between PCK and effect size. We conjecture that this may be because although teachers were developing more sophisticated interpretations of student ideas, they were not yet able to use those interpretations to make instructional decisions that aligned with student needs and supported students in developing more model-based accounts of water in environmental systems. It is possible that after continued professional development related to the Water Systems Learning Progression and experience using learning progression-based curriculum materials, teachers' KS and KI would develop further, leading to a significant correlations to effect size.

Discussion

Pedagogical content knowledge, as a construct, has had a troubled past. Although it is referred to commonly as the specialized knowledge necessary for teaching, researchers have had difficulty measuring it and showing its effect on teaching (e.g., Friedrichsen, Van Driel, & Abell, 2010; Settlage, 2013). Our results provide insights into both the possibilities and limitations of PCK as a useful construct for teaching and for realizing the potential of learning progressions for classroom instruction.

To begin, our results help us think about why students reach level 3 phenomenological reasoning on the Water Systems Learning Progression but few reach level 4 model-based reasoning. That category B had the highest percentage of teachers in both pre- and post-assessment results and our interpretation that teachers moved from category A to B but fewer teachers moved from category B to C shows that phenomenological reasoning of school science Discourse has a strong normalizing influence on learning and teaching. Teachers develop their pedagogical content knowledge in the context of the curricula that they use (Van Driel et al., 1998). The typical school science curriculum emphasizes school science stories about the processes that move water through the water cycle and common narratives about teaching as explaining what students do not know still prevails (Capps & Crawford, 2013). Therefore, teachers' CK and PCK reflect knowledge necessary for level 3 phenomenological reasoning and teaching level 3 school science stories. This result does not mean that middle and high school teachers are not capable of teaching level 4 model-based accounts, but that in the context of the curricula and expectations for teaching that are common in schools, teachers' learning goals, interpretations of students, and instructional choices align with knowledge for teaching level 3 phenomenological school science stories. We argue that the Discourse of traditional school science narratives about what students should learn about water in environmental systems, how students think about water, and how teachers should teach about water constrain the development of teachers' CK and PCK, limits teachers' instructional potential, and caps students' understanding of water in environmental systems at level 3 on the Water Systems Learning Progression.

Nevertheless, we are not ready to give up on the hope that teachers can develop the CK and PCK necessary to teach for model-based reasoning. Our results give some hints that as teachers learn about the Water Systems Learning Progression, their learning goals can become more aligned with the domain defined by the learning progression, they have new resources for interpreting student ideas, and they gain more tools for deciding their next instructional moves. At the same time, we acknowledge that change is not quick. The changes we saw in teachers' pedagogical content knowledge were small at best. Furthermore, the biggest changes were from category A to category B. This shift amounts to learning the PCK of the Discourse of teaching school science narratives. Shifting from category B to C will involve developing the PCK of another Discourse of teaching for model-based reasoning. Evidence from one of our projects suggests that teachers who use learning progression-based curriculum resources for a second year have a greater effect size than they did the first year (Covitt, Gunckel, & Salinas, 2015). Therefore, we conclude that developing the PCK of category C may require multiple years of consistent support to learn a new Discourse of model-based teaching.

In addition, not all dimensions of PCK changed equally. It seems that learning progressions and learning progression-based curriculum resources may have the most potential for supporting teachers in focusing learning goals (KC-LG) and understanding student ideas (KS), but that supporting teachers in changing instruction (KI) may take more time or different approaches. Furthermore, deepening and bringing coherence to PCK is not the only important aspect of changing instruction to support students in reaching level 4 model-based reasoning about water. The relatively modest correlations between PCK and effect size show that PCK is just a small part of what is necessary for effective instruction. Changes in teaching practice depend on more than just changes in knowledge for teaching. Teaching for model-based reasoning represents a significant shift from the normalized Discourse of school science teaching. The extent to which learning progression-based curriculum materials include instructional approaches and rely on teaching practices that differ from teachers' existing practice and diverge from teachers existing goals and values affects how likely teachers are to use new or innovative approaches and practices (Janssen, Westbroek, Doyle, & Van Driel, 2013). Therefore, while supporting teachers in developing more coherent pedagogical content knowledge relative to the domain of water in environmental systems is important, it is not the only aspect important for supporting teachers using in learning progressions and learning progression-based resources for teaching model-based reasoning.

References

Achieve, Inc. on behalf of the twenty-six states and partners that collaborated on the NGSS. (2013). Next Generation Science Standards. from www.nextgenscience.org

Alonzo, A. C., & Gotwals, A. W. (Eds.). (2012). *Learning Progressions in Science: Current Challenges and Future Directions*. Rotterdam, Netherlands: Sense Publishers.

Braaten, M., & Windschitl, M. (2011). Working toward a stronger conceptualization of scientific explanation for science education. *Science Education, 95*, 639-669.

Capps, D. K., & Crawford, B. A. (2013). Inquiry-based instruction and teaching about nature of science: Are they happening? *Journal of Science Teacher Education, 24*, 497-526.

Cohen, R., & Yarden, A. (2009). Experienced junior-high-school teachers' PCK in light of a curriculum change: "The cell is to be ctudied longitudinally". *Research in Science Education, 39*, 131-155.

Corcoran, T. B., Mosher, F. A., & Rogat, A. (2009). Learning progressions in science: An evidence-based approach to reform. New York: Center on Continuous Instructional Improvement, Teachers College, Columbia University.

Covitt, B. A., Gunckel, K. L., & Salinas, I. (2015, April). *Learning about water flow as a result of learning progression-based instruction*. Paper presented at the annual international conference of NARST, Chicago, IL.

Covitt, B. A., Syswerda, S. P., Caplan, B., & Cano, A. A. (2014, April). *Teachers' use of learning progression-based formative assessment in water instruction*. Paper presented at the annual international conference of NARST, Pittsburgh, PA.

Duncan, R. G., & Hmelo-Silver, C. E. (2009). Learning progressions: Aligning curriculum, instruction, and assessment. *Journal of Research in Science Teaching, 46,* 606-609.

Duschl, R., Maeng, S., & Sezen, A. (2011). Learning progressions and teaching sequences: A review and analysis. *Studies in Science Education, 47,* 123-182. doi: 10.1080/03057267.2011.604476

Friedrichsen, P., Van Driel, J. H., & Abell, S. K. (2010). Taking a closer look at science teaching orientations. *Science Education, 95,* 358-376.

Furtak, E. M. (2012). Linking a learning progression for natural selection to teachers' enactment of formative assessment. *Journal of Research in Science Teaching, 49,* 1181-1210.

Gee, J. P. (1991). What is literacy? In C. Mitchell & K. Weiler (Eds.), *Rewriting Literacy: Culture and the Discourse of the Other* (pp. 3-11). Westport, CT: Bergin & Garvey.

Grossman, P. L. (1990). *The making of a teacher: Teacher knowledge and teacher education*: Teachers College Press New York.

Gunckel, K. L., Covitt, B., & Salinas, I. (2014, April). *Teachers' uses of learning progression-based tools for reasoning in teaching about water in environmental systems*. Paper presented at the annual international conference of NARST, Pittsburgh, PA.

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

Gunckel, K. L., Mohan, L., Covitt, B. A., & Anderson, C. W. (2012). Addressing challenges in developing learning progressions for environmental science literacy. In A. Alonzo & A. W. Gotwals (Eds.), *Learning progressions in science* (pp. 39-76). Rotterdam, The Netherlands: Sense Publishers.

Janssen, F., Westbroek, H., Doyle, W., & Van Driel, J. H. (2013). How to make innovations practical. *Teachers College Record, 115*(7), 1-43.

Magnusson, S. J., Krajcik, J., & Borko, H. (1999). Nature, sources, and development of pedagogical content knowledge for science teaching. In J. Gess-Newsome & N. G. Lederman (Eds.), *Examining Pedagogical Content Knowledge*. Netherlands: Kluwer Academic Publishers.

National Research Council. (2007). Taking science to school: Learning and teaching science in grades K-8. In Committee on Science Learning Kindergarten through Eighth Grade, R. A. Duschl, H. A. Schweingruber & A. W. Shouse (Eds.). Washington, D.C.: National Academies Press.

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

Park, S., & Chen, Y.-C. (2012). Mapping out the integration of the components of pedagogical content knowledge (PCK): Examples from high school biology classrooms. *Journal of Research in Science Teaching, 49,* 922-941.

Park, S., & Oliver, J. (2008). Revisiting the conceptualisation of pedagogical content knowledge (PCK): PCK as a conceptual tool to understand teachers asprofessionals. *Research in Science Education*, *38*, 261-284.
Pinker, S. (2007). *The stuff of thought: Language as a window into human nature.* . New York: Penguin Group.
Settlage, J. (2013). On acknowledging PCK's shortcomings. *Journal of Science Teacher Education*, *24*, 1-12.
Shulman, L. S. (1986). Those who understand: Knowledge growth in teaching. *Educational Researcher, 15*(2), 4-14.
Sztajn, P., Confrey, J., Wilson, P. H., & Edgington, C. (2012). Learning trajectory based instruction: toward a theory of teaching. *Educational Researcher, 41*(5), 147-156.
Talmy, L. (1988). Force dynamics in language and cognition. *Cognitive Science, 12,* 49-100.
Van Driel, J. H., Beijaard, D., & Verloop, N. (2001). Professional development and reform in science education: The role of teachers' practical knowledge. *Journal of Research in Science Teaching, 38*, 137-158.
Van Driel, J. H., & Berry, A. (2010). The teacher education knowledge base: Pedagogical content knowledge. In P. L. Peterson, E. Baker & B. McGraw (Eds.), *Third international encyclopedia of education* (Vol. 7). Amsterdam, The Netherlands: Elsevier.
Van Driel, J. H., Verloop, N., & de Vos, W. (1998). Developing science teachers' pedagogical content knowledge. *Journal of Research in Science Teaching, 35*, 673-695.