Students' Developing Understanding of Water in Environmental Systems

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Running head: UNDERSTANDING WATER IN ENVIRONMENTAL SYSTEMS

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Abstract

A framework for water science literacy is offered that includes understanding the structure of connected human and natural water systems, and processes that move water and other substances through these systems. Results of a study examining 120 grades 3 through 12 students' understanding of water in environmental systems are presented. Over grade levels, students gain understanding of the structure of systems, but parts of systems (e.g., how water exists underground) remain invisible. Students demonstrate increasing understanding of the need for processes to move water and other substances. However, how these processes work remains poorly understood. Through our work, we are developing a curricular framework for helping K-12 students develop more robust and connected environmental water literacy.

Key Words

environmental science literacy, water education, connected human and natural systems,
K-12 science curriculum

Students' Developing Understanding of Water in Environmental Systems

The need to protect water quality and distribution provides an impetus for developing science education that will prepare people to be competent decision makers about water systems. Having an understanding of water in environmental systems is a necessary, though not sufficient, component of environmental water literacy. Without understanding how water moves through environmental systems and interacts with other substances, it is not possible to make informed decisions about water at an individual or societal level. For example, an individual who does not know which substances will dissolve in and move with water underground will be unprepared to participate in a community decision about how to manage an aging municipal landfill.

Developing connected understanding of water in environmental systems should be an education goal for high school students. A college degree should not be required to develop the knowledge and practices needed for citizenship. Currently, high school science curricula are often designed to prepare students for college science courses, rather than to prepare students to make personal decisions and participate in societal decisions (Aikenhead, 2006). In this educational environment, students often do not develop the practical science understanding they need to be environmentally literate citizens.

In this paper, we describe our framework of knowledge and practices related to water needed for environmental citizenship. We also present findings concerning how students of various ages think and reason about water in connected human and natural systems. The examples and patterns in students' thinking that we describe highlight how the understandings that students develop are often insufficient for effective decision making. These findings have implications for reforming the K-12 science curriculum to better support developing students' understanding of water in connected human and natural environmental systems.

Environmental Science Literacy for Water

We define environmental science literacy as the capacity to understand and participate in evidence-based decision making about the effects of human actions in environmental systems (Authors, 2006). This definition aligns with Coyle's description of third level learning, or "true" environmental literacy (Coyle, 2005). The need for an environmentally literate citizenry is evident given the scientific consensus that human populations are fundamentally altering the natural systems that sustain life on Earth (e.g. Keeling & Whorf, 2005; Wilson, 2001). Today, all citizens need to be able to understand environmental issues and make informed decisions that will help maintain and protect Earth's life supporting systems. Science can serve as one critical tool in making informed environmental decisions. Citizens who use science as a tool should be able to:

1. engage in *scientific inquiry* to develop and evaluate scientific arguments from evidence
2. use *scientific explanations* of the material world as tools to predict and explain
3. use scientific reasoning in *citizenship practices* of environmental decision making

In this study, we focus on the scientific explanations component of environmental science literacy. Because environmental science is vast and constantly changing, it would not be possible for a citizen to learn all scientific explanations they might need as they encounter various issues. However, individuals who have a fundamental understanding of water science should be able to draw on this understanding to reason about new data and scientific arguments they encounter.

Our water literacy framework is adapted from the Loop Diagram developed by the Long Term Ecological Research Network (Long Term Ecological Research Network Research Initiatives Subcommittee, 2007) (Figure 1). This diagram illustrates the connected understandings necessary to reason about water in natural and human engineered water systems.

The framework includes two connected boxes – natural systems and human engineered systems. The arrows connecting boxes represent the environmental services that natural systems provide for humans and the impacts that humans have on natural systems. Within both natural and human engineered systems, environmentally literate citizens should understand the structure of systems through which water flows and be able to trace matter (water and other substances) through systems. Tracing matter requires understanding of processes that move water and substances and processes that change the composition (quality) of water.

Figure 1 about here

Review of Research on Children's Understandings of Water

Previous research provided a starting point for our efforts to investigate children's understanding of water in environmental systems.

Structure of Water Systems

Several researchers have examined children's ideas about watersheds and rivers. Dove, Everett & Preece (1999) found common features in children's drawing of rivers, including that children frequently conceive of rivers in rural rather than urban environments, that they draw where rivers end but not where they begin, and that their rivers usually flow south. Recently, Shepardson, Wee, Piddy, Shellenberger, & Harbor (2007) studied children's ideas about watersheds and identified four common conceptions: watershed as a human-built facility (e.g., a "shed"), watershed as a natural feature for storage of water (e.g., a lake), watershed as a natural system including some hydrologic processes such as precipitation and evaporation, and watershed depicted as a river or system of rivers including a more developed view of the hydrologic cycle (precipitation, evaporation, runoff, infiltration). Shepardson et al. found more upper elementary and middle school students than high school students held the most developed conception of watershed, possibly because the water cycle is a common topic in elementary and middle schools.

Several researchers have also explored children's ideas about groundwater. Meyer (1987) identified common conceptions that are linked to vernacular ways of talking about underground water (e.g. underground rivers). More recently, Dickerson and colleagues (Beilfuss *et al.*, 2004; Dickerson *et al.*, 2007a; Dickerson *et al.*, 2005; Dickerson & Dawkins, 2004) have documented alternative groundwater conceptions including groundwater as underground lakes, sewers, or layers; inaccuracies in the size of pore spaces or the scale of aquifers; and groundwater as a dead-end not connected to other hydrologic processes.

Water Moving through Systems

Research concerning students' understanding of the water cycle highlights the difference between being able to draw a diagram of the water cycle (a task many second and third graders are able to do) and having deep understanding of the processes that operate within the water cycle. A large amount of research has been conducted in this area. Some common naïve conceptions are listed in Table 1.

Table 1 about here

Several researchers have examined how students' ideas of evaporation and condensation change over time. Holgersson and Löfgren (2004), Löfgren and Helldén (2007), and Tytler (2000) show that as students get older, they are able to draw on their broader experiences with evaporation and condensation and greater domain-specific knowledge to develop more complex explanations. Furthermore, older children use more sophisticated epistemological criteria for deciding what counts as an acceptable explanation; they are more aware of a "need to understand what really happens in the processes," (Löfgren and Helldén, 2007, p. 20) rather than just describing the processes.

Other Substances That Move with Water through Systems

Finally, several researchers have examined children's understanding of pollution and sources of pollution. Brody (1991) found that around 4th-grade, children think of pollution as stuff people throw on the ground. By 8th-grade, their definitions includes chemicals. By 11th-grade, children begin to understand that pollution can have more than one source; its effects are proportional to concentration; and that water, air, land, and living systems are interconnected. In 2000, Suvedi, Krueger, & Shrestha looked closely at Michigan residents' knowledge about the relationship between land use practices and groundwater quality. While most residents understood that land-use practices impact groundwater quality, most perceived that their own home practices did not adversely affect groundwater quality.

Research Questions

In this study, we focus on two aspects of water literacy, structure of systems and tracing matter through systems. Our research questions are:

1. What do students at different grade levels know and how do they reason about the *structure of environmental systems* through which water flows?
2. How do students at different levels *trace matter* through coupled human engineered and natural environmental systems?

Method for the Study

Instruments

Data come from assessment questions asked of students in 3rd through 12th grades in the 2005-2006 school year. Two assessment tests were developed, one for elementary and one for middle and high school students. There was overlap between tests because we were interested in exploring how students of different ages reason about similar concepts.

The assessments explored how students make sense of water concepts and use their understanding in the context of coupled natural and human systems. The questions addressed surface water, groundwater, atmospheric water, and water in human engineered systems. In developing the questions, we drew on previous research about understanding of water (e.g., Bar, 1989; Bar & Travis, 1991; Dickerson & Dawkins, 2004; Dove, 1997; Meyer, 1987; Osbourne & Cosgrove, 1983; Shepardson *et al.*, 2002), and added items about coupled natural and human systems. Most questions asked for a short written answer. In addition, several questions asked students to draw a picture, or to choose among options and provide an explanation for their choice.

Participants and Procedure

We administered assessments to elementary, middle, and high school students from eleven classes in multiple regions of a Midwestern state. Tests were administered one time and were not connected to a particular unit of study about water. A total of 608 assessments were collected. From the collected assessments we chose a sample representing equal numbers of elementary, middle and high school students from the various settings. The distribution of analyzed tests is shown in Table 2.

Table 2 about here

Analysis

We chose six questions to report. These questions address structure of systems and tracing matter in four of five systems identified in the water literacy framework. Table 3 shows the distribution of questions across systems.

Analysis of student responses consisted of an iterative process of rubric development. To develop a question rubric, a research team member grouped similar answers and described characteristics of answers in each group. The researcher then gave the rubric to another research team member to use to code a set of student responses. The researchers then met to compare their coding and to make revisions to the rubric. The revised rubrics were used to code the sample of 120 student assessments. Interrater agreement for all questions was ≥.75.

Table 3 about here

Results

The analyses helped to enrich our picture of students' understandings about water.

Drinking Ocean Water Questions

Students were asked why humans cannot drink ocean water. This question requires students to put together understandings about solutions, surface water, atmospheric water, evaporation, and condensation. Figure 2 shows that most students at each grade level recognized the ocean is salt water, which humans cannot drink. Fewer students, however, were able to trace water out of the ocean through the process of evaporation. Middle and high school students were asked how they could make ocean water drinkable. Only about 20% of students described the full distillation process (boiling the salt water, condensing the evaporate) (Figure 3). About 20% of students mentioned boiling but not condensing. While some students may have forgotten to mention condensation, other students likely believed that boiling would treat ocean water the same way boiling can make biologically contaminated water safe to drink. Similarly, about 20% of middle school students stated that water could simply be cleaned or purified.

Figure 2 about here

Figure 3 about here

Watershed Question

Students were provided with a map of rivers, one of which flows into a lake (Figure 4). They were asked, “If a water pollutant is put into the river at Town C, which towns would be affected and why?” This question required students to apply understanding of the structure of watersheds to reason about the movement of water and other substances. Many students indicated that a pollutant put into a river at Town C would contaminate water in Town B (Figure 5). When asked why certain towns would be affected, about 60% of students who thought Town B would be affected explained that all the towns were connected by the rivers. Students did not recognize that Town B was higher in elevation than the main river and that the water carrying the pollutant could not flow upstream to Town B.

Figure 4 about here

Figure 5 about here

Groundwater Question

This question stated, “Wells get water from under the ground. Draw a picture or explain what it looks like underground where there is water.” Elementary students had various conceptions of groundwater, including water in underground tanks, pipes, streams, and lakes (Figure 6). By high school, some students drew groundwater in spaces and cracks in rocks and sediment, but most still indicated that groundwater occurs in open layers underground (e.g., Figure 7).

Figure 6 about here

Figure 7 about here

While the question did not specifically ask students to draw a well, many students did, providing some evidence of their understanding of human engineered water systems. A common conception was an iconic image of a hole in the ground surrounded by a stone wall with a bucket and a rope for retrieving water (e.g., Figure 7). By high school, more students recognized a well as a vertical pipe that intersects the water table.

Landfill Question

In a tracing matter question, we asked students if a landfill (garbage dump) could contaminate water in a well and to explain their answer. 85% of students thought that a landfill could contaminate a well. Among elementary students the most common explanation was above-ground mechanism, indicating that garbage blows out of the landfill and falls down a well (Figure 8). By high school, most students explained that contamination occurs underground with liquids. Few, however, articulated the role water plays in transporting contaminants. Instead, students often indicated that contaminants seep or leak through the ground, without acknowledging that the contaminants are dissolved in water and that groundwater movement is necessary for contaminants to move.

Figure 8 about here

Human Systems Question

Students were asked, “Where does water come from before it gets to your home? And where does it go to after it leaves your home?” Answers illustrate some common ideas about the structure and processes of the human engineered water system. 80% of all students recognized that their household water comes from a natural source. But only 20% of elementary and 40% of high school students recognized that domestic water supplies are usually treated before arriving at their house. Similarly, only 12% of elementary and 25% of middle school students indicated that wastewater is treated after it leaves their house (either in a municipal wastewater treatment plant or in a septic tank). By high school, 55% of students indicated that wastewater is treated, but interestingly, 40% of them also stated that treated wastewater is recycled back to other people's houses rather than being discharged into the natural environment.

Synthesis of Results

These results show that students' understandings of water in natural and human engineered environmental systems are currently incomplete and unconnected. Students at all grade levels recognize a limited portion of natural and engineered systems. Many parts of systems remain invisible to students. Invisible parts may be either microscopic or very large in scale. For example, few students recognized the atomic-molecular nature of water and other substances when explaining how to make ocean water drinkable or the landscape scale of watersheds when explaining where a pollutant would move in a river system. Students also do not recognize invisible parts of systems hidden from everyday view, such as water in aquifers or water in pipes under streets. Drinking water or wastewater treatment plants may be invisible to students because they usually do not have much contact with these facilities. Recognizing invisible parts of systems sometimes requires students to reason using tools, such as using a map to understand landscapes, or cross-sections to visualize aquifers underground, which few students were able to do.

As students progress through grade levels, they demonstrate increasing understanding of the need for processes to move water and other matter. However, how these processes work remains poorly understood. For example, compared with younger students, more high school students recognize that landfills can contaminate a well through the movement of liquids through the system. However, few high school students recognize that water plays an important role by transporting these contaminants. The engineered system question shows a similar pattern, with more high school students recognizing that drinking water and waste water must be treated, but few high school students understanding where the water is treated. For many students, the drinking water and waste water treatment plants were the same. Some questions, such as the watershed question and the ocean water question, show no increasing understanding across grade levels of processes that move water and other materials through systems.

Students' incomplete and unconnected understanding of water in coupled human and natural systems has consequences for their reasoning about their personal actions and societal decisions. For example, we have found in conversations with children that when asked to identify what they could do to protect water quality, they most commonly respond, "don't litter." This answer demonstrates little meaningful understanding of the causes of water pollution or the impacts of human actions. While unaesthetic, macroscopic trash contributes little to water quality problems (U.S. Environmental Protection Agency, 2002). However, the "don't litter" response makes sense given the level of water systems understanding that many students demonstrate. If, for example, a student thinks that groundwater can become polluted from trash falling down a well hole, then picking up trash would be a reasonable action to take to protect water quality. Students' incomplete and unconnected understanding of water limits their potential to be effective environmentally literate citizens.

Discussion and Implications

The state of students' incomplete and unconnected understandings about water reveals a major shortcoming of the current K-12 curriculum. The current school science curriculum is not helping students develop the connected understanding necessary to trace water and other materials through coupled human and natural systems Currently in the K-12 curriculum and in science standards documents (NRC, 1996), students study water systems and processes in separate science disciplines: phase changes are studied in physical science, the "water cycle" is studied in Earth science, and aqueous solutions are studied in chemistry. Furthermore, some systems and processes are not well represented in the curriculum. Dickerson (Dickerson & Callahan, 2006; Dickerson *et al.*, 2007b) has discussed the lack of attention in the standards to groundwater concepts. Human engineered systems may not ever be examined in school. Finally, what is studied in one grade may never be connected to what is studied in later grades. The recent focus on learning progressions in science education argues that a curriculum that supports students in developing successively more sophisticated ways of thinking about a topic over a broad span of time is needed to help students develop deep understanding of big ideas (Duschl *et al.*, 2007; Smith *et al.*, 2006). Clearly, the current K-12 science curriculum does not support such learning about water in human and natural systems. This lack of coherence in the K-12 science curriculum has important negative consequences for developing a citizenry capable of understanding and acting responsibly on environmental issues related to maintaining and protecting water quality for all life systems on Earth.

We have several initial recommendations for educators based on our study. First, both formal and informal educators should provide experiences with water systems that help make invisible parts of systems visible. Groundwater is invisible because it is underground, but groundwater models that can be manipulated by students make groundwater processes visible. Similarly, work with watershed models and solar stills make large scale surface water systems and evaporation into the atmosphere visible and manipulable for students. Trips to a waste water treatment plant can help students develop scientific understanding of municipal, human engineered water systems. Educators can use these experiences to help students revise their conceptions about water systems and develop more complete understandings of the structure and processes involved in connected water systems.

Second, the K-12 curriculum needs to work toward developing connected understanding of multiple systems over time. In our experience, students as young as second grade can draw and label diagrams of the water cycle. This practice, however, does not demonstrate a deep understanding of water in environmental systems. Instruction needs to first address the structure and movement of water and other substances in individual systems, and then gradually move toward building connections among these systems to help students develop deep and meaningful understanding. Without having an understanding of structure and processes within systems, being able to draw a water cycle diagram means very little.

Conclusion

Having a connected understanding of water in environmental systems is not sufficient to ensure responsible environmental decision making. Other factors including understanding of social and economic systems, and personal values and practices also play important roles in the decisions people make (e.g., Dietz, 2003; Gardner & Stern, 2002). However, we argue that without a fundamental understanding of water in environmental systems, citizens cannot reason effectively about how human actions impact natural systems and environmental systems services. Consequently, without water science literacy, citizens cannot make informed decisions even if they want to. Our water literacy framework provides an overview of fundamental science understandings we believe citizens need to be environmentally literate about water.

Our research on students' understandings shows that they are not developing fundamental water literacy in school. One response would be to blame students and teachers for this short-coming. However, we argue that the current K-12 standard science curriculum does not support curriculum materials developers or educators in designing instructional plans that will help students develop water literacy. While there are many domains to be addressed in preparing students for citizen responsibilities, we cannot neglect the importance of building a strong K-12 science curriculum that provides students with tools necessary to make informed decisions.

This research is on-going and our next steps involve further exploration of students' developing understandings about water, and the implementation and analysis of experimental curriculum materials based on this research and on our water literacy framework. Through this work, we will develop a curricular framework and instructional tools for helping students develop more robust and connected environmental water literacy over the course of their K-12 school science careers.

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Figures for
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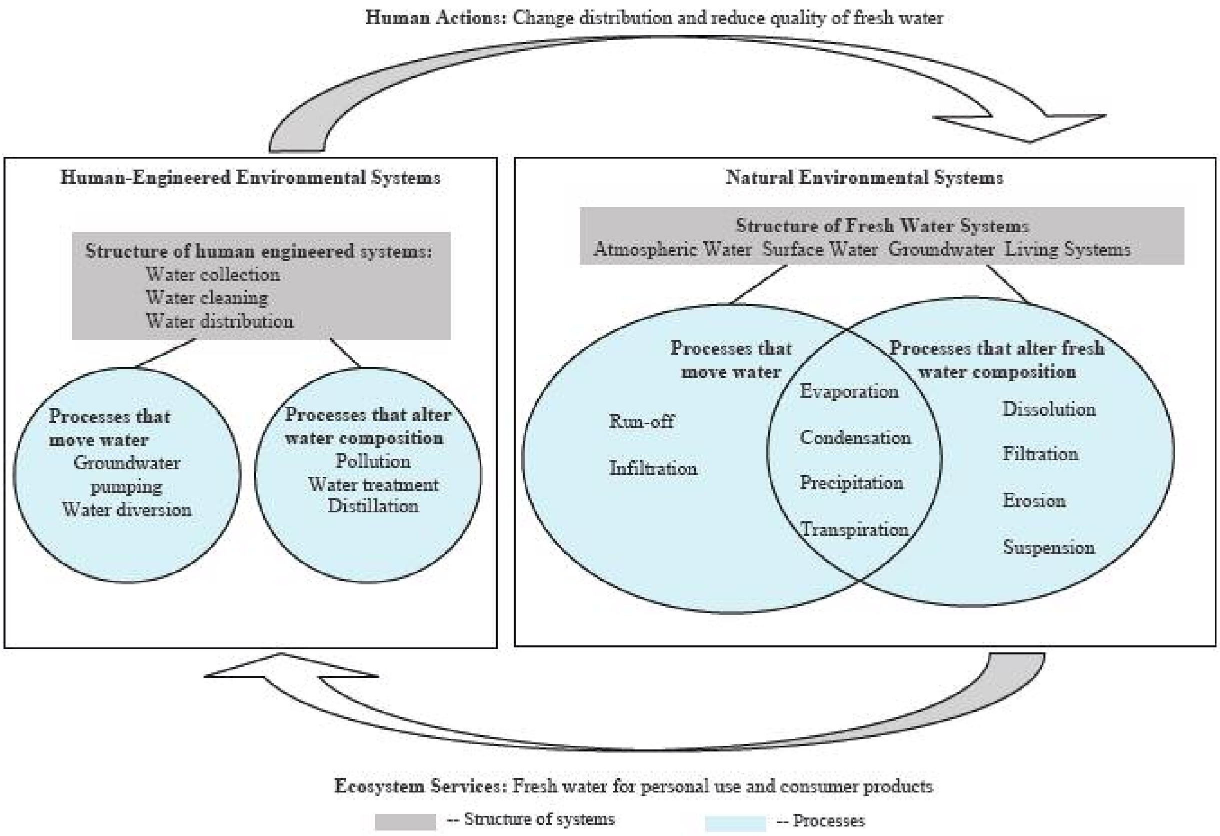


Figure 1: Water Literacy Framework

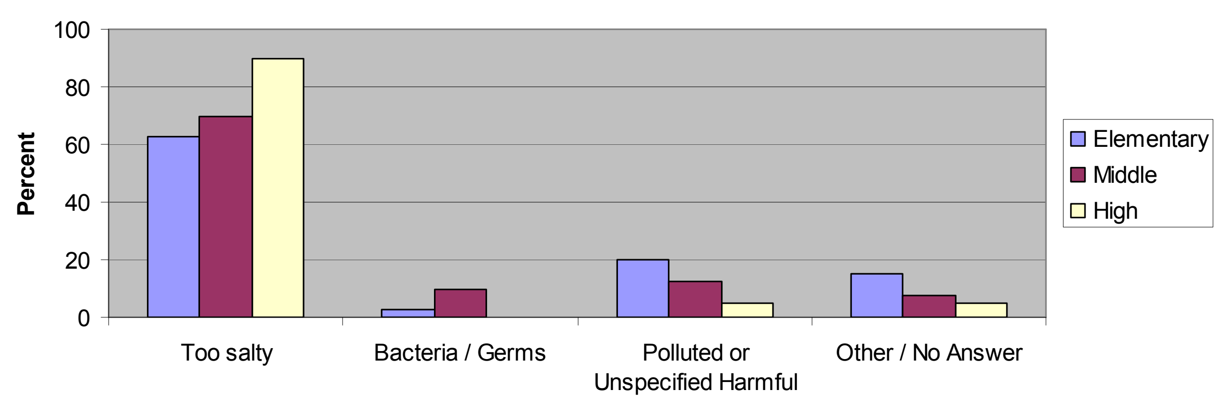


Figure 2: Why can't we drink ocean water?

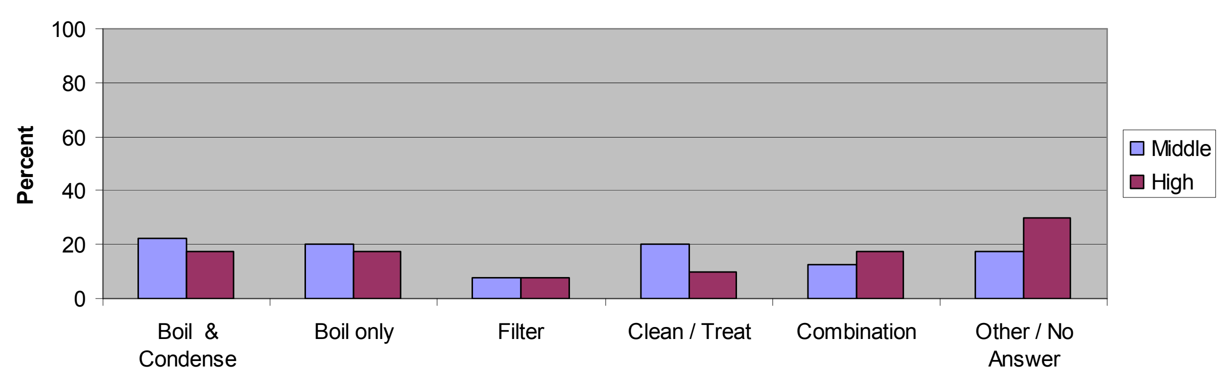


Figure 3: How would you make ocean water drinkable?

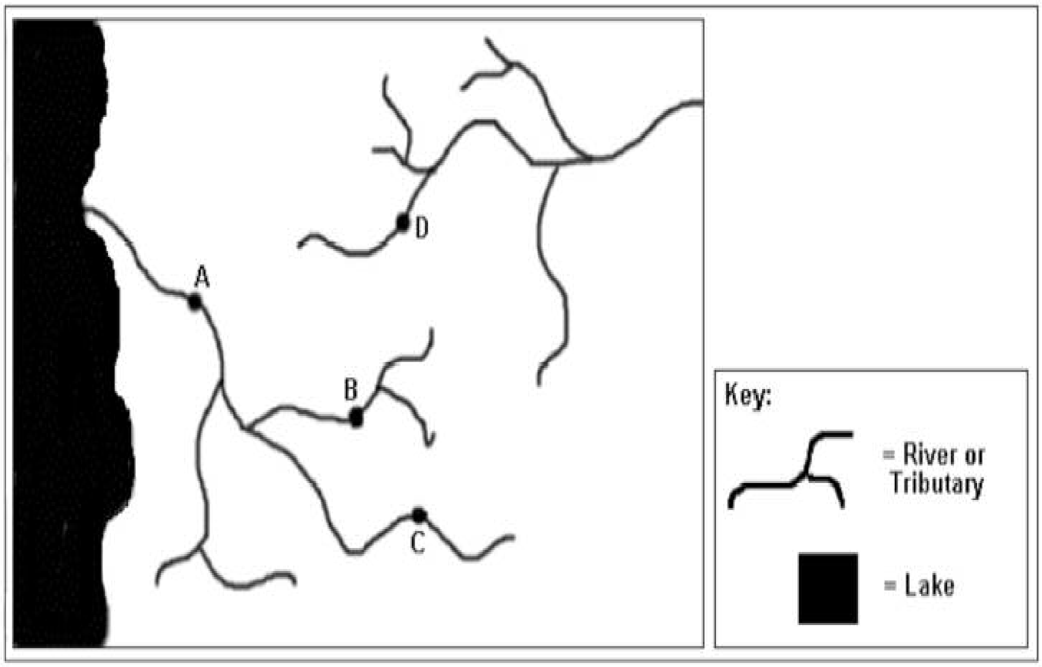
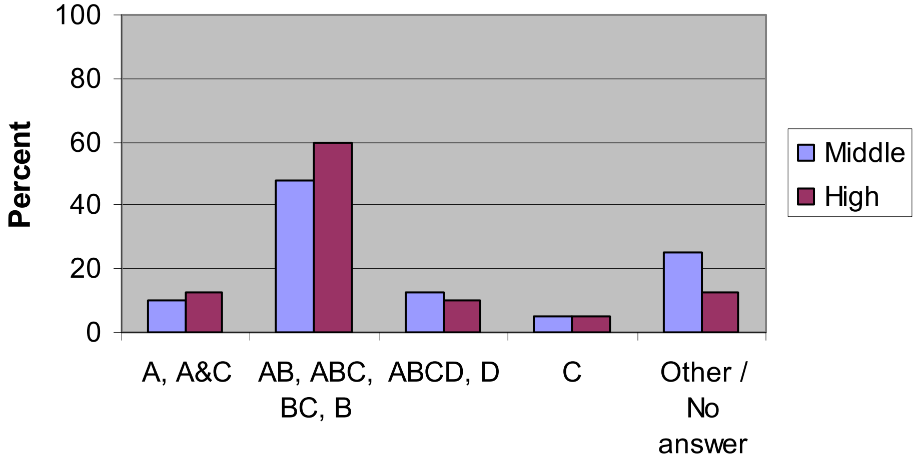


Figure 4: Map of rivers for watershed question.

Figure 5: Which towns will be affected?



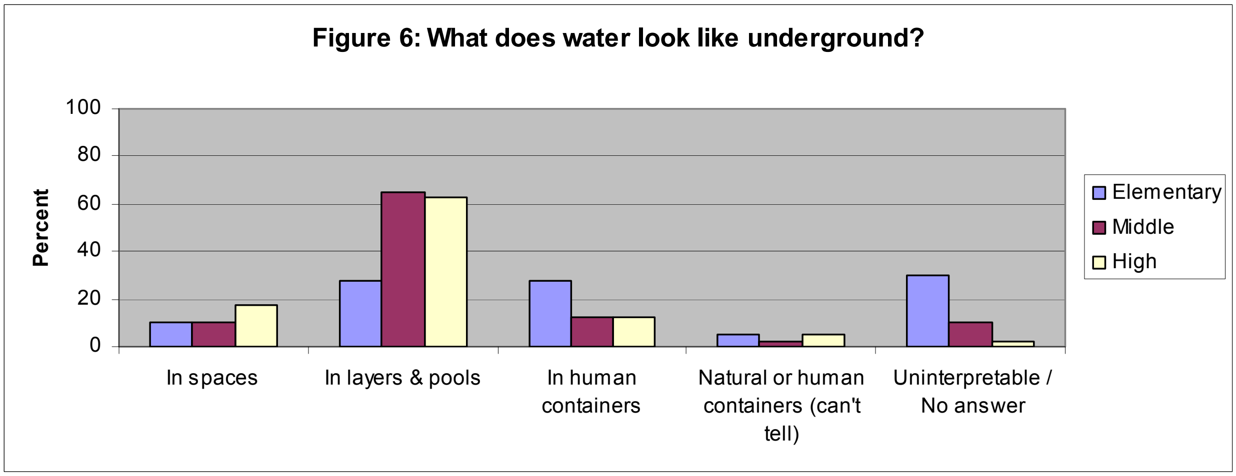
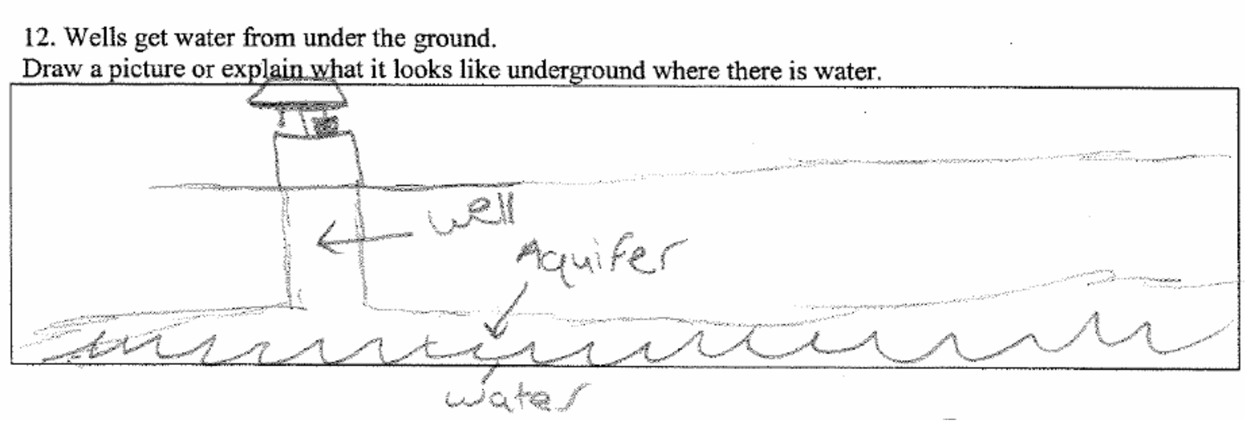


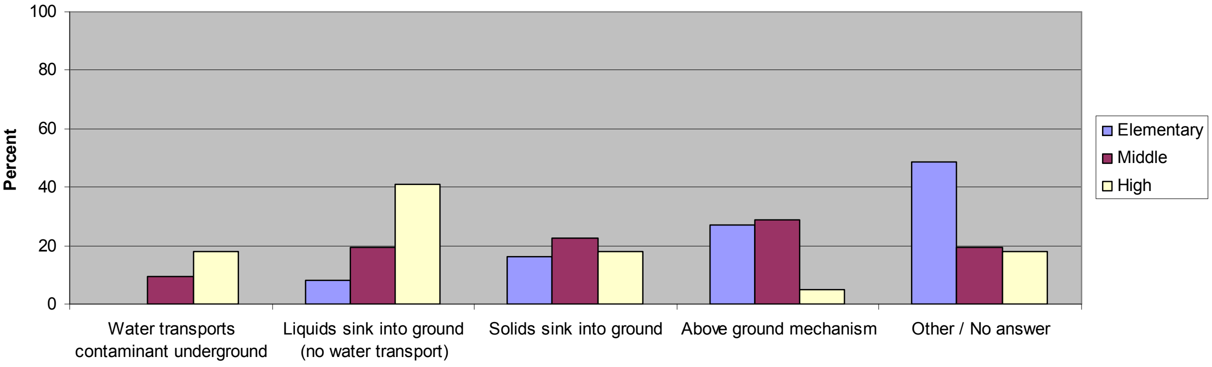
Figure 6: What does water look like underground?



12. Wells get water from under the ground.
Draw a picture or explain what it looks like underground where there is water.

Figure 7: A high school student's depiction of groundwater

Figure 8: If a landfill can pollute a well, how?



Tables for
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Table 1. Common Naïve Conceptions of the Water Cycle

Conceptions	**Sources**
What is evaporation?	
• Water disappears (5-7 yrs) • Water penetrates solid objects (7-9 yrs) • Water evaporates into a container (9-15 yrs) • Water changes into air (10-17 yrs)	Bar, 1989; Bar & Travis, 1991; Osborne & Cosgrove, 1983; Gonzalez, 1997; Tytler, 2000
What are clouds made of?	
• Bags of water (5-7 yrs) • Sponge with drops of water inside (7-9 yrs) • Smoke • Wool/cotton • Water vapor	Bar, 1989; Taiwo, 1999; Piaget, 1930; Gonzalez, 1997
What is water vapor?	
• Separate oxygen & hydrogen molecules • Air • Visible water in the air	Bar & Travis, 1991; Gonzalez, 1997
What are bubbles in boiling water composed of?	
• Air • Heat • Separate Oxygen and Hydrogen atoms	Osborne & Cosgrove, 1983; Bar & Travis, 1991
What is condensation (e.g., on a glass)?	
• Oxygen & Hydrogen atoms recombine • Sweat • Coldness changed to water • Water moves through the glass	Osborne & Cosgrove, 1983; Bar & Travis, 1991; Ewing & Mills, 1994; Tytler, 2000

Table 2. Distribution of Tests

Level	Number of Tests	Number and Grade Level of Teachers	Number of Tests selected per teacher	Urban, Suburban and Rural Distribution of Schools
Elementary	40	One 3rd grade Three 5th grade	10 randomly selected from each teacher's returned tests	2 Urban 1 Suburban 1 Rural
Middle School	40	Two 7th grade One 8th grade	13 or 14 randomly selected from each teacher's returned tests	1 Urban 1 Suburban 1 Rural
High School	40	Two biology One chemistry One Earth science	10 randomly selected from each teacher's returned tests	3 Suburban 1 Rural

Table 3. Distribution of Questions

	Systems			
	Atmosphere	**Surface**	**Groundwater**	**Engineered**
Structure of systems questions		Why can't we drink clean ocean water?	Draw a picture of what it looks like underground where there is water.	
Both structure of systems and tracing matter questions*	How could you make ocean water drinkable?	If a water pollutant is put into the river at Town C, which towns would be affected and why?	Could a landfill contaminate a nearby well? Explain how.	Where does water come from before it gets to your shower? Where does it go after it goes down the drain?

*We found that tracing matter questions also require understanding of structure of systems.