Overview

Water systems understandings: a framework for designing instruction and considering what learners know about water

Troy D. Sadler,* Hai Nguyen and Deanna Lankford

Water is critical to the existence of Earth in its current form; therefore, it stands to reason that a student's science education experiences ought to support the development of increasingly sophisticated ideas about water in socio-ecological systems. Despite the significance of water, it has tended not to receive systematic treatment in the science curriculum. A framework is advanced to help educators and curriculum developers conceptualize water systems in the science curriculum. The framework is composed of physical dimensions of water systems and aspects of water systems understandings. This framework can be used to plan for curriculum, instruction, and assessment; it can also be used to organize a review of existing research on student ideas about water and associated misconceptions. Misconceptions that have been documented regarding the various physical dimensions of water systems (surface water, groundwater, atmospheric water, water in biotic systems, and water in engineered systems) are discussed.

How to cite this article:
WIREs Water 2016. doi: 10.1002/wat2.1178

INTRODUCTION

Water is critical to human existence, and questions associated with access to and quality of water pose some of the major challenges facing society in the 21st century. Important issues such as weather and climate cannot be adequately understood or explained without a basic scientific understanding of the water cycle and the ability of water to transmit heat.[1] Therefore, understanding the dynamic nature of water systems is becoming increasingly important as many nations experience water scarcity resulting from multiple factors including drought and pollution with the potential to rapidly degrade both surface and groundwater stores.[2] It stands to reason that promoting students' understandings of water should be a specific focus of education. In this overview article, we consider how water, as a curricular topic, is featured in K-12 education and present a framework for conceptualizing what it means to understand the science of water. The Understandings of Water Systems (UWS) framework can be conceptualized as a matrix composed of *physical dimensions of water systems* and *aspects of water systems understandings*. The *physical dimensions of water systems* describe where water (and substances in water) exists. They comprise surface water, groundwater, atmospheric water, water in biotic systems, and water in engineered systems. In referring to *aspects of water systems understandings*, we highlight varying facets of student thinking about water systems such as processes and mechanisms, energy, scale, representations, and dependency and human agency. We discuss ways in which the framework might be used for designing curriculum and assessments related to water. Finally, we use the

*Correspondence to: sadlert@missouri.edu

College of Education, University of Missouri, Columbia, MO, USA

Conflict of interest: The authors have declared no conflicts of interest for this article.

framework to organize a review of research from the field of science education that explores learners' ideas and misconceptions about water.

WATER IN THE CURRICULUM

Water has potential to serve as an interdisciplinary theme for multiple areas of the curriculum, but water as a curricular topic tends to be addressed most frequently in science classes. Despite (or perhaps because of) the ubiquity of water and the significance of water in an enormous range of physical, chemical, biological, and environmental processes, water tends not to be featured in a systematic way across the science curriculum. Instead, water shows up across school science rather idiosyncratically.[3] For instance, the Next Generation Science Standards (NGSS)[4] elementary performance expectations (K-LS1-1; 2-LS2-1; 4-ESS2-1) focus on water as a requirement for life or on water as a cause of erosion.[4] Middle school NGSS performance expectations (MS-ESS2-4; MS-ESS2-5) are somewhat vague and only address water specifically in terms of the cycling of water through Earth systems driven by energy from the sun or interactions between air masses resulting in variations in Earth's weather.[4] NGSS high school performance standards are very broad and address water indirectly within the context of photosynthesis, climate, Earth systems, and management of natural resources (HS-LS1-5; HS-ESS2-4; HS-ESS3-5; HS-ESS3-6; HS-ESS3-3). Gross et al.[5] note that the NGSS often makes content, critical for developing deeper understanding of Earth's systems, implicit within the standards and the role of water in biotic and abiotic systems within the environment is only vaguely addressed with limited focus on recognizing patterns.

The most prominent treatment of water in the K-12 curriculum is the presentation of the water cycle. Students in elementary school, middle school science classes, and high school Earth science and/or physical science classes often learn about the water cycle. These presentations highlight processes that drive phase changes as water moves through environmental systems. As such, the movement of surface water into the atmosphere through evaporation; the transition of gaseous water to liquid water through condensation; and the return of water from the atmosphere to the surface system through precipitation tend to receive the most prominent attention.[6] To that end, a study of junior high students' perception of the water cycle indicated that students possessed knowledge of the role of water in biotic processes (e.g., photosynthesis, cellular respiration) but lacked an understanding of the dynamic nature of the water cycle and the infiltration of surface water into the Earth to become groundwater. School-based presentations of the water cycle devote far less attention to other dimensions of water in ecological systems such as transpiration, groundwater, freezing and thawing, and movement of water beyond evaporation and precipitation.[7] While it is true that most elementary and middle school aged students are exposed to a basic model of water cycling through the environment, these students may not have opportunities to think more deeply and broadly about the multidimensional nature of water in environmental systems and the dependence of human communities on water.

Beyond the water cycle, ideas about water largely disconnected within the science curricula.[3] In early grades, water is often used to explore the idea of phase changes and in investigations of buoyancy and density. In both of these cases, water serves as a primary example of the underlying processes or principles. In other words, the instructional focus is on student understanding of density (or the fact that substances can change states) as opposed to anything particular about water. In physical science and chemistry classes, students are often encouraged to think about water as they make sense of ideas such as mixtures, solutions, and suspensions, but here again, instructional foci tend to be on underlying issues of solubility and less on water itself. In high school biology, osmosis is a standard topic, but treatment of this topic tends to be taught within the context of cell structure and function and not connected to a broader systems orientation. In contrast, some chemistry courses encourage deeper explorations of the chemistry of water and ways in which the unique properties of water enable life and shape the Earth.

Curricula are typically organized around scope and sequence charts which provide learning objectives to be mastered for each grade level, however, these objectives are typically discrete and may not be connected to one another in a meaningful way for students.[8] An alternative to this disconnected approach to teaching water science would be an approach that emphasizes the role and positioning of water in socio-ecological systems. The Environmental Literacy group at Michigan State University (http://envlit.educ.msu.edu/) advanced this idea of conceptualizing water in socio-ecological systems as a part of their work to build an empirical model of how learners develop increasingly sophisticated ideas about the science of water.[3] This model, formally known as a 'learning progression' describes how learners' ideas about water change over time in coordination with instruction.[9] One end of the progression is characterized by the intuitive ideas that students often hold when they enter school. The other end of the progression can be described as the ideas and practices that scientists use in thinking about water systems. The idea behind a learning progression is that it can help educators understand the trajectories that learners follow as they move from naïve interpretations of the world toward sophisticated understandings consistent with the goals of science education.

The Environmental Literacy group's water systems learning progression lays out four progress levels. At the lowest level (force dynamic), students' accounts of water tend to highlight the role of people in moving and using water. At the second level, students continue to emphasize the role of actors in the movement of water but begin to incorporate mechanisms and an awareness of the physical world. The third level is characterized by partial accounts of the kinds of water science ideas that are featured in school science. So, students begin describing properties of water and parts of the water cycle, but their descriptions tend to be incomplete and not entirely accurate. The fourth and highest level of the progression involves model-based accounts of the science of water. At this level, learners can conceptualize water and related processes at multiple scales (from molecular to global) in multiple places (ground, surface, atmosphere, and in human-engineered systems). The water systems learning progression suggests five elements of student accounts of water, and these elements are represented in each of the four successive levels. These elements are (1) structures and systems, (2) scale, (3) scientific principles, (4) representations, and (5) dependency and human agency.

A FRAMEWORK FOR UNDERSTANDINGS OF WATER SYSTEMS

Our own work in the area of water systems education relates to a project in which we are interested in supporting middle school students' learning of water in socio-ecological systems. The conceptual tools developed by the Environmental Literacy group including the water systems learning progression were instrumental in our efforts to conceptualize the overall project. However, when specifying targeted learning objectives, the learning progression covered too much conceptual ground with too few markers of progress. In other words, the grain size of the learning progression was too big for informing specific curricular design decisions. (It should be noted that providing this level of guidance was not the intent of the Environmental Literacy group's work.) To address this gap and inform our design work, we developed a framework to account for the range of ideas necessary for understanding water systems.

Water in socio-ecological systems subsumes many ideas, relationships, and processes; therefore, a framework that can potentially inform curricular decisions can help to highlight more manageable (and understandable) units of the overarching system. We have chosen to create these more manageable units by conceptualizing the *physical dimensions of water systems* and *aspects of water systems understandings*. *The physical dimensions of water systems* describe where water (and substances in water) exists. They comprise surface water, groundwater, atmospheric water, water in biotic systems, and water in engineered systems. There are important connections among these dimensions; in fact, some of the most interesting parts of the system are those in which water is moving through one dimension to another.

In highlighting *aspects of water systems* understandings, we create an organizational scheme, based on the learning progression from Gunckel et al.[3] that accounts for varying facets of student thinking about water systems. These aspects are necessarily interdependent but the disaggregation makes it possible to more effectively showcase what we want students to know and learn about water. The aspects of water systems understandings include: (1) processes and mechanisms, (2) energy, (3) scale, (4) representations, and (5) dependency and human agency. The aspects of water systems understandings cut across the dimensions of water systems; therefore, these two organizational schemes can be represented in a matrix. In framing this two-dimensional matrix, we are suggesting that accounting for understandings of and thinking about water systems can be characterized through the consideration of the various subsystems in which water is located and moves (i.e., physical dimensions of water systems) in conjunction with facets of student thinking about water systems (i.e., aspects of water systems understandings). We use this matrix as a primary representation of the UWS framework.

As suggested above, we initially explored the learning progression categories proposed by the Michigan State Environmental Literacy group.[3] Operationalizing learning goals for curriculum development presented related, but different challenges than establishing and representing a learning progression. Like our work, the learning progression utilized a two-dimensional matrix of water system elements and levels of understanding. Our goal was not to characterize intermediate points of understanding, but rather, to offer a more detailed accounting and representation of target understandings across the topic of water systems. Therefore, we opted not to focus on levels of performance or understanding. This allowed us to discretize some dimensions of water systems embedded within some of the learning progression categories. For example, the learning progression offered ‘structures and systems’ as a progression category; we were able to take much of what was captured in ‘structure and systems’ and represent (and further detail) these ideas across multiple groupings within the *physical dimensions of water systems*. We also decided to highlight *processes and mechanisms* and *energy* as discrete aspects of water understandings; whereas, the learning progression combines these ideas within a single ‘scientific principle’ category. Given the significance of the ideas in these groupings, we reasoned that our more detailed approach was warranted. There is a greater degree of consistency between the UWS matrix and the learning progression categories in the representation of the other three aspects of water systems of understandings: *scale*, *representations*, and *dependency and human agency*.

Table 1 presents the UWS matrix along with sample learning goals that correspond to each cell of the matrix. For example, the cell in the upper left corner of the matrix (labeled 1-S) corresponds to processes and mechanisms, an aspect of water systems understandings that affect surface water, a physical dimension of water. Learning objectives associated with this cell include the following: students should be able to explain the relationship between gravity and water movement through a watershed; students should be able to predict the spread of a soluble pollutant introduced in a river; and students should be able to explain processes that may affect the water level of a lake. This list of objectives is by no means comprehensive, but it provides a sample of how objectives might be organized within this matrix. For the sake of space, the table offers just one objective for each cell as a means of demonstrating how different ideas and competencies can be represented by the framework.

The UWS framework partitions physical dimensions and aspects of understandings as an organizational device, but, of course, there are important connections that span the partitions in multiple directions. For example, the process of transpiration sits within the processes/mechanisms column, but it does not reside neatly within a single row of the matrix. The idea is that transpiration sits at the boundary of water in biotic systems and atmospheric water. In using the matrix for planning, we would indicate that learning objectives related to transpiration should be highlighted in matrix cells 1-B and 1-A. Similarly, there are relevant competencies that span multiple aspects of water systems. For example, predicting the spread of dissolved materials through a watershed based on a topographic map involves an ability to think about surface water at multiple scales (aspect 3), from molecular to landscape levels, while simultaneously interpreting information provided through a representational tool (aspect 4). Here again, our convention is to match the objective to multiple cells; in this case matrix cells 3-S and 4-S.

USING THE UWS FRAMEWORK

As mentioned above, our motivation for the development of the UWS framework stemmed from a need to operationalize learning goals associated with a curriculum development project. Our design target was an educational game embedded within a three-dimensional virtual environment that immerses learners in situations that require them to develop ideas about water systems as they engage in challenging tasks related to management of water resources in the virtual environment.[10] In this case, we were committed to moving beyond the relatively simple and disconnected ways that water is typically addressed in science curricula, but we required a means by which to consider the sequencing of ideas as well as ensuring coverage of the domain.

We created the UWS framework to meet these needs: as we conceptualized different levels of the game, we mapped out target learning objectives on the matrix. This allowed us to see possible gaps in the curriculum as well as plan for conceptually coherent connections across the levels. For example, early experiences within the game called for students to interact extensively with surface water both in terms of processes and mechanisms that move water across a landscape and through representations of surface water as in watershed diagrams and topographic maps. A successive level of the game was designed to encourage student thinking about how water interacts at the boundaries of surface and atmospheric systems. This focus created opportunities for students to think about water at different scales (including landscape and molecular). As design work for the educational game progressed, we continued to check plans against the matrix. In doing so, we realized

TABLE 1 | Understandings of Water Systems Matrix With Sample Learning Goals

		Processes Mechanisms–1	Energy Transfer–2	Scale–3	Representations–4	Dependency/ Human Agency–5
Dimensions of Water Systems	Surface water, S	1-S: Explain the relationship between gravity and water movement	2-S: Clarify the role of radiant energy in the evaporation of water	3-S: Predict the boundaries of a watershed including shape and size	4-S: Use a topographic map to identify directions of water flow	5-S: Discuss the impact of human activities on the distribution of surface water
	Groundwater, G	1-G: Predict rates of infiltration based on the porosity of the substrate	2-G: Describe potential and kinetic energy in the movement of water underground	3-G: Explain why water moves through sand more freely than clay	4-G: Create a cross sectional image to demonstrate differences between confined and unconfined aquifers	5-G: Monitor the impact of agricultural irrigation on groundwater supplies
	Atmospheric water, A	1-A: Describe condensation and cloud formation	2-A: Explain the transfer of energy as liquid water enters the atmosphere as a gas	3-A: Compare sizes of gaseous water molecules and condensation nuclei	4-A: Interpret a diagram depicting a rain shadow	5-A: Explain the formation of smog
	Water in biotic systems, B	1-B: Explain the role of pressure in the movement of water through a plant	2-B: Interpret the transformation of radiant energy into chemical energy through photosynthesis	3-B: Calculate the amount of water that flows through one tree and one acre of trees in the Amazon	4-B: Represent biotic inputs and outputs in a water cycle diagram	5-B: Analyze the amount of water required to raise a pound of corn and a pound of beef
	Water in engineered systems, E	1-E: Trace the movement of water from municipal treatment facilities to homes	2-E: Relate kinetic energy to the production of electrical energy through hydroelectric dams	3-E: Rank order by size pollutants that are removed during water treatment processes	4-E: Interpret a schematic diagram for a reverse osmosis system	5-E: Describe the importance of hydrologic engineering for managing impacts of floods and droughts

that early levels of the game provided very few opportunities for students to interact with water in biological systems; this result pushed us to change our design work to ensure better coverage of ideas. Our initial intent in creating the UWS matrix was to inform design of coherent curriculum materials, in particular, the educational game referenced above. As the work progressed, it became apparent that the matrix could serve other purposes as well. As we considered ways to assess the efficacy of the game environment and associated curriculum materials, we used the matrix as the source of design specifications for assessment instruments. This process allowed us to ensure alignment of goals, learning materials, and assessments; such alignment is critical to success of educational interventions and yet is often not achieved.[11,12]

The final way that we have employed the UWS matrix relates to cataloging the kinds of ideas that students tend to naturally hold about water systems. As science educators, we know that one of the most critical factors associated with the learning of any science content is the ideas that students bring with them to a learning experience.[13] An extensive body of empirical research has documented ways in which students' existing ideas about the natural world significantly shape the meanings they construct when confronting new learning experiences.[14] Learners of all ages hold a wide range of ideas about how the world works. These ideas can come from individuals' intuitive interpretations of their first-hand experiences with the world. They can also come from interpretations of previous instruction or vicarious experiences received through accounts communicated to them by teachers, media, family members, and others.[15] Regardless of where students' ideas come from, students have many ideas about the world and should not be considered 'blank slates' when it comes to teaching new science ideas.[16] Many of the intuitive ideas that students hold vary substantially from scientific accounts of how the world works. These naïve ideas have been termed misconceptions or alternative ideas.[17] While the label is not likely all that important, the fact that students possess these non-normative ideas is critically important because they shape the ways in which learners interact with presentations of science content.[18] Therefore, designing new learning experiences necessitates deliberate attention to the ideas (misconceptions or alternative ideas) typically held by learners. In planning for our work on the development of the water systems educational game, we needed to account for the kinds of ideas that students hold about water systems. Here again, we found the UWS matrix to be a useful tool. The matrix provides an organizational tool to sort, order, and draw relationships among students' ideas, some of which may be non-normative with respect to scientific accounts of water systems. Categorizing potential misconceptions on the basis of the UWS matrix makes it easier for curriculum designers and educators to consider which misconceptions may be most likely to interact with targeted learning objectives (such as those presented in Table 1). Unlike a learning progression, the UWS matrix does not prescribe a course of ideas ranging from naïve to more sophisticated, but rather it should be considered as a tool to organize ideas (including non-normative ideas) across the broad domain of water systems. In the section that follows, we use the UWS matrix as a means of organizing a review of literature related to students' ideas about water systems.

STUDENT IDEAS ABOUT WATER SYSTEMS

Many studies have explored K-12 students' ideas about water. Like curriculum which tends to focus on relatively simple representations of water, the research on students' ideas emphasizes discrete dimensions of water, such as the water cycle, as opposed to more complex accounts of students' reasoning about water systems.[19] Figure 1 presents a graphic representation of the water cycle with explicit reference to the role of energy as a driver of the system.[20–22] The cyclic transfer of energy occurs through multiple processes including convection, evaporation, condensation, and the transfer of energy, water, and momentum among, the land, plants, ocean surfaces, and the atmosphere.[23] Radiant energy from the sun is transformed into kinetic energy as liquid water is warmed by radiant energy. This results in a change of state as molecules of liquid water undergo an increase in kinetic energy causing increased molecular motion and ultimately enter the atmosphere as water vapor. Solar energy is also captured by plants through photosynthesis which converts carbon dioxide and water into simple sugars and transforms radiant energy into chemical energy which serves as food for living organisms.[21] Plant leaves are essentially factories for photosynthesis where chloroplasts utilizing the light reactions and the Calvin cycle (dark reactions) convert a small portion of the water and carbon dioxide from the atmosphere into simple sugars. Much of the water is not utilized for photosynthesis and water released as a waste product of photosynthesis enters the atmosphere through evapotranspiration. In addition, human agency also accounts for second generation energy transformation through building of hydroelectric dams. Hydroelectric power plants are able to capture the energy of flowing water and through electrical turbines convert the kinetic energy of water into electrical energy for use in society.[24,25]

Students often hold misconceptions or alternate conceptions relative to the cycle just presented and these misconceptions have potential to interfere with their understanding of accurate explanations for the cycling of water into and out of the atmosphere.[1] The concept of a cycle can be problematic for

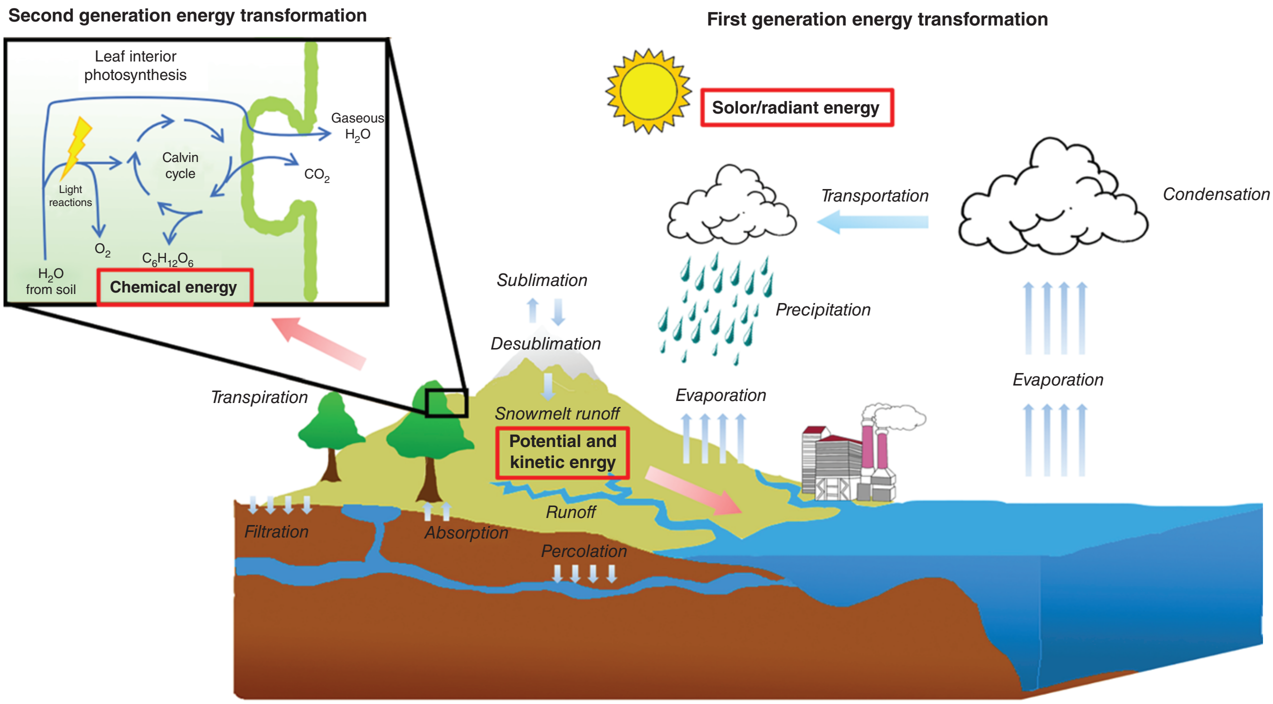

FIGURE 1 | Diagram of the water cycle including energy transfer processes.

students; Agelidou et al.[26] noted that students often perceive natural cycles as based in time (e.g., life cycles or the cycling of seasons) rather than the movement of matter as indicated in the water cycle. Henriques[27] noted that students studying the water cycle must have an understanding of the properties of water and the heat exchanges between Earth and the sun. Furthermore, concepts of the energy transfer in the water cycle are difficult for many students because they deal with a state of matter that is often invisible. Discussions about energy level, such as potential versus kinetic energy tend to be abstract rather than concrete, which increases the probability of misconceptions.[27–30] For the purposes of this review, we use the physical dimensions of water systems construct as an initial organizing frame and then discuss aspects of water systems understandings within each of the dimensions.

Surface Water

The surface water system is likely the most easily understood dimension of water systems because it represents the dimension that students can most easily access and interact with. Most students have opportunities to see, hear, and touch surface water features such as streams, lakes, and oceans, and these kinds of personal experiences can support learning of the science related to them.[31] However (or possibly because personal interactions are so likely), learners hold a variety of alternative ideas about surface water. Many young students have misconceptions regarding the distribution of water across the surface system. They struggle to understand the proportion of water volumes in various reservoirs.[32] The concept of watersheds and the role of gravity as a driving force behind the movement of water across the surface system (as well as other dimensions of the water systems) can be difficult for students. The concept of transformation of potential energy into kinetic energy to explain how and why water flows from areas of high elevation to areas of lower elevation within a watershed can also be a challenging concept for students.[3] Even the language we use can introduce challenges for the emergence of coherent reasoning in regards to water; some young learners interpret a 'watershed' to mean a shed or building that holds water.[33]

The notion of watersheds is central to scientific accounts of surface water (as well as groundwater), and a range of research has identified multiple ways in which students struggle to understand watershed processes, scale, and representations. Students seem to understand that water and materials within a watershed will move to a common area of lower elevation; however, they tend to think about watersheds only in terms of a single river. They also tend not to understand differences between and implications of point and nonpoint sources of water pollution.[33] Despite some basic understandings of materials moving with water, learners struggle to trace the likely path of dissolved materials in water.[32] Students interpreting the movement of materials in water such as pollutants often cannot show how those materials will likely flow through discrete components of the watershed as opposed to diffusing through the entire watershed as if elevation and direction of water flow did not matter.[34] Students often fail to understand the nested nature of watersheds and the interaction of multiple watersheds in larger systems. Some students only think about watersheds in mountainous terrain with high levels of relief and extensive elevation changes. This suggests misunderstandings of the way that gravity relates to elevation changes of any degree. Many learners only conceptualize water and watersheds in natural areas; natural movement and stores of water are typically not considered within environments with extensive human impacts such as urban areas.[33,35,36] In a recent analysis of representations of surface water in science textbooks, Vinisha and Ramadas[37] suggest that the diagrams and figures created for the purpose of teaching students about watersheds may, in fact, be the most common source of some of these misconceptions.

One of the issues that students struggle with is conceptualizing water at the landscape scale.[38] This has implications for their abilities to think about the volume of water involved in surface water processes. Students can also struggle with interpreting representations of surface water. Learners often interpret representations of surface water with a heuristic that rivers always flow in a southerly direction.[38,39] When asked to create their own representations of surface water, student often shows rivers moving down their paper regardless of the geographic orientation of the system they are attempting to represent.[40]

Groundwater

Groundwater is a dimension of water systems that is far more difficult for students to experience directly, as compared to surface water, and this leads to a number of conceptual challenges.[7] Many students have limited ideas regarding the connections between surface water and groundwater and the geology that mediates these interactions.[33] Until they experience instruction focused on geology, most learners are unaware of the dynamic relationships between soil type and rock composition with water movement above and below ground.[38] Not surprisingly, students struggle with issues of scale when considering groundwater. Moving from the idea of water molecules suspended in microscopic spaces between soil particles to the vast quantities of water stored in aquifers that can stretch across a continent can be challenging to fully comprehend.[41]

Students can relatively easily come to appreciate the fact that water can be stored underground, but misconceptions regarding processes and structures that impact groundwater storage are prevalent. Students often recognize the movement of water through porous rock layers in the upper portions of the soil; however, beyond initial infiltration student ideas tend to diverge. For some students, underground water moves to surface reservoirs such as lakes and oceans.[42] The most common misconception about groundwater is that it collects in underground caverns as subsurface lakes.[7] Lost for many students, even college level learners, is the idea that significant volumes of water are found in the interstitial spaces of rocks and soils.[41]

Whereas many learners can explain some dimensions of pollution of surface water, they often struggle to understand and explain the flow of pollutants in groundwater.[7] This may likely be a result of the fact that many students struggle to connect water cycling with the groundwater. It is much more likely for students to feature water and processes in the atmospheric and surface systems when depicting and explaining the water cycle.[32,43]

Atmospheric Water

As mentioned above, the water cycle, or at least parts of it, is a common topic covered in school science, particularly in elementary grades, and water in the atmospheric system receives a fair amount of attention through this coverage. So, young learners tend to understand that significant amounts of water are in the atmosphere and that processes change water phases, but several misconceptions about these processes are prevalent.[7,28,44–47] School treatments of the water cycle often focus on precipitation, so many students conceptualize the water cycle as a weather phenomenon as opposed to a dynamic system that moves water.[42] In fact, some elementary students think of the water cycle as an entity that only serves as a source of water (i.e., through rain),[42] and students at all levels have been shown to struggle with the idea of the water cycle *not* having a fixed beginning or ending point. In these cases, the proposed 'start' of the water cycle is usually rain.[48]

In studying atmospheric water, researchers have documented several conceptual difficulties learners have related to processes of evaporation and condensation. Some students think that cloud formation is the direct result of the sun boiling sea water.[49] Other learners attribute cloud formation to a supernatural power.[38,39,49] Still others conceptualize clouds as permanent fixtures within the atmosphere that operate like sponges. A functional explanation with this conception is that clouds move over an ocean, draw up water, and then move to a land area before releasing water through rain.[32,39] Energy is transferred into the atmosphere as water undergoes a change of state from the liquid state held by abiotic factors (surface water, soil, etc.) and biotic (plants and animals) factors into a gaseous state as water vapor enters the atmosphere.[23] During evaporation, energy enters the atmosphere stored within molecules of water vapor as radiant energy converts liquid water into a gaseous form; conversely, energy is released or transferred to other molecules within the atmosphere as kinetic energy during condensation, when water molecules undergo a change of state from a gaseous form to a liquid form.[23,50]

Water in Biotic Systems

Students often omit components of the biosphere such as humans, plants, and animals when describing the water cycle.[7] For example, the transfer of water from plants into the atmosphere involves energy to facilitate the change of water from a liquid state to a gaseous state. Evapotranspiration occurs when liquid water in plant leaves is warmed by the sun and enters the atmosphere as water vapor. A similar process occurs when animals release liquid water through respiration, perspiration, and waste production. The energy absorbed by water molecules results in a change of state which transfers radiant energy into kinetic energy within the atmosphere.[22]

There has been limited research on learners' ideas about water in biotic systems. A few studies have highlighted the fact that most young learners do not think of plants or humans as a part of natural water systems.[38,39] Even college level students seem to not include aspects of the biosphere in their thinking about water.[32] Assaraf et al.[39] explored student ideas about water consumption but found that students tended to only consider humans as water consumers. Beyond these basic errors of omission, we know little about how learners think about organisms as a part of Earth's water systems and processes such as transpiration.

Water in Engineered Systems

The research literature is similarly limited with respect to students' understandings of water in engineered systems. Most students seem to know little about the systems that societies create for moving and cleaning water. Many students do not know where their drinking water comes from.[32,38] When pushed to think through the origins of water in municipal systems, most learners hold the idea that humans get their water directly from natural sources rather than water being processed through treatment facilities.[19] In a range of studies with elementary, middle, and high school students, a number of misconceptions regarding the path of water in engineered systems have been presented. Some students do not perceive the differences between drinking water treatment plants and wastewater plants. Others have been shown to think that treated wastewater moves back into municipal distribution systems rather than the natural environment, and some younger learners do not even think of wastewater as being treated before being returned to natural environments.[32,39] In work with college students, Sammel and McMartin[32] found that this group held generally more sophisticated ideas about the systems that humans engineer for water, but they still held limited ideas regarding conservation. For instance, many of the college students did not equate activities such as taking shorter showers and turning taps off as strategies for water conservation (Box 1).[32]

CONCLUSION

In our work, we start with the assumption that students ought to learn about water in socio-ecological systems as a part of their educational experiences. An extensive body of research, primarily from the field of science education, has been conducted related to the kinds of misconceptions, alternative conceptions and limited ideas that learners tend to hold regarding water and the processes that affect movement, distribution, availability, and quality of water. Most learners have extensive experience with surface water, but they tend to struggle with several ideas related to watersheds, representations of watersheds and the multiple scales at which water processes operate. Students have more limited experiences with groundwater and they often hold misconceptions about the distribution of water below ground. Research related to student understandings of atmospheric water has revealed a number of misconceptions related to evaporation, condensation, and precipitation. Students tend to have more limited ideas regarding water in biotic and engineered systems, both of which

BOX 1

NEXT GENERATION SCIENCE STANDARDS [NGSS] – PERFORMANCE EXPECTATIONS ADDRESSING WATER IN THE K-12 CURRICULUM

Elementary School Performance Expectations

2-LS2-1. Plan and conduct an investigation to determine if need sunlight and water to grow.
3-LS4-4. Make a claim about the merit of a solution to a problem caused when the environment changes and the types of plants and animals that live there may change.
4-ESS2-1. Make observations and/or measurements to provide evidence of the effects of weathering on the rate of erosion by water.

Middle School Performance Expectations

MS-PS1-1. Develop models to describe the atomic composition of simple molecules and extended structures.
MS-PS1-4. Develop a model that predicts and describes changes in particle motion, temperature, and state of substance when thermal energy is added or removed.
MS-PS3-4. Plan an investigation to determine the relationship among the energy transferred, the type of matter, the mass, and the change in the average kinetic energy of the particles as measured by the temperature of the sample.
MS-LS1-6. Construct a scientific explanation based on evidence for the role of photosynthesis in the cycling of matter and flow of energy into and out of organisms.
MS-ESS2-2. Construct a scientific explanation based on evidence for how geoscience processes have changed Earth's surface at varying time and spatial scales.
MS-ESS2-4. Develop a model to describe the cycling of water through Earth's systems driven by energy from the sun and the force of gravity.
MS-ESS2-5. Collect data to provide evidence for how the motions and complex interactions of air masses results in changes within weather conditions.
MS-ESS3-1. Construct a scientific explanation based on evidence for how the uneven distributions of the Earth's mineral, energy, and groundwater resources are the result of past and current geoscience processes.
MS-ESS3-3. Apply scientific principles to design a method for monitoring and minimizing a human impact on the environment.

High School Performance Expectations

HS-PS1-1. Use the periodic table as a model to predict the relative properties of elements based on the patterns of electrons in the outmost energy levels of atoms.
HS-LS1-5. Use a model to illustrate how photosynthesis transforms light energy into stored chemical energy.
HS-ESS2-4. Use a model to describe how variations in the flow of energy into and out of Earth's systems result in changes in climate.
HS-ESS3-5. Analyse geoscience data and the results from global climate models to make an evidence-based forecast of the current rate of global or regional climate change and associated future impacts to Earth systems.
HS-ESS3-6. Use a computational representation to illustrate the relationships among Earth systems and how these relationships are being modified due to human activity.
HS-ESS3-3. Create a computational simulation to illustrate the relationships among management of natural resources, the sustainability of human populations, and biodiversity.

represent sets of ideas that receive less curricular attention than other dimensions of water systems.

The framework presented here is designed as a tool for unpacking what it means to understand Earth's water system, which is complex and multifaceted. As such, the associated matrix can be used to organize ideas (including learning objectives and water related misconceptions) and inform the design of curricular materials and assessments. However, the framework certainly does not account for all of the factors that will interact with learning. For instance, affective factors such as attitudes and values significantly influence learning processes and outcomes,[51] but the framework presented in this article does not address the affective dimension of learning. Instead, it offers a tool that can be used for informing cognitive dimensions of learning in the context of water systems.

The UWS framework, which is based on the intersections of various dimensions of water systems and aspects of water systems understandings, provides a tool that helps to organize extant evidence on student ideas about water. The framework can also be used in the design and development of new learning materials for water systems content as well as well-aligned assessment. We believe that the framework can help advance the broader range of work being done in the name of enhancing scientific literacy related to water. In our work with development of a new middle school curriculum, involving innovative technologies, the UWS framework will be a useful heuristic in sequencing ideas and ensuring appropriate coverage of topics.

FURTHER READING

Arnell NW. Global water cycle. In: *eLS*. Hoboken, NJ: John Wiley & Sons, Ltd; 2001.

Goldman C, Kumagai M, Robarts RD, eds. *Climatic Change and Global Warming of Inland Waters: Impacts and Mitigation for Ecosystems and Societies*. Oxford: Wiley; 2014. doi:10.1002/9781118470596.

REFERENCES

1. Romine WL, Schaffer DL, Barrow L. Development and application of a novel rasch-based methodology for evaluating multi-tiered assessment instruments: validation and utilization of an undergraduate diagnostic test of the water cycle. *Int J Sci Educ* 2015, 37:2740–2768.
2. Lall U. Debates—the future of hydrological sciences: a (common) path forward? One water. One world. Many climes. Many souls. *Water Resour Res* 2014, 50:5335–5341.
3. Gunckel KL, Covitt BA, Salinas I, Anderson CW. A learning progression for water in socio-ecological systems. *J Res Sci Teach* 2012, 49:843–868.
4. NGSS Lead States. *Next Generation Science Standards: For States by States*. Washington: National Academies Press; 2013.
5. Gross P, Buttrey D, Goodenough U, Koertge N, Lerner L, Schwartz M, Schwartz R. *Final Evaluation of the Next Generation Science Standards*. Washington: Thomas B Fordham Institute; 2013, 67.
6. Márquez C, Izquierdo M, Espinet M. Multimodal science teachers' discourse in modeling the water cycle. *Sci Educ* 2006, 90:202–226.
7. Assaraf OBZ, Orion N. Development of system thinking skills in the context of earth system education. *J Res Sci Teach* 2005, 42:518–560.
8. Duncan RG, Hmelo-Silver CE. Learning progressions: aligning curriculum, instruction, and assessment. *J Res Sci Teach* 2009, 46:606–609.
9. Council NR. *Taking Science to School: Learning and Teaching Science in Grades K-8*. Washington, DC: National Research Council; 2007.
10. Laffey JM, Sadler TD, Goggins SP, Griffin J, Babiuch RN. *Mission HydroSci: Distance Learning through Game-Based 3D Virtual Learning Environments*. Hershey, PA: Information Science Reference; 2016.
11. Moore GW, Slate JR, Edmonson SL, Combs JP, Bustamante R, Onwuegbuzie AJ. High school students and their lack of preparedness for college: a statewide study. *Educ Urban Soc* 2010, 42:817–838.
12. Webb NL. Issues related to judging the alignment of curriculum standards and assessments. *Appl Meas Educ* 2007, 20:7–25.
13. Bransford JD, Brown AL, Cocking RR. *How People Learn: Brain, Mind, Experience, and School*. Washington, DC: National Academy Press; 1999.
14. Duit R, Treagust DF. Conceptual change: a powerful framework for improving science teaching and learning. *Int J Sci Educ* 2003, 25:671–688.
15. Hewson MG, Hewson PW. Effect of instruction using students' prior knowledge and conceptual change strategies on science learning. *J Res Sci Teach* 2003, 40: S86–S98.
16. Posner GJ, Strike KA, Hewson PW, Gertzog WA. Accommodation of a scientific conception: toward a theory of conceptual change. *Sci Educ* 1982, 66:211–227.
17. Taber KS. Shifting sands: a case study of conceptual development as competition between alternative conceptions. *Int J Sci Educ* 2001, 23:731–753.
18. Scott P, Asoko H, Leach J. *Student Conceptions and Conceptual Learning in Science*. Mawah, NJ: Lawrence Erlbaum Associates; 2007.
19. Covitt BA, Gunckel KL, Anderson CW. Students' developing understanding of water in environmental systems. *J Environ Educ* 2009, 40:37–51.

20. Manabe S. Climate and the ocean circulation 1: i. The atmospheric circulation and the hydrology of the earth's surface. *Mon Weather Rev* 1969, 97:739–774.
21. Deardorff J. Efficient prediction of ground surface temperature and moisture, with inclusion of a layer of vegetation. *J Geophys Res Oceans* 1978, 83:1889–1903.
22. Pitman A. The evolution of, and revolution in, land surface schemes designed for climate models. *Int J Climatol* 2003, 23:479–510.
23. Sellers P, Dickinson R, Randall D, Betts A, Hall F, Berry J, Collatz G, Denning A, Mooney H, Nobre C. Modeling the exchanges of energy, water, and carbon between continents and the atmosphere. *Science* 1997, 275:502–509.
24. Gleick PH. Water and energy. *Annu Rev Energy Environ* 1994, 19:267–299.
25. Banos R, Manzano-Agugliaro F, Montoya F, Gil C, Alcayde A, Gómez J. Optimization methods applied to renewable and sustainable energy: a review. *Renew Sustain Energy Rev* 2011, 15:1753–1766.
26. Agelidou E, Balafoutas G, Gialamas V. Interpreting how third grade junior high school students represent water. *Int J Environ Educ Inform* 2001, 20:19–36.
27. Henriques L. Children's ideas about weather: a review of the literature. *School Sci Math* 2002, 102:202–215.
28. Canpolat N. Turkish undergraduates' misconceptions of evaporation, evaporation rate, and vapour pressure. *Int J Sci Educ* 2006, 28:1757–1770.
29. Boyes E, Stanisstreet M. Pupils' ideas concerning energy sources. *Int J Sci Educ* 1990, 12:513–529.
30. Miller RL, Streveler RA, Nelson MA, Geist MR, Olds BM. Concept inventories meet cognitive psychology: using beta testing as a mechanism for identifying engineering student misconceptions. In: *Proceedings of the 2005 American Society for Engineering Education Annual Conference and Exposition*, Portland, OR 2005.
31. Driver R, Asoko H, Leach J, Scott P, Mortimer E. Constructing scientific knowledge in the classroom. *Educ Res* 1994, 23:5–12.
32. Sammel AJ, McMartin DW. Teaching and knowing beyond the water cycle: what does it mean to be water literate? *Creat Educ* 2014, 5:835–848.
33. Shepardson DP, Harbor J, Wee B. Water towers, pump houses, and mountain streams: students' ideas about watersheds. *J Geosci Educ* 2005, 53:381.
34. Gunckel KL, Covitt BA, Anderson C. Teacher responses to assessments of understanding of water in socio-ecological systems: a learning progressions approach. In: *Annual International Conference of the National Association for Research in Science Teaching*, Philadelphia, PA, 2010.
35. Gill SE, Marcum-Dietrich N, Becker-Klein R. Model my watershed: connecting students' conceptual understanding of watersheds to real-world decision making. *J Geosci Educ* 2014, 62:61–73.
36. Sell KS, Herbert BE, Stuessy CL, Schielack J. Supporting student conceptual model development of complex Earth systems through the use of multiple representations and inquiry. *J Geosci Educ* 2006, 54:396.
37. Vinisha K, Ramadas J. Visual representations of the water cycle in science textbooks. *Contemp Educ Dialogue* 2013, 10:7–36.
38. Schwartz KL, Thomas-Hilburn H, Haverland A. Grounding water: building conceptual understanding through multimodal assessment. *J Geosci Educ* 2011, 59:139–150.
39. Assaraf OB-Z, Eshach H, Orion N, Alamour Y. Cultural differences and students' spontaneous models of the water cycle: a case study of Jewish and Bedouin children in Israel. *Cult Stud Sci Educ* 2012, 7:451–477.
40. Dove J. Student preferences in the depiction of the water cycle and selected landforms. *Int Res Geogr Environ Educ* 1997, 6:135–147.
41. Dickerson D, Callahan TJ, Van Sickle M, Hay G. Students' conceptions of scale regarding groundwater. *J Geosci Educ* 2005, 53:374.
42. Shepardson DP, Wee B, Priddy M, Schellenberger L, Harbor J. Water transformation and storage in the mountains and at the coast: midwest students' disconnected conceptions of the hydrologic cycle. *Int J Sci Educ* 2009, 31:1447–1471.
43. Assaraf OBZ, Orion N. System thinking skills at the elementary school level. *J Res Sci Teach* 2010, 47:540–563.
44. Cardak O. Science students' misconceptions of the water cycle according to their drawings. *J Appl Sci* 2009, 9:865–873.
45. Coştu B, Ayas A. Evaporation in different liquids: secondary students' conceptions. *Res Sci Technol Educ* 2005, 23:75–97.
46. Coştu B, Ayas A, Niaz M. Promoting conceptual change in first year students' understanding of evaporation. *Chem Educ Res Pract* 2010, 11:5–16.
47. Stavy R. Using analogy to overcome misconceptions about conservation of matter. *J Res Sci Teach* 1991, 28:305–313.
48. Orion N. An Earth systems curriculum development model. In: Mayer VJ, ed. *Global Science Literacy*. Springer; 2002, 159–168.
49. Bar V. Children's views about the water cycle. *Sci Educ* 1989, 73:481–500.
50. Allen PA. *Earth Surface Processes*. Hoboken, NJ: John Wiley & Sons; 1997.
51. Hidi S, Renninger KA. The four-phase model of interest development. *Educ Psychol* 2006, 41:111–127.

The research described herein is supported by the US Department of Education's Institute of Education Sciences (R305A150364) and Investing in Innovation (i3) program (U411C140081). The ideas expressed are those of our project team and do not necessarily reflect the views of the funders.