Developing a Framework for Assessing Students’ Understanding of Groundwater

Julia Spencer

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Developing a Framework for Assessing Students’ Understanding of Groundwater

By

Julia Spencer

M.S., University of Wyoming, 2016

Plan B Project

Submitted in partial fulfillment of the requirements for the degree of Masters in Science in Natural Science/Mathematics in the Graduate College of the University of Wyoming, 2016

Laramie, Wyoming

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Abstract

Groundwater is an important part of the Earth’s hydrologic system. The Next Generation Science Standards ask middle school students to incorporate groundwater into a model of resource distribution that requires an understanding of the mechanisms and scientific principles that influence groundwater movement and distribution. Physical models that replicate groundwater systems are an essential tool for helping students develop understanding of hidden phenomena such as groundwater, but are often expensive. Wyoming EPSCoR seeks to mitigate this challenge by providing a physical groundwater model to K-12 teachers within the state, however the provision and use of physical models poses its own set of challenges to teachers. Without appropriate training and integration into larger curriculum, models and toolkits often serve as isolated experiences with little to no lasting influence on students’ scientific understanding. In addition assessment for student understanding during and after the use physical models is rarely incorporated. This research aims to answer the question of what are the essential components of an authentic assessment framework that measures student-learning outcomes from the use of a physical, interactive groundwater model at a middle school level. It provides an assessment framework meant to increase the utility of the model to teachers, and increase student understanding by incorporating it into a progression for learning and assessment of groundwater. This assessment framework also provides a means for EPSCoR to evaluate the efficacy of outreach materials in terms of student learning outcomes form the use of the model.
Acknowledgments

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## Table of Contents

LIST OF TABLES ............................................................................................................................................... vi

LIST OF FIGURES ........................................................................................................................................ vii

CHAPTER 1 INTRODUCTION .......................................................................................................................... 1
  Background and Purpose .................................................................................................................................. 1
  Statement of Problem ...................................................................................................................................... 3
  Statement of Purpose ..................................................................................................................................... 4
  Research Questions ....................................................................................................................................... 4
  Definition and Discussion of Terms .............................................................................................................. 5

CHAPTER 2 REVIEW OF LITERATURE .............................................................................................................. 8
  Introduction .................................................................................................................................................. 8
  Methodology for Literature Search ........................................................................................................... 9
  NGSS and Groundwater: The Need for a New Assessment Framework ......................................................... 9
  Challenges in Groundwater Education ....................................................................................................... 13
  Physical Models and Toolkits in the Classroom ............................................................................................ 19
  Assessing Student’s Mental Models of Groundwater: Model Oriented Assessment ..................................... 25
  Essential Elements in Assessing Student Understanding of Groundwater .................................................. 29

CHAPTER 3 METHODOLOGY FOR CREATING AN ASSESSMENT FRAMEWORK .................................................. 31
  Introduction .................................................................................................................................................. 31
  Formative Assessment and Scientific Modeling ............................................................................................. 32
  Setting Learning Goals and Performance Tasks: Backward Design ............................................................. 34
  Developing a Pre and Post Test ...................................................................................................................... 38
  Assessing Skills and Content: Model Oriented Assessment & Learning Progressions .................................. 38
  Limitations .................................................................................................................................................. 45

CHAPTER 4 RESULTS: GROUNDWATER ASSESSMENT FRAMEWORK .................................................................. 47
  Overview ..................................................................................................................................................... 47
  Groundwater Assessment framework ........................................................................................................... 49

CHAPTER 5 DISCUSSION .................................................................................................................................... 62
  Introduction .................................................................................................................................................. 62
  Challenges in Assessing Groundwater ........................................................................................................... 62
  Strategies to Address Challenges .................................................................................................................... 65
  Recommendations for Use ............................................................................................................................. 70
List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Groundwater Core Concepts</td>
<td>37</td>
</tr>
<tr>
<td>2</td>
<td>Levels of student model-based understanding of water within a learning</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>progression</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Characteristics of model-based accounts of water at each level of understanding</td>
<td>43</td>
</tr>
<tr>
<td>4</td>
<td>A learning progression for understanding models</td>
<td>44</td>
</tr>
<tr>
<td>5</td>
<td>Assessment Progression</td>
<td>53</td>
</tr>
<tr>
<td>6</td>
<td>Characteristics of model-based accounts at each understanding level: a</td>
<td>59</td>
</tr>
<tr>
<td></td>
<td>framework for learning progressions</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Rubric for PT—1 based upon the levels of understanding in the</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>groundwater learning progression</td>
<td></td>
</tr>
<tr>
<td>A1</td>
<td>Groundwater Core Concepts Matrix</td>
<td>86</td>
</tr>
</tbody>
</table>
## List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NGSS Relevant to Groundwater</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>Picture of enVision 2000 Groundwater Flow Model</td>
<td>31</td>
</tr>
<tr>
<td>3</td>
<td>A model for embedding assessment into curriculum</td>
<td>32</td>
</tr>
<tr>
<td>4</td>
<td>Backward Design</td>
<td>35</td>
</tr>
<tr>
<td>5</td>
<td>Stages of mental model building</td>
<td>39</td>
</tr>
<tr>
<td>6</td>
<td>Elements of model-based understanding of waters’ movement through environmental systems</td>
<td>42</td>
</tr>
<tr>
<td>7</td>
<td>Desired Results and Assessment Evidence</td>
<td>49</td>
</tr>
<tr>
<td>8</td>
<td>Simplified Formative Assessment Cycle</td>
<td>57</td>
</tr>
<tr>
<td>9</td>
<td>Pre- and Post-Test</td>
<td>58</td>
</tr>
<tr>
<td>10</td>
<td>Ecology of Assessment</td>
<td>69</td>
</tr>
<tr>
<td>A1</td>
<td>Diagram of Sand &amp; Gravel Groundwater Simulator</td>
<td>81</td>
</tr>
</tbody>
</table>
Chapter 1
Introduction

Background and Purpose

Water is rapidly becoming a scarce and precious resource that needs to be understood and managed by future generations. The increasing global population and demand for fresh water will generate increased conflict among human and ecological users of water (Reinfried, 2006). To manage resulting challenges, requires an understanding of how water moves through environmental systems and interacts with human demands. Groundwater provides the largest source of usable fresh water in the United States (http://water.usgs.gov/edu/hydrology.html) but is a piece of watershed systems not well understood among many teachers and students (Dickerson, Penick, Dawkins & Van Sickle, 2007; Duffy, 2012; Covitt, Gunckel & Anderson, 2009). The need to protect water quality in integrated systems should be an impetus for increased groundwater education in the context of larger watershed science curricula in k-12 classrooms.

The Next Generation Science Standards (NGSS) explicitly include groundwater in two topic areas: Earth’s systems and Earth and human activity (NGSS Lead States, 2013). At the middle school level both areas require students to develop models and construct scientific explanations of how water moves through natural systems and interacts with human resource demands. Both of these standards incorporate the science and engineering practice of developing and using models. Middle school students are required to use models to describe phenomena and to describe unobservable mechanisms, like characteristics underground that influence movement and distribution of groundwater (NGSS Lead States, 2013, http://www.nextgenscience.org/msess-es-earth-systems).
The increasing human demand for water and the new standards both call for better understanding of groundwater (Ben-zvi-Assaraf & Orion, 2005; Covitt, Caplan & Cano, 2014; Covitt & Gunckel, 2012; Covitt et al., 2009; Dickerson et al., 2007; Gunckel, Covitt, Salinas & Anderson, 2012). The existing gap in this understanding in k-12 education indicates the need for new curricular materials, specifically the need for physical models that can make visible the unseen phenomena of groundwater. These types of physical models can often be expensive and difficult to acquire for individual schools or educators, but larger public and grant funded institutions, like universities, can fill the gap in providing such tools and resources to individual educators and schools.

The University of Wyoming is currently funding watershed science education outreach programs through the National Science Foundation’s Experimental Program to Stimulate Competitive Research (EPSCoR). The Wyoming Center for Environmental Hydrology and Geophysics (WyCEGH), an interdisciplinary research group at the University formed as part of the program, works to utilize advanced technology and partner with k-12 educators to increase understanding of Wyoming watersheds across the state. A piece of the educational outreach is the provision of water science toolkits, developed in partnership between the University of Wyoming and the Utah Natural History Museum (http://www.uwyo.edu/epscor/ci-water/). These toolkits contain materials to address four major themes around water: properties of water, water in the environment, human use and impact, and next steps: “what do I do now?” (http://www.uwyo.edu/epscor/toolbox.html). One component of these toolkits is a physical groundwater model, manufactured by enVision (See Appendix A) that includes materials to demonstrate how groundwater flows, is stored underground and how humans can influence the
movement, quality and quantity of groundwater. This resource is available as part of the larger toolkit for teachers to reserve and use in their classrooms throughout the school year.

Toolkits that incorporate physical models have been identified as a potential resource to help teachers and students develop mental models of complex and hidden phenomena such as groundwater (Covitt, et al., 2014; Dickerson et al., 2007; Duffy, 2012; Reinfried, 2006). Physical models can help students develop the spatial reasoning necessary to think in terms of interconnected, complex systems (Dickerson et al., 2007; Duffy, 2012). These models and toolkits however have limitations and weaknesses. One of the major challenges for educators using physical models is incorporating them into larger curricular units and placing them in relevant contexts for students (Bodzin & Shive, 2004; Watts & Wray, 2012). If toolkits are used or taken as isolated learning experiences in the school year students are less likely to gain enduring understandings of concepts, or the ability to apply the experience to other situations. Another weakness identified in the use of external toolkits and physical models is the lack of quantifiable assessment on student learning outcomes from the use of the materials (Bodzin & Shive, 2004; Sharples et al., 2014; Watts & Wray, 2012). Assessment should be included as a necessary part of toolkit use so that teachers and external programs, such as EPSCoR, can evaluate efficacy of toolkits and provided curricular materials in terms of increased student understanding.

The gap in assessment of toolkits and models is accompanied more generally by inadequate assessment of students’ concepts of groundwater (Dickerson et al., 2007). Traditional assessments of science concepts often include definitions and the use of vocabulary that can hide misconceptions and lack of complete coherent understandings of complex systems (Covitt et al.,
Assessing Student Understanding of Groundwater

2009; Dickerson et al., 2007). This demands more comprehensive, variable, and authentic assessments to be used while evaluating student understandings of groundwater.

Objectives

This study sets out to one, develop a case for the assessment needed to accompany the use of physical groundwater model, and two, to provide an assessment framework that allows educators to authentically assess middle school students’ understanding of groundwater. The framework is meant to help teachers assess students’ learning in the context of their own curriculum and eventually to allow EPSCoR to assess program efficacy in the form of student learning outcomes. The assessment and accompanying literature review will contribute to a body of research aimed at helping teachers and programs such as EPSCoR improve the quality of watershed science education and improve the efficacy of resources and materials provided to teachers to enhance students’ learning.

Statement of Purpose

This paper sets out to explore, through existing literature and programs, the authentic assessment of learning outcomes from the use of a transportable groundwater model as part of a watershed science toolkit provided to teachers. The goal is to develop an assessment framework to be used as part of the EPSCoR water science toolkits that is flexible enough for teachers to use with different curricular goals and objectives, but also standardized enough to use for overall program evaluation.

Research Questions

Research Question:
What are the essential components of an authentic assessment framework that measures student-learning outcomes from the use of a physical, interactive groundwater model at a middle school level?

**Additional Questions:**

- Why is assessment an important piece of the design and use of watershed science toolkits?
- What are the essential components of assessments in watershed science education, specifically in the context of the Next Generation Science Standards?

**Definition of Terms**

*Educational assessment* – A ‘formal attempt to determine students’ status with respect to educational variables of interest’ (Popham, 2010, p. 7).

*Authentic assessment:*

- Is realistically contextualized
- Requires judgment and innovation
- Asks the students to “do” the subject.
- Replicates real life challenges.
- Assesses students’ ability to efficiently and effectively use a repertoire of knowledge and skill to negotiate a complex and multi-stage task.
- Allows appropriate opportunities to practice, incorporate new information, receive feedback and refine products.

(Wiggins & McTighe, 2005, p. 154)
*Performance Task* – Challenging tasks performed by students that reveal their understanding as transferability of core ideas, knowledge, and skill in multiple contexts to solve problems (Wiggins & McTighe, 2005).

*Formative assessment*—“The process by which teachers gather information about what students know and can do, and interpret and compare this information with their goals for what they would like their students to know and be able to do, and take action to close that gap by giving students suggestions as to how to improve their performance.” (Shavelson et al., 2008, p. 22)

*Diagnostic Assessment* – Assessments designed to obtain information about where the learner is coming from, what their perspectives are, and what do they already know or understand about a subject (Wiggins & McTighe, 2005).

*Summative Assessment* – An assessment that provides a summary judgment about students’ learning over some period of time. The goal is generally to inform external audiences primarily for evaluation, certification, and accountability (Shavelson et al., 2008).

*Modeling Oriented Assessment*-- An integrated form of assessment that can be used both as a way to determine students’ status with respect to variables from a modeling perspective and a way to facilitate and enhance student learning through modeling. It encompasses three dimensions: assessment of modeling products (what students themselves create), assessment of modeling practices (how students use, construct and revise models), and assessment of meta-modeling knowledge (what do students know about their modeling process) (Namdar & Shen, 2015).

*Model* – A human construct used to represent a system or parts of a system under study to aid the development of questions, explanations, to generate data that can be used to make
predictions, and to communicate ideas to others (Namdar & Shen; 2015; NGSS Lead State, 2013).


*Physical Model* – includes diagrams, physical replicas, mathematical representations, analogies, and computer simulations (NGSS Lead States, 2013).

*Systems Thinking* -- The process of understanding how components in a system influence one another within a whole (Duffy, 2012).

*Toolkits* – Any combination of pre-fabricated, pre-designed supplemental educational and curricular materials provided by external entities such universities or museums meant to enhance and support student learning (Bodzin & Shive, 2004; Sharples et al., 2014; Watts & Wray, 2012).
Chapter 2
Review of Literature

Introduction

Exploring assessment of a specific aspect of watershed science education, is important in the larger context of developing a complex and accurate understanding of watershed systems. Thirty percent of the Earth’s freshwater is classified as groundwater, sixty-nine percent is stored in glaciers and ice caps and only one percent is comprised of lakes, rivers etc. (http://water.usgs.gov/edu/earthwherewater.html). Groundwater is an essential source of freshwater for both ecosystems and human consumption. Developing an understanding of groundwater and related essential scientific principles will enable students to make complex future decisions regarding water resource distribution and management necessitated by increasing global population and climate change (Gunckel et al., 2012).

Assessment of student understanding is critical in developing a more comprehensive and engaging approach to groundwater education. This literature review constructs an argument for one, the need for authentic assessment with the use of physical models and two, identifying the essential components of a valid and authentic assessment framework that measures student-learning outcomes from the use of a physical, interactive groundwater model at a middle school level. It explores these questions through a review of the research literature in four broader categories defined by the researcher: groundwater in NGSS; challenges in groundwater education; limitations and advantages of using pre-fabricated toolkits and physical models; and assessment of student’s mental models of scientific phenomena. These four categories were chosen with the view of covering the field of model-based groundwater education and assessment.
Methodology for Literature Search

To find literature and resources primarily entailed searching educational databases such as ERIC and psycINFO. Searches were organized around the four themes. Relevant research referenced in preliminary sources were then sought out, using similar library or database resources, sometimes using non-topic specific databases such as WorldCat and ProQuest. Recommendations on resources and relevant research was also sought from field experts and University of Wyoming faculty such as the literature on FOSS kits, a very well researched program that provides pre-fabricated science toolkits and curriculum to elementary and middle school teachers. Supplemental research on groundwater modeling and groundwater education at a university level was found using Web of Science and GeoRef. Not all research reviewed is included in this synthesis of literature. Research that was related to groundwater education or the four themes, but did not directly address the research questions were excluded from the review. An example is research by J.M. Peckenham, T. Thornton and P. Peckenham (2012), examining the validity of student data collected on groundwater quality. This study is related to groundwater education, however it does not help answer the targeted research questions about assessment that guided this study.

NGSS and Groundwater: The Need for a New Assessment Framework

The NGSS, based upon the National Research Council’s A Framework for K-12 Science Education: Practices, Cross-Cutting Concepts, and Core Ideas (NRC, 2012), emphasize science as an interrelated, practice-based discipline (Namdar & Shen, 2015; Wysession, 2013). This emphasis is particularly clear in the Earth and Space Sciences (ESS), where a systems-based approach is applied to student performance expectations (NRC, 2012; Wysession, 2013). This
new systems approach creates new assessment challenges for educators. This review thus explores literature that identifies new ideas and practices for assessment of NGSS.

NGSS addresses groundwater explicitly in a middle school performance task under the Disciplinary Core Idea (DCI) of Earth and Human Activity (NRC, 2012). This standard, along with another middle school standard under the DCI of Earth’s Systems that asks students to model water cycling, provide the lens through which the literature under this category is focused as well as the context for the broader importance of this study. Both of these standards emphasize the importance of water resources in Earth’s systems, and take an integrative approach in terms of blending skills and ideas that students are expected to achieve. In fact NGSS specifically uses the word practices in order to better describe the blending of content and skills necessary to engage in science. Figure 1 is a visual representation of the two NGSS performance expectations with the incorporated Science and Engineering Practices (SEP), Disciplinary Core Ideas (DCIs), and Cross Cutting Concepts (CCC).

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<th></th>
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</thead>
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<td>MS-ESS2-4: Develop a model to describe the cycling of water through the Earth’s system driven by energy from the sun and the force of gravity.</td>
<td><strong>Developing and Using models:</strong> Modeling in 6–8 builds on K–5 experiences and progresses to developing, using, and revising models to describe, test, and predict more abstract phenomena and design systems.  - Develop a model to describe unobservable mechanisms.</td>
<td><strong>ESS2.C: The roles of water in Earth’s surface processes</strong>  - Water continually cycles among land, ocean, and atmosphere via transpiration, evaporation, condensation and crystallization, and precipitation, as well as downhill flows on land.  - Global movements of water and its changes in form are propelled by sunlight and gravity.</td>
<td><strong>Energy and Matter:</strong> Within a natural or designed system, the transfer of energy drives the motion and/or cycling of matter.</td>
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<td><strong>MS-ESS3-1:</strong> Construct a scientific explanation based on evidence for how the uneven distribution of Earth’s mineral, energy, and groundwater resources are the result of past and current geoscience processes.</td>
<td><strong>Constructing explanations and designing solutions:</strong> Construct a scientific explanation based on valid and reliable evidence obtained from sources (including the students’ own experiments) and the assumption that theories and laws that describe the natural world operate today as they did in the past and will continue to do so in the future.</td>
<td><strong>ESS3.A: Natural Resources:</strong> Humans depend on Earth’s land, ocean, atmosphere, and biosphere for many different resources. Minerals, fresh water, and biosphere resources are limited, and many are not renewable or replaceable over human lifetimes. These resources are distributed unevenly around the planet as a result of past geologic processes.</td>
<td>a) <strong>Cause and Effect:</strong> Cause and effect relationships may be used to predict phenomena in natural or designed systems. b) <strong>Influence of Science, Engineering and Technology on Society and the Natural world:</strong> All human activity draws on natural resources and has both short and long-term consequences, positive as well as negative, for the health of people and the natural environment.</td>
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</tbody>
</table>

**Figure 1.** NGSS Relevant to Groundwater. This figure contains the performance expectations and associated SEP, DCI, and CCC from the Next Generation Science Standards (Lead States, 2013), that mention groundwater and water cycling in earth’s systems.

Little research explicitly addresses groundwater in the context of the new standards, however there is an emerging body of literature that examines the new integrative systems approach required by the standards, and the benefits and challenges it poses to science educators. M. Wysession (2013) examined changes in the standards, and new emphasis placed on Earth and Space Science (ESS). He highlighted the new systems approach taken in ESS: ESS are an integrated system composed of interrelated concepts that cut across traditional science disciplines such as physics, chemistry and biology.

The two standards highlighted in Figure 1 emphasize this kind of interdisciplinary skills based approach. The first standard MS-ESS2-4 incorporates the SEP of mental modeling based on the use of physical systems models. It is important to look at the distinction between physical models and mental models as they are outlined in the standards.
The SEP of developing and using models is based on the following definitions. First is the definition of a “physical” model or representation: “Models include diagrams, physical replicas, mathematical representations, analogies, and computer simulations” (NGSS Lead States, 2013, Appendix F, p. 6). Students are expected to be able to use these types of models or systems representations to increase understanding of phenomena and proficiency in the scientific practice of modeling: “In science, models are used to represent a system (or parts of a system) under study, to aid the development of questions and explanations, to generate data that can be used to make predictions, and to communicate ideas to others” (NGSS Lead States, 2013, Appendix F, p. 6). Embedded with these more mechanical definitions are expectations of what students should be able to achieve in terms of using physical models to develop deeper understanding of content and scientific practice:

All models contain approximations and assumptions that limit the range of validity and predictive power so it is important for students to recognize their limitations ( . . . )

Students can be expected to evaluate and refine models through an iterative cycle of comparing their predictions with the real world and then adjusting them to gain insights into the phenomenon being modeled. As such, models are based upon evidence. When new evidence is uncovered that the models can’t explain, models are modified. (NGSS Lead States, 2013, Appendix F, p. 6).

Students are expected to use models as a method for practicing science and acquiring new knowledge and thus continually develop and revise their own mental models of scientific phenomena. This definition in and of itself is complex and its incorporation into the standards demands that educators not only assess students on their content knowledge but also on their understanding and practice of scientific modeling.
The standards relating to groundwater and the hydrologic cycle call for students to develop and use models as they are outlined in the SEP. The model must apply concepts from multiple disciplines to describe an accurate model of the earth’s hydrologic system with the driving forces behind circulation of water resources in the hydrosphere, including human activity.

This integrative approach, while exciting in its provision of a more realistic and engaging approach to ESS education, poses challenges, particularly in the realm of existing assessments and assessment practices (Herman National Center for Research on Evaluation, Standards, and Student Testing, 2013; Namdar & Shen, 2015; Wysession 2013).

The NGSS performance expectations, and Earth and Space Sciences in particular, will pose special challenges to their implementation. Most current science assessments test memorized facts. Shifting toward testing what students can do, instead, will require new approaches to assessment. (Wysession, 2013, p. 37)

This challenge calls for researchers, educators and curriculum developers to think creatively about new forms of assessment that accurately represent and capture student skills and knowledge integral to scientific practice and understanding. Groundwater presents a particular challenge because it is an essential, yet invisible part of the hydrologic cycle.

**Challenges in Groundwater Education**

The invisible nature of groundwater makes it a difficult subject for teachers to teach and for students to understand. Students and teachers cannot physically see or experience groundwater which is a major barrier to a conceptual understanding of what groundwater is, how it exists, and how it interacts with the rest of Earth’s systems (Ben-zvi-Assaraf & Orion 2005;
The difficulty in conceptualizing groundwater is compounded by the necessity for spatial reasoning ability in constructing accurate mental models of groundwater (Dickerson et al., 2007; Duffy, 2012; Covitt et al., 2009). Students are typically asked to use two-dimensional static diagrams and representations to build mental models of three dimensional dynamic phenomena (Duffy, 2012). Without development of spatial reasoning this leap is difficult and can lead to misconceptions about the scale and form of groundwater. Covitt et al. (2009) found that even by the end of high school many students still struggled with conceptualizing the invisible parts of the hydrologic system, specifically at the microscopic and macroscopic scales. These parts of the invisible system include aquifers, water treatment systems, and water vapor in the atmosphere.

The importance of scale and of systems is captured in two of the NGSS crosscutting concepts. These two concepts are:

*Scale, proportion, and quantity.* In considering phenomena, it is critical to recognize what is relevant at different measures of size, time, and energy and to recognize how changes in scale, proportion, or quantity affect a system’s structure or performance.

*Systems and system models.* Defining the system under study—specifying its boundaries and making explicit a model of that system—provides tools for understanding and testing ideas that are applicable throughout science and engineering. (NGSS Lead States, 2013, Appendix G, p. 1)

While neither of these concepts are explicitly associated with the two middle school standards from Figure 1, both CCCs require students to use systems and models that integrate concepts across disciplines. The two crosscutting concepts above are essential to building mental models
and identifying systems. Systems thinking is the process of understanding how components in a system influence one another within a whole (Duffy, 2012). To understand groundwater and other hidden parts of the hydrologic cycle, including human engineered ones, students need support in developing spatial reasoning and systems thinking approaches to scientific phenomena.

Gaps in student spatial reasoning ability and an inability to define systems leads to student conceptions of groundwater as an isolated, dead-end entity existing underground, with little or no connection to other parts of the hydrologic system (Ben-zvi-Assaraf & Orion 2005; Gunckel et al., 2012). Gunckel et al. (2012) found that eighty-nine percent of high school students could not provide model-based accounts of the hydrologic system. Students often focus only on atmospheric components of the water cycle such as clouds and precipitation, ignoring processes and parts of the cycle such as interactions between surface and groundwater, and water’s role in Earth’s atmospheric, biological, and geological systems (Ben-zvi-Assaraf & Orion 2005; Gunckel et al., 2012; Dickerson et al., 2007).

Despite the importance of groundwater, why is there such a gap in student understanding? At least part of the answer lies in inadequate instruction in scientific practices such as modeling, but also in inadequate preparation of science teachers to teach interdisciplinary, complex scientific concepts (Dickerson et al., 2007; Gunckel et al. 2010; Windschitl, 2009).

Necessity and demand for hydrologic systems education poses challenges to educators at both K-12 and postsecondary levels (Dickerson, 2007; Covitt et al. 2009; Gleeson, et al., 2012). As Gleeson et al. put it in their review of current practices in hydrogeology education, “Developing an educational framework that allows for exposure to the multidisciplinary nature
of current hydrogeological problems, incorporation of emerging techniques and coverage of the scientific fundamentals are key to dealing with our planet’s groundwater issues” (2012, p. 2160). Although this study is focused on undergraduate education it points out a shortcoming in hydrogeology education: Instructors are often unprepared to teach in the interdisciplinary way that effective instruction in hydrogeology demands, even at a college level. The authors argue that an instructional framework needs to include appropriately balanced time spent on field studies, laboratory and computer exercises, and classroom instruction (Gleeson et al., 2012).

The previous study identifies a deficiency in postsecondary hydrogeology education. While this may seem unimportant to K-12 education, it highlights the difficulty in teaching hydrogeologic concepts even at a collegiate level. For many K-12 educators to effectively teach concepts such as groundwater they will need further professional development and support to tackle these challenging concepts, and engage their students in developing mental models of groundwater and hydrologic systems required by the standards.

Supporting student development of model-based scientific reasoning, especially around groundwater, demands that teachers have strong and conceptually connected knowledge of science content and science practices (Covitt & Gunckel, 2012, Dickerson et al., 2007; Windschitl, 2009). NGSS asks students to connect complex concepts and build scientific explanations based on evidence (NGSS Lead States 2013). Unfortunately research conducted with both pre and in-service teachers found that teachers’ scientific accounts of groundwater and other scientific phenomena lack the depth of understanding and strong integration across science topics needed to support effective instruction (Covitt et al., 2014; Covitt & Gunckel, 2012; Dickerson et al., 2007; Gunckel, Covitt, Salinas, & Anderson, 2010; Windschitl, 2009). In fact,
teachers’ accounts of phenomena in hydrologic systems often differ very little from their students’ (Dickerson et al., 2007; Covitt et al., 2009).

Research by Covitt and Gunckel (2012), conducted as a part of the Pathways to Environmental Literacy Project (http://www.pathwaysproject.kbs.msu.edu), demonstrates that most teacher accounts of hydrologic systems do not meet the expectations for student understanding at the end of high school described in the Framework for K-12 Science Education (National Research Council, 2012). Researchers define this highest (fourth level) of understanding in their hydrologic systems learning progression, as Scientific Model-based Accounts that “acknowledge driving forces and constraining factors on pathways for water and substances in water” (Covitt & Gunckel, 2012, p. 2). These accounts include descriptions across scales ranging from molecular to landscape. Most teachers in the study instead provided what the researchers qualify as level-three responses. These accounts are called Science Stories that trace water along hidden and visible pathways and at multiple scales. What these accounts lack are the causal relationships between mechanisms and how and why events occur, and the recognition of driving forces and constraining factors that define how water moves through a system (Covitt & Gunckel, 2012). The researchers argue that model-based reasoning is what is necessary to develop environmentally literate citizens as well as meet the science understandings and practices outlined in NGSS. These standards will be difficult to achieve if teacher levels of scientific reasoning are not at the level the standards ask for.

Mark Windschitl (2009), in a review of literature on current science teaching practices, argues that a lack of content knowledge and proficiency in science practice account for the deficiency of model-based reasoning among some K-12 teachers. He asserts that “teachers with limited subject matter preparation tend to emphasize memorization of isolated facts ( . . . ) they
use lower level questioning and rule-constrained classroom activities” (p. 12). This type of instruction does little to support students in developing the science literacy described by Covitt & Gunckel (2009).

Dickerson et al., (2007) explore the reasons for a gap in understanding among teachers pertaining to groundwater. Like Windschitl’s (2009) study, Dickerson et al. (2007) found that inadequate formal instruction for teachers, specifically in groundwater and earth science concepts, leads them in their practice to either “avoid teaching the concept or use instructional strategies that severely reduce student autonomy to limit student questions to the realm of teacher’s content understanding” (p. 49). Currently practicing science teachers who have had little exposure to groundwater content and science modeling practices will need support in order to help their students in achieving the performance tasks set out by the new standards and in assessing student status against them.

The lack of teacher and student understanding of groundwater as part of a larger hydrologic, biologic, geologic and human system, illuminates the push in the NGSS for students to apply disciplinary core ideas, crosscutting concepts and science and engineering practices to develop more integrative and sophisticated models of Earth’s systems. This demand however will require support for currently practicing teachers in the form of professional development and classroom resources. In the case of groundwater and hydrologic content, these opportunities need to include content knowledge as well as tools and assessments that accurately enhance and capture student understanding of content as well as their mental models that explain hydrologic phenomena. If teachers do not have the requisite understanding to teach hydrologic concepts such as groundwater then they will not be able to support their students in achieving the
standards or to effectively assess student understanding as it relates to the performance expectations laid out by the standards.

**Physical Models and Toolkits in the Classroom**

Providing support to teachers requires targeted professional development around watershed science and systems combined with the provision of hands-on materials and classroom curricular support. These materials should enable teachers to engage in active inquiry and model development with their students and assess student progress and understanding throughout the course of a project or unit. For teaching parts of hydrologic systems like groundwater, which are inherently hidden from view, resources such as virtual and physical representations help teachers uncover these hidden phenomena and help students build accurate mental models (Bodzin & Shive, 2004; Duffy, 2012; Sharples et al., 2014).

These tools and materials often are in the form of online modules, computer simulations, inquiry toolkits, diagrams, and physical models. A number of studies evaluated the use of computer or web-based toolkits that facilitate collaborative inquiry in STEM classrooms. Three studies in particular went through the process of developing and or evaluating computer-based and physical STEM inquiry toolkits (Bodzin & Shive, 2004; Sharples et al., 2014; Watts & Wray, 2012). All three of the studies aimed to support teachers in incorporating inquiry practices into their classrooms with the hope of increased student engagement in STEM fields.

Bodzin and Shive (2004) identified essential components for a web-based watershed inquiry toolkit. Through a collaborative process of interviews with one middle- and two high school teachers the researchers and teachers identified these components: a motivating entry point, opportunities to make sense of a relevant setting, access to authentic data, opportunities to
make sense of the data, a goal of developing explanations based on the data, and the development of some kind of final product or culminating experience.

Another study (Sharples et al., 2014) investigated the use of a digital scripted inquiry toolkit in two different classrooms. The goal of the tool was to support teachers without experience in teaching inquiry to implement inquiry practices in their classroom. They found that after the use of the toolkit students were able to, with the guidance of the teacher, apply the inquiry process to a problem outside the classroom.

The third study (Watts & Wray, 2012) is an evaluation of three different commercially developed toolkits in STEM subjects. The findings indicate that that all the toolkits were successful in generating and developing student communication, engendering student enjoyment of an interactive activity, giving students a framework for vocabulary, and generating an appreciation for nonlinear processes.

It is useful at this point to revisit the definition of models and modeling used in NGSS. Under the NGSS definition models represent “a system (or parts of a system) under study, to aid in the development of questions and explanations, to generate data that can be used to make predictions, and to communicate ideas to others” (NGSS Lead States, 2013, Appendix F, p. 6). All three of the studies above describe outcomes from the use of inquiry toolkits that incorporate the essential pieces of using and developing scientific models. Inquiry is a tool that helps students engage in scientific thinking and processes and allows them to use and develop mental models. While this potential strength of inquiry toolkits is indicated in all three studies, there are limitations in the use of toolkits and their real influence on student understanding of scientific phenomena.
All three studies reveal a gap in assessing the outcomes from the use of STEM toolkits on long-term student understanding of STEM fields. Sharples et al., write “as with many educational innovations, there are no straightforward conclusions as to whether scripted inquiry learning changed the young people’s inquiry skills and attitudes to science” (2014, p. 337). Watts and Wray (2012) evaluated three different toolkits. They identified two shortcomings associated with the use of toolkits are a general lack of applicability to broader STEM concepts, and lack of effective embedded assessment for student learning during and after use. All three studies mention that use of inquiry toolkits, unless connected with a larger curriculum and put into the context of larger, real world problems, such as global freshwater distribution, is limited in its ability to increase student understanding of concepts and of scientific processes (Bodzin & Shive, 2004; Sharples et al., 2014; Watts & Wray, 2012).

Physical models and inquiry toolkits, despite their utility in uncovering hidden phenomena, and engaging students in parts of the scientific modeling process, are limited in what they can actually represent. The NGSS specify that students as part of the SEP of developing and using models must identify the limitations of a representational model in actually capturing the variability and complexity of the system as it is in the real world (NGSS Lead States, 2013). Without measuring student progress in understanding of content, scientific skills and processes, it is difficult to then assess student application of knowledge to novel scientific situations and systems that exist outside the classroom, and to uncover student misconceptions that might arise from the use of toolkits and physical models.

This all indicates the need for assessments to be developed and included with toolkits and for the toolkits to be integrated into larger curricular goals. The assessments accompanying toolkits should not only align with learning goals, but also align with the new standards to
maximize support for teachers in meeting them. Full Option Science Systems (FOSS), a research-based science curriculum developed at the Lawrence Hall of Science, University of California Berkeley, is an example of a toolkit-type resource for teachers that includes physical and multimedia digital models integrated into curriculum and learning progressions. The FOSS learning progressions include embedded formative and summative assessment systems (http://www.fossweb.com/what-is-foss).

FOSS in many ways seeks to resolve or overcome the limitations inherent in the use of externally developed curricular materials (such as toolkits) aimed at helping teachers and students engage in hands-on, inquiry-based science. The Lawrence Hall of Science developed an evaluation framework called assessing science knowledge (ASK) to accompany FOSS kits. This framework had two objectives: one, developing daily classroom assessment practices that guide student learning and enhance teacher instructional practices, and two, developing assessments needed to provide accountability to schools and districts (Long & Malone, 2006). The program also has a robust body of evaluative literature on the influence of using FOSS curricula on both teachers and students (Deutscher, 2009 & 2010; Long & Malone, 2006; Long, Malone & De Lucchi, 2008; Robardey, Allard & Brown, 1994).

In one study, twenty-nine third and fourth grade teachers and twenty-five fifth and sixth grade teachers, who participated in a 48 hours of a FOSS training and assessment course, taught at least one FOSS lesson to their classmates to check understanding of FOSS concepts, and subsequently taught at least one FOSS lesson to their students. One particularly interesting aspect of this study was that the researchers specifically left out the hands-on curricular materials from the kits they provided to their study participants. Rather they focused on providing them training on how to use the written FOSS curriculum provided. Their results found that teachers who
participated significantly increased their confidence toward teaching science, science content knowledge, and attitude toward teaching science (Robardey, et al., 1994). It suggested that professional development and training for teachers is an essential piece of providing curricular support materials, both written, and hands-on models and materials. The materials in isolation may not support teaching and learning if teachers do not feel confident in using the materials and have the content knowledge to support their teaching.

Another study specifically examined the challenges in the use of multimedia materials accompanying FOSS kits (Deutscher, 2009). The study surveyed 539 middle school teachers who had used FOSS multimedia modules in order to identify and evaluate the challenges in use of these modules. The results indicated that teachers generally felt challenged in knowledge of how to use certain pieces of the multimedia, i.e. whether it would be better as a teacher demonstration or as an interactive student experience. As a result most teachers defaulted to using it as demonstration, depriving students of a potentially enriching inquiry experience. The multimedia accompanying FOSS kits is structured partially for student-interactive experience, and partially for use in teacher demonstration, however this is not clearly stated in the instructions provided. This is paired with a challenge in providing appropriate professional development around use of multimedia. The study found that trainers often demonstrated and discussed multimedia in a way that they wouldn’t necessarily use it in the classroom. The lack of appropriate instruction with the modules and the inadequate professional development in how to use them with students, limits the potential benefits to students in the use of such curricular materials.

This is important in light of the potential utility of digital and physical media in combination with curricula in helping students grasp difficult to see phenomena and concepts.
such as space science and groundwater (Deutscher, 2010; Duffy, 2012). It suggests that simply providing digital and physical media to teachers in isolation is not enough to increase student or teacher understanding or enable students to achieve the new science standards.

Limitations exist even when the use of toolkits is embedded within curricula and include assessment. One in particular is that teachers need adequate training in how to use the modules, including the materials and assessments, the other is that educators and curriculum developers need to be careful that students do not misinterpret the content being presented in digital or physical models (Deutscher, 2010). This particular problem of being sure to uncover student misconceptions before progressing is one that could be addressed by formative assessment, which gives teachers a method of eliciting student understanding and adapting teaching practice to address gaps and misconceptions (Long et al., 2008).

The use of curricular support materials can be an important resource for teachers to help them develop their practice and thus help students develop the content knowledge and scientific skills needed to engage in the practice of scientific modeling. They can help increase teacher confidence in teaching subject matter, help students conceptualize hidden material, and engage students in hands-on scientific processes. To effectively support teachers in meeting their goals and the standards, and in developing student understanding of complex concepts such as groundwater, these toolkits cannot be used in isolation. They need to be incorporated into a larger curriculum that connects to larger science themes and concepts and include embedded assessments that inform classroom practice, uncover misconceptions, and ask students to apply knowledge to real world situations such as groundwater resource distribution.
Assessing Student’s Mental Models of Groundwater: Model Oriented Assessment

Physical models provide a bridge between scientific theory and systems as they exist in reality; they can be used as tools for representation as well as prediction and evaluation (Gilbert, 2004). In education, the blending of content knowledge, skills, and application all come together in the practice of scientific modeling if done in a way that reflects the practice as it exists in the scientific community (Duffy, 2012; Gilbert, 2004; Krajcik, 2013; Namdar & Shen, 2015). The NGSS use synthesized Science and Engineering Practices, Crosscutting Concepts, and Disciplinary Core Ideas to create student performance expectations. Learning a core idea or concept is achieved by its use in a science or engineering practice such as modeling (Krajcik, 2013). This blending of the three dimensions is embedded in learning progressions meant to help students gradually build more sophisticated and accurate mental models of scientific phenomena (Herman et al., 2013).

This emphasis on blending three dimensions is meant to provide students with a more authentic and relevant science education. Gilbert (2004) argues that for science education to improve, curricula need to be designed around scientific modeling. This however also requires authentic and valid assessment of modeling practices. To this point very little research has been done on how the assessment of mental models can successfully measure student progress in all three pillars of the NGSS (Namdar & Shen, 2015). The development of a unified framework for assessing mental models of scientific phenomena, particularly those that are difficult to conceptualize, is an essential and useful step in helping educators teach and evaluate scientific material and practices that they may not have a solid grasp of themselves. This is a challenge in light of the dynamic nature of modeling practices such as revision, incorporation and communication which are all intertwined throughout the learning process rather than achieved in
a linear progression (Namdar & Shen, 2015). This challenge is also reflected in the difficulties in teaching hydrology and groundwater to students at all levels. There is a need for a dynamic curricula that include practical, hands-on, and contextualized instruction with multiple opportunities and avenues for students to explore groundwater concepts and incorporate concepts from multiple disciplines (Covitt et al., 2009; Gleeson et al., 2012; Reinfried, 2006; Wysession, 2013).

Most studies on model-oriented assessment rely on pre- and post-tests to evaluate student’s development of mental models. Although this is an important tool for gathering quantifiable data, it can be limited in its actual validity in assessing student’s progression of mental model building and the content and skills associated with the model (Namdar & Shen, 2015). As mentioned above it is difficult with traditional pre and post-test type assessments, pencil and paper assessments, to capture the dynamic aspects of mental model building and its connection with conceptual understanding. To assess students’ modeling practice, modeling products, and meta-modeling knowledge, necessitates the evaluation of students performing authentic modeling tasks that allow to them demonstrate all aspects of their understanding (Namdar & Shen, 2015).

Research conducted by Bamberger and Davis (2013) supports the connection between model-based instruction and improvement of scientific modeling practice as well as an increase in scientific content knowledge. They evaluated improvement in both areas by administering a pre and post-test to sixth grade students participating in a pilot curriculum based on the nature of matter that included scientific modeling practices. The most compelling finding was in their evaluation of transfer of modeling practices to other or new content areas. Students were able to apply modeling practices, specifically explanation, comparativeness, abstraction, and labeling, to
a new content area, friction, that was not taught in the curriculum. The student’s content understanding of friction however, did not show any significant increase. This is unsurprising in light of its not explicitly being taught in the curriculum and it brings up an interesting gap in understanding about how the interplay between content and model oriented instruction informs student understanding of scientific phenomena and their ability to build accurate mental models.

It is not enough to simply give students modeling tools without context and expect them to improve their content understanding in new realms.

If the use of physical models to help build accurate mental models of phenomena is meant to help students engage in authentic scientific practice, then students need to apply concepts from models used as external spatial representations in the classroom to the actual phenomena (Rivet & Kastens, 2012). The Scientific community builds physical models to express or test scientists’ understanding of how real dynamic systems works. This model then goes through a process of revision based on data from the real systems modeled and the model is thus refined (Rivet & Kastens, 2012). This scientific practice is incorporated into NGSS under the skills required for scientific modeling:

All models contain approximations and assumptions that limit the range of validity and predictive power so it is important for students to recognize their limitations...Students can be expected to evaluate and refine models through an iterative cycle of comparing their predictions with the real world and then adjusting them to gain insights into the phenomenon being modeled. As such, models are based upon evidence. When new evidence is uncovered that the models can’t explain, models are modified. (NGSS Lead States, 2013, Appendix F, p. 6).
To this point very little is known about how to develop learners’ abilities to participate in this important aspect of scientific discourse about the limitations of a representational model, and how to change it in light of new evidence and data (Rivet & Kastens, 2012). This will require a form of assessment that provides feedback to students as they explore physical models, and data and evidence gathered from the real system being represented (Herman et al., 2008; Namdar & Shen, 2015; Shavelson, 2008). Along with this process, students should undergo informal and formal assessment that helps teachers evaluate their progress, and provides students feedback on their progress towards meeting knowledge and skills objectives related to scientific modeling of the system under study.

To understand how students are constructing understanding and scientific mental models, assessment must be present throughout the process that helps students grasp the content as well as the practices associated with model building (Herman et al., 2008; Shavelson et al., 2008). These assessments should also inform teachers and researchers as to how students are constructing increasingly sophisticated models in order to improve instruction and assessment practices.

Namdar and Shen (2015) in a synthesis of research from 1980 to 2013 on Model Oriented Assessment (MOA) identified gaps in the literature and generated recommendations for building an authentic unified framework that assesses students’ model making capabilities. They argue that authentic and valid MOA should be guided by a framework with three basic principles: first, MOA should be framed in an ecology of assessment that works to evaluate all aspects of scientific modeling and their connections to each other and to content understanding. Second, the media through which students engage in modeling activities, such as a physical model, should also be the media through which students are assessed. Third, it must be clear to the students and
the teacher what essential aspects or skills of modeling are being assessed (Namdar & Shen, 2015). These assessments, in some combination should assess students modeling capabilities, the modeling products they produce and students’ meta-modeling knowledge. The authors argue that for MOA to move forward and for teachers to assess students’ mental models effectively, there needs to be continued research on the development and use of a framework for model oriented assessment.

**Essential Elements in Assessing Student Understanding of Groundwater**

The NGSS ask students to engage in the use of mental model building and evaluation to build their understanding of real world systems. One of these is the Earth’s hydrologic system, including groundwater as a resource available and affected by human use (NGSS Lead States, 2013). For teachers to accomplish effective instruction in groundwater, it will require the use of physical models or representations of groundwater to help students build understanding and scale that understanding to groundwater as an integral part of a larger hydrologic system (Dickerson et al., 2007, Duffy, 2012; Gilbert, 2004). Physical representational models are a bridge between abstract invisible phenomena such as groundwater that exist at too large a scale to bring into a classroom and the phenomena as they exist in Earth’s Systems (Rivet & Kastens, 2012). Thus it is important that these models are incorporated into classrooms in a way that allows for students and teachers to authentically explore phenomena through the use of physical models and develop accurate mental models that they can apply to the real world. This application requires teachers to have the tools necessary to assess and support their students through the process of constructing mental models of groundwater.
In synthesizing the literature the following challenges and recommendations emerged in developing an authentic and valid assessment framework of students’ understanding of groundwater with the use of a physical groundwater model:

1. The physical model must be incorporated into a learning progression, with embedded assessments.
2. These assessments should measure student progress against established learning goals that flow directly from relevant NGSS.
3. These assessments should support students in building more accurate mental models of groundwater and in developing scientific modeling practices.
4. Effective modeling oriented assessments must evaluate students’ blending of content understanding and skills in the practice of scientific modeling.

The methods section will describe the tools and theory used to address these challenges and develop an assessment framework for student understanding of groundwater with the use of a physical groundwater model at a middle school level.
Chapter 3
Methodology for Creating an Assessment Framework

Introduction

The goal this assessment framework is to help educators effectively use and incorporate the physical groundwater model into their teaching and evaluate student outcomes and learning from the use of the model. The groundwater model being used as part of the EPSCoR toolkit, and teacher professional development, was manufactured by enVision, a manufacturer of environmental education products and groundwater flow models (http://www.gwmodel.com). The model simulates groundwater flow in sand and gravel aquifers including the interactions between surface and groundwater and groundwater’s role in the hydrologic cycle (Figure 2). A full description of the model and the materials included in the kit can be found in Appendix A.

Figure 2. The enVision 2000 Groundwater Flow Model. This model is included in the CI-water toolkits provided by EPSCoR for use in Wyoming K-12 classrooms.

The use of the model is an opportunity for teachers and students to uncover misconceptions about groundwater, test preconceptions, and develop new understandings about groundwater and
Assessing Student Understanding of Groundwater

its place in a larger hydrologic system. The developed assessment is meant to guide teachers through this process with the appropriate strategies and prompts.

**Formative Assessment and Scientific Modeling**

The groundwater assessment framework embeds formative assessment throughout a potential learning progression for groundwater, providing prompts, questions and activities that will help teachers assess student understanding throughout use of the groundwater model. It supports students in building accurate models of groundwater and developing modeling practices, as well as provide a constant stream of information to teachers about how learning is progressing in their classroom.

Figure 3 provides one example of how and in what ways formative assessment can be embedded into learning progressions and curriculum. Teachable moments are moments that arise spontaneously in the course of a lesson that can reveal gaps in student understanding, or misconceptions. For example if a student asks the question: “How does water get into the ground?” it is an opportunity for the teacher to direct a lesson or activity towards understanding permeability and porosity, both of which are fundamental concepts in groundwater education.

![Figure 3. A model for embedding assessment into curriculum](source: Shavelson et al., 2008; modified.)
Planned formative assessments are those formulated in advance that elicit specific information at specific times, such as targeted or central questions that relate to larger learning goals and essential concepts. Formal planned assessments are those explicitly embedded into the curriculum at critical transitions: places in the learning progression where it is essential to know what students understand before moving on (Shavelson et al., 2008). In the groundwater assessment framework these benchmark assessments take the form of performance tasks that students must complete at three junctures throughout the assessment progression. In this way the performance tasks serve as both formative and summative assessments that allow teachers to authentically assess student progress and provide accountability to external assessors such as administrations.

The framework has a repeated formative assessment cycle that progressively builds toward meeting learning goals. If student misconceptions or lack of understanding is uncovered during the cycle, it directs teachers to go back and revisit or identify where the gaps are and what they must do in order to fill them (Herman et al., 2008; Popham, 2008).

Formative assessment is also a critical element in the framework to create authenticity of the assessment of students’ mental models (Covitt et al., 2014; Namdar & Shen, 2015). This connection is not made explicit in much of the literature, however, an essential practice in both scientific modeling and formative assessment is feedback provided within the context of a respectful scientific community (Covitt et al., 2014; Rivet & Kastens, 2012; Wiliam, 2008). Feedback should be directly relevant to learning goals and students’ progress relative to those goals (Wiliam, 2008). The framework uses formative assessment to help teachers and students give and receive feedback that will guide students through the process of building and developing mental models.
The framework also addresses an important practice in authentic scientific modeling: reflection and meta-cognition on the modeling process (Namdar & Shen, 2015; Rivet & Kastens, 2012), by asking students to reflect on their own mental models and the practices used to develop them. In this way the framework treats model oriented and formative assessments as integrated parts of an authentic assessment framework for evaluating understanding of scientific phenomena such as groundwater.

**Setting Learning Goals and Performance Tasks: Backward Design**

For assessments, diagnostic, formative, and summative, to be authentic they must measure progress against learning goals (Herman et al., 2013; Namdar & Shen, 2015; Shavelson, 2008; Wiggins & McTighe, 2005). The framework developed from this research, uses the theory and structure of backward design to align learning goals and assessments. Backward design is the process of developing curriculum guided by long-term goals through a three-stage design process: desired results (learning goals), assessment evidence, and learning plans (Wiggins & McTighe, 2005). The first two stages are explicitly used in the groundwater assessment framework by setting goals for understanding and learning based on larger themes and established goals such as NGSS and providing assessment evidence aligned with those goals. The goals developed are a guide for the use of the groundwater model, and are also the metrics against which student performance is measured. The design does not include stage three learning plans, but does include a diagnostic, formative, and summative assessment progression embedded in learning events.

Figure 4 demonstrates connections between established goals from EPSCoR and NGSS, guiding curricular goals, and essential questions used to develop the assessments included as part of the larger assessment framework. Performance tasks directly address and answer essential
questions, help students achieve enduring understanding using the physical groundwater model and serve as both formative and summative assessments (Wiggins & McTighe, 2005). This framework provides an example of learning goals and assessments developed to help students understand groundwater and develop scientific modeling capacity.

Figure 4. Backward Design. Connections between established goals and curricular goals. The arrows represent connections between specific established program goals, NGSS, and curricular goals and essential questions. The repeated colors demonstrate the sustained connection to broad program themes throughout the stage 1 design process.

The process of backward design can be limiting in its ability to actually capture the flexibility and dynamic nature of assessments needed to ascertain student understanding of groundwater (Cho & Trent, 2005). Because this understanding necessitates an accurate mental
model, which will look different for each student, the framework asks students to share and justify their own perspectives as part of a process of collaboration and feedback with peers and instructors (Cho & Trent, 2005; Namdar & Shen, 2015; Shavelson, 2008). In the framework formative assessment is embedded in backward design to help expand the curricular framework to be more inclusive and student centered, rather than synoptic and heavily reliant on more formal traditional assessments (Cho & Trent, 2005; Shavelson, 2008; Wiliam, 2008). This guiding gives the framework authenticity in creating an assessment for student understanding of groundwater. The incorporation of formative assessment in the framework guides students and teachers through a productive and inclusive dialogue with multiple opportunities to demonstrate understanding and receive and provide feedback, that supports the students in building understanding and providing authenticity to the assessment (Shavelson et al., 2008).

**Fundamental concepts that guide learning goals.**

In this assessment framework the fundamental concepts needed for students to develop accurate understanding and mental models of groundwater were identified through a process of interviews with hydrologists and hydrogeologists, both in the academic and professional realm, as well as a survey of literature on groundwater education and watershed science education in general (Brody, 1995; Dickerson et al., 2007; Duffy, 2012; Gunckel et al., 2009). The full matrix of concepts identified, as well as relevant notes can be found in Appendix B. The concepts that were used in the assessment framework are found at the beginning of the unit in chapter 4 and listed in Table 1 and identified as core concepts for building understanding of groundwater. The decision of what concepts appear in the framework was based upon the frequency with which experts identified the concept as essential to a conceptual understanding groundwater, verified by research literature and the conceptual relevance to the NGSS.
Table 1

*Groundwater Core Concepts*

<table>
<thead>
<tr>
<th>Concept</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water has unique chemical and physical properties</td>
<td>Physical and Chemical structure of water. How it bonds, its polarity, how it interacts with other substances.</td>
</tr>
<tr>
<td>Porosity</td>
<td>Groundwater exists in the pore spaces between grains or units of material. Different materials have different porosities. It also exists in fractures in bedrock.</td>
</tr>
<tr>
<td>Permeability</td>
<td>The ability of a material to transport water through itself (How rapidly does water move through a substance?)</td>
</tr>
<tr>
<td>Structure</td>
<td>What does it look like underground where groundwater exists? The underlying geologic structure of the Earth determines, how and where groundwater exists.</td>
</tr>
<tr>
<td>Pressure Gradients and Force Dynamics</td>
<td>Groundwater flows along gradients from areas of high pressure to areas of low pressure.</td>
</tr>
<tr>
<td>Velocity and Directional Flow</td>
<td>How rapidly does water move through soil or rock? This is influenced by the permeability and porosity of the rock or substrate, and the pressure gradients that exist. Water can move both vertically and horizontally through the ground.</td>
</tr>
<tr>
<td>Connection between groundwater and surface water</td>
<td>Groundwater is part of the whole connected hydrologic system. Groundwater levels can influence base flow in rivers. A depletion of groundwater can lower the base flow in rivers. There is exchange between groundwater and surface water.</td>
</tr>
<tr>
<td>Humans use Groundwater</td>
<td>Groundwater serves many purposes, with the largest amount going towards Agricultural Production. It comes out of our taps in our homes, and goes into producing our food and products we use every day (<a href="http://water.usgs.gov/edu/wugw.html">http://water.usgs.gov/edu/wugw.html</a>). Humans drill wells to access water in both confined and unconfined aquifers.</td>
</tr>
<tr>
<td>Humans influence the distribution and quality of groundwater resources.</td>
<td>Human use can deplete or recharge groundwater supplies. Human activity can contaminate or clean up groundwater sources.</td>
</tr>
</tbody>
</table>

*Note:* These concepts were developed from personal communications and literature on groundwater and water education (Brody, 1995; N. Claeys, personal communication, January 28, 2016; Dickerson et al., 2007; Duffy, 2012; Gunckel et al., 2009; G. Moser, personal communication, May 24, 2106; USGS Water Science School (http://water.usgs.gov/edu/mearthgw.html); Y. Zhang, January 29, 2016, personal communication.).

These concepts guided the development of each assessment. They serve as a foundation upon which to build understanding and can all be demonstrated, taught, and assessed using the physical groundwater model. These core concepts underlie the transfer goals, enduring
understandings, and essential questions. These goals, understandings, and questions ask students to integrate these fundamental concepts and apply them, in order to engage them in the process and skills of scientific modeling and understanding content.

**Developing a Pre and Post Test**

In the framework pre and post-tests provide relatively straightforward accountability that external agencies and standards often require (Shavelson et al., 2008; Wiliam, 2008). They are included in the developed framework as a piece of evidence that is part of a larger assessment. The development of pre and post-test questions stem directly from the transfer goals, enduring understandings, and essential questions used in stage one of the curriculum design.

The pre-/post-test developed in this framework measures students’ understanding of the goals and objectives from stage one. The test was developed by adapting questions on groundwater from a pre- and post-test developed by Gunckel et al. (2009), meant to inform the development of a learning progression for students’ understanding of water in environmental systems. New questions were developed, or existing ones enhanced in order to make the test align with stage one design objectives. Questions include elements that ask students to draw, verbally describe, or add to images of groundwater systems, or parts of a system.

**Assessing Skills and Content: Model Oriented Assessment and Learning Progressions**

This section describes the methods used to develop a learning, understanding and assessment progression that is meant to evaluate student progress relative to established goals, as well as support student learning in building understanding of groundwater content knowledge and modeling practice.

The progression starts with diagnostic assessment to engage and uncover the student’s prior understanding then works through a cycle of diagnostic and formative assessments leading
up to each performance task. The progression cycles are based on a model-building strategy identified by Taylor, Barker, and Jones (2003) and modified by Reinfried (2006).

*Figure 5.* Phases of mental model building. *Source:* Taylor et al., 2003; Reinfried, 2006; modified.

Figure 5 represents the strategy for building and understanding models with examples from the groundwater assessment framework. It includes feedback and formative assessment throughout the cycle. Each learning event or activity provides students and teachers with information about student progress and understanding.
This cycle repeats itself in three phases of the learning progression building up to each performance task. The performance tasks are meant to elicit understanding and practice gained through all of the phases of the model building cycle. Content knowledge is inherently included in the cycle, as it is the material being explored by the teacher and the students.

To measure student levels of understanding, a progression of increasingly complex integration of skill and content was developed to evaluate levels of student understanding against learning goals. This progression of understanding is then applied to the development of rubrics for grading the performance tasks and assessing student status along a groundwater learning progression. The framework’s progression of understanding was developed by surveying the literature on modeling progressions and assessments that evaluated and identified different levels of model-based reasoning and understanding (Bamberger & Davis, 2013; Namdar & Shen, 2015; Reinfried, 2006; Rivet & Kastens, 2012; Seel & Ifenthaler, 2012; Schwarz et al., 2009; Taylor et al., 2003). These levels were then compared and synthesized with levels of understanding identified by Gunckel et al. (2009 & 2012), who presented a learning progression-based formative assessment for understanding of water in environmental systems. These different levels of understanding defined by Gunckel et al. (2009 & 2012) are summarized in Table 2. The progression of understanding in the framework follows a learning progression that incorporates both understanding of groundwater and development of mental modeling abilities. It is used to both guide formative assessment as well as be the metric for grading summative assessments (performance tasks and post-tests) throughout the progression.

<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 4: Scientific Model-based Accounts</td>
<td>Accounts acknowledge driving forces and constraining factors on pathways for water and substances in water</td>
</tr>
<tr>
<td>Level</td>
<td>Description</td>
</tr>
<tr>
<td>-------</td>
<td>-------------</td>
</tr>
<tr>
<td>Level 3: Incomplete School Science Accounts</td>
<td>Accounts provide detailed, although frequently incomplete, stories of water pathways. These stories include hidden and invisible aspects of systems.</td>
</tr>
<tr>
<td>Level 2: Force-dynamic Accounts with Mechanisms</td>
<td>Accounts rely on actors or perceived natural tendencies of water to explain water movements or changes in water quality.</td>
</tr>
<tr>
<td>Level 1: Human-centric Force-dynamic Accounts</td>
<td>Accounts identify water in visible, familiar contexts, focus on human uses and experiences with water and rely on humans to move water or change water quality.</td>
</tr>
</tbody>
</table>

Source. Gunckel et al., (2009 & 2012); modified

Elements that necessarily make up students’ understanding of groundwater were identified so that students’ incorporation of content and skills can be evaluated in an organized and logical way. This organization is achieved in the framework by adapting part of a model developed by Gunckel et al. (2009 & 2012) that uses five elements of knowledge and practice (content and skills) necessary to understand and reason about water and other substances moving through complex systems: structures and systems, scale, scientific principles, representations and models, and dependency and human agency. These elements provide themes or categorizations to organize more specific content and practices that should be incorporated into student models of water in environmental systems (Gunckel et al., 2009 & 2012).

In the framework the content and practices that make up the broader elements are the groundwater core concepts from Table 1, relevant NGSS crosscutting concepts, and modeling skills (Figure 6). Included in Figure 6 are also the NGSS performance tasks used to develop the learning goals for the progression to demonstrate alignment between desired outcomes and assessments. These elements progress through the four levels of model-based accounts (student responses) identified in Table 2. The framework synthesizes the elements (figure 6) with these levels a progression of understanding (Table 2) as a basis upon which to evaluate student status relative to learning goals.

The Four levels of understanding (Table 2) and the essential elements identified for understanding (Figure 6) by Gunckel et al. (2009) are incorporated into a progression of student
understanding (Table 3). The progression represented in Table 3 was developed by Gunkel et al. (2009 & 2012) through a four year iterative design process. It began by identifying the elements necessary to reason about water and other substances moving through complex systems, and then
Figure 6. Elements (knowledge and skills) of accounts necessary to demonstrate a model-based understanding of movement of water through environmental systems.

by administering short answer assessments for 2nd-12th graders, with refinements and adjustments made after each cycle of assessment (Gunckel et al., 2009). This progression provided the structure used to create the progression of understanding in the groundwater assessment framework.

Table 3

<table>
<thead>
<tr>
<th>Level</th>
<th>Structures and systems</th>
<th>Scale</th>
<th>Scientific Principles</th>
<th>Representations and models</th>
<th>Dependency and human agency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 4: Qualitative model-based accounts</td>
<td>Provide multiple detailed, accurate pathways through environmental systems. Account for chemical nature of substances during mixing and moving.</td>
<td>Atomic-molecular through large scale.</td>
<td>Includes driving forces e.g. gravity, pressure.</td>
<td>Interpret constraining factors inferred from representations.</td>
<td>Identify limitations to human agency or dependence on environmental systems.</td>
</tr>
<tr>
<td>Level 3: Incomplete school science accounts</td>
<td>Provide multiple pathways through hidden and invisible connections including human-engineered systems in moderate detail. Identify different types of substances in water.</td>
<td>Microscopic to landscape scale. May refer to smaller particles such as atoms or molecules.</td>
<td>Put events in order. No driving forces or constraining factors.</td>
<td>Connect representations to three-dimensional physical world. Do not infer driving forces or constraining variables.</td>
<td>Include human systems as part of environmental systems. Do not recognize limitations of either human agency or environmental systems.</td>
</tr>
<tr>
<td>Level 2: Force-dynamic accounts with mechanisms</td>
<td>Identify familiar and visible connections, include general connections to human systems. Water quality is referred to as a function of “good” and “bad” stuff.</td>
<td>Broader macroscopic to large-scale focus on familiar and visible dimensions.</td>
<td>Identify mechanisms rely on actors or agents. Fit particular circumstances.</td>
<td>Included limited (e.g., two-dimensional) connections from representations to the physical world.</td>
<td>Portray human systems as operating separately from natural systems, but human systems can be impacted by natural systems.</td>
</tr>
<tr>
<td>Level 1: Force-dynamic accounts</td>
<td>Water is represented only in isolated, visible locations. Water quality is referred to as a function of types of water.</td>
<td>Limited to macroscopic and visible structures and phenomena.</td>
<td>Focus on human structures, actions and needs with no mechanisms for phenomena included.</td>
<td>No connections from representations to the physical world.</td>
<td>Portray humans as sources and movers of water, and water serves human needs.</td>
</tr>
</tbody>
</table>

Source: Gunckel et al., 2012; modified
These levels of model-based accounts and reasoning were synthesized with four levels of understanding models in a similar progression, as both tools for predicting and explaining and as changeable entities developed by Schwarz et al. (2009). These levels of understanding and practice are found in Table 4. In the framework these two progressions, one a model for understanding watershed science (Table 3), the other for understanding and using models (Table 4), are synthesized along with the groundwater core concepts and elements, to generate a progression for students’ model-based understanding of groundwater and related phenomena.

Table 4

<table>
<thead>
<tr>
<th>Level</th>
<th>models as generative tools for predicting and explaining</th>
<th>models as changeable entities</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Students construct and use models spontaneously in a range of domains to help their own thinking. Students consider how the world could behave according to various models. Students construct and use models to generate new questions about the behavior or existence of phenomena.</td>
<td>Students consider changes in models to enhance the explanatory power prior to obtaining evidence supporting these changes. Model changes are considered to develop questions that can then be tested against evidence from the phenomena. Students evaluate competing models to consider combining aspects of models that can enhance the explanatory and predictive power.</td>
</tr>
<tr>
<td>3</td>
<td>Students construct and use multiple models to explain and predict more aspects of a group of related phenomena. Students view models as tools that can support their thinking about existing and new phenomena. Students consider alternatives in constructing models based on analyses of the different advantages and weakness for explaining and predicting these alternative models possess.</td>
<td>Students revise models in order to better fit evidence that has been obtained and to improve the articulation of a mechanism in the model. Thus, models are revised to improve their explanatory power. Students compare models to see how different components or relationships fit evidence more completely and provide a more mechanistic explanation of the phenomena.</td>
</tr>
<tr>
<td>2</td>
<td>Students construct and use a model to illustrate and explain how a phenomenon occurs, consistent with the evidence about the phenomenon. Students view models as a means of communicating their understanding of a phenomenon rather than a tool to support their own thinking.</td>
<td>Students revise models based on information from authority (teacher, textbook, peer) rather than evidence gathered from the phenomenon or new explanatory mechanisms. Students make modifications to improve detail, clarity or add new information, without considering how the explanatory power of the model or its fit with empirical evidence is improved.</td>
</tr>
<tr>
<td>1</td>
<td>Students construct and use models that show literal illustrations of a single phenomenon. Students do not view a model as tool to generate new knowledge, but do see models as a means of showing others what the phenomenon looks like.</td>
<td>Students do not expect models to change with new understandings. They talk about models in absolute terms of right or wrong answers. Students compare their models to assess, if they are good or bad replicas of the phenomenon.</td>
</tr>
</tbody>
</table>
The framework integrates backward design, formative assessment, model oriented assessment, and assessment embedded in learning progressions as the method for authentically assessing students understanding of groundwater with the use of a physical groundwater model. All of these elements help teachers assess students relative to established NGSS learning goals, as well as support students in building content knowledge and skills necessary to meet the standards.

**Limitations**

This study set out to develop a framework to authentically assess student understanding of groundwater with the use of a physical groundwater model. As with any type of research, this project has its limitations. First, the challenges and necessary elements in developing such an assessment were identified through different bodies of literature that provided a theoretical foundation upon which to base the assessment. This theoretical foundation may be incomplete or not include all relevant bodies of knowledge. In particular it is missing interviews and information collected from teachers and practitioners, which is an essential perspective that needs to be incorporated as a next step of this project to increase and validate the utility of the assessment framework.

Second, the assessment framework within the scope of this project was developed for use with a specific groundwater model provided by Wyoming EPSCoR. This may limit the framework’s broader applicability, even though the assessment identified in this study attempts to model incorporation into a broader water science curriculum based on established goals.

Third, this study does not provide an entire curriculum that incorporates the use of the physical model, even though this was identified as an essential element of authentic model oriented assessment. It does attempt to provide an assessment strategy that can be applied to
different curricula that teachers or programs develop. Entire curriculum development was outside the scope of this research, but would be a useful addition and help increase the utility of both the tool and the assessment.

Finally, there is limited research available on how NGSS can be successfully incorporated into science classrooms and guide science curriculum development. This framework is an experimental attempt at creating an assessment that is relevant to new standards, and assesses a physical model that could help teachers in incorporating and meeting those standards in their classrooms.
Chapter 4

Results: Groundwater Assessment Framework

Overview

The Groundwater Assessment Framework is an educational resource developed for use with a physical model of groundwater in middle school classrooms. The learning goals, assessments and assessment progression are supported by research comprised of a review of educational research on NGSS and groundwater, groundwater education, science toolkit use and development, and model oriented assessment. It uses the practices of backward design, formative assessment, and model oriented assessment to build an assessment framework embedded in a learning progression. This chapter includes the framework for assessing student understanding of groundwater with the use of a physical groundwater model. It has five parts: stage one: desired results, stage two: assessment evidence, an assessment progression, the pre- and post-test and rubric for evaluation.

Stage one: desired results.

This stage includes a general overview and purpose statement, core concepts for exploring and understanding groundwater, associated vocabulary, and stage one desired results including relevant established goals from EPSCoR and NGSS that were used to guide the framework. These educational goals fall under the categories of student transfer, understanding, knowledge, skills, and essential questions (see Figure 7).

Stage two: assessment evidence.

Following the desired results is the assessment evidence to be collected throughout the assessment progression. This is broken down into prior knowledge and skills assessment and
performance tasks. The prior knowledge and skills assessments, when applied, are diagnostic and formative assessments that comprise the skeleton of the framework and appear as a repeated cycle in the assessment progression (Table 5). The performance tasks are graded benchmark assessments that have both summative and formative characteristics (Figure 7).

**Assessment progression.**

The assessment progression (Table 5) incorporates the prior knowledge and skills assessments and the performance tasks into a three phase assessment and learning progression. Each phase can be looked at as a cycle of assessment for learning that builds towards the associated performance task. Each progressive cycle builds on the understandings from the previous cycle in order to achieve desired results, and assess students against the learning goals (Table 5).

**Pre and post-test.**

A pre- and post-test is included as both a diagnostic tool and summative tool for use at the beginning and at the end of the assessment progression. This test provides a more quantifiable way for teachers and for EPSCoR program evaluators to assess student progress or change in understanding of groundwater (Figure 9).

**Learning progression for understanding groundwater.**

The progression of understanding at the end of the framework outlines four levels of student understanding relative to the desired results. It progresses from level one understanding, which encapsulates the very basic level of understanding needed to even conceptualize knowledge through level four, which encapsulates above average or exceptional understanding of groundwater (Table 6).
Assessing Student Understanding of Groundwater

Groundwater Assessment Framework

Groundwater in Earth’s Systems

Grade Levels: 6-8  Dates: TBD  Author: Julia Spencer

Overview and Purpose Statement

Science exploration empowers students. It gives them tools to successfully navigate and positively interact with their ecosystem and community. It allows them to observe the natural and social world, draw conclusions based on evidence, and make informed and productive decisions.

Water is rapidly becoming a scarce and precious resource. The increasing global population and demand for fresh water will generate increased conflict among human and ecological users of water. To manage these impending challenges, will require understanding of how water moves through environmental systems and interacts with human demands and impacts on the landscape. Groundwater provides the largest source of usable freshwater in the United States (http://water.usgs.gov/edu/hydrology.html) but is often the least-understood portion of watershed systems. The need to protect water quality in integrated systems is an impetus for increased groundwater education in the context of larger watershed science curriculum.

Groundwater is a predominantly unseen yet essential part of watershed systems that requires students to conceptualize water at an unseen scale, both large and microscopic. Physical models can help students develop more accurate mental models of how groundwater exists within Earth’s systems and its interactions and influence on surface water. The use of a physical groundwater model is a powerful teaching and assessment tool for groundwater education. It can help students visualize how groundwater flows through the subsurface and how it interacts with surface water. It also can demonstrate how humans use and interact with groundwater, allowing students to generate ideas about the influence of humans on hydrologic systems.

Groundwater Core Concepts

These core concepts are things students must know and integrate to gain a comprehensive understanding of groundwater and its role in the Earth’s hydrologic system. These concepts are a synthesis of fundamental ideas identified in interviews with both scientific and professional experts in the fields of hydrology, geohydrology, and groundwater management as well as a review of literature on concepts in groundwater and watershed science education.

The physical groundwater model can be used to explore most if not all of these concepts, but many of them may require instruction in advance of the use of the model, and the assessment of students’ prior knowledge of these concepts before engaging with the model.

1. Water has unique chemical and physical properties – Physical and Chemical structure of water. How it bonds, its polarity, how it interacts with other substances.
2. Porosity – Groundwater exists in the pore spaces between grains or units of material. Different materials have different porosities. It also exists in fractures in bedrock.
3. Permeability – The ability of a material to transport water through itself (How rapidly does water move through a substance?)
5. Pressure Gradients and Force Dynamics: Groundwater flows along gradients from areas of high pressure to areas of low pressure.
6. Velocity and Directional Flow – How rapidly does water move through soil or rock? This is influenced by the permeability and porosity of the rock or substrate, and the pressure gradients that exist. Water can move both vertically and horizontally through the ground.
7. Groundwater and surface water are part of a connected system: Groundwater is part of the whole connected hydrologic system. Groundwater levels can influence base flow in rivers. A depletion of groundwater can lower the base flow in rivers. There is exchange between groundwater and surface water.
8. Humans use groundwater – Groundwater serves many purposes, with the largest amount going towards irrigation and crops. It comes out of our taps in our homes, and goes into producing our food and products we use every day (http://water.usgs.gov/edu/wugw.html). Humans drill wells to access water in both confined and unconfined aquifers.
9. Humans influence the distribution and quality of groundwater resources – Human use can deplete or recharge groundwater supplies. Human activity can contaminate or clean up groundwater sources.

Vocabulary
Porosity-- a measure of the water-bearing capacity of subsurface rock. With respect to water movement, it is not just the total magnitude of porosity that is important, but the size of the voids and the extent to which they are interconnected, as the pores in a formation may be open, or interconnected, or closed and isolated. For example, clay may have a very high porosity with respect to potential water content, but it constitutes a poor medium as an aquifer because the pores are usually so small.

Permeability-- the ability of a material to allow the passage of a liquid, such as water through rocks. Permeable materials, such as gravel and sand, allow water to move quickly through them, whereas less permeable materials, such as clay, don't allow water to flow freely.

Groundwater-- (1) water that flows or seeps downward and saturates soil or rock, supplying springs and wells. The upper surface of the saturate zone is called the water table. (2) Water stored underground in rock crevices and in the pores of geologic materials that make up the Earth's crust.

Aquifer-- a geologic formation(s) that is water bearing. A geological formation or structure that stores and/or transmits water, such as to wells and springs. Use of the term is usually restricted to those water-bearing formations capable of yielding water in sufficient quantity to constitute a usable supply for people's uses.

Unconfined Aquifer-- an aquifer whose upper water surface (water table) is at atmospheric pressure, and thus is able to rise and fall.

Confined Aquifer-- soil or rock below the land surface that is saturated with water. There are layers of impermeable material both above and below it and it is under pressure so that when the aquifer is penetrated by a well, the water will rise above the top of the aquifer.

Water Table-- the top of the water surface in the saturated part of an aquifer.

Infiltration-- flow of water from the land surface into the subsurface.

Percolation-- (1) The movement of water through the openings in rock or soil. (2) The entrance of a portion of the streamflow into the channel materials to contribute to groundwater replenishment.

Base flow-- sustained flow of a stream in the absence of direct runoff. It includes natural and human-induced stream flows. Natural base flow is sustained largely by groundwater discharges.
### Stage 1 - Desired Results

<table>
<thead>
<tr>
<th>Established Goals:</th>
<th>Transfer Goals: Students will be able to independently use their learning to…</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Transfer Goals:</strong></td>
<td>TG1 – Apply the properties of water and model-based reasoning to predict how water will move through different or new systems.</td>
</tr>
<tr>
<td>Established Goals:</td>
<td>TG2 – Predict how human actions will influence movement, distribution, and quality of groundwater resources.</td>
</tr>
<tr>
<td><strong>Established Goals:</strong></td>
<td>TG3 – Design action plans for management, mitigation of pollution, and use of groundwater resources based on scientific understanding of groundwater.</td>
</tr>
</tbody>
</table>

| NGSS Standards Addressed: | **Establishing Goals:** Establish goals: EPSCoR CI water toolkit themes: - Properties of water - Water in the environment - Human use and impact - Next steps "what do I do now?"
| MS-ESS2-4: Develop a model to describe the cycling of water through the Earth’s system driven by energy from the sun and the force of gravity. | **NGSS Standards Addressed:** SEP: Developing and Using models DCI: ESS2.C: The roles of water in Earth’s surface processes CCC: Energy and Matter |
| **NGSS Standards Addressed:** | **Meaning** Enduring Understandings: Students will understand… |
| MS-ESS3-1: Construct a scientific explanation based on evidence for how the uneven distribution of Earth’s mineral, energy, and groundwater resources are the result of past and current geoscience processes. SEP: Constructing explanations and designing solutions DCI: ESS3.A: Natural Resources CCC: a) Cause and Effect b) Influence of Science, Engineering and Technology on Society and the Natural world | **Enduring Understandings:** EU1 – The physical and chemical properties of water influence how water occupies space and flows underground. EU2 – The earth’s structure under the surface influences the location and flow of groundwater EU3 – Groundwater is an unseen but essential resource for Earth’s biological (including human) systems. EU4 – Humans have an impact on the distribution and quality of groundwater. EU5 – Groundwater is linked to Earth’s surface water and makes up a large portion of the water contained in the hydrologic cycle. |
| **NGSS Nature of Science Middle School Level Understandings:** | **Acquisition NGSS Modeling Practices Grades 6-8** |
| - Science is a way of knowing used by many people, not just scientists. -Science assumes that objects and events in natural systems occur in consistent with patterns that are understandable through measurement and observation. | Modeling in 6–8 builds on K–5 experiences and progresses to developing, using, and revising models to describe, test, and predict more abstract phenomena and design systems. |
| **Essential Questions:** Students will keep considering… | - Evaluate limitations of a model for a proposed object or tool. - Develop or modify a model— based on evidence – to match what happens if a variable or component of a system is changed. - Use and/or develop a model of simple systems with uncertain and less predictable factors. - Develop and/or revise a model to show the relationships among variables, including those that are not observable but predict observable phenomena. - Develop and/or use a model to predict and/or describe phenomena. - Develop a model to describe unobservable mechanisms. - Develop and/or use a model to generate data to test ideas about phenomena in natural or designed systems, including those representing inputs and outputs, and those at unobservable scales. |

(NGSS Lead States, 2013)
Science limits its explanations to systems that lend themselves to observation and empirical evidence.

Science knowledge can describe consequences of actions but is not responsible for society’s decisions.

Science investigations use a variety of methods and tools to make measurements and observations.

Science knowledge is based upon logical and conceptual connections between evidence and explanations.

A hypothesis is used by scientists as an idea that may contribute important new knowledge for the evaluation of scientific theory.

### Acquisition Groundwater Specific (learning objectives)

<table>
<thead>
<tr>
<th>Knowledge: Students will…</th>
<th>Skills: Students will be skilled at…</th>
<th>Affective: Students will feel…</th>
</tr>
</thead>
<tbody>
<tr>
<td>KO1 -- Integrate core groundwater concepts into their mental models of groundwater.</td>
<td>SO1 -- Using the physical groundwater model to test hypotheses and gather data.</td>
<td>AO1 -- Greater confidence in the process and practice of scientific modeling.</td>
</tr>
<tr>
<td>KO2 -- Connect groundwater to Earth’s hydrologic and human systems.</td>
<td>SO2 -- Using the groundwater model as a representation of how humans can influence groundwater systems focusing on cause and effect.</td>
<td>AO2 -- Comfortable giving and receiving feedback from peers and teachers.</td>
</tr>
<tr>
<td>KO3 -- Recognize the physical groundwater model as a limited representation of a real system.</td>
<td>SO3 -- Evaluating models for discrepancies and inaccuracies based on data.</td>
<td></td>
</tr>
<tr>
<td>KO4 -- Analyze the importance of groundwater to human and ecological systems.</td>
<td>SO4 -- Incorporating new information based on evidence into their own mental models of groundwater.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SO5 -- Communicating results to their peers and audiences.</td>
<td></td>
</tr>
</tbody>
</table>

### Stage 2 - Assessment Evidence

**Prior Knowledge and Skill Assessment:** *Students conceptions and skill levels will be uncovered by…*

**Pre-test** – This will include items that test students understanding of the core concepts needed to understand groundwater as well as their ability to make connections between elements of the hydrologic system.

**Groundwater Group Diagrams** - Students will create and share their conceptualization of groundwater before seeing or using the model. This will help compile a body of existing class knowledge about groundwater and conception of subsurface structure, and help uncover any misconceptions that need to be addressed. The will continue to revise and develop models throughout the entire unit and these revised models will be used as formative assessment checks.

**Properties of Water:** Ask students to build an individual water molecule and then ask students to place all of their water molecules together to form a “droplet” of water. Why do the molecules stick together so well? What kinds of bonds exist between them?

**Formative Assessments During Demonstration and Exploration of Model Throughout Learning Progression** – Examples include asking students to generate hypotheses about how the water in the model is flowing, which direction do they think it is going? How is water getting from the surface into the ground?

**Small Group Inquiry** – After exploring the groundwater model structure and connection to the water cycle, ask the groups to make a prediction about which direction they think the water will be flowing and how fast they think it will flow. They should justify their answers with information they have learned already and give reasons for their predictions. After making these predictions, each group will design an experiment to test their hypothesis. Repeat this process throughout the use of groundwater model as new concepts or pieces of the system are added or introduced.

**Science Notebook Prompts:** These will be planned formative assessments at the end of each day that help gauge student learning and progress. These prompts can include written accounts, data analysis and paper and pencil diagrams.
Performance Tasks: Students will demonstrate that they really understand through…

PT1 – Creation of hypothetical model—graded
Students will be asked in groups to create their own groundwater models based on understandings gained from the use of the pre-fabricated model and instruction in class. Limitations and materials (e.g. a diagram of a different subsurface structure) will be provided and the students will be asked to present to the rest of the class how their model is different and how water is moving and flowing through the model.

PT2 – Precipitation and distribution model -- graded
Each group of students will be given different precipitation data, and data of water usage for the geographic area they live in. This data will include different users, how much they use. Students will then be asked to create a predictive model of what will happen to water level both underground and on the surface. They will then present their scenarios to the class, using the physical model as a tool for demonstration.

PT3 – Water resource management plans -- graded
Students in groups will create a water resource management plan based on data gathered from the physical model on flow velocity and contamination, as well as using precipitation and streamflow data. They will present the plans to the class and each plan will have a comment period. Students (after the comment period) will have an opportunity to incorporate feedback into their final management plan.

Other Evidence: Students will demonstrate that they achieved Stage 1 through…
1) Post-tests administered at the end of lesson or unit.
2) Design of experiments to collect data on flow velocity in groundwater.
3) Science notebooks

Figure 7. Desired Results and Assessment Evidence

Table 5
Groundwater Assessment progression

<table>
<thead>
<tr>
<th>Task</th>
<th>Type of Assessment</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 1 (MS-ESS2-4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre-test</td>
<td>Diagnostic</td>
<td>• Asses student prior understanding of groundwater</td>
</tr>
</tbody>
</table>
| Groundwater Group diagrams | Formative          | • Assess student prior knowledge and understanding of groundwater and modeling skills.  
<p>|                       |                    | • Compare multiple models.                                           |
|                       |                    | • Student lead discussion and clarification of each other’s models and ideas. |
|                       |                    | • Identify gaps and misconceptions.                                   |
|                       |                    | • Opportunity to make modeling practices explicit through peer and teacher feedback. |
|                       |                    | • Metacognition: Give students opportunity to reflect and articulate the process they went through to create the model. |
| Properties of Water   | Formative          | • Assess prior knowledge of properties.                               |
|                       |                    | • Provide vocabulary in context of properties and their relationship to groundwater. Explore permeability and porosity. |
|                       |                    | • Identify gaps and misconceptions.                                   |
| Demonstration of Groundwater Model | Formative         | • Compare multiple models, asking them to identify what components from their own models are different from the groundwater model. |
|                       |                    | • How are students able to incorporate new information?                |
|                       |                    | • Can students recognize limitations of the model?                    |</p>
<table>
<thead>
<tr>
<th>Task</th>
<th>Type of Assessment</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small group inquiry</td>
<td>Formative</td>
<td>• How well can students engage with the model as a tool for making predictions and generating data?</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Opportunity to explore fundamental concepts of flow, pressure gradients and velocity.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Are students already able to incorporate these concepts into their rationale or will more instruction be needed after testing predictions?</td>
</tr>
<tr>
<td>Science Notebook Prompt 1</td>
<td>Formative</td>
<td>• Can students modify their own model-based on evidence from the physical groundwater model?</td>
</tr>
<tr>
<td>PT 1 – Creation of new hypothetical model</td>
<td>Summative &amp; Formative</td>
<td>• Have students met learning goals included in stage 1?</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• What needs to be reviewed? Are there any concepts or elements students don’t understand?</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Do students have what they need to move forward?</td>
</tr>
<tr>
<td>Phase 2 (MS-ESS3-1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Science Notebook Prompt 2</td>
<td>Diagnostic/Formative</td>
<td>• Extension/application of understanding of groundwater.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Evaluation of prior knowledge about geologic processes and structure.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Do students grasp that the subsurface is different in different places?</td>
</tr>
<tr>
<td>Groundwater group diagrams and small class inquiry</td>
<td>Formative</td>
<td>• Another opportunity for students to compare their models and evaluate them using the physical model.</td>
</tr>
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<td></td>
<td></td>
<td>• Revisit and evaluate student understanding of porosity, permeability and flow.</td>
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<td></td>
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<td>• Evaluate students’ ability to generate an experiment to collect data that tests their predictions.</td>
</tr>
<tr>
<td>Groundwater model: Test student predictions</td>
<td>Formative</td>
<td>• How well do students incorporate new evidence and data into their models?</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Are students able to point out any limitations in the physical model in comparison to their model?</td>
</tr>
<tr>
<td>Groundwater Model: Model Comparison</td>
<td>Formative</td>
<td>• Comparison of multiple models.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Evaluation of multiple models.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Can students synthesize information from both models into a more complete understanding of groundwater?</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Can students differentiate between different materials (rock or substrate types) below the surface?</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Can students predict how old the water is depending on where it is?</td>
</tr>
<tr>
<td>Task</td>
<td>Type of Assessment</td>
<td>Use</td>
</tr>
<tr>
<td>------</td>
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<td>-----</td>
</tr>
</tbody>
</table>
| Groundwater group diagrams: Human use and small group inquiry | Formative & Diagnostic | - Identify student prior understanding and perception of human interaction with groundwater.  
- Identify gaps & misconceptions.  
- Compare multiple models.  
- Evaluate student understanding of human impacts and dependency on earth's systems.  
- Evaluate students' ability to generate an experiment to collect data that tests their predictions. |
|  |  | - Begin by asking students how humans access groundwater?  
- Ask same groups to go back to their models and include how they think humans use and access groundwater, including the influences that use could have on water levels.  
- Design experiment using physical model to test predictions. |
| Groundwater Model: Well demonstration | Formative | - Another opportunity for students to compare their models and evaluate them using the physical model.  
- How well do students incorporate new evidence and data into their models?  
- Are students able to point out any limitations in the physical model in comparison to their model? |
|  |  | - Ask students to predict how drawing water from one well, will influence another?  
- Ask students to predict if increased human use of groundwater can influence river levels? |
| Science Notebook Prompt 3 | Formative | - Student self-evaluation of progress.  
- Evaluate students' metacognitive ability about developing models.  
- Evaluate student progress in understanding and modeling. |
|  |  | - How has your understanding of groundwater changed? What have we done as a class that has caused or influenced this change? |
| PT2—Precipitation and distribution model (group) | Summative & Formative | - Have students met learning goals included in stage 2?  
- What needs to be reviewed? Are there any concepts or elements students don’t understand?  
- Do students have what they need to move forward? |
|  |  | - Graded benchmark assessment: Do students know fundamental concepts covered, and can they apply and integrate them to a different model/scenario? |
| Phase 3 (MS-ESS3-3) |  |  |
| Science Notebook Prompt 4 | Formative & Diagnostic | - Identify gaps & misconceptions.  
- Engage prior knowledge.  
- Can students connect human use to broader impacts on the Earth’s hydrologic and biologic systems? |
|  |  | - Should people manage or keep track of where groundwater is and how much of it is used? |
| Pollution small group inquiry | Formative | - Another opportunity for students to compare their models and evaluate them using the physical model.  
- Evaluate students' ability to generate an experiment to collect data that tests their predictions. |
|  |  | - Can and how could groundwater become polluted from human and natural sources?  
- Design a way to test this using the model. |
| Small group inquiry: Real Data Evaluation | Formative | - Evaluate ability to use real data to generate predictions and develop models.  
- Evaluate ability to communicate models and predictions, and accept and provide feedback.  
- Compare multiple models. |
|  |  | - Ask students in small groups to use precipitation, surface water, and groundwater and water use data to come up with a water availability "model" or prediction.  
- Compare group models. |
| PT3 – Water Resource Management Plans | Summative | - Have students’ met learning goals for unit?  
- Can students apply scientific modeling skills and principles of groundwater to real world solutions? |
|  |  | - Graded benchmark assessment: Do students know fundamental concepts covered, and can they apply and integrate them to a different model/scenario? |
| Post-test | Summative | - Has overall understanding increased? |
Table 5 provides a basic framework for using multiple assessment tools specifically designed to delineate understanding about student models of groundwater, in a formative and summative assessment cycle. The repetition of model building practices in conjunction with increasingly complex integration of concepts and content allows students to build on prior understanding and assess their own progress. It also guides teachers through an evaluation of student progress through learning events that incorporate the use of the physical groundwater model.

What the above framework does not include is a model of how a teacher might work through a formative assessment cycle. Below (Figure 8) is an example of a simple formative cycle, including sample student answers, and teacher responses. This cycle is from phase 1 of the assessment framework. It uses a commonly held misconception that many students visualize groundwater as mimicking surface water: it exists in underground lakes or rivers (Dickerson et al., 2007). This misconception, once identified, needs to be addressed through a cycle of instruction and feedback between the teacher and student. Instructional decisions will depend upon the student responses to learning activities. If student misconceptions are changed through instruction, the student moves on to the next planned formative assessment activity. If student misconceptions persist, the teacher must reevaluate instruction and adapt to address the misconception in a different way.
Figure 8. Simplified formative assessment cycle that identifies a potential misconception, teacher response, and instructional tool or strategy to address the misconception. Feedback should be provided to the student and to the teacher throughout the cycle.
Assessing Student Understanding of Groundwater

Groundwater pre-test

1. Draw a water molecule. What happens to salt when it dissolves in water and why?

2. Draw a picture of what you think it looks like underground where there is water?

3. Would water flow faster through sand or through clay? Justify your answer.

Reference the following diagram to answer the questions #4, #5 and #6

4. Could pumping from well #1 affect the water in the river? Could pumping from well #2 affect the water in the river? Explain your answers.

5. Is the water underground flowing? If you think so in what direction is the water in Aquifer 1 naturally flowing?

6. If a well is built near a river could it affect the amount of water flowing in the river? If you think it could, explain how.

7. How does water get into a river? How does water get into the ground? Draw a labeled diagram of this process.

8. How would a drought (lack of rainfall) influence the water level of a river? Would this influence the amount of water in the ground?

*Figure 9. Pre- and Post- Test Note:* Groundwater pre and post-test adapted from Gunckel et al. (2009).
Included in this section is a progression of understanding for assessing different levels of students’ model-based understanding of groundwater (Table 6). There is one generic progression meant to serve as general guide for assessment of groundwater understanding. This can and should be adapted to fit a teacher’s specific developed performance tasks and formative assessment cycle. It should also be kept in mind that not all questions will facilitate students using all elements of model-based understanding and that the progression is broad enough to be modified for assessment of model-based accounts of other phenomena.

**Table 6**

*Characteristics of model-based accounts at each understanding level: a framework for learning progressions*

<table>
<thead>
<tr>
<th>Level</th>
<th>Structures and systems</th>
<th>Scale</th>
<th>Scientific Principles</th>
<th>Representations and models</th>
<th>Dependency and human agency</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Provides multiple, detailed accurate pathways of exchange b/w groundwater and surface water systems accounting for chemical nature (properties) of water as it moves. Incorporates multiple models to predict how the world could behave.</td>
<td>Distinguishes phenomena from an atomic-molecular through large scale.</td>
<td>Includes driving forces, mechanisms and constraints e.g. pressure gradients and gravity, properties of water, permeability, porosity</td>
<td>Interprets limitations of models and combines models to enhance predictive and representational power.</td>
<td>Identifies limitations to human agency or dependence on systems.</td>
</tr>
<tr>
<td>3</td>
<td>Provides multiple pathways through hidden and invisible connections including human-engineered systems identifying different types of substances in water. Students consider alternatives in constructing models of systems based on advantages and weaknesses of those models.</td>
<td>Distinguishes phenomena from a microscopic to landscape scale, may refer to smaller particles such as atoms or molecules</td>
<td>Puts events in order</td>
<td>No driving forces of constraining factors included</td>
<td>Connects 3D representations to physical world and revise model-based on evidence to enhance explanatory power. Compares models to evaluate different components.</td>
</tr>
<tr>
<td>2</td>
<td>Identifies familiar and visible connections to human systems. Water quality or properties are in binary terms such as good and bad. Use ones model to explain how groundwater occurs based on evidence about groundwater.</td>
<td>Only distinguishes broader macroscopic to large-scale. Focuses on familiar and visible dimensions</td>
<td>Identifies mechanisms that rely on actors such as people or agents such as Lakes and Rivers. Their models fit particular circumstances not broad systems.</td>
<td>Includes limited (two dimensional) connections from representation to physical world. Illustrative representations based on information from authority rather than built and revised based on evidence.</td>
<td>Portrays human systems as separate from groundwater systems, but human systems can be influenced by natural systems.</td>
</tr>
</tbody>
</table>
Groundwater is represented only in isolated areas that mimic surface water (e.g. underground rivers or lakes). Water quality is referred to as a function of types of water. Models are illustrative of single phenomena.

Distinguish only macroscopic and visible structures of phenomena

Focuses on human structures, actions and needs with no mechanisms for phenomena included.

No connections from representations to physical world. Models are only used as simple replicas and are static, not dynamic.

Portrays humans as sources and movers of water, and water serves human needs.

Source: Gunckel et al., (2009 & 2012); Schwarz et al. (2009); modified.

Below (Table 7) is the above progression of understanding applied to a rubric for quantitatively evaluating the first performance task. Notice that the element of dependency and human agency is not included in the rubric for this performance task, because it has not yet been a part of the learning progression, but it would be included in the evaluation of the second and third performance task.

Table 7
Rubric for PT—1 based upon the levels of understanding in the groundwater learning progression

<table>
<thead>
<tr>
<th>Level</th>
<th>Structures and systems</th>
<th>Scale</th>
<th>Scientific Principles</th>
<th>Representations and models</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>4</strong></td>
<td>Model includes pathways of exchange between surface and groundwater: permeability, porosity and infiltration. Includes an accurate representation of what it can look like under the surface where water exists. The explanation should include reference to the groundwater model and how their understanding has changed. Almost all core concepts included.</td>
<td>The model should include reference to water at a microscopic scale within pore spaces and how it moves (properties of water) through those spaces. It should also include the larger scale, and how groundwater is connected to the hydrologic system.</td>
<td>Includes driving forces, Mechanisms and constraints e.g. pressure gradients and gravity, properties of water, permeability, porosity. These mechanisms should all influence the movement and existence of groundwater.</td>
<td>Students’ articulate that their model is only one-way in which groundwater can be represented. They can articulate that systems are dynamic and cannot be represented by one model alone. Their responses to questions should include predictions about how water will behave in their model-based on evidence gained from the physical groundwater model.</td>
</tr>
<tr>
<td><strong>3</strong></td>
<td>Model includes some of the pathways of exchange that are below the surface. They should mention infiltration and permeability. Students provide a mostly accurate representation of what it can look like underground where water exists.</td>
<td>Models articulate that water exists in pore spaces or in fractures, but does not include how it moves through those spaces. It includes a larger scale representation of how groundwater</td>
<td>Articulates the relative timing of a cycle of water moving from the surface to the ground and then potentially back to the surface.</td>
<td>Students make connections to physical groundwater model, and differentiate between their model and the physical model, but don’t articulate any limitations to their model or the physical model.</td>
</tr>
<tr>
<td>1</td>
<td>Groundwater is represented only in isolated areas that mimic surface water (e.g. underground rivers or lakes). Models do not accurately represent the structure of the subsurface and do not make connections between groundwater and surface water. Groundwater is represented as an isolated phenomena. No core concepts included.</td>
<td>No microscopic structures or processes such as pore spaces, or the properties of water are recognized. Model only contains visible and obvious surface water and groundwater mimics these bodies.</td>
<td>Has no mechanisms or driving forces included for the exchange or movement of groundwater. Models are static with no representations of the dynamic nature of systems. Models are not compared or differentiated from the physical model. No evidence is used, and no explanations or predictions provided.</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Identifies familiar and visible connections to human systems. But does not identify unfamiliar aspects such as how groundwater exits in pore spaces or fractures. Does not identify the subsurface connections between groundwater and surface water. Students provide a somewhat accurate structure of what it can look like underground but do not connect this to groundwater’s existence Limited core concepts included.</td>
<td>Includes only the larger scale picture. Groundwater is represented underground as a large unified body, but how and why it exists in pore spaces and fractures is not articulated. Water bodies such as rivers and lakes are represented</td>
<td>Models do not include mechanism of exchange b/w groundwater and surface water, nor how groundwater moves and flows into and through the subsurface. If there are mechanisms they are human actions. Models are two-dimensional and do not recognize the three dimensional nature of systems. Students’ model replicates physical model, but does not base explanations of water movement on evidence gathered, but rather on previous conceptions. Students do not recognize limitations or models.</td>
<td></td>
</tr>
<tr>
<td>Some core concepts included.</td>
<td>is connected to the hydrologic system.</td>
<td>No driving forces of constraining factors included</td>
<td>They are able to use evidence from the physical groundwater model to predict how water will move through their own model.</td>
<td></td>
</tr>
</tbody>
</table>
Chapter 5
Discussion

Introduction

The purpose of this research was to create a valid and authentic assessment framework that measures student-learning outcomes from the use of a physical, interactive groundwater model at a middle school level. An assessment framework was created with the eventual goal of use with the groundwater model provided by WYCEHG to teachers in Wyoming classrooms in order to assess program efficacy in terms of increased student understanding of groundwater. This chapter discusses the factors influencing the development of the framework including challenges and recommendations identified in the literature, assessment strategies used to address these challenges and recommendations, and finally suggestions for use and future research.

Challenges in Assessing Groundwater

The difficulties in assessing groundwater in large measure flow directly from the same difficulties in teaching about groundwater. The hidden nature of groundwater makes it difficult to conceptualize for both students and teachers. The scale of groundwater is another particularly challenging aspect, since classrooms and schools are limited in what they can accommodate in a classroom in terms of materials, models, and real experience with groundwater.

The NGSS ask students at a middle school level to incorporate groundwater into a larger natural resource systems model, which requires incorporation of both spatial and temporal scale. Many teachers at all levels do not have the solid content knowledge of groundwater to teach about it, let alone teach how to incorporate it into a more complex and dynamic system. Teaching and assessing groundwater will thus require particular support for teachers in
developing content knowledge around hidden and complex scientific phenomena and in incorporating the practice of scientific modeling into their instruction and assessment of their students.

Physical models of hidden phenomena, such as groundwater, and toolkits that support watershed science education can be powerful resources for helping teachers and students conceptualize groundwater as part of the larger hydrologic system. These resources, however, if used in isolation, without being incorporated into a teacher’s larger curriculum or learning goals, will serve as isolated experiences with little impact on lasting student understanding of groundwater and watershed systems.

The analysis of four areas of educational research (NGSS and groundwater, challenges in groundwater education, the use of physical models and toolkits in classrooms, and model oriented assessment) identified four recommendations for creating an authentic assessment of students’ understanding of groundwater with the use of a physical groundwater model:

1. The physical model must be incorporated into a learning progression, with embedded assessments.

2. These assessments should measure student progress against established learning goals that flow directly from relevant NGSS.

3. These assessments should support students in building more accurate mental models of groundwater and in developing scientific modeling practices.

4. Effective modeling oriented assessments must evaluate students’ blending of content understanding and skills in the practice of scientific modeling.
These recommendations reflect the shift made by the Next Generation Science Standards towards a more practice and progression based way of understanding science, rather than as a body of isolated facts, and assessing students accordingly.

The standards’ focus on learning progressions and the assessment of student understanding that encompasses both scientific content knowledge and scientific skills relative to these progressions, not just their factual recall, necessitates new kinds of assessments to be developed (Wysession, 2013). These assessments must incorporate ways that students are able to demonstrate their understanding along an integrated content and skills progression.

This assessment framework was created with this particular challenge in mind, and used the recommendations developed out of the literature to design methods that meet each recommendation. The methodology can be thought of as strategy for addressing the challenges in creating the new forms assessment needed to meet the NGSS and to help students develop a comprehensive understanding of groundwater.

What needs to come next, in terms of further developing the framework and making it useful, is to test its validity. Valid assessment is assessment that obtains the most appropriate evidence of the desired results or learning goals. Validity refers to meaning we can or cannot properly make of specific evidence (Wiggins & McTighe, 2005). To test the validity of the groundwater assessment framework, it needs to be implemented by educators, and data collected in order to see if the questions being asked, and the performance tasks, are the most appropriate measures of the learning goals established in the framework. The opportunity to do this will potentially come in the next year, when WYCEGH and EPSCoR will be evaluating the impact of their outreach programs on student understanding of water in the state of Wyoming. Future graduate students will have the opportunity to work with teachers to implement assessments,
gather data, and refine the framework. The validity of the theoretical framework itself should also be tested by application to other complex scientific concepts. This could be achieved by using as a tool to assess not just student understanding of groundwater, but of all parts of the hydrologic system, and student understanding of water in Wyoming. Even without the framework being tested, this research provides a theoretical foundation to address the challenges in assessing students’ model-based understanding of scientific phenomena.

**Strategies to Address Challenges**

Namdar and Shen (2015) in their review of literature on model-based instruction and model oriented assessment (MOA) recommend that model oriented assessments be framed in an “ecology of assessment” (p. 1012). An ecosystem is comprised of complex, dynamic relationships between living and non-living elements of a system. It is interesting to think about framing student understanding of groundwater in this kind ecology made of different related components necessary to evaluate the content and skills that make up that understanding.

The authors advocate that this ecology not only include modeling practices, such as evaluation, and reflection, but also the relationships between content knowledge and modeling skills. This is important in light of the NGSS performance expectations that couple science practices and content. In order to authentically assess students against these performance expectations a framework is needed that helps teachers and other assessors to develop a clear understanding of the relationship between content and practice assessments, which to this point are largely missing from the field of model oriented assessment and science assessment in general (Namdar & Shen, 2015).

The pieces of the framework that address the challenges and recommendations make up the components of the ecological system. These components: formative assessment, backward
design and model oriented assessment, work together to create a learning and assessment
progression that allows teachers to authentically assess student progress against learning goals
and to use assessment as a means to build student understanding of groundwater content and
modeling practice.

**Formative Assessment.**

Using formative assessment as a strategy for developing a learning progression with
embedded assessment, helps teachers assess student progress in understanding and also
facilitates students building of content understanding and modeling practice. The use of
formative assessment is a strategy for one: embedding assessment into a learning progression,
and two: for supporting students in building more accurate mental models of groundwater
through a cycle of learning events, feedback, and revision.

**Backward Design.**

Using backward design provided a method for establishing desired outcomes (learning
goals) upon which to base assessments and a learning progression. It addresses the
recommendation of developing learning goals that flow directly from relevant NGSS. The
strength of this method in particular lies in its structure for creating both skills and content
understanding goals asked for by NGSS performance expectations. It also allows teachers to
design multiple performance tasks that measure student progress relative to NGSS expectations
and learning goals. These goals serve as a metric for incorporating the physical groundwater
model into instruction as a means of meeting and assessing student understanding of desired
outcomes.

The use of backward design in combination with formative assessments allows students
and teachers to explore groundwater and increase understanding as a cycle that incorporates
content and skills, eventually building towards the completion of a performance task. It gives students multiple opportunities to share and revise their ideas, knowledge and understanding. The establishment of learning goals ensures that formative and summative assessments are valid, that is that at each stage students’ are being evaluated against established learning goals.

**Model Oriented Assessment.**

Model oriented assessment is assessment that evaluates students’ ability to engage in the practice of scientific modeling in order to create accurate mental models of scientific phenomena. Access to physical models that represent real world systems is an essential piece of building student modeling capacity and increasing content knowledge. This strategy was used in order to build a learning and assessment progression that allows students to authentically engage in the skills of scientific modeling as part of learning cycle that progressively incorporates more complex content and elements of a system.

This is an essential tool in the authentic assessment of student understanding of groundwater. Groundwater is part of a hydrogeologic system with a complex array of mechanisms and constraints. In order for students to authentically engage with groundwater, as scientist engage with it in the real world, it must be integrated into the practice of scientific modeling, and assessments need to be designed to evaluate both the content and the skills associated.

**The question of authenticity.**

Model oriented assessment is one of the ways in which students’ model-based knowledge of groundwater can be authentically assessed, but this framework presents a more complex picture of what creates authenticity in assessment of complex scientific phenomena. The framework was designed with the idea that assessments, to be authentic, must serve the needs of
the student above all else (Shavelson, 2008). Assessments need to support students in their learning through a process of feedback and iteration that allows them to build their confidence in engaging with complex systems and using skills and content necessary to understanding scientific phenomena.

The framework does this by presenting assessment as multiple cycles that integrate model oriented and formative assessment that build upon one another in a learning progression. These cycles also incorporate performance tasks that ask students to engage with models, and provide real-world context through the use of data to solve real problems, such as water resource use and allocation. It thus serves the students by giving them multiple opportunities to engage skills and content, applying them to solve real problems with multiple opportunities for reflection and feedback.

**Ecology of Assessment: a generalized framework.**

The framework developed in the results chapter can thus be thought of as an ecology of assessment that authentically builds, targets and evaluates student understanding of groundwater. It frames the assessment of student understanding around the NGSS performance expectations relevant to groundwater. It integrates groundwater core concepts with the scientific practice of modeling in order to assess students’ systems understanding of groundwater. It also incorporates relationships between classroom practice and authentic assessment by embedding assessments within a formative and model oriented assessment cycle and learning progression that uses the physical groundwater model for both learning and evaluation. Figure 10 represents the generalized ecology of assessment used in the framework.
Figure 10. Ecology of Assessment. A model for developing authentic and valid assessment of students’ model-based understanding of scientific phenomena. LE = Learning Events.
Figure 10 is a synthesis of the recommendations from the literature review and solutions for implementation from the methods section. The ecology uses backward design as structure to develop learning objectives that flow directly from the NGSS performance expectations and that blend the necessary content and skills to achieve understanding. It then uses these learning goals to develop a learning progression that incorporates content and modeling practices, allowing students to gradually build understanding and for teachers to track student progress through the use of embedded formative assessment. This cycle builds towards completion of a performance task designed to evaluate student understanding against NGSS performance expectations and learning goals.

While this study developed an assessment framework specifically to evaluate students’ understanding of groundwater with the use of a physical groundwater model, it is possible that this framework for model-oriented assessment of scientific phenomena could be used more broadly to help teachers and students achieve NGSS performance expectations.

**Recommendations for Use**

This assessment framework is designed to assess student-learning outcomes from the use of a physical groundwater model in middle school classrooms. However, for the model and the assessment framework to achieve efficacy in increasing student understanding of groundwater and authentically evaluating that increase, should not be used in isolation. The findings of this study indicate that the physical model and the accompanying framework should be utilized as part of a learning progression that meets teachers’ goals for student understanding of groundwater.

The framework helps teachers incorporate the physical groundwater model as tool for learning and as a tool for evaluation. The learning goals and assessment evidence provide
examples of how teachers can use the model to meet standards and increase student understanding about groundwater as an essential part of the hydrologic cycle. It also supports teachers through a groundwater learning progression that incorporates groundwater content and the practice of scientific modeling.

The University of Wyoming EPSCoR currently partners with The Teton Science Schools to run professional development workshops for Wyoming teachers that provide training in local geology, hydrology, and groundwater models. These professional development workshops are an opportunity to work with teachers on how they can successfully integrate groundwater into their curriculum in order to meet standards and increase student engagement and understanding of the hydrologic cycle. This professional development is an essential aspect in successfully using the groundwater model and implementing the assessment framework. Teachers, as indicated in the literature, need support in both content knowledge and modeling practice, in order to successfully engage with their students about groundwater.

These professional development workshops are an opportunity for teachers to engage in training on how to use the model and the framework and then implement the training in their classrooms. The framework is meant to provide useful information to teachers about student understanding of groundwater as well as provide information to EPSCoR about the efficacy of their education outreach programs and materials.

**Recommendations for Future Research and Development**

As suggested by the literature there is a need for more research on the development of new assessments that will effectively support the implementation of NGSS. These assessments need to authentically evaluate students’ ability to integrate the three pillars of the standards: Disciplinary Core Ideas, Crosscutting concepts, and Science and Engineering Practices.
This framework provides a specific theoretical basis for assessment of student understanding of groundwater with the use of a physical groundwater model and attempts to address the assessment challenges posed by NGSS. To increase its utility and efficacy it needs to be given to teachers, to one, provide feedback on its practicality and utility, and two, to implement it with their students to test its validity and authenticity. Can an assessment framework help educators more effectively use physical models to help students develop mental models for complex scientific phenomena?

This research set out to develop an authentic assessment, however through the course of the study it was found that to do this, assessment needed to be embedded into a learning progression that incorporated both groundwater content and scientific modeling practice. In this way it became closer to curriculum development than just the development of an assessment tool. The next step would be to actually develop this framework into a whole curriculum for understanding the hydrologic cycle that incorporates relevant NGSS standards.

A curriculum would be useful in terms of providing EPSCoR a means through which they could improve their educational outreach materials in order to meet their goals, and assess outcomes on student learning from their educational outreach programs. Providing teachers with hands on materials integrated into curriculum that meets established goals and standards could potentially increase the success of educational outreach in general. Provided with appropriate professional development these materials have the potential to help teachers in meeting the NGSS and increasing scientific understanding among their students.

It is essential therefore that assessments are developed with the goals of supporting and evaluating student understanding of scientific phenomena, and providing data to programs such as EPSCoR to appraise efficacy and improve their educational outreach programs. The general
ecology, or framework, for model oriented assessment developed through this research would be interesting to study in terms of its applicability to other scientific phenomena, or its broadening to assess students’ understanding of the earth’s hydrologic system. This would help it align more completely with the goals of Wyoming EPSCoR and potentially serve as a resource for any teacher teaching watershed science.

Conclusions

There are many challenges facing educators in the adoption of the NGSS. The standards shift the emphasis from learning scientific facts, to a progression-based development of understanding that incorporates both content and scientific practices. One of the challenges presented is in developing assessments that authentically and validly assess this blending of practice and content.

The groundwater assessment framework has the potential to help teachers successfully navigate new standards, and help students develop the necessary understanding to achieve NGSS performance expectations. These understandings, particularly around watershed science and groundwater, are not only important in terms of meeting standards, but also in terms of developing a scientifically literate citizenry that can make decisions about critical water resources. For students and teachers to be successful in this endeavor they must have the opportunity to explore phenomena typically inaccessible in the classroom, through models and representations incorporated into dynamic and interactive learning progressions.

The assessments needed to evaluate student outcomes should be an integral part of this dynamic learning process. They should incorporate multiple methods and means of assessment, such as formative and model oriented, which allow students and teachers to approach understanding authentically and from multiple pathways, and build accurate models of scientific
Assessing Student Understanding of Groundwater

phenomena. This research lays some of the groundwork for continued development of assessments and curricular materials that authentically evaluate and engage students in groundwater and hydrologic systems and poses a model for authentic and valid assessment of student model-based understanding of scientific phenomena.
References


Duffy, D.L.F, (2012). The nature and role of physical models in enhancing sixth grade students’ mental models of groundwater and groundwater processes. (Unpublished doctoral dissertation). *Old Dominion University, Norfolk, VA.*


Assessing Student Understanding of Groundwater

APPENDIX A

ENVISION 2000 GROUNDWATER FLOW MODEL DESCRIPTION

Figure A1. Diagram of Sand & Gravel Groundwater Simulator

Introduction

The Envision 2000 Groundwater Flow Model has two compartments, a front aquifer compartment and a rear water reservoir compartment. The aquifer compartment represents a 1-inch thick vertical slice of the earth. The front face of the Model, therefore, is a geologic cross section or profile. (See illustration #1 and back cover.) The cross section is what you might see if you were standing in a gravel pit, a trench or road cut. Three principal sand and gravel aquifers and one aquitard are depicted in the Model. The sand and gravel layers may also be described to an audience as sandstone and conglomerate. The aquitard, a mixture of clay and crushed...
Assessing Student Understanding of Groundwater

limestone (or plastic layer), may also be described as limestone or shale. Behind the aquifer compartment, the water reservoir compartment stores water that is circulated through the aquifer compartment.

**Description**

1. At the very top of the aquifer compartment is a thin green material representing vegetation and soil covering the uppermost aquifer. The uppermost aquifer, a fine sand (or fine-grained sandstone), represents an unconfined (water-table) aquifer. A small, low-permeability, gray clay (plastic) lens is located below the UST (Underground Storage Tank) and Septic Tank. The thin, dark brown sand layers are added for color contrast and do not significantly affect the principal aquifers of the Model.

2. The middle coarse sand (sandstone) aquifer is actually the lower part of the unconfined (water-table) aquifer. It is a more permeable layer than the fine sand above.

3. The confining layer (aquitard) is a very low permeability, gray plastic layer which can also be described as a glacial till, lacustrine (lake) deposit, shale, limestone or a similar aquitard material. Note that the aquitard does not extend across the entire model. This allows water to recharge the gravel aquifer below it on the right and to discharge to the river/ocean above it on the left.

4. At the bottom of the model is a confined (artesian) aquifer of coarse sand or gravel. It could also be described as a coarse sandstone or conglomerate.

5. The base of the model could be considered to be an aquiclude such as clay, shale, granite, or some other impermeable or extremely low permeability material.

6. The vertical tubes numbered 1 through 8 represent water wells, but may also represent other types of wells such as irrigation wells, oil and gas wells, wastewater disposal wells,
etc... Wells 1, 2 and 3, Wells 4, 5 and 6, and Wells 7 and 8 are arranged in clusters of wells at different depths pumping from different aquifers. Wells 6, 7 and 8 are artesian wells. Wells 7 and 8 are flowing artesian wells producing from the middle unconfined (water-table) aquifer and confined lower aquifer. Note that there are holes in these wells above the ground surface. These holes allow artesian flow at the surface and when covered with tape allow the water to rise above the holes to their artesian level. Well 6 is a non-flowing artesian well that also produces from the confined aquifer.

7. The small, semi-circular lake can also be described as a pond or river. The lake valve can be used to control the flow of water from the lake and the level of water in the lake. By closing the lake valve, lowering the water table, and injecting dye directly into the lake, the lake can also be used to represent a waste lagoon, landfill, sinkhole or similar surface source of contamination.

8. The river on the left side of the Model can also be described as a lake or the ocean. The river valve can be used to control the level of water in the river/ocean. When coupled with the rate at which water is introduced into the aquifer compartment (at the Recharge Area), it can also be used to control the hydraulic gradient of the aquifers and the discharge of water from the aquifer compartment. The back reservoir compartment can also be described as an ocean, with the pump representing evaporation (suction tube) and precipitation (discharge).

9. To the right of the lake are a septic tank system and UST (underground storage tank) such as a service station gasoline tank or home fuel oil storage.

10. The Recharge Area for the Model is normally located on the upper right and the groundwater flows through the Model right to left into the Discharge Area (in the Model, the river/ocean).
Recharge of the aquifer can occur anywhere along the aquifer compartment where water can percolate or soak into the aquifer (green material or sometimes the lake).\textsuperscript{1}

\textsuperscript{1} Description and Diagram from: The Envision Environmental Education Groundwater Model Manual for Instructors & Operators. Copyright Richard Passero, Ph.D. Used with Permission.
Informal Interview Questions

The following questions were used to start and guide each informal interview with groundwater experts. They were not the only questions asked, as new questions arose out of conversations during each interview.

1. In your opinion, what are some of the concepts fundamental to understanding groundwater?

2. What do you think it is important for students and for the public to know about groundwater?

3. What do you think is essential for professionals going into the field of water resource and groundwater resource management to know?

Groundwater Response Matrix

This matrix is a table of concepts and their descriptions based on responses to the above questions and the conversations that followed during interviews. It also includes concepts identified by previous research as fundamental to understanding of groundwater and watershed systems. These concepts were then compared and analyzed to develop the core concepts used in the groundwater assessment framework.
Table A1

**Groundwater Core Concepts Matrix**

<table>
<thead>
<tr>
<th>Interviewee or Source</th>
<th>Concept</th>
<th>Notes</th>
<th>Source</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Niels Claes, PhD candidate Hydrology</td>
<td>Structure</td>
<td>Underlying geology and an understanding of what the subsurface looks like.</td>
<td>Ye Zhang Associate Professor: Geological Modeling and Simulation Hydrology</td>
<td>Important to get a visual on the subsurface/underlying geology. Understanding the heterogeneity of the subsurface.</td>
</tr>
<tr>
<td>George Moser: State Engineers Office groundwater division: Groundwater division Staff, degree in geology with specialty in hydrogeology</td>
<td>How Groundwater exists underground (structure)</td>
<td>Emphasizing that it is not &quot;magic&quot; that it has real limits and bounds.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Niels Claes, PhD candidate Hydrology</td>
<td>Porosity</td>
<td>Groundwater exists in the pore spaces between grains or units of material. Example water in sand as it becomes saturated.</td>
<td>Storage (storativity)</td>
<td>Unconfined aquifer: Porosity, matrix composition, water composition. How much water or space can water occupy in an unconfined system?</td>
</tr>
<tr>
<td>George Moser: State Engineers Office groundwater division: Groundwater division Staff, degree in geology with specialty in hydrogeology</td>
<td>Velocity and Flow</td>
<td>How rapidly water can flow through certain materials.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Niels Claes, PhD candidate Hydrology</td>
<td>Molecular properties of water</td>
<td>Understanding the water molecule, how it bonds, how this allows for existence in pore spaces, how it flows, how it conducts.</td>
<td>Properties of Water</td>
<td>Specifically how those properties interact to influence velocity, flow, and spread of contaminants.</td>
</tr>
<tr>
<td>George Moser: State Engineers Office groundwater division: Groundwater division Staff, degree in geology with specialty in hydrogeology</td>
<td>Permeability</td>
<td>How water percolates and flows through different substrates e.g. clay vs. sand. Important for understanding time scale in groundwater movement and flow and for thinking about where recharge zones for aquifers are.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>George Moser: State Engineers Office groundwater division: Groundwater division Staff, degree in geology with specialty in hydrogeology</td>
<td>Pressure gradients/force dynamics</td>
<td>Water at the surface generally flows from areas of high topographical relief to low areas.</td>
<td>Velocity and Flow</td>
<td>The idea that water level may not change (steady state system) but that</td>
</tr>
<tr>
<td>George Moser: State Engineers Office groundwater division: Groundwater division Staff, degree in geology with specialty in hydrogeology</td>
<td>Pressure Gradient</td>
<td>Specifically related to flow gradient and how drawdown</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Assessing Student Understanding of Groundwater

<table>
<thead>
<tr>
<th>Base level/River relationship</th>
<th>Understanding that groundwater is part of whole connected hydrologic system. River level is directly influenced by the water table and groundwater level. A reduction in groundwater level can lower the base level or flow in rivers.</th>
<th>Relationships between groundwater and surface water</th>
<th>Base Level, how groundwater and surface water interact.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Research and technology</td>
<td>Even though groundwater is not visible to the eye we have the tools and technology to understand and visualize what is happening underground. We know where groundwater is and what it looks like underground.</td>
<td>Abstract Concept to real application: How to make it concrete. Provide a problem and a context</td>
<td>Suggestion of using a relevant news story for students to critically analyze that had a local context and that is in the real world.</td>
</tr>
<tr>
<td>Local Context</td>
<td>Groundwater is everywhere and a ubiquitous part of the hydrologic system. Putting groundwater education into the context of relevant local problems (brings up the toolkit issue).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Humans use groundwater</td>
<td>Humans use groundwater as a primary source of irrigation and municipal sources, we influence the entire hydrologic system by doing so.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table A1 (contd.)

*Groundwater Core Concepts Matrix*

<table>
<thead>
<tr>
<th>Interviewee or Source</th>
<th>Concept</th>
<th>Notes</th>
<th>Concept</th>
<th>Notes</th>
<th>Concept</th>
<th>Notes</th>
<th>Concept</th>
<th>Notes</th>
<th>Concept</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>USGS Water Science School</td>
<td>Rock Types and Structure</td>
<td>Underlying geology and an understanding of what the subsurface looks like.</td>
<td>Scale (vertical)</td>
<td>How deep underground is the water? What is the scale of the subsurface structure?</td>
<td>Water is essential for all life to exist</td>
<td>Structure underground</td>
<td>Structure underground</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Porosity</td>
<td>Groundwater exists in the pore spaces between grains or units of material. Example water in sand as it becomes saturated.</td>
<td>Porosity</td>
<td>How porosity varies between different materials, e.g. limestone vs granite.</td>
<td>Water Connects all Earth's Systems</td>
<td>Porosity</td>
<td>Porosity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Properties of Water</td>
<td>Understanding the water molecule, how it bonds, how this allows for existence in pore spaces, how it flows, how it conducts.</td>
<td>Water volume &amp; residence time</td>
<td>How long is water staying in an unconfined aquifer?</td>
<td>Water has unique physical and chemical characteristics</td>
<td>Properties of Water</td>
<td>Properties of Water</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Permeability</td>
<td>How water percolates and flows through different substrates e.g. clay vs. sand. Important for understanding time scale in groundwater movement and flow and for thinking about where recharge zones for aquifers are.</td>
<td>Permeability</td>
<td>How water can flow/percolate through different substrates.</td>
<td>Water is a natural resource</td>
<td>Permeability</td>
<td>Permeability</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Idea of a &quot;water Table&quot;</td>
<td>Water at the surface generally flows from areas of high topographical relief to low areas. Groundwater in contrast flows along whatever pressure gradient exists: from areas of high pressure to areas of low pressure. This can be demonstrated by well levels with</td>
<td>Groundwater movement related to high and low pressure gradients</td>
<td>Mechanisms or scientific principles that move groundwater.</td>
<td>Water resources are managed</td>
<td>How water flow through a system</td>
<td>Direction and flow of water movement.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
the model or by removing a partition between two areas.

<table>
<thead>
<tr>
<th>Rivers Contain Groundwater</th>
<th>Understanding that groundwater is part of whole connected hydrologic system. River level is directly influenced by the water table and groundwater level. A reduction in groundwater level can lower the base level or flow in rivers.</th>
<th>Water resources exist within social constructs</th>
<th>How water gets into a river</th>
<th>Connection b/w groundwater and surface water.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Even though groundwater is not visible to the eye we have the tools and technology to understand and visualize what is happening underground. We know where groundwater is and what it looks like underground.</td>
<td>Water resources exist within cultural contexts</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Confined vs. Unconfined Aquifer</td>
<td>Groundwater is everywhere and a ubiquitous part of the hydrologic system. Putting groundwater education into the context of relevant local problems (brings up the toolkit issue).</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wells</td>
<td>Humans use groundwater as a primary source of irrigation and municipal sources, we influence the entire hydrologic system by doing so.</td>
<td>Well Construction</td>
<td>Human influence on groundwater &amp; how humans access groundwater resources.</td>
<td>Influence of wells and pumping on groundwater.</td>
</tr>
</tbody>
</table>

Sources: Brody, 1995; N. Claes, personal communication, January 28, 2016; Dickerson et al., 2007; Duffy, 2012; Gunckel et al., 2009; G. Moser, personal communication, May 24, 2106; USGS Water Science School (http://water.usgs.gov/edu/mearthgw.html); Y. Zhang, January 29, 2016, personal communication.
APPENDIX C

GROUNDWATER AND WATERSHED SCIENCE EDUCATION RESOURCES

enVision Environmental Education: http://www.envisionenviroed.net/

National Groundwater Association Educator Resources:
http://www.ngwa.org/Fundamentals/teachers/Pages/default.aspx

Pathways Project: http://www.pathwaysproject.kbs.msu.edu/

University of Wyoming EPSCoR: http://www.uwyo.edu/epscor/

USGS Educational Resources for Secondary Grades (7-12):
http://education.usgs.gov/secondary.html

USGS Water Science School: http://water.usgs.gov/edu/