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Developing an Understanding of Systems in the Context of Ecohydrological Citizen Science Research

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Developing an Understanding of Systems in the
Context of Ecohydrological Citizen Science Research

DISSERTATION

submitted in partial satisfaction of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

in Education

by

Jennifer Joan Long

Dissertation Committee:
Associate Professor Rossella Santagata, Chair
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Professor Travis Huxman

2015

DEDICATION

To

Mom, Penny, and Jen

without whom I would never have finished this,

Ed

without whom I would never have started this,

and

my good friend, Jacob

who constantly reminds me that…

“The important thing is not to stop questioning. Curiosity has its own reason for existing.”

– “Albert”

“…for what you learn today, for no reason at all, will help you discover
all the wonderful secrets of tomorrow.”

– Norton Jester, *The Phantom Tollbooth*

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ACKNOWLEDGMENTS

I first want to acknowledge my design and implementation team who spent countless hours discussing ideas, providing feedback, and most importantly, teaching our kids. They worked tirelessly to create a challenging, safe, and intellectually nurturing environment, and they were always respectful of the research. The impact that they had on me and on every child with whom they worked cannot be over stated, and I am more grateful than they will ever know.

Second, I want to acknowledge all the kids with whom we worked. They sometimes let us push them farther than they wanted to go, and they always pushed us farther than we ever thought possible. Also, they made us laugh.

I am also deeply grateful for the support and guidance of my dissertation committee. First, I want to acknowledge, with my deepest gratitude, the interest and enthusiasm of my advisor and dissertation chair, Dr. Rossella Santagata. Her support has been unwavering from the moment I sat down at her lunch table with this crazy idea. Over these last years, she has believed in me, even when I couldn't quite believe in myself. Second, I want to thank Dr. Beth van Es. I have learned more from her about research than anyone else—she has been so generous with her time and attention over these last years. I remember sitting in Beth's Design class during my first year as a graduate student and thinking that this was exactly why I decided to go back to school. Finally, I want to thank Dr. Travis Huxman for so graciously opening his lab (and his expensive equipment) to me and for being willing to let me use his research as an intellectual playground for 9 – 11 year olds. This experience, I think, forever changed the way that they—and I—look at the environment and at science research, and for that, I will always be grateful to Travis

I want to acknowledge the staff at Crystal Cove Alliance and State Park, who paved the way for this work. I especially want to thank Harry Helling, who has been, over the many years that I have known him, a respected colleague and a trusted friend. It was from him that I learned that no matter how good we are, we can always be better.

I am grateful to the principal, staff, teachers, and PTA at El Morro Elementary School, who opened their doors to me and let us work with their students.

I want to acknowledge the Newkirk Center for Science and Society at the University of California, Irvine for their support through the Graduate Student Fellowship Award.

I especially want to thank Jennifer Jacques. She generously gave her time and her tremendous talent to this project and to me, and the conversations that we had over the years we worked together pushed my thinking in directions and distances that I never thought possible. She is a talented teacher and an even more talented friend.

Finally and most importantly, I want to acknowledge my family and friends, who left me alone when I needed it and who distracted me when I wanted it. I want to thank Huy Chung, who has always been willing to listen and to council. And, I especially want to thank my Mom and my sister, Penny. They both read every word of this dissertation. But more than that, they found it compelling (at least that's what they told me). I will never be able to express my profound gratitude for the support, encouragement, and comfort they both offered over these last years.

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Helling, H., Magdziarz, S., **Long, J. J.**, Laughlin, M., Kasschau, J., Camp, J. (2008). Forecast—Cloudy with a chance of educational reform: New weather and water partnership offers some relief from the drought. In R.E. Yager & J. Falk (Eds.), Exemplary Science in Informal Education Settings: Standards-based Success Stories (pp. 113-131). Arlington, Virginia: NSTA Press.

WORK SUBMITTED FOR REVIEW

Rutherford, T., **Long, J. J.,** van Es, E. A., & Farkas, G. "Understanding the relationship between ST Math teacher professional development and its impact on students." *Teaching and Teacher Education.*

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ABSTRACT OF THE DISSERTATION

Developing an Understanding of Systems in the
Context of Ecohydrological Citizen Science Research

By

Jennifer Joan Long

Doctor of Philosophy in Education

University of California, Irvine, 2015

Associate Professor Rossella Santagata, Chair

Systems thinking can serve as an important tool for making informed decisions about our world, but the complex nature of systems makes systems thinking challenging to teach and particularly challenging for young children to learn. This dissertation tells the story of the Citizen Scientists' After-school Club, a citizen science based approach to learning about complex systems, detailing the learning outcomes associated with participation, the theoretical contributions of the design, the challenges that arose from implementation, and the resulting lessons learned. Through design-based methodology, I examined the both the learning outcomes and the programmatic components necessary to cultivate systems thinking in nine youth ages 9-11 as they participated in ecohydrological citizen science research. Qualitative methods were used to study the learners' changes in systems thinking as well as the extent to which the design of the after-school club may have influenced these changes. The conceptual model that served as the foundation of the design predicted that learners would engage in increasingly complex systems thinking as they participated in the steps of science research. Overall, the results revealed that learners did engage in a pattern of systems thinking predicted by the model. Despite the learners' initially fragmented view of the ecohydrological system, most of them made

progress in their ability to understand and explain the core features of a complex interacting system. The design of the learning environment supported their learning by affording access to tasks, tools, and participation structures associated with authentic research, thus engaging the learners in the *doing of science*. This research showed that in spite of their minimal initial systems thinking abilities, most of the learners made meaningful progress in their systems thinking skills. Prior work with learners of this age suggested that there may be limits to the complexity of systems thinking reasoning of youth ages 9 – 11; however, the results of the study suggest that although systems thinking is regarded as a high order thinking skill, with designed supports in an authentic context, learners as young as nine years old can develop systems thinking skills.

INTRODUCTION

In a world filled with the products of science and technology, being scientifically literate is necessary for everyone—an understanding of science is essential to participate fully in personal, professional, and civil life (Feinstein, 2011; Roth & Van Eijck, 2010). It has become increasingly important that all citizens are able to understand complex environmental issues and make intelligent decisions that will maintain and protect Earth's life-supporting systems. Over the last two decades, the main goal of science education has shifted from preparing future scientists to educating future citizens who are capable of navigating complex scientific concerns. Effective science education must provide people with the tools and experiences that help them solve personally meaningful problems, that directly affect their material and social circumstances, that shape their behavior, and that inform their practical and political decisions (Feinstein, 2011). Science knowledge in general, and an understanding of systems in particular, can serve as important tools for making informed decisions about our world. However, the complex nature of these ecological systems and processes makes it challenging to teach ecology at all education levels, but it is particularly challenging for elementary students to learn (Jacobson & Wilensky, 2006). Thus, identifying effective approaches to learning that foster systems thinking is a high priority in science education.

Current research on science learning suggests that learners generate science knowledge and understanding by engaging in authentic learning experiences that include asking questions and defining problems; developing and using models; and engaging in argument from evidence (Lehrer & Schauble, 2006; National Research Council, 2012). The Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas (National Research Council, 2012) emphasizes learner participation in these key science practices as one way to learn the crosscutting scientific concepts, including systems and systems models, that unify scientific study. This particular area of emphasis focuses on what students need *to do* to learn science, a view that "embodies the dialogic knowledge-building processes that are at the core of science, namely, obtaining and using principles and evidence to develop explanations and predictions that represent our best-reasoned beliefs about the natural world" (Duschl, 2008, p. 269). Research related to science learning suggests that engaging learners in these authentic learning experiences plays a critical role in learners' developing science understandings. Authentic activities are powerful in that they establish real purposes for undertaking them. They allow learners to engage in the ordinary practices of science such that they take up and use cultural tools as a means of asking and answering questions (Brown, Collins, & Duguid, 1989; Duschl, Schweingruber, & Shouse, 2007; Edelson, 1998). However, science learning as generated through this notion of *science-as-practice* is both complex and ambitious, leading to a number of important questions. What does science education as science-as-practice look like, and how do we develop and sustain appropriate and authentic contexts in which to engage non-scientists, particularly youth? Specific to this current research, can youth develop systems thinking through participation in the ways of knowing and doing science; and if so, which forms of practice provide the greatest educational leverage for their emerging understandings of systems?

Research on the effectiveness of citizen science projects may provide interesting answers to these questions. Citizen science refers to the engagement of non-professionals in genuine scientific investigations. At the core of citizen science are scientific questions or environmental issues that need high quality data to address (Bonney, Ballard, Jordan, McCallie, Phillips, Shirk, & Wilderman, 2009). Activities that do not produce new scientific knowledge—for example, teaching labs where the outcome is known, data-collection activities where the data are not analyzed, or projects where the knowledge generated is not communicated beyond the participants—are not included in my use of the term citizen science (Miller-Rushing, Primack, & Bonney, 2012).

Because citizen science engages non-scientists in authentic research with the intention of generating useful and usable data, participation in these types of projects may offer powerful ways for learners to develop science inquiry capabilities, generate specific ecological knowledge and engage in community-based experiences (Dickinson, Shirk, Bonter, Bonney, Crain, Martin, Phillips, & Purcell, 2012). Indeed, current research on the effectiveness of citizen science in supporting learning outcomes suggests that involvement in citizen science may lead to learner gains in content knowledge, more positive attitudes toward science, and deeper understandings of the scientific processes, with the possibility of more extensive outcomes arising from more collaborative involvement (Bonney, Ballard et al, 2009). As such, citizen science may have potential benefits for individual participants as they develop deeper understandings of science; for the larger education community since involving youth in authentic science learning experiences early on may prevent youth drop out from science related courses in middle and high school; and for environmental scientists as they build extensive data sets that expand both the space and time axes over which to evaluate a phenomena.

Through design-based methodology, I examined the programmatic components necessary to cultivate systems thinking in youth ages 9-11 as they participated in citizen science research in Crystal Cove State Park. Recognizing that studying "interesting forms of scientific thinking cannot progress very far unless those forms of thinking are brought into being" (Lehrer & Schauble, 2006, p. 154), design-based researchers focus on creating the structure and operationalizing the instruction to effectively study the resulting learning (Brown, 1992; Barab, 2006; Cobb et al., 2003; Collins, 1992; Collins et al., 2004). Thus, the overall purpose of this research was to design and implement an eight-week after-school club in order to examine both youth learning and the means by which that learning was generated and supported. I was particularly interested in studying the effectiveness of the theoretically derived design principles and related learning conjectures and in identifying the practical constraints and core challenges of implementing authentic projects for youth, especially in the context of systems thinking. Specifically, I asked:

1. To what extent will participation in collaborative citizen science research facilitate youths' development of systems thinking?
2. What are the core design features of an after-school citizen science club that involves youth ages 9-11 in learning the science of ecohydrology and in systems thinking? What are the challenges of designing and implementing such learning experiences?

The Citizen Scientists' After-school Club was implemented in the winter of 2014 and was designed around environmental research in the field of ecohydrology. Ecohydrology is the study of the interactions and interrelationships between hydrological processes and the pattern and dynamics of vegetation (Breshears, 2005). This under-studied area of environmental science (i.e., landscape water balance) directly relates to land restoration and management (i.e., watershed monitoring), a context that is appropriate for studying the development of systems thinking in youth as well as an area of particular interest to the Crystal Cove State Park land managers.

Over the course of the eight-week program, participants conducted environmental research in the context of issues related to ecosystem management through restoration – what features of the environment and biology can be manipulated by property owners to add value to a landscape? The overarching research topic focused on “where the water goes,” with the specific question relating to water as it flows through restored, under restoration, and degraded landscapes in Moro Canyon. In order to answer the question they were given, youth participants worked in small research teams to conduct background research and investigations on the general topic and the specific question under study; create representations of water movement in the canyon; generate a testable hypothesis based on their representation; learn to use equipment, including soil moisture meters and leaf porometers (used to gather plant transpiration data); follow protocols to gather water and weather data; graph and analyze their data; and then draw conclusions from their analyses. Finally, youth met with State Park staff and other community members to share the findings from their work. I have outlined specific details of the instructional design in Chapter 3.

In the following chapters, I detail the specific aspects of this study. In chapter 1, I review the foundational literature in the areas of science-as-practice, citizen science as a context for science-as-practice, and systems thinking. Together, these three areas of study informed the development of my conceptual model about systems thinking development through citizen science, which in turn, informed both the research questions and the intervention design. In chapter 2, I introduce and discuss the theoretical underpinnings of design-based research, detail the structure and design of this study, and discuss the initial stages of design as they related to drafting the design principles, learning conjectures, and conjecture map. In chapter 3, I describe the design approach for the Citizen Scientists’ After-school Club and provide an overview of the design principles and conjectures for learning and the elements in which each conjecture was embodied. I also present the conjecture map, which details the proposed links between design elements and learning outcomes that I used for the design of the intervention and the research.

Chapter 4 includes a discussion of the learners' systems thinking outcomes and an overview of the measures and analytic strategies. In chapter 5, I discuss the ways in which the educational intervention was studied as a means of considering how the individual components of the design were woven together to mediate specific learning outcomes. This chapter includes details on each research phase, including design, implementation, and revision; the research strategy I employed; the outcomes related to design features that I found; and the lessons learned, including the emerging challenges as they related to the overall system of learning. I also describe my methods of data collection, data analysis, and inference in the hope that such explicitness will lead to increased understanding of one way that this type of research can be conducted (Cobb, 2001; Collins et al., 2004; Hammer & Berland, 2014; Sandoval, 2004, 2014). In chapter 6, I revisit my conceptual model, discussing revisions based on the findings from this study.

CHAPTER 1

Designing and Studying a Citizen Science Approach to Systems Thinking: The Theoretical Foundation

Design-based research uses the close study of a designed learning environment as it passes through multiple iterations to test and/or develop learning theories, artifacts, and practices that support learning that can be appropriated in other settings (Barab, 2006). The goal of this particular type of research is to advance both theory and practice by constructing and refining design principles and embodied conjectures that guide the designers and impact learners (The Design-Based Research Collective, 2003; Edelson, 2002; Kelly, Back, Lesh, & Bannan-Ritland, 2008; Sandoval, 2004, 2014). In this chapter, I focus on the literature that influenced the conceptual model from which the design principles, conjectures about learning, and the resulting design strategies were derived, including 1) the theoretical grounds for science learning conceived as science-as-practice; (2) the science-as-practice learning context of collaborative citizen science; and (3) the theoretical model for systems thinking as developed through previous designed interventions.

Science-as-Practice

In their work on science thinking and science literacy, Lehrer and Schauble (2006) identify and discuss three images of science literacy and learning that have attracted broad research support: science-as-logic, science-as-theory, and science-as-practice. I situate this study within the image of science-as-practice, which places an emphasis on the *doing of science* in order to build ways of talking and thinking about natural phenomena. This image evokes the notion that learning science involves grappling with “a system of interconnected ways of thinking in a social context to accomplish the goal of working with and understanding the scientific ideas" (Duschl, Schweingruber, & Shouse, 2007, p. 38) and stresses that a conceptual understanding of natural systems is linked to the ability to develop explanations and carry out investigations in order to evaluate these explanations. Science-as-practice highlights science thinking as part of a larger collection of structures and activities, including participating in a community of practice composed of networks of participants and institutions (Latour, 1987; Lave & Wenger, 1991); developing specialized ways of talking and writing (Lemke, 1990; Mortimer & Scott, 2003); and developing and using specialized representations that make science phenomena accessible, visualizable, and transportable (Goodwin, 1994). Thus, we generate knowledge through the productive participation in scientific practices and discourse. As Warren and Rosebery (1996) summarize:

> From this perspective, learning in science cannot be reduced simply to the assimilation of scientific facts, the mastery of scientific process skills, the refinement of a mental model, or the correction of misconceptions. Rather, learning in science is conceptualized as the appropriation of a particular way of making sense of the world, of conceptualizing, evaluating, and representing the world (p. 104).

I derive my notion of science-as-practice from a perspective of learning that views science, science learning, and research on science learning as human social activities conducted within cultural frameworks. This particular view has important implications for the study of science learning. First, it means giving substantial weight to the role of social interaction, seeing it as central and necessary to learning (Vygotsky, 1978); second, it means formulating questions around the role of social interaction in science learning (Lemke, 2001); and third, it means seeing scientific study of the world as inseparable from the social organization of scientists' activities (Latour, 1987). To study learning experiences built on the notion of science-as-practice, we document and analyze the ways that participants appropriate and use the tools of science as they engage in social interaction around authentic science work.

The image of science-as-practice provides a useful lens through which to study the mechanisms that support learning and the nature of the contexts that give rise to these mechanisms. As previously discussed, social interactions, framed here as dialogic knowledge-building processes, play a role in building knowledge and developing higher-order thinking capabilities (Vygotsky, 1978). Vygotsky's work emphasizes the fundamental relationship between language and individual thought. His notion of language as a cultural tool for meaning making has profound implications for how we conceptualize the relationship between thought and language. First, learning to talk is very much about learning to think; second, language does more than simply reflect thought—thought is refracted through language; and third, language is a socially and culturally shaped tool that is bound up with the cultural practices of a society (Lillis & McKinney, 2003).

All higher mental functions have social origins—they are first expressed *between* individuals on an interpersonal plane, but over time, they are internalized *within* the individual on an intrapersonal plane. Thus, learning is the "transformation of socially shared activities into internalized processes" (John-Steiner & Mahn, 1996, p. 191). Language serves an important self-regulatory function, as people use it to guide, plan, and monitor their activities. This "private speech," as Vygotsky called this self-regulatory language, is used as a tool for thinking. These understandings about the role that language plays in the nature and processes of learning have particularly relevant implications for the design and study of learning environments.

To determine how learners internalize knowledge and the kinds of thinking generated as a result, it is critical to understand the ways in which social practices relate to learning. According to Vygotsky (1978), learning takes place within one's zone of proximal development (ZPD). Brown, Ellery, and Campione (1997) define the ZPD as "a learning region that learners can navigate with aid from a supporting context…[and] defines the distance between current levels of comprehension and levels that can be accomplished in collaboration with other people or powerful artifacts" (p. 359). Bruner refers to the supporting context as "scaffolding" (Bruner, 1978). We can distinguish scaffolding by the appearance of certain distinguishing characteristics, specifically the diagnosis of learner ability and the provision of an adaptive level of support that fades over time (Pea, 2004). It occurs when a "more knowledgeable other," which can be an adult, a peer, a tool, or a visual representation, assumes "the responsibility for arranging and managing the activity so that the child can participate at a level just beyond his or her current capabilities" (Gauvain, 2001, p. 146). Research has demonstrated that these scaffolding agents can enhance the educational benefits of collaborative conversation because they make private thinking accessible to learners as well as encourage deep learning by facilitating learner reflection (Lehrer & Schauble, 2006; Cobb, 2002; Kelly, Crawford, & Green, 2001). These scaffolding agents thus act to create situations in which the learner can concentrate on aspects of a particular task that are within her or his grasp.

There is, however, an open problem in the field of learning sciences related to the nature and type of learner support structures that we design into educational programs. Early work on scaffolding identified several different ways that learning can be scaffolded: by reducing the degrees of freedom for a task by providing constraints that increase the learner's effective action; by focusing the learner's attention on relevant task features; and by modeling more advanced solutions to the task (Wood et al, 1976). However, questions remain about how much and what type of supports should be available. Current research in this area aims to uncover the nuances of scaffolding by asking if the type of support should vary depending on the specific learning outcomes (Koedinger & Aleven, 2007; Koedinger, Pavlik, McLaren, & Aleven, 2008).

The process of learning described here is not one that involves ideas being transferred directly from one person to another. Rather, each learner is constructing knowledge by engaging in an ongoing process of comparing and checking her or his own understandings with the ideas that are being rehearsed by and with others (Mortimer & Scott, 2003). Thus, meaning making is dialogic in nature—it always involves bringing together and working on ideas that are explored and negotiated until some understanding is reached (Bakhtin, 1981). As argued by Voloshinov (1929):

> To understand another person's utterance means to orient oneself with respect to it… For each word of the utterance that we are in process of understanding, we, as it were, lay down a set of our answering words. The greater their number and weight, the deeper and more substantial our understanding will be… Any true understanding is dialogic in nature (p. 102).

Science knowledge, dialogic in nature as well because it is developed and validated through social processes, can be seen as a product of a scientific community that has a distinctive way of talking and thinking about the natural world. Learning science therefore involves being introduced to and coming to understand the language of the scientific community (Lemke, 1990; Mortimer & Scott, 2003). Ultimately, it involves being introduced to the concepts, tools, conventions, and practices of science and coming to appreciate how this knowledge can be applied to social, technological, and environmental issues. Thus, knowledge building is a social practice that learners have to appropriate and internalize. Duschl (2003) describes the social processes involved in developing and communicating scientific understandings and emphasizes the importance of making learners' ideas public through discourse as a way to help them examine and evaluate their developing understandings of scientific knowledge as well as science practice. Since science is a collaborative enterprise, learners should be encouraged to work in groups to reason collectively and reach decisions together. The discourse skills involved in these social practices, which may be difficult for many learners and must be scaffolded, are developed through their use in activity (Ryu & Sandoval, 2012).

Making science learning more closely resemble science practice has long been a common goal of many education practitioners and researchers who hold that *authentic* learning experiences play an important role in learners' developing science understandings (Bevin et al., 2009; Edelson, 1998). Brown, Collins, and Duguid (1989) describe authentic activities as the "ordinary practices of the culture" where their "meanings and purposes are socially constructed through negotiations among present and past members" (p. 34) and then argue that "authentic activity…is important for learners, because it is the only way they gain access to the standpoint that enables practitioners to act meaningfully and purposefully" (p. 36).

When conducting science investigations, scientists are involved in a wide range of activities, including conducting background research, asking questions, hypothesizing, planning, making observations, collecting and analyzing data, proposing explanations, and communicating results (Edelson, 1998; Duschl, Schweingruber, & Shouse, 2007). Science is not just conducting investigations to gather data. Rather, it "advances in large part through interactions among members of research community as they test new ideas, solicit and provide feedback, articulate and evaluate emerging explanations, develop shared representations and models, and reach consensus" (Duschl, Schweingruber, & Shouse, 2007, p. 40). Authentic activities are powerful in that they establish real purposes for undertaking them. Learning experiences set within the social organization of science provide access to and involvement with the tools for making sense of the natural world, including language, visual representations, and specialized discourses and practices (Lemke, 2001), and educational experiences that aim for authenticity should reflect the "diverse ways in which scientists study the natural world and propose explanations based on the evidence derived from their work" (National Research Council, 1996, p. 23). Further, they should reflect the interconnections and interactions between the tools, techniques, and social interactions that characterize science-as-practice (Edelson, 1998). Authentic activities allow learners to take up and use cultural tools of science to achieve their goals, allowing participants to use these tools—including science equipment (i.e., thermometers, soil moisture meters, leaf porometers), language (i.e., asking questions and generating hypotheses, engaging in scientific argumentation), and science techniques (i.e., modeling) and others—because they are the means for asking and answering meaningful questions (Bevan et al., 2009; Duschl, Schweingruber, & Shouse, 2007). As culturally transmitted resources for constructing knowledge, these tools are useful for guiding oneself through problems and for negotiating meaning with others.

To participate fully in authentic science experiences in the learning context, learners need to develop a shared understanding of both the features of and the participation norms for engaging in scientific practice. Edelson (1998) organizes the key features of scientific practice into three categories: (1) tools and techniques, which are the methods through which scientists pose and investigate a range of questions; (2) attitudes, which are the understandings that science is the pursuit of unanswered questions, that scientific practice is characterized by uncertainty, and that both the process and the products of scientific inquiry are subject to continual reexamination and change; and (3) social interaction, which is the way in which new ideas are tested, feedback is provided and solicited, emerging explanations are articulated and evaluated, representations are developed and shared, and consensus is reached. These practices have been developed and refined over the history of any specific field of science and are shared across a community of like-practicing scientists, and any authentic translation of scientific practice into an educational intervention must include these features as well as mechanisms for providing support as learners develop an understanding of the ways in which to effectively participate in science.

Citizen Science as a Context for Science-as-Practice

Citizen science has the potential to provide learners with authentic science experiences by providing access to the key features of scientific practice. Its defining characteristic is the public's participation in genuine scientific research, which means that it generally includes a partnership between amateur (someone who is not a professional scientist) and professional scientists. In recent years, it has gained attention as a way of tackling research questions that require extensive datasets (Miller-Rushing, Primak, & Bonney, 2012) and as a mechanism for engaging the public in the scientific process with the goal of improving science literacy (Couver et al., 2008; Bonney et al., 2009a, 2009b; Silvertown, 2009). The research that is conducted can be hypothesis-driven, based on natural history observations, or relate to environmental monitoring that can be used to generate hypotheses or make land management decisions (Miller-Rushing et al., 2012).

Although citizen science is sometimes discussed as if it were new, non-scientists have been involved in science research for centuries. Historically, the earliest published information about ecology and natural history came primarily from "amateur" naturalists, people like Henry David Thoreau and John Muir (Dickinson & Bonney, 2012). In fact, the public has both informally and formally participated in science research since the nineteenth century, with early projects including lighthouse keepers documenting bird strikes starting in 1880, the National Weather Service Cooperative Observer Program that started in 1890, and the National Audubon Society's first annual Christmas Bird Count in 1990 (Shedd Aquarium, 2014). There were few professional scientists, so it was not unusual for non-professionals to contribute to the scientific body of knowledge.

Although the field has shifted over the last 150 years from research driven by highly skilled amateurs to research conducted by highly trained professionals, non-scientists still play an important role in science research (Miller-Rushing et al., 2012). Today, people across the United States participate in multiple projects, contributing data and observations to a range of different topics, from plant and animal populations to water quality and astronomy. Moreover, there are some types of research that are best accomplished with the involvement of citizen scientists (Catlin-Groves, 2012). For example, because research scientists are incentivized to study questions that advance knowledge of the field and to avoid projects that are local in scope, they may be less likely to pursue research that addresses local or context-specific environmental issues. Local citizen scientists, however, have successfully undertaken important work related to issues in their communities, with the data that they collect influencing local land policy and management decisions (Miller-Rushing et al., 2012).

Generally, citizen science projects originate with scientists, who are interested in building data sets across both time and space to advance knowledge of a particular scientific area (Miller-Rushing et al., 2012). To carry out their projects, scientists recruit networks of volunteers who collect, and on occasion, analyze data (Cooper, Dickinson, Phillips, & Bonney, 2007). Because these projects are built upon active involvement in authentic scientific research, they have the potential to engage participants in personally meaningful science inquiry and to provide them with powerful ways to contribute to the generation of science knowledge (Dickinson et al., 2012; McCallie, Bell, Lohwater, Falk, Lehr, Lewenstein, Needham, & Wiehe, 2009). However, there are questions about the extent to which these top-down projects can have a deep and sustained impact on participants.

When purposefully designed, citizen science projects can and should benefit both researchers and public participants as learning goals, data, and results overlap. Because interest in citizen science has been increasing, researchers have begun to consider various approaches for public participation in science research. In their 2009 report for the Center for Advancement of Informal Science Education, Bonney and colleagues (2009) describe three different categories of participation based on level of involvement:

- Contributory projects, which “are generally designed by scientists and for which members of the public primarily contribute data.”
- Collaborative projects, which “are generally designed by scientists and for which members of the public contribute data but also may help to refine project design, analyze data, or disseminate findings.”
- Co-created projects, which “are designed by scientists and members of the public working together and for which at least some of the public participants are actively involved in most or all steps of the scientific process” (p. 11).

These categories differ chiefly in the extent to which individuals are involved in the process of scientific research—from asking questions to analyzing data and disseminating results. For example, in Contributory projects, participation may be limited to data collection and possibly data analysis. Collaborative projects, however, may engage participants in the added dimensions of interpreting data and drawing conclusions. Finally, co-created projects might have participants participating fully, from asking questions and designing protocols for data collection; to collecting, analyzing, and drawing conclusions about data; and discussing results, disseminating conclusions, and asking new questions (Bonney, Ballard et al., 2009) (see Table 1.1).

Table 1.1
Categories of Citizen Science Involvement (Bonney, Ballard et al, 2009)

Steps in Scientific Process[1]	Steps included in Contributory Projects	Steps included in Collaborative Projects	Steps in Co-created Projects
Choose/define question(s) for study			X
Gather information and resources			X
Develop explanations (hypotheses)			X
Design data collection methodologies		(X)	X
Collect samples and/or record data	X	X	X
Analyze samples	(X)	X	X
Interpret data and draw conclusions		X	X
Disseminate conclusions	(X)	(X)	X
Discuss results and ask new questions		(X)	X

X = public involved in steps; (X) = public sometimes involved in steps

These categories focus on the process of scientific research for several reasons. First, because citizen science inherently aims to generate scientific knowledge, the research process is a common element across all projects (Shirk et al., 2012). Second, there appears to be a relationship between the degree of participation and the project outcomes, with research suggesting that increased participation can lead to increased opportunities for learning (Hickey & Mohan, 2004; Wulfhorst et al., 2008). Thus, although the Contributory approach has been most productive in generating peer-reviewed publications, the Collaborative and Co-created approaches have the potential to generate deeper educational outcomes, including knowledge of scientific concepts and processes (Bonney, Ballard et al., 2009).

A review of citizen science in the field of environmental research suggests that projects vary along four major axes: (a) who initiates the project—professional scientists, educators, or the public; (b) the scale and duration of the project, whether local or global and short term or

[1] This is not to imply that all scientific research includes all of these steps or a defined order. Rather, these steps provide a range of common research activities in which a learner might participate.

long term; (c) the types of questions being asked, ranging from pattern detection to experimental hypothesis testing; and (d) the project goals, which include research or management, education, or behavioral change (Dickinson & Bonney, 2012). Interestingly, when informally asked to weigh different project goals, citizen science project developers indicate that as the weighting of science or environmental education increases, the weighting of science or environmental research decreases. Thus, there appears to be a tradeoff between the goals of education and scientific research (Dickinson & Bonney, 2012). Because we define citizen science as generating usable and trustworthy data, the science research must drive the design of the intervention. However, when there are educational outcomes to consider, one of the key challenges of citizen science is to identify and design around the critical research and education trade-off points so that learners achieve the learning outcomes while maintaining the rigor of the science research, the quality of the data, and the authenticity of the experience (Shirk et al., 2012).

Both science learning researchers and science educators are increasingly interested in citizen science as a vehicle for developing and studying participants' interest in and learning of science content, processes, and ways of thinking (Michaels, Shouse, & Schweingruber, 2008; National Research Council, 2009). Previous research suggests that people can increase their science understanding (McCormick et al., 2003). Evans and colleagues (2005) saw increases in biological content knowledge, and Turmbull and colleagues (2000) suggest that involvement in citizen science may result in broader science literacy, with participants engaging in scientific and inquiry-related thinking. At a minimum, by providing the observational tools necessary for participation, citizen science involvement usually increases awareness of scientific processes (Nerbonne & Nelson, 2004; Pattengill-Semmen & Semmens, 2003). In the context of environmental problems, citizen science participation has increased civic awareness and engagement as well as other environmental action-oriented behaviors (Nerbonne & Nelson, 2004; Weber, 2000).

Although existing research on the effects of citizen science suggests that involvement in research can lead to gains in specific content knowledge (Evans, Abrams, Reitsma, Roux, Salmonsen, & Marra, 2005), most studies report only limited gains (Brossard, Lewenstein, & Bonney, 2005; Jordan, Ballard, & Phillips, 2012). This may be because the projects in which scientists choose the research question, design the protocols, and analyze the data may offer fewer opportunities for participants to engage more deeply in the processes of science (Jordan, Ballard, & Phillips, 2012). However, when there is a mutual exchange of knowledge, there might be more opportunities for both scientists and participants to develop new or more nuanced understandings of issues and opportunities (McCallie et al., 2009).

More research is needed to understand the specific impacts of a collaborative level of involvement on participants' outcomes. Moreover, no studies have specifically examined the impact of participation in citizen science on youth ages 9-11 or the ways in which participating in authentic science research may influence understanding of how natural systems function. Recent systems approaches to ecosystem ecology suggest that citizen science may play a role in helping to understand and address the complexity of natural systems as they vary across space and time, including feedback loops, time lags, and multivariate outcomes (Machlis, Force, & Burch, 1997). This study fills in these gaps in the literature by uncovering the design principles, implementation challenges, and learning outcomes associated with a collaborative level of involvement in citizen science research related to ecosystem ecology by youth ages 9-11. It is important to note that the study of the effectiveness of Co-created projects on knowledge construction is beyond the scope of this study. However, the theoretical and programmatic knowledge generated by this study will be invaluable in designing and studying citizen science projects that engage participants in deep and sustained research.

Systems Thinking

During recent years, there have been an increasing number of calls to develop a science education system that allows learners to build understandings of the concepts that cut across multiple science disciplines, including systems and system models (National Research Council, 2012). According to Jacobson and Wilensky (2006):

> The conceptual basis of complex system ideas reflects a dramatic change in perspective that is increasingly important for students to develop as it opens up new intellectual horizons, new explanatory frameworks, and new methodologies that are becoming of central importance in scientific and professional environments (p. 12).

Thinking in terms of complex systems helps people build links between disparate elements of curriculum and provides opportunities to build unifying and coherent conceptual frameworks. Thus, a critical component of science education should be helping learners develop the ability to think in terms of the ways that systems function (National Research Council, 2012).

A *system* is "an entity that maintains its existence and functions as a whole through the interaction of its parts" (Ben-Zvi Assaraf & Orion, 2005). More specifically, it is a recognizable set of components that is coherently organized, related, and interconnected in a pattern that produces a characteristic set of behaviors and that has a specific purpose (Meadows, 2008). All of the components of the system must be present for the system to carry out its purpose. The system attempts to maintain its stability through cause and effect feedback loops, which means that the status of one or more components effects the status of the other variables. Finally, the properties of the system as a whole are not those of the individual components that make up the system (Ben-Zvi Assaraf & Orion, 2005).

Systems thinking refers to our ability to recognize patterns of relationships and interconnections between components and then to synthesize these patterns into a unified view of the whole (Senge, 1990). The goal of systems thinking education is to help learners see the world differently—to "enhance their ability (and inclination) to attend to various aspects of particular systems in attempting to understand or deal with the whole" (American Association for the Advancement of Science, 1993, p. 262). Developing this type of thinking enables us to reason effectively about complex dynamic systems, to transfer that skill and knowledge to future situations we would like to understand, and to identify leverage points when solving problems, including where we can intervene with positive results and how to avoid unintended consequences of these interventions. It requires sophisticated cognition that extends beyond classic scientific reasoning about manipulation of variables to understand the dynamic balances among these multiple systems, subsystems, and processes, including plants and animals, water, geological processes, pollution, and restoration (Hmelo-Silver & Aevedo, 2006). For example, to reflect intelligently and prudently on key issues of resource management—in this research, the management of State Park land, we must understand such aspects of systems as multi-causality, multivariate outcomes, positive and negative feedback loops, linear and nonlinear relationships, interacting features at multiple temporal and spatial scales, and so on.

Understanding and reasoning about complex systems is difficult and often counterintuitive, especially since systems operate in ways that conflict with many commonly held every day beliefs (Jacobson & Wilensky, 2006; Wilensky & Resnick, 1999). Most people, because of their educational experiences, prefer explanations that assume central control and single causality (Resnick & Wilensky, 1998). Hmelo-Silver, Marathe, and Liu (2007) suggest that learners display limited understanding of complex systems because systems are composed of multiple interrelated levels that interact in dynamic ways over both space and time. Feltovich and colleagues (2001) found that multicomponent phenomena that are invisible, dynamic, and interdependent are particularly difficult to understand and that prior experience often impedes learners' ability to understand complex systems. Kali, Orion, and Eylon (2003) and Ben-Zvi Assaraf and Orion (2005) have shown that middle school students tend to see a system as unrelated parts or pieces of information and lack dynamic and systematic perceptions of systems. Prior to formal training in systems thinking, learners generally default to descriptive, surface features (Booth Sweeney & Sterman, 2007). One explanation is that traditional school curricula and pedagogy often ignore the complexity of systems and instead have learners focus on memorizing the names of the parts of the system and encourage incomplete and reductive thinking about complex systems by focusing on "cycles," "food chains," and "chain reactions" as isolated events rather than on the way that components of systems as well as systems themselves interact (Ben-Zvi Assaraf & Orion, 2005; Hmelo-Silver & Azevedo, 2006). With natural phenomena framed in this way, it is not surprising that "most people understand complex systems as a collection of parts with little understanding of how the system works" (Hmelo-Silver & Azevedo, 2006, p. 54).

Despite the difficulties in learning about complex systems, understanding them is foundational for many areas of learning and offers the potential to integrate across multiple disciplines (Jacobson & Wilensky, 2006). For example, by learning about the Earth's water systems, youth can develop an understanding of the important role that water systems play in both local and global ecosystems. Learning about complex systems and how to support learning about complex systems are key research issues. Ben-Zvi and Orion's (2005) research on middle school students learning of systems thinking identified eight emergent characteristics of systems thinking and suggested that the students' ability to think in terms of systems developed hierarchically, with learners sequentially engaging with each new group of characteristics (Ben-Zvi Assaraf & Orion, 2005. Thus, each level served as the foundation for the next higher level of skills. Table 1.2 summarizes the mapping of systems thinking characteristics and levels to key ideas in ecohydrology, the focus of this citizen science research.

Table 1.2
Systems Thinking Characteristics in the Context of the Ecohydrology (adapted from Ben-Zvi Assaraf & Orion, 2005)

Level 1: Analysis of System Components	
Systems Thinking Characteristic	*Ecohydrologic Cycle Examples*
1. The ability to identify system components and processes	System components: • Biosphere: plant, leaf, root, human, animal; Hydrosphere: oceans, rivers, lakes, streams; Atmosphere: sun, rain, water vapor, clouds; Geosphere: soil, groundwater System Processes: • evaporation, transpiration, interception, condensation, precipitation, infiltration, percolation, underground and surface flows, human water consumption
Level 2: Synthesis of System Components	
Systems Thinking Characteristic	*Ecohydrologic Cycle Examples*
2. The ability to identify simple relationships between or among system components	(1) Heated water evaporates and turns into water vapor, and cooled water vapor condenses into liquid water, (2) The amount of soil moisture in a particular area is related to the species of plants in an area, and (3) The amount of soil moisture in a particular area is related to the number of plants in that area
3. The ability to identify dynamic relationships within the system	(1) Humans influence groundwater through watershed management practices and/or pollution, (2) water in the soil is differentially influenced by plants and their specific rates of transpiration
4. The ability to organize the system components, processes, and their interactions within a framework of relationships	The ecohydrological system is a complex web of processes and relationships occurring in the atmosphere, in the ocean, on land, and underground
5. The ability to identify cycles of matter and energy within the system	(1**)** The coupling of evaporation and precipitation in the ocean water cycle, (2) the coupling of evaporation, transpiration and precipitation in the land-surface water cycle, (3) the coupling of land and ocean water cycles through river flow, and (4) the coupling of the land and ocean water cycles through soil water, evapotranspiration, and atmospheric transport of water vapor
Level 3: Implementation of System Components	
Systems Thinking Characteristic	*Ecohydrologic Cycle Examples*

6. The ability to identify hidden dimensions of the system—to understand natural phenomena through patterns and interrelationships not seen on the surface	(1) Water vapor in the atmosphere, (2) Transpiration from plant leaves, (3) Surface versus subsurface water flow, (4) infiltration versus percolation, (4) water that is partitioned by vegetation – either evaporation or transpiration, and (5) the hydrologic cycle in the atmosphere – how weather moves water up the mountain
7. The ability to make generalizations — to make scientific hypotheses, propose explanations based on data, and solve problems based on understanding system mechanisms	(1) Making scientific predictions related to the components and processes of the ecohydrological cycle, (2) proposing explanations based on data related to system mechanisms, and (2) Understanding how human management of watersheds (vegetation management) impacts hydrologic cycle components and how interventions can be implemented to prevent environmental threats in the context of a dynamic system.
8. The ability to think spatially and temporally—retrospection and prediction; error propagation	(1) Retrospection – present quantity of water in the stream is a result of events and processes that this water went through along geologic and human history; Prediction – the amount of water available in the future depends on the number and type of plants in a particular area and how plants are influenced by weather. (2) Error propagation – understanding that errors associated with measurements can propagate through models, affecting how model results are interpreted.

Although we are still in the early stages of research into how people learn about complex systems, studies do suggest that students from approximately middle school through college can learn and benefit from important concepts and perspectives related to the scientific study of complex systems, and current work is starting to shed light on the factors that contribute to learning difficult systems thinking ideas (Jacobson & Wilensky, 2006). Ben-Zvi Assaraf and Orion (2005) have shown that, with appropriate instructional tools and concrete experiences, middle and high school learners can develop the ability to think in terms of complex systems, showing considerable gains in their reasoning abilities. The very limited research with youth suggests that learners as young as 10 years of age can begin to understand important concepts and perspectives related to complex systems (Ben-Zvi Assaraf & Orion, 2010). Indeed, Forrester (2007) and Jacobson and Wilensky (2006) have emphasized the importance of introducing complex systems in the early school years, with Forrester (2007) suggesting that "developing such a systems perspective takes less time with a young, inquisitive, and open mind than with a mind that has already been conditioned to see the world in terms of unidirectional cause to effect" (p. 356).

One way to help learners develop the ability to think in terms of complex systems may be to situate the exploration of complex phenomena in contexts where learners are not merely observers but are actual participants (Levy & Wilensky, 2004). Additionally, work in the area of systems thinking highlights the potential of outdoor learning environments to provide learners with opportunities to experience concrete phenomena and tools as they appear and are used in the real world (Ben-Zvi Assaraf & Orion, 2010; Kali, Orion, & Eylon, 2003). However, there is no research on the development of systems thinking through involvement in authentic research. We need to understand better the ways in which authentic research may be leveraged to support youths' development of systems thinking. Such research can contribute to both the discussion of "what is hard" and "why it is hard" to develop systems thinking.

Figure 1.1 illustrates my conceptual model of the relationship between different steps of the citizen science and the development of systems thinking characteristics through dialogic knowledge-building processes. Each step affords particular type of activities, which in turn, afford the development of particular ways of knowing and thinking. Thus, as learners collaboratively engage in the different steps of citizen science, they can build the knowledge and understanding of the ways in which systems operate. In this study, I focused on youth involvement in steps 2 – 6 of the conceptual model.

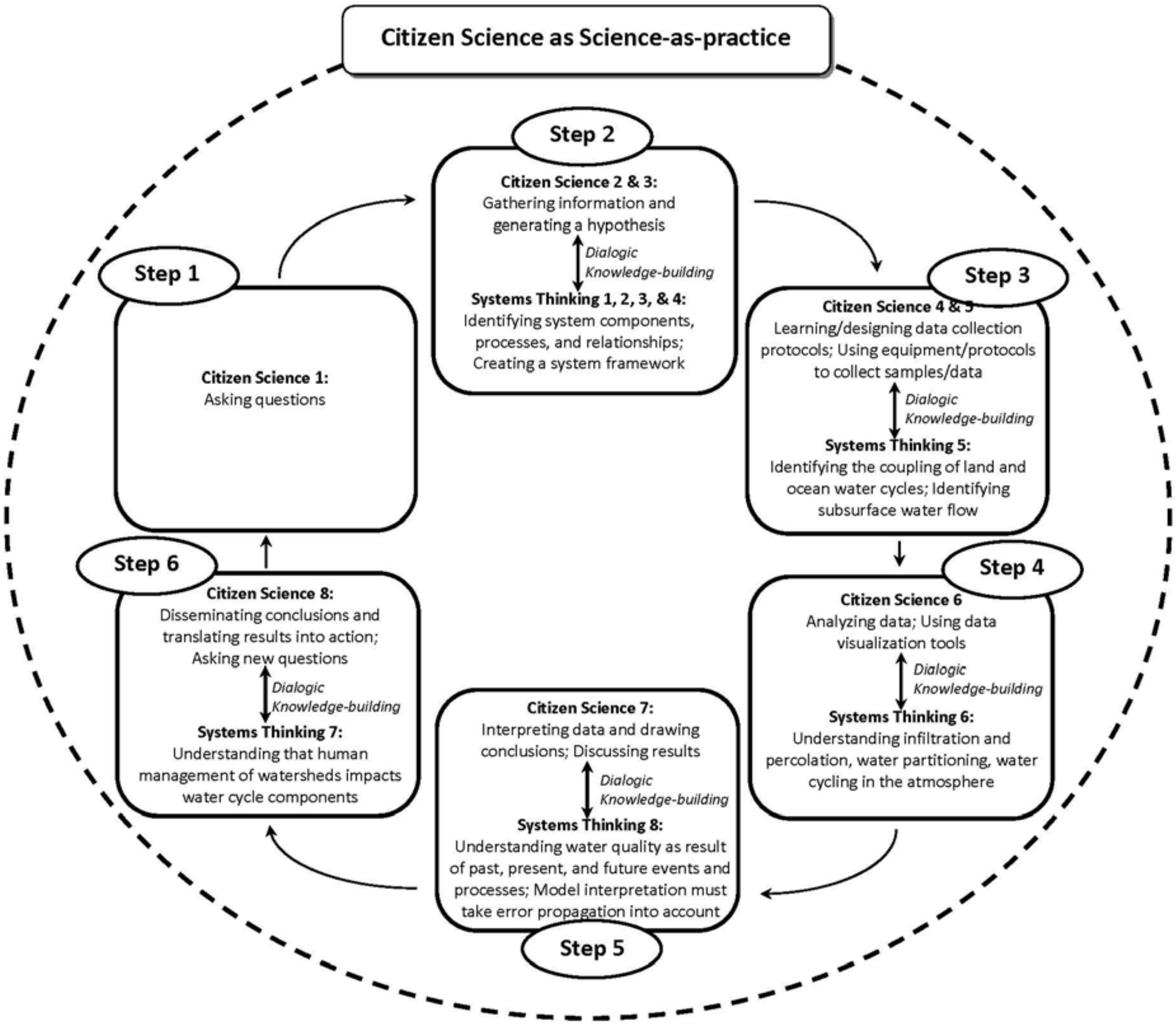


Figure 1.1 Conceptual Model of Citizen Science as Science-as-Practice: Citizen Science and Systems Thinking Characteristics Integration (see Table 1.2 for systems thinking characteristics)

CHAPTER 2

Method for Designing and Studying the Learning Environment: Design-based Research

> Design experiments ideally result in greater understanding of a *learning ecology*—a complex, interacting system involving multiple elements of different types and levels—by designing its elements and by anticipating how these elements function together to support learning. Design experiments therefore constitute a means of addressing the complexity that is a hallmark of educational settings... We use the metaphor of an ecology to emphasize that designed contexts are conceptualized as interacting systems rather than as either a collection of activities or a list of separate factors that influence learning. Beyond just creating designs that are effective and that can sometimes be affected by 'tinkering to perfection,' a design theory explains why designs work and suggests how they may be adapted to new circumstances. Therefore, like other methodologies, design experiments are crucibles for the generation and testing of theory (Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003, p. 9).

We can trace design-based research back to the early 1990s, when Ann Brown (1992) first published work on what she called "design experiments," arguing that such a methodology could be useful in developing important theoretical insights into mechanisms for learning in naturalistic contexts in ways that more easily controlled laboratory experiments cannot (Sandoval, 2004). At the same time, Allan Collins (1992) called for a design science of education in which researchers investigate how different learning environments affect identified outcomes, what he called "dependent variables," in teaching and learning. Since then, design-based research has grown into a paradigm of educational research for those who are interested in "producing change in actual learning settings and understanding the factors that support or hinder reform" (Sandoval, 2004, p. 214). According to the Design-Based Research Group (2003), design-based research is "an emerging paradigm for the study of learning in context through the systematic design and study of instructional strategies and tools" (p. 5), and they argued that this paradigm can help to both create and extend knowledge about developing, implementing, studying, and sustaining innovative learning environments. Collins, Joseph, and Bielaczyc (2004) suggested that design-based research evolved to address multiple issues central to the study of learning, including the need to address theoretical questions about the nature of learning in context and the need for approaches to the study of learning in the real world rather than in the laboratory. Thus, design-based research has developed into an approach that has certain outcome commitments, including producing innovative learning environments, generating knowledge about how these environments work in the settings for which they were designed, and adding to our theoretical knowledge about learning (Sandoval, 2014).

The Design-Based Research Collective (2003) proposed five characteristics of good design-based research: (a) the central goals of designing learning environments and developing theories are intertwined; (b) both the learning environment design and the research on that design take place through continuous cycles of design, implementation, analysis, and redesign, (c) research on designs must lead to sharable theories that communicate relevant implications, (d) research must account for how designs function in authentic settings—it must document successes and failures as well as focus on interactions that refine our understandings of the learning issues involved, and (e) the development of these accounts relies on methods that document and connect the processes of implementation to outcomes of interest. Thus, design studies entail the 'engineering' of particular forms of learning in particular contexts followed by the systematic study of those forms of learning and the context that supports them through the tight and cyclical interaction between instructional design and theory. The approach involves a theory-driven process of design and a data-driven process of refining instructional interventions in which the successive iterations play a role similar to systematic variation in experiment (Cobb et al., 2003). Thus, design research attempts to: (a) design interventions, (b) explain their effectiveness or ineffectiveness in a particular context, and (c) re-engineer them where possible, while adding to the science of design and learning (Barab, 2006; Brown, 1992; Collins, 1992; Cobb et al., 2003; Kelly et al., 2008).

Cobb (2001) proposed a design research cycle as a mechanism for studying the systematic relationship between design, context, and outcomes. This process starts with a "thought experiment" that synthesizes the salient theories in a series of theoretical conjectures (Cobb, 2001, p. 456). These theoretical conjectures generate a particular design trajectory that describes the potential means of supporting meaningful learning across the proposed trajectory. A research trajectory monitors the design and implementation of the learning trajectory, providing feedback on both the design and the learning outcomes for the given learning context (Cobb, 2001).

It is important to note that the conjectures inherent in the hypothetical design for learning trajectory are tentative, provisional, and revisable in that they are tested and revised on a daily basis once the design experiment begins (Cobb, 2001). The goal then is not to demonstrate that the instructional design formulated at the outset works. Instead, it is to improve the design by testing and modifying conjectures by ongoing analysis of learner reasoning and learning context. Thus, from a structural perspective, the design research cycle is made of minicycles covering daily learning tasks that embody the conjectures, which then make up the longer-term macrocycles that span an entire experiment (Gravemeijer, 1998 as cited in Cobb, 2001). This longer-term cycle involves a retrospective analysis that is conducted once the design experiment is complete—the findings then "feed forward" to guide the revised learning trajectory for follow-up experiments (Cobb, 2001, p. 459). The findings also guide the development of emergent or local theories of learning (Cobb, 2001; The Design-based Research Collective, 2003).

Bannan-Ritland (2003) suggested a structure for design-based research that provides an effective nest for Cobb's (2001) minicycles and macrocycles of study. This framework attempts to provide a comprehensive and flexible mechanism that positions design-based research as a "socially constructed, contextualized process for producing educationally effective interventions with a high likelihood of being used in practice" (Bannan-Ritland, 2003, p. 21). The goal of the framework is to allow researchers to both construct propositions about learning and teaching while engineering effective learning environments. A modified version of this framework integrated with Cobb's (2001) notion of minicycles informed and organized the research design of this study (see pages 33-36 for an overview of the project research and design structure).

Methodological Challenges

Despite the numerous articles discussing the usefulness of design-based research, there have been both useful critiques and methodological challenges raised related to design-based research as an approach for generating theoretical understandings and innovative learning environments. I will first address the critique of credibility and then address the more general methodological challenge. With respect to the issue of credibility, Barab and Squire (2004) argued that the researcher plays multiple roles in design-based research, including that of conceptualizer, designer, developer, implementer, and researcher, which makes it challenging to make credible and trustworthy assertions about the outcomes (Barab & Squire, 2004), while Kelly (2004) specifically asks,

> "What operational caveats exist to guide sensible use of design study methods? How does the researcher select episodes for analysis? How does he or she decide which aspects of the chosen episodes are meaningful? What about contrary instances? What about outliers? What is not being said about the miles of videotape left unwatched and student 'artifacts' unread? What does triangulation mean in this context? And what is the function of inter-rater reliability?" (p. 124)

This critique and these questions are familiar to many qualitative researchers. How do we make credible assertions about the work that we do? To address multiple issues of credibility, including researcher bias, related to qualitative research, Onwuegbuzie and Leech (2007) introduced the *Qualitative Legitimation Model*, which attempted to integrate many of the types of validity identified by qualitative researchers and described 24 methods for assessing the truth value of qualitative research. In addition, Hammer and Berland (2014) proposed guidelines for reporting the quantification of qualitative data (which will be done here) with the aim of making the complexities of the work more transparent as well as the discussion of the work more substantive and productive. Finally and importantly, Anderson and Shattuck (2012) argued that the researchers themselves, with their biases, insights, and deep understanding of the context, are the best research tool, suggesting that this “inside knowledge” adds as much as it detracts from research validity. Design-based research demands skepticism and detachment as wells as a willingness to support the intervention, marking the narrow line between objectivity and bias as both a challenge and a defining feature of quality of design-based research (Anderson & Shattuck, 2012).

In addition to concerns about credibility, there have been and still remain specific questions about design-based research as a methodology (Barab & Squire, 2004; Dede, 2004; Kelly, 2004; Sandoval, 2014). Kelly (2004) suggested that if the goals of design-based research are to be realized, design studies must develop from a “loose set of methods to a methodology” (p. 118). A method, he suggested, is a procedure, a process that includes a set of steps to follow, and design studies were most frequently described primarily using a set of process descriptors (e.g., interventionist, iterative, collaborative, theory-driven). In order for design-based research to contribute to our theoretical understandings of learning, it needs to have an underlying conceptual and methodological structure that forms the basis for the warrants that are made and constraining the interpretation of qualitative descriptors (Kelly, 2004). In other words, it requires a mature methodology that links elements of the designed learning environments to the processes through which these designs are implemented to the observed outcomes (Dede, 2004; Sandoval, 2014).

A Methodological Approach to Design-based Research: Conjecture Mapping

In response to these concerns about methodology, Sandoval (2004, 2014) describes *conjecture mapping* as one method for specifying the links between the theoretically derived design principles, the conjectures about learning, and the ways in which design features embody these conjectures. The design of learning environments is a theoretical activity in which the environment “embodies design conjectures about how to support learning in a specific context that are themselves based on theoretical conjectures of how learning occurs in particular domains” (Sandoval, 2004, p. 215). A conjecture map highlights the links between multiple elements, including design principles, conjectures for learning, and the ways in which these conjectures are embodied in the tools and materials, tasks structures, and participation structures that make up the design. The map reflects the ways in which these features work together to guide a particular design and to provide a way of systematically testing how these conjectures work together in specific contexts.

The central element of a conjecture map is the embodied conjecture, a tool for conceiving the multiple ways in which theoretical propositions about learning might be reified within designed environments to support learning. There are two critical features of embodied conjectures to consider. First, they are derived from our understandings of learning within particular domains. They are, however, different from design principles in that design principles are articulated at a very high and general level, making them empirically untestable. Embodied conjectures, in contrast, are articulated at a more specific level, making them subject to empirical refinement or rejection. Second, the testing and refinement of embodied conjectures can lead to both improvements in the designed intervention as well as refinements in learning theory, the central goal of design-based research. From a methodological perspective, conjectures are different from hypotheses in that conjectures are embodied in multiple aspects of the design. Each conjecture is reified in the particular task structures, tools and materials, and participation structures that make up the designed environment in ways that embody its hypothesized role in supporting learning.

This approach is instrumental in managing what Sandoval (2014) considers to be the basic tension in design-based research—“the dual commitment to improving educational practices and furthering our understanding of learning processes” (p. 20) because it provides the design model on which both the intervention and the research are based. The construction of a conjecture map requires that researchers are specific about what they are trying to design, what particular features of the design are expected to do, how they are expected to work together, whether they are enacted in the implementation of the design, and what they ought to produce (Sandoval, 2014). Thus, conjecture maps can organize research by focusing researchers’ attention on the aspects of the designed intervention that are theoretically salient. In Chapter 3, I include the conjecture map tested by this research.

Ecohydrology Citizen Scientists’ After-school Club: The Intervention Design and Study

In this study, I employed design-based methodology to answer the following questions:

1. To what extent will participation in a collaborative citizen science project facilitate youths’ development of systems thinking?
2. What are the core design features of an after-school citizen science project that involves youth ages 9-11 in learning the science of ecohydrology and systems thinking? What are the challenges of designing and implementing such a learning experience?

A central question of this study is how to design an intervention that moves beyond describing "what is" or confirming "what works" to designing "what strategies might work better" for the development of youths' systems thinking. As such, I view this designed intervention as a socially constructed object that must be systematically articulated, studied, and revised over a number of cycles rather than as a standard "treatment" intended to test a hypothesis (Bannan-Ritland, 2003). Because design experiments such as this develop theory in practice, they can lead to interventions that are trustworthy, credible, transferable, and ecologically valid (Barab, Thomas, Dodge, Carteaux, & Tuzun, 2005).

To investigate the processes of learning and the influence of the design on learning, I systematically mapped the learning context (Sandoval, 2004, 2014), engaging in what Shavelson and Towne (2002) described as an "analytic approach for examining [how or why something is happening] that begins with theoretical ideas that are tested through the design, implementation, and systematic study of educational tools that embody the initial conjectural mechanism" (p. 135). This work is both interventionist and theory driven, in that I am testing theory by studying the effectiveness of the intervention on learning outcomes; it is iterative, in that I am modifying instructional activities with the intention of increasing its effectiveness; and it is practical, in that I am concerned with producing benefits for instruction (Barab & Squire, 2004; Confrey, 2006; Edelson, 2002; Richland, Linn, & Bjork, 2007).

Research and Design Structure.

The design and research structure of this particular study took place in three phases (see Figure 2.1) (Bannan-Ritland, 2003; Cobb, 2001; Edelson, 2002; Sandoval, 2004).

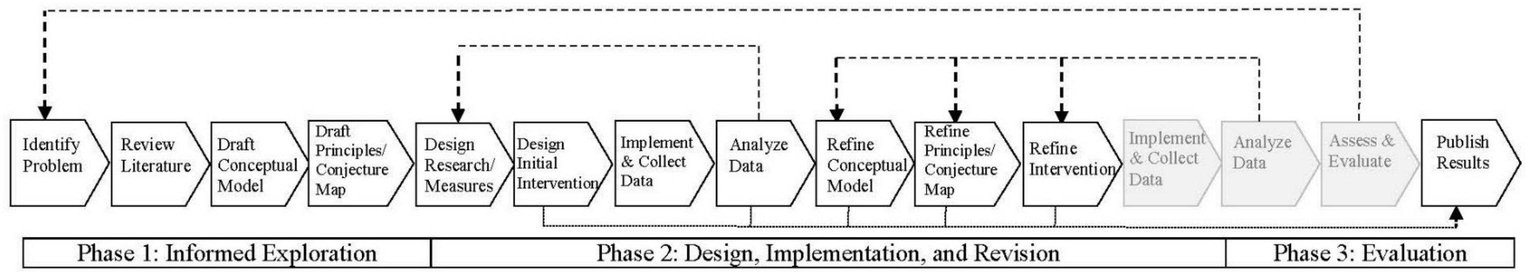


Figure 2.1 Sequence of Research and Design. The grayed steps are not included in the final dissertation. (Adapted from Bannan-Ritland, 2003.)

The first phase of this research consisted of informed exploration. During this phase, I identified the problem (systems thinking), conducted a comprehensive review of the literature, and drafted the conceptual model (see Figure 1.1), which was the theoretical guide for the conjecture map (see pages 45 – 46 for detailed information on Conjecture Mapping). Also during this phase, I identified members of the design team and worked with a local elementary school administration and Parent Teacher Association to recruit participants. See Figure 2.2 for the workflow of the Informed Exploration phase.

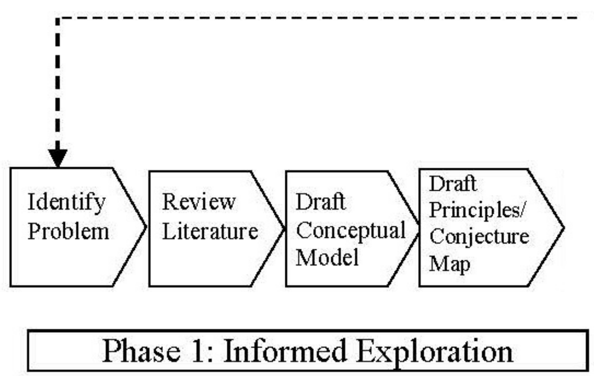


Figure 2.2 Work Flow of Informed Exploration Phase

The second phase of the design and research structure consisted of the design, implementation, and revision steps, during which I refined the research plan and worked with design team members and environmental scientists to develop the ecohydrological citizen science research around which the after-school club was developed (Bonney, Cooper et al., 2009). The design team conducted background research; identified the scientific research question; developed, tested, and refined protocols and data forms, including an online app for data collection; and addressed data quality issues. In addition, the team worked with the environmental scientists to adapt the systems thinking outcome measures for the ecohydrological content.

Concurrent with developing the ecohydrological research project, the team also designed the educational intervention, from the overall structure and sequence of the program to the specific aspects of the design, including tasks structures, tools and materials, and participation structures in which the learning conjectures were embodied. Finally, we implemented the intervention with our youth participants, and collected data throughout the implementation, generating a comprehensive record of the ongoing design and implementation process.

The goal of the second phase was to improve the initial design by testing and revising the foundational conjectures through an ongoing analysis of the ways in which the different aspects of the design mediated youths' knowledge and reasoning (Cobb, 2001; Sandoval, 2014). This analysis was the primary means of assessing the effectiveness of the citizen science intervention as a support for youth development of systems thinking. I used the data that was collected and analyzed during and following the initial intervention, including observations of the implementation and the resulting youth interactions and data on youths' development of systems thinking capabilities, to refine both the conceptual model and the conjectures embodied in the initial intervention design. The outcome of this phase was a comprehensive set of lessons learned that was used to redesign the intervention. Thus, the redesigned approach is based on a deeper understanding of the aspects of the learning ecology that support the theoretical target of the research, in this case systems thinking. An in-depth review of learner outcomes is included in Chapter 4 and lessons learned are included in Chapter 5. See Figure 2.3 for the workflow of the Design, Implementation, and Revision phase.

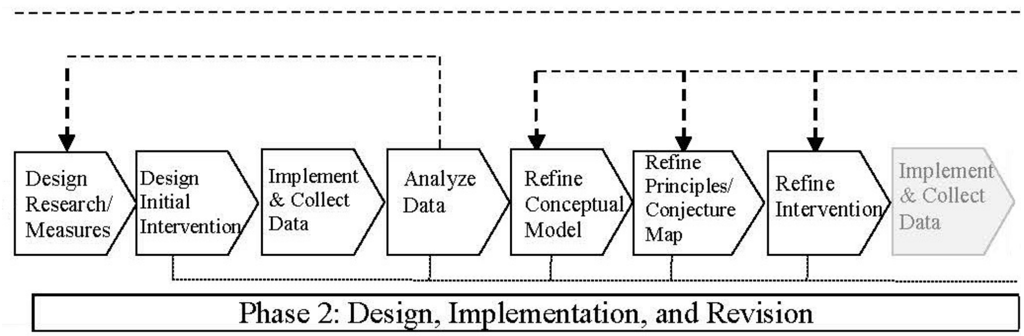


Figure 2.3 Work Flow of Design, Implementation, and Revision Phase

The third phase of the design and research structure consists of an analysis of data collected during the second round of implementation and of the publication of results of the multiple implementations. It is important to note that I did not implement a redesigned intervention, so additional data was not collected or analyzed.

CHAPTER 3

Theory-driven Design of an Innovative Learning Environment

This chapter describes the design approach for the Citizen Scientists' After-school program ("Club"). First, I introduce the design and implementation team, study site, study participants, and science context for learning. Second, I describe the ways in which the conceptual model guided the design of the Club, providing an overview of the design principles and conjectures for learning and the elements in which the conjecture were embodied. Finally, I present the conjecture map for the design of the Club, which shows the proposed links between the design elements and the learning outcomes, that was used for the design of the intervention and the research.

The Design and Implementation Team

The design team consisted of four members, including me as the lead researcher and designer, a graduate student in biological sciences, and two undergraduate students who were each working on a degree in science concurrent with a teaching credential. The graduate student along with the ecohydrological environmental researcher (who was not a member of the design team) served as content and environmental research reviewers, and the undergraduate students provided support for the design of the educational intervention. The team met weekly over the course of three months to discuss the design of the unit, tasks, tools and materials, participation structures, and the research measures.

The implementation team consisted of four members, three of whom were on the design team. The fourth was added to replace one of the original design team members who could not participate in the implementation. This undergraduate student, like the student she replaced, was concurrently working on a science degree and a teaching credential.

During program implementation, I served as the primary facilitator, providing both whole group instruction and small team facilitation. The other members of the implementation team served as program aids and worked with learner research teams. See Table 3.1 for the design and implementation team members (names are pseudonyms), their backgrounds, the aspect(s) of the projects in which they participated, and the research team they facilitated (designated by color).

Table 3.1
Design and Implementation Team Members

Name	Background	Design	Implementation	Team Facilitator
Joan	Lead researcher and designer; graduate student in Education	X	X	Yellow
Alice	Graduate student in Biological Sciences and Educational Media Design	X	X	Red
Laura	Undergraduate student in Earth System Science and Cal Teach	X	X	Green
Katie	Undergraduate student in Biology/Education and Cal Teach	X		
Jacque	Undergraduate student in Chemistry and Cal Teach		X	Blue

Study Site, Study Participants, and Science Context for Learning

Study site.

The study took place at a local elementary school and in Crystal Cove State Park. The park was an ideal location for this research because: (1) the State Park was interested in studying citizen science as a possible mechanism for Park education and outreach and had a number of management needs that could be effectively translated into citizen science, (2) researchers from School of Biological Sciences at the local university are already conducting environmental research in the State Park and were interested in effective education and outreach mechanisms, and (3) the elementary school from which study participants were recruited was located adjacent to the State Park. This adjacency allowed easy access to research locations as well as provided a motivational hook for participants who were familiar with and interested in conducting research in their own community related to issues that directly impacted their daily lives and their community resources (Pandya, 2012).

I implemented the Club in the winter of 2014. The elementary school's Parent Teacher Association provided after-school programming for the student body, and I established an agreement with the school principal and the PTA to include the Club in their ongoing after-school offerings. The Club included 14 contact hours, distributed in one after-school hour, twice a week, for one eight-week session (the school was on holiday for one of the weeks during the session). Of those 14 hours, participants spent nine hours on the school campus, two of which were used to administer research measures. In addition, we spent one unplanned hour on campus because of the weather—we could not collect data in the rain. We spent the remaining five hours in the field, either at various locations around the Park or at specific data collection plots. Daily attendance was not mandatory, so a number of the participants did not attend all of the sessions (see Appendix A for a record of attendance). See Table 3.2 for the location of each session.

Table 3.2
Location of Citizen Science After-school Club Sessions

Session	Location of Sessions
Day 1: Jan 14	School Campus (Introduction)
Day 2: Jan 16	School Campus (Pre-test)
Day 3: Jan 21	Park
Day 4: Jan 23	Park
Day 5: Jan 28	School Campus
Day 6: Jan 30	School Campus
Day 7: Feb 4	Park (Data Collection Plots)
Day 8: Feb 6	School Campus (Rain)
Day 9: Feb 11	Park (Data Collection Plots)
Day 10: Feb 13	School Campus
Day 11: Feb 25	School Campus
Day 12: Feb 27	School Campus
Day 13: Mar 3	Park
Day 14: Mar 6	School Campus (Post-test)

Study participants.

I recruited participants from a pool of roughly 240 students (four 4th and four 5th grade classrooms) who attended the elementary school. Approximately 18% of students at this school are from under-represented minority groups and 15% are socio-economically disadvantaged. Information about the Club was posted on the PTA's After-school Club website where parents could review the session offerings and enroll their children in clubs of interest (see Appendix B for the recruitment text that was posted on the PTA's website). Club topics ranged from gardening to art to sports to Mad Scientists, and most were fee-based, with costs ranging from $20 to $135 per student. There was no cost to parents for their child to participate in the Club.

Enrollment was set at a maximum of 16 students, and we had 15 students who participated in the Club. Before the first day, the school mailed study consent forms to the parents of the enrolled students. Interested parents completed the consent forms and returned them to the office. On the first day of the club, students with signed consent forms were introduced to the study, and interested students signed assent forms. Of the 15 students enrolled, nine took part in the study. All the Club participants worked in small teams of four or five, with team composition determined first by study participation and then by grade level (in general, 4th grade students worked together and 5th grade students worked together). We designated research teams by color, with the Green and Yellow teams as study teams. The two 5th grade study participants—both on the Yellow team—started their in-class water unit on Day 5 of the Club. Evidence of this appears in the transcripts and was accounted for in the analysis of their conversations. See Table 3.3 for the participants listed by team and age (all names are pseudonyms).

Table 3.3
Research teams by Participants, Age, and Grade

Team	Participant	Age	Grade
Green	Noah	9	4th
	Ethan	9	4th
	Tim	9	4th
	Sean	9	4th
Yellow	Isabel	10	5th
	Nancy	10	5th
	Abby	9	4th
	Eric	9	4th
	Fred	9	4th

Ecohydrological research context for learning.

In this section, I detail the environmental science background information for the citizen science research to clarify aspects of the intervention design description. I situated the citizen science intervention within the context of the scientific study of ecohydrology, with the overarching question “where does the water in Moro Canyon go?”. The field of ecohydrology seeks to understand the interactions and interrelationships between hydrological processes and the pattern and dynamics of vegetation (Breshears, 2005), involving the study of water’s role in ecosystem dynamics and the interrelationships between hydrological processes and the pattern of vegetation and the interactions between humans and the environment related to water and land use practices.

How water cycles in the oceans, in the atmosphere, and across the land surfaces integrates many features of the Earth System. Earth System Models predict substantial change in precipitation for many regions of the terrestrial surface in the near future (IPCC, 2007). Indeed, in the southwestern United States, including California, these predictions may currently be occurring (McAfee & Russell, 2008). The hydrologic cycle is also affected by our management of the land-surface, from the conservation of forested systems to the proliferation of non-native species of plants—anthropogenic influences in ecosystems may change how water behaves in the future (Wilcox et al., 2012). Thus, understanding where water goes is a grand challenge facing both science and resource management.

Despite its importance, researchers still struggle with quantification, theory development, and prediction surrounding ecohydrology. This arises from both a lack of sufficient measurement to capture the dynamics of the hydrologic process and a lack of knowledge of the physical processes occurring. For a defined area, the hydrologic cycle can be conceptualized as a mass balance:

$$P = E + T + R + D + \Delta S$$

where P is precipitation, E is evaporation of water from soils, T is plant transpiration of water back to the atmosphere, R is water that drains in rivers through a watershed, D is water that is transported to depth, usually to an aquifer, and ΔS is the change in water stored in the surface soil (the Water Balance equation). For the last decade, science has been attempting to understand how changes in ecosystem structure (e.g., restoration) affects the partitioning of rainfall into the hydrologic components (e.g., evaporation and transpiration) (Adams et al., 2012; Huxman et al., 2005)—how will a change in plant population influence the loss of water back to the atmosphere and change patterns of stream flow or aquifer recharge? Simply put, we do not have a good means of describing "where all the water goes" when rain falls in a watershed.

I chose this particular area of study as the learning context because the hydrologic cycle, especially when integrated with biological mechanisms, is a useful organizing tool for helping youth develop systems thinking for several reasons. First, the system operates on a global, a local, and an personal scale, providing learners with opportunities to explore research related to global patterns in water distribution, to State Park resource management, and to the role that the water cycle plays in their own communities and lives. Second, it was both interesting and developmentally appropriate for the target participants (California's 4th grade students study ecosystems and 5th grade students study the water cycle). Finally, the data collected by the learners could be used by environmental scientists to highlight areas of interest and by State Park land managers to inform management decisions, including the selection of plant material for restoration.

Designing the Learning Environment

Citizen Scientists' After-school Club conjecture map

In this section, I detail the design process to clarify both the intervention and the study designs. As discussed previously, a conjecture map serves the duel function of aiding both design and research. Figure 3.1 shows a generalized form of a conjecture map, which contains six major elements and their relationships (read from left to right) (adapted from Sandoval, 2004).

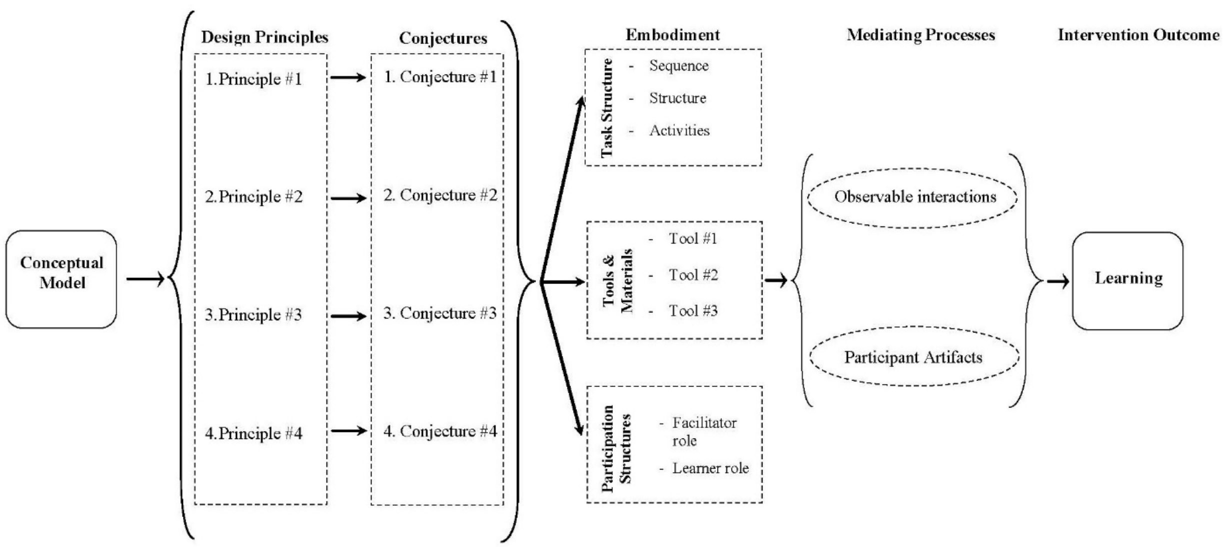


Figure 3.1 Generalized conjecture map for design-based research

All learning environment designs begin with a high-level conceptual model about how learning occurs within the particular design. This model drives the identification of design principles, which, because they are written at a general level, are empirically untestable. To test the design, these principles are then translated into testable conjectures about learning.

Conjectures contain knowledge of procedures, results, and context such that readers may determine if the insights generated by the study may be relevant to their own specific settings. To test the conjectures, they are embodied in specific features, or elements, of the design environment to support learning (Sandoval, 2004). Specifically, they are reified in the particular design aspects that make up the design intervention, including task structure, tools and materials, and participant structures. *Task structure* refers to the structure of the task—the goals, structure and organization, activities, and outcomes—that learners are expected to do. *Tools and materials* include the instruments, materials, media, and other resources that are designed as integral aspects of the program. *Participant structures* refers to how participants (learners and facilitators) are expected to participate in tasks, the roles and responsibilities participants take on when engaging in the designed tasks. Not all design features of the learning environment are theoretically important. Those that do are expected to lead to mediating processes—for example, the use of a particular tool for a specific task is intended to produce certain kinds of interactions, which, in turn, are expected to produce certain kinds of outcomes (Sandoval, 2014). In the sections that follow, I detail each element and relationship of the conjecture map and then discuss how the conjecture map influenced the design of the intervention.

Design principles and conjectures for supporting systems thinking

As previously stated, one of the primary goals of design-based research is to extract learning principles that may be appropriated and applied across multiple contexts (Barab, 2006; Cobb et al., 2003). Design principles are theoretically derived, general ideas about learning that can inform future development and implementation decisions (Edelson, 2002; Lin, Davis, & Bell, 2004). Jacobson and Wilensky (2006) discuss five design principles that may yield promising research and learning knowledge on youth development of systems thinking capabilities:

> (a) experiencing complex systems phenomena; (b) making the complex systems conceptual framework explicit; (c) encouraging collaboration, discussion, and reflection; (d) constructing theories, models, and experiments; and (e) learning trajectories for deep understandings and explorations (p. 19).

During the initial phase of this work, I drafted five design principles that were drawn from this literature on systems thinking (Jacobson & Wilensky, 2006) and were based on the notion that youth who engage in authentic science research in collaboration with environmental scientists and with each other will develop systems thinking. To guide the intervention design, each general principle represented an aspect of my approach to supporting the development of systems thinking, and each was translated into a more specific conjecture about learning that was, in turn, reified in features of the design and implemented with the Club participants. To guide the research, each high-level principle was derived from learning theory at a general level and led to more a testable conjecture that could be empirically tested and refined or rejected. As such, they each suggest which aspects of the designed intervention need to be examined to assess the possible influence of the design on learners' development of systems thinking.

Design Principle 1: Experience systems phenomena in authentic contexts.

Thinking in terms of the ways that systems operate over space and time is difficult and often counterintuitive (Jacobson & Wilensky, 2006; Wilensky & Resnick, 1999). One way to help learners develop the ability to think in terms of complex systems may be to situate the exploration of complex phenomena in contexts where learners are not merely observers but are actual participants (Levy & Wilensky, 2004). We know from the large body of work on science learning that for people to learn science, they must build on their experiences and knowledge about the world (National Research Council, 2000). From these experiences, people construct understandings about how things in the world behave. Making these learning experiences more closely resemble science practice is a common goal of many education practitioners and researchers who hold that authentic learning experiences play an important role in learners' developing science understandings (Bevin et al., 2009; Edelson, 1998). Authenticity relates to the "real-worldness" of the experiences, including the type and structure of tasks, the ways that different tools are used, and the mechanisms for participation. These experiences rise to a level of authenticity when learners are actively working with abstract concepts and real-world cognitive challenges in a realistic—and highly social—context that mimics "the ordinary practices of the culture" (Brown, Collins, & Duguid, 1989, p. 36). Thus, learners need opportunities to experience complex systems phenomena in ways that will let them build knowledge and conceptual understanding of the ways that systems operate over space and time.

When intentionally designed, citizen science can provide an authentic context for learning science and developing systems thinking because it affords access to the key features of scientific practice. Indeed, systems thinking approaches to ecosystem ecology suggest that citizen science can play a role in helping participants understand and address the complexity of natural systems (Machlis, Force, & Burch, 1997). In schools, learners typically experience scientific phenomena indirectly through textbooks, lectures, and demonstrations (Jacobson & Wilensky, 2006). Rarely are students, especially elementary students, afforded opportunities to engage directly in science through authentic practices in authentic environments—in this case, conducting research in an outdoor setting. When engaged in citizen science, learners have direct experiences with complex systems phenomena by generating and analyzing data related to the system under study. However, the practices used by highly trained scientists are typically complicated and unfamiliar to nonprofessionals, and youth would likely lack an understanding of the ways to work productively in an authentic context. Thus, this ecohydrology citizen science research with its specific and detailed systems thinking learning outcomes required a design that supported and scaffolded learners by reducing the complexity of the practices while retaining their key elements as they were apprenticed into the practice of science. This included designing opportunities that allowed learners to take up and use the cultural tools of science to achieve their goals, including science equipment (e.g., soil moisture meters, leaf porometers, weather stations, data sheets), science language (e.g., asking questions, generating hypotheses, arguing from evidence), and science techniques (e.g., gathering data, creating data visualizations, building models).

Design Principle 2: Make systems thinking framework explicit.

The second design principle was to make the organizing conceptual framework explicit to the learner. The specific details of the intervention will be discussed at length later, but it is necessary here to introduce the learning theory that served as the basis for the design. Learners construct knowledge as they engage in an ongoing process of comparing and checking their understandings with the ideas that are being rehearsed by and with others (Mortimer & Scott, 2003). This notion of dialogic knowledge building coupled with a constructivist theory of learning—that existing knowledge is used to build new knowledge—was used as the foundation for designing the inquiry-based curriculum for the Club. A commonly held misconception of this theory is that learners should never be told anything directly but, instead, should always be allowed to construct knowledge for themselves (National Research Council, 2000). This perspective confuses a theory of teaching with a theory of knowing. In fact, research suggests that although inquiry learning can be effective (Minner, Levy, & Century, 2010), a more structured approach to inquiry in which learners are provided a question and a method but are responsible for data collection, analysis, and interpretation may allow younger learners to better grapple with complex material (Blanchard, Southerland, Osborne, Sampson, Annetta, & Granger, 2010; Kali, Orion, & Eylon, 2003). Thus, tasks become productive spaces and tools become productive mechanisms for learning when the organizing framework is made explicit. This then makes salient the specific ideas related to the conceptual model.

This work tests the importance of using the core characteristics of systems thinking as an explicit organizing and integrating framework for learning, of attending to learners' evolving understandings, and of using designed tools and materials as well as verbal interactions to support and scaffold growing understandings of complex systems. Since complex systems are counterintuitive and difficult to understand, the design of the tasks, tools and materials, and participation structures should explicitly highlight the links between citizen science steps and the systems thinking characteristics (e.g., the link between equipment, data collection, and the way that rainfall is partitioned into hydrologic components). As well, facilitation should explicitly highlight the links between what learners observe as they engage in the steps of the ecohydrology citizen science and the different characteristics of systems thinking (e.g., making links between the data sheets, the data collected, and the components and processes of the ecohydrological system).

Design Principle 3: Encourage collaboration, discussion, and reflection.

As previously discussed, science advances through the interactions that take place among members of the research community as they test new ideas, articulate explanations, develop shared representations, and reach consensus (Duschl, Schweingruber, & Shouse, 2007). Indeed, we construct and shape our knowledge and beliefs about the world in situated and socially mediated contexts (Brown, Collins, & Duguid, 1989; National Research Council, 2000).

Learning is a social activity; it is intimately associated with connections to other people and with the tools and materials that they develop. Environments in which learners come to experience and to construct their understandings about complex systems may be made more powerful by involving learners in tasks that both require and support collaborative and cooperative interactions (Jacobson & Wilensky, 2006). Thus, learning activities should be set within a social organization that allows learners to participate fully with each other to develop a shared understanding of both the features of and the participation norms for engaging in scientific practice.

Since knowledge and beliefs about the world are socially mediated, learning environments that support systems thinking should be designed to foster collaboration, discussion, and reflection. The task structure, tools and materials, and participation structures should involve opportunities for discussion and collaboration such that learners are provided with metacognitive scaffolding and questions for reflection. A study of mechanisms for collaboration and reflection could help us understand how collaborative interactions and construction of shared artifacts and representations help learners articulate the ideas about complex systems, reflect on their initial ideas and theories, and help them to see how complex systems ideas might be useful for understanding the ecohydrological system.

Design Principle 4: Encourage construction of theories, models, and investigations.

Constructivist conceptions of learning assume that learners build knowledge based on their interpretations of experiences in the world—we actively construct understandings rather than passively absorb facts. One key strategy for promoting learning is designing or selecting tasks that embody or engage common misconceptions and then having learners make predictions and explain their reasoning (National Research Council, 2000). Experiences that allow learners to construct theories, predict outcomes, and explain findings emphasize the *doing of science* rather than the *knowing of facts*. Indeed, recent research in pedagogical strategies to help learners develop understandings of complex systems suggest that learners should generate questions, theories, and hypotheses about different phenomena and then participate in knowledge integration activities, including observational investigations and/or creating conceptual models, that are related to their theories (Ben-Zvi Assaraf, & Orion, 2005, 2010; Evagorou, Korfiatis, Nicolaou, & Constantinou, 2009; Kali, Orion, & Eylon, 2003; Levy & Wilensky, 2004; Stieff, & Wilensky, 2003; Westra, Boersma, Waarlo, & Savelsbergh, 2007).

Since learners construct knowledge through experience, multiple features of the designed environment must provide opportunities to ask questions, develop theories, build models, hypothesize about, and test various phenomena related to ecohydrology. Moreover, since understanding and reasoning about complex systems is difficult, learners—especially younger learners—need to engage in this type of work at all levels of systems thinking. Learners construct more useful, robust, integrated, and sophisticated knowledge and understandings when they have help. Thus, they need support as they integrate the various processes of science research with the characteristics of systems thinking (e.g., gathering information to construct a representation of where water goes, and then using this representation to generate a testable hypothesis related to the new ideas about the system).

Design Principle 5: Encourage sustained and organized investigation.

The final principle is rooted in the notions of time and of sequence over time. Several aspects of this principle are important to consider. First, authentic problems cannot be solved in a matter of minutes or even hours. Instead, authentic tasks that require the use of multiple tools of science necessitate a significant investment of time and intellectual resources on the part of the learner. Second, a community of practice needs time to develop as members—in this case, the learners—participate in practices that encourage their own membership as well as develop and sustain the community itself (Lave & Wenger, 1991).

Since the literature suggests that the ability to think in terms of systems develops hierarchically, engaging in the multiple steps of citizen science affords opportunities for sustained learning of complex systems. Citizen science also requires that learners engage in a particular sequence of activities related to science research: a) asking questions, b) building background information, c) generating hypotheses, d) gathering data, e) analyzing data, and f) communicating findings. Thus, the designed activities should be carefully sequenced such that when learners are engaged in the sequential processes of science, they acquire and then build on the appropriate skills and knowledge related to systems thinking. Prior research on systems thinking identified eight emergent characteristics of systems thinking and suggested that the ability to understand systems develops hierarchically, with learners sequentially engaging with and learning each new level, which then serves a foundation for learning the next level (Ben-Zvi Assaraf & Orion, 2005, 2010). This is the foundation of the conceptual model, which suggests that as learners engage in the sequential steps of citizen science, they will develop systems thinking. See Table 3.4 for the Design Principles and Draft Conjectures that were then embodied in the design.

Table 3.4
Design Principles and Related Conjectures

Learning Theory
Authentic experiences (i.e., collaborative citizen science) engage learners in the collaborative knowledge building processes that support the development of systems thinking characteristics.

Design Principle	Related Conjecture
Experience complex systems phenomena in authentic contexts Activities are authentic when students work with tasks, abstract concepts, facts, and tools in a realistic and highly social context that involves the ordinary practices of the scientific culture.	*Support and scaffold learner involvement in authentic activities* Learners may lack an understanding of the ways to work effectively in an authentic context. Thus, task structure, tools and materials, and participation structures must be designed to scaffold task involvement, tool use, norms of discourse, and dialogic participation structures.
Make the systems thinking conceptual framework explicit Activities and tools become productive spaces and mechanisms for learning when the organizing conceptual framework is made explicit, which then makes specific ideas salient.	*Identify and make explicit aspects of systems through representational tools* Since complex systems are counterintuitive and difficult to understand, task structure, tools and materials, and participation structures must make explicit the links between what learners observe and the different characteristics of systems thinking.
Encourage collaboration, discussion, and reflection Success and understanding are achieved by working collaboratively. Authentic activities make collaboration integral to the task, both within the activity and in the real world.	*Provide opportunities and scaffolds for collaboration, discussion, and reflection* Since knowledge and beliefs about the world are socially mediated, task structure, tools and materials, and participation structures must provide opportunities and scaffold norms to collaborate, discuss, and reflect.
Encourage construction of theories, models, and investigations Activities designed around constructing theories, models, and investigations afford learners opportunities to construct new understandings rather than passively receive and absorb isolated and unconnected facts.	*Provide opportunities, tools, and scaffolds to run observational ecohydrological investigations* To allow learners to generate questions, theories, and hypotheses about various phenomena, task structure, tools and materials, and participation structures must allow learners to use tools and techniques of ecohydrological research.
Encourage sustained and organized investigation to develop deep understanding Problems cannot be solved in a matter of minutes or even hours. Instead, authentic activities comprise complex tasks to be investigated over a sustained period of time, requiring significant investment of time and intellectual resources.	*Support and scaffold learners in hierarchical levels of systems thinking over time* Since the literature suggests that systems thinking develops in over time, engaging in the multiple steps of citizen science affords opportunities for deeper learning. Thus, task structure, tools and materials, and participation structures must reflect the citizen science sequence as it unfolds over time so that learners engage in hierarchical levels of systems thinking.

Conjectures as they are embodied in design elements.

Engaging learners in citizen science raises several challenges for project designers, especially when there are learning objectives—in this case, systems thinking—involved. The first of these is pedagogical—how do we help learners deal with the complexity of authentic practices as well as the complexity of systems, and the second is practical—how to we leverage our limited time and resources to support the type of tasks that engage learners in authentic practices? In this section, I focus on the three components, a) the structure of the tasks in which learners engage, b) the tools and materials available in the learning environment, and c) the social structures in and through which learners participate in the tasks. These components are important elements of the project conjecture map, which I present at the end of this section.

Task structure.

I will cover three aspects of task structure in this section: a) task sequence, b) task goals, and c) activity selection. *Task sequence* relates to the order in which learners were exposed to and engaged in aspects of science research as well as the structure of each activity as it related to time allotment. I took a constructivist approach when designing the Club because it provided a means of integrating systems thinking outcomes with citizen science research. This approach allowed me to situate the practices of science in an authentic and meaningful context, making the practices accessible to the learners (Edelson & Reiser, 2006; Jonassen, 1999). To provide an organizing framework for the learners, the overall research task was anchored in the effectiveness of the State Park restoration and the partitioning of rainfall into the different hydrologic components. Anchoring events are ideas about the relationships between natural phenomenon and a causal explanation that helps us to understand why a phenomena unfolds the way it does. Phenomena are events or processes that are observed by the senses or detectable by instruments (Ambitious Science Teaching, 2014). Simply put, learners were asked to describe "where all the water in Moro Canyon goes." To support learners as they engaged with the anchoring question, the learning activities were sequenced in a developmental progression, providing increasingly complex tasks through which learners experienced the increasingly abstract characteristics of systems thinking (Collins 2006). See Table 3.7 for an overview of task structure by citizen science step, day, task, and activity.

In addition to sequencing the tasks throughout the program, it was important to sequence activity structure and time in each activity such that learners would have an appropriate amount of time to draw on prior knowledge, investigate the phenomena under study, and then collaboratively reflect on their experiences. Research suggests that lessons are often unbalanced such that learners are often given so much time for investigation that there is little time left for reflection (Kolodner et al., 2003). To address this issue, we identified or designed activities that would not be too time consuming, and then we carefully nested these activities in an organization with the goal of providing learners with time to extract from their experiences what they had learned. The structure of each day was similar in that we met as a group for the introduction, broke into research teams to conduct investigations, build representations, or gather and analyze data, and then regrouped at the end to share our observations and findings. See Table 3.5 for an overview of the unit structure and associated time allotment for each type of activity.

Table 3.5
Generalized Time Allotment per Session

Location & Grouping	Activity	Time Allotment of 60 Minutes
On Campus		
Whole Group	Overview of Day/Introduction to Task	10 minutes
Small Research Teams	Investigation or Activity & Discussion	35 minutes
Whole Group	Discussion/Wrap-up	15 minutes
In Park		
Whole Group	Overview of Day	5 minutes
Whole Group	Hike into Park	12 minutes
Small Research Teams	Investigation or Data Collection & Discussion	20 – 25 minutes
Whole Group	Discussion/Wrap-up	5 – 10 minutes
Whole Group	Hike out of Park	13 minutes

Task goals refers to the nature and desired outcomes of the tasks in which learners are engaged. The theoretical model for designing constructivist learning environments conceives of a meaningful and ill-defined question as the focus of the experience, with the various intellectual supports and scaffolds that surround it. The goal of the learner working in this type of environment is to interpret the question and then to work through the scientific process to arrive at an answer (Jonassen, 1999). Through supportive experiences and facilitated discussion, learners develop possible theories or hypotheses to answer the question. They work together in a social setting to construct a shared primary conceptual model that explains the topic at hand, while facilitators provide supports and scaffolds for the learning as it unfolds across the experience. The research question, which was given to the learners and that anchored the design of the citizen science research was, “Does different landscape type—degraded, under restoration, or restored—influence where the water in Moro Canyon goes?”

Because I designed the Club as a citizen science project, the designed tasks engaged learners in gathering and analyzing data as a means of answering their question. Although this involved having learners learn and follow procedures, it was important that the learners engaged and understood with the conceptual ideas at the foundation of the procedures so that they were not followed mindlessly. Thus, the tasks related to these procedures had to be designed to help learners make sense of their work.

Well-crafted tasks have several features, including real-world relevance, accessibility, feasibility, and, most importantly, high-cognitive demand. Tasks that have real-world relevance are those that connect to issues or experiences beyond the classroom and that have meaning and value that extends to the surrounding world, thus providing learners with a sense of purpose for engaging in the tasks. Accessible tasks are those that build on learner’s prior knowledge and skills and have potential for helping learners advance their understanding about the situations in which their newly acquired knowledge and skills can be applied. A task is feasible if learners can complete it given the resources and materials that are available. Finally, high-cognitive tasks typically focus on sense-making by the learners, generally by asking learners to do something with ideas, much like professionals do in their everyday work life. Thus, high-cognitive demand tasks provide opportunities for learners to grapple both with their question and with the process by which they will answer their question. Table 3.6 presents characteristics of high-cognitive demand tasks.

Table 3.6
Characteristics of High Cognitive Demand Tasks (adapted from Ambitious Science Teaching, 2015)

Type of Tasks	Characteristic
Processing ideas	Tasks or questions that require learners to use (not regurgitate) ideas and information in ways that expand understanding, including tasks that require learners to: • Create or interpret representations of information • Make connections between representations of information • Recognize and use evidence to support explanatory claims • Distinguish between "what," "how," and "why" explanations • Create and critique explanatory models • Apply knowledge in contexts different for that where initial learning occurred
Connecting activity with ideas	Tasks that require learners to • Engage in thinking—the task may use a procedure, but it cannot be followed mindlessly. Learners need to engage with conceptual ideas and understand what they mean in order to successfully complete the task • Process information to come up with a solution, which is not evident
Seeking "why" explanations	Tasks that require a why explanation such that learners • Use evidence, information, and logic to tell a causal story that involves unseen, underlying events and processes that have to be connected in a logical way to explain observable events

Activity selection refers to the choices that are made regarding the program activities. Each selected or designed activities should help learners understand some aspect of the anchoring question, and the purpose of these activities is to establish a shared experience around which a common language and set of ideas can be built, so each selected or designed activity should help learners understand some aspect of the anchoring question. The designed or selected activities should allow learners to understand how each experience connects to the others, to their anchoring question, and to the real world phenomena. They should provide opportunities for learners to use tools of science to measure processes; to explore different ways to represent their data; to analyze data related to the anchoring question; and to construct an argument evidenced by data and supported by reasoning. As part of this research, I will examine both the design and the implementation of the task sequence, task goals, and activity selection to study their influence on learner outcomes. See Table 3.7 for an overview of task structure by citizen science step, day, task, and activity and Appendix C for the task sequence as it was aligned with citizen science steps and systems thinking characteristics.

Table 3.7
Overview of Task Structure by Citizen Science Step, Day, Task, and Activity

Step	**Day**	**Task**	**Activity**
Step 1	Day 1	Introduction to Club	Learners were introduced to the research topic: *Understanding effectiveness of the State Park restoration through an exploration of where the water in Moro Canyon goes*, and began building a learning community.
Step 2	Day 2	Exploring scientific process; Building a simple water cycle model	Learners were given their research question: *Does landscape type—degraded, under restoration, or restored—influence where the water in Moro Canyon goes?* In research teams, they began building background knowledge of the water cycle based on observations of the components and process in a water cycle dish. The questions for the day were, *"Where does rain come from? What happens to the water on the ground when the rain stops and the sun comes out?"*
	Day 3	Exploring Soil Moisture: Soil Percolation Test	In research teams, learners continued to build background knowledge of the water cycle, focusing on soil moisture, based on an investigation of soil percolation. The questions for the day were, *"What happens to rain when it falls on the soil? Do different types of soil absorb water at the same rate?"*
	Day 4	Exploring Transpiration: Plant Terrariums & Evaporation Tents	In research teams, learners continued to build background knowledge of the water cycle, focusing on transpiration, based on observations of plant terrariums and evaporation tents. The questions for the day were, *"What happens to the water that is taken up by plants? Do all plants use water at the same rate?"*
	Day 5	Drawing a Representation & Generating a hypothesis	In research teams, learners drew representations of the ecohydrologic system based on their background research. The representations depicted their framework of dynamic relationships among components and processes and represented their theory of how water moves through the system. In the whole group, learners used their representations to generate a hypothesis about where water goes in each landscape type.
Step 3	Day 6	Learning to use equipment and enter data	As a whole group, learners identified the data they needed to collect—soil moisture, plant transpiration, and weather. In research teams, they learned to use soil moisture meters, leaf porometers, weather stations, and iPads to enter the data. The questions for the day were, *"What data do we need to collect, and how do we collect that data?"*
	Days 7 – 9	Field Work: Gathering data	In research teams, learners followed research protocols to gather soil moisture, transpiration, and weather data at degraded, under restoration, and restored plots. They entered data on paper and electronic data sheets.

	Day 10	Creating tables & graphs	In research teams, learners graphed their data in an appropriate graphical format for our question. The questions for the day were, *"What does our data look like, and how do we graph our data?"*
Step 4	Day 11	Making and justifying inferences	In research teams, learners analyzed their data by a) creating a representation of where water goes in each landscape based on their graphed data, b) comparing their hypothesis representation to their data-based representation, and c) jointly constructing and justifying their explanations using their representations. The questions for the day were, *"Does our data support our hypothesis, and how do we know?"*
Steps 5 & 6	Day 12	Designing Posters to Disseminate results	In research teams, learners continued to construct explanations as they decided how to communicate their findings. Learners designed a poster with the following sections: Introduction, Question, & Hypothesis; Methods; Results; Discussion & Future Work. The questions for the day were, *"What is our story, and how do we tell our story to other people? What new questions do we have?"*
	Day 13	Disseminating results, Asking new questions	As a whole group, learners participated in a culminating task as they presented their work to State Park managers and staff, their principal, their parents, and other interested members of the community.

Tools and materials.

I will identify and provide examples of the three types of designed tools used by learners in this section: a) material/physical tools, b) cognitive/relational tools and materials, and c) social tools. In this study, I broadly defined tools as objects that allowed us to do work. More specifically, I categorized each tool by the nature of the work it allowed us to do. Several aspects of tools, their use, and my study of them are important to highlight here. First, each of the tools discussed may cross boundaries between tool types, but I have defined each by their primary function in the program. Second, as objects that allow us to do our work, these tools work in support of, rather than scaffold, learning because they do not fade over time as learners build knowledge, skills, and understandings. Finally, there were a number of tools used in this program; however, the scope of this study did not allow for an analysis of many of the tools that were available to the learners. Further in-depth studies may reveal interesting information related to specific tools that are not discussed here.

Material/physical tools were the objects that we used in the real work to accomplish physical tasks. In this research, for example, physical tools included the leaf porometers, soil moisture meters, and weather stations. They allowed us to gather data on transpiration, soil moisture, and weather—important ecohydrological processes, but without the support of cognitive/relational tools, the information that each provide was conceptually meaningless. However, used in conjunction with other tool types, they could be leveraged to help learners make connections between different aspects of their research and different components and processes of the ecohydrological system. Thus, important questions of this research are whether and how these scientific tools supported learner development of systems thinking.

Cognitive/relational tools were the intellectual devices that learners used to visualize the task they were performing, to organize the data and information they were gathering, or to supplant learner thinking as it related to procedural tasks. In this research, for example, learners used conceptual models as a way to represent what they knew and what they were learning and compare their predictions to their results. They also created graphs to visually represent their data that they then used to support their claims about their findings. The Citizen Scientists' Notebook and the data sheets are examples of organizational tools. Learners used both to keep track of the ideas and information they were building and the data they were gathering as part of their research. As a result, the notebook became a public record of learner thinking and the data sheets became a public record of learner skills as they evolved over the course of the program. Finally, the equipment instructions and the data collection protocols, which were both included in the notebooks, are examples of tools that were used to offload thinking. A critical aspect of the Club was gathering useful and usable data and distinguishing between useful and un-usable data; thus, it was important that learners had access to simple data collection protocols and equipment instructions. As a note, although the data collection protocols did offload some of the learners' thinking, it was important that the teams did not follow them blindly. Use of cognitive/relational tools were designed to help learners make explicit connections between different aspects of their research, between their work and the real world phenomena, and between different components and process of the ecohydrological system.

Social Tools were those tools that provided access to both shared information and shared knowledge-building tools to help learners collaboratively construct socially shared knowledge. Learning most naturally occurs not in isolation but by teams of people working together to solve problems. In this research, several social tools were used to ensure collaboration. First, the learners were divided into smaller research teams so that individual members would have more opportunities to collaborate. Second, each team had one shared science notebook, and during each investigation or activity, all team members were required to sign off on the outcome. The science notebooks included the tools that each team would use to record observations, create representations, gather data, and construct representations. Most activities were organized such that each team created its own representations or graphs that they then shared with and compared to the other team's representations and graphs. This provided opportunities for teams to reorganize their thinking and the group as a whole to come to consensus regarding the phenomena under discussion. Thus, both were designed to be public representations of each research team's as well as the whole group's thinking as it evolved over time. Third, learners were provided with a tool that supported the participation structures (which will be discussed in the next section) by helping to create and maintain a safe place for learner conversation. This tool, which was both printed in their notebook and posted on the wall, provided a list of norms to create a safe space for conversation and sentence frames to help learners agree or disagree with each other in productive ways.

Participation structures.

Participation structures refers to the how facilitators and learners are expected to participate in tasks, including the roles and responsibilities each is responsible for and takes on as they are collectively engaged in the different tasks. The role of learners was to work together, pooling resources and experiences, to grapple with the complexities of their research task. The role of the facilitators was to support and scaffold collaboration and learning through a mixture of structuring, constraining, questioning, modeling, and coaching. To scaffold productive collaboration such that learners actively listened to, critiqued, and respectfully responded to ideas, facilitators provided sentence frames—on a poster and in the notebooks—for learners to use, including "Can you be more specific?", "I disagree with your idea/reasoning because…", "I agree with you, but I also think…". Over the course of the Club, facilitators modeled the use of these frames and coached teams to use them effectively during their interactions. To scaffold learning to use the equipment, facilitators included a mixture of modeling (facilitator-centered activity), coaching (learner-centered activity), and questioning. First, facilitators demonstrated how we use a piece of equipment to gather data as learners observed. Second, learners attempted to use the equipment with guidance and help from the facilitator. Third, learners taught each other how to use the equipment, with the support of facilitator questions.

Questioning played the primary role in providing support and scaffolding as facilitators used a variety and pattern of questions to elicit learner ideas, highlight salient features of a particular problem, elicit learners' initial ideas, press for explanations, probe for understanding, and help learners make connections between different ideas. See Table 3.8 for examples of questions that were designed into the lesson plans to scaffold learning (Ambitious Science Teaching, 2015).

Table 3.8
Examples of Questions used to Scaffold Learning (Ambitious Science Teaching, 2015)

Goal of Question: To help learners	Question
Share, expand, clarify thinking	Say more – “Can you say more about that?” – “What do you mean by that?” – “Can you give me an example?” Clarify – “Let me see if I understand what you are saying. Are you saying…?
Deepen reasoning	Asking for evidence or for reasoning – “Why do you think that?” – “What is your evidence?” – “What patterns do you see in these data?” – “What reasons might there be for these patterns?” – “Can you give me a convincing argument for that statement?” – “Do you think that data/answer/argument is reasonable? Why?” – “How did you come to that conclusion?” – “What conclusions can you make from these data?” Challenge or counterexample – “Does it always work that way?” – “How are these two ideas related?’ – “How does this idea compare to her/his idea or example?”
Listen to each other	Rephrase or repeat – “Who can repeat what she/he just said?” – “Can you put what she/he said in your own words?”
Think with others	Agree/disagree and why – “Do you agree/disagree? Why?” – “What do people think about what she/he said?” – “Does anyone want to respond to that idea?” Add on – “Who can add onto her/his idea?” – “Can anyone take that suggestion and push it a little further?” Explain what someone else means – “Who can explain what she/he means when she/he says that?” – “Who thinks she/he can explain why she/he came up with that answer?” – “Why do you think she/he said that?”

Reading the conjecture map.

Figure 3.2 shows the conjecture map that I used to design both the intervention and the research on the intervention. By tracing observed effects back to specific conjectures, I could uncover theoretical knowledge about systems thinking development by identifying specific aspects of the instructional context that influenced learning; and I could present a refined Citizen Scientists’ After-school Club curriculum. In this way, both the theoretical conjectures about learning and the overall design of the learning environment were refined and revised. In Chapter

5, I will present each conjecture about learning, show how each was embodied in different aspects of the program, and identify the learning outcomes predicted by each embodiment.

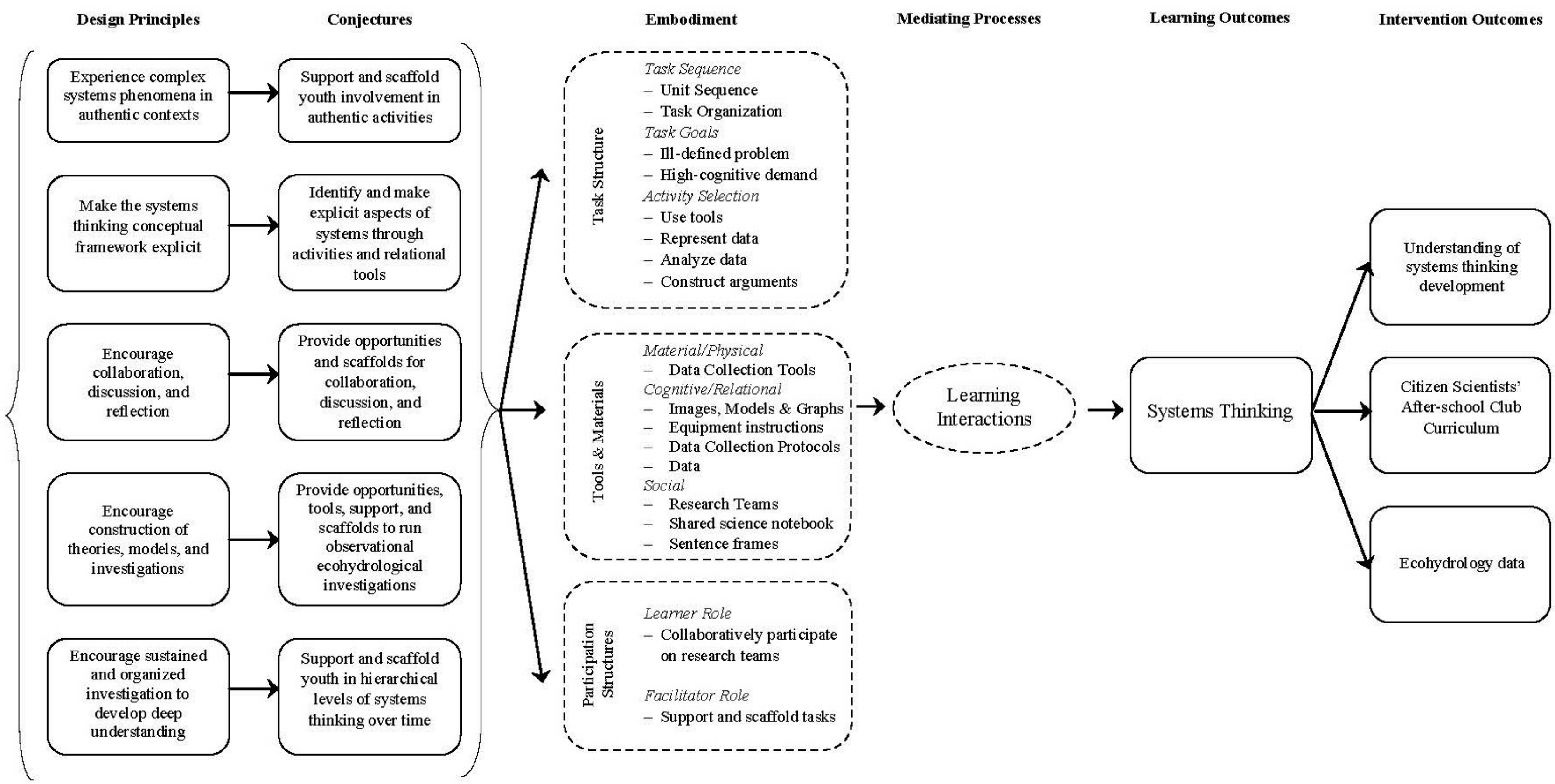


Figure3.2. Citizen Scientists' After-school Club Conjecture Map

CHAPTER 4

Systems Thinking Outcomes

"There isn't a beginning and there isn't an end either because the water evaporates or transpires up into the clouds and then it rains and back into and back down and that water evaporates or transpires into the clouds again and then it rains and on and on and on forever"

4th Grade Citizen Scientist, Day 6

We live in a world that is increasingly governed by complex systems that operate on multiple scales over long periods of time, and understanding the way that these complex systems operate has become an essential focus of science education and research into science learning (National Research Council, 2012). Much of the current research on systems thinking is guided by the fundamental question of how we develop the ability to think in terms of systems as they connect and operate over space and time. Systems thinking refers to our ability to recognize patterns of relationships and interconnections and then synthesize these patterns into a unified whole (Senge, 1990). It provides people with opportunities to build unifying theories and coherent conceptual frameworks by building links between seemingly disparate elements of different disciplines. In recent years, there has been a proliferation of research on complex systems and on learners' abilities to understand them as they operate over space and time (Ben-Zvi Assaraf & Orion 2005, 2010; Hmelo-Silver, Marathe, & Lui, 2007; Hmelo-Silver & Pfeffer, 2004; Wilensky & Resnick 1999). Collectively, this research suggests that developing an understanding of complex systems is difficult, especially for younger learners (Ben-Zvi Assaraf & Orion, 2005; 2010; Jacobson & Wilensky, 2006; Wilensky & Resnick, 1999). This research also suggests that, with proper support, learners as young as 10 years are capable of attaining a level of abstract thinking required to develop systems thinking (Ben-Zvi Assaraf & Orion, 2010). In their work with elementary aged children, Ben-Zvi Assaraf & Orion found that studying the nature of the learning context that supports the development of systems thinking, including the design of experiences that engage learners with the more abstract aspects of systems, is a critical direction for research into systems thinking learning. Thus, the central question of this research was whether youth can develop systems thinking and, if so, under what conditions.

This chapter addresses the first part of this question, exploring whether 9 and 10 year old learners developed systems thinking as they engaged in citizen science research. Citizen science refers to the engagement of non-professionals in genuine scientific investigations, thus providing an authentic context in which the learners could explore systems phenomena. Specifically, I asked a) What were the initial systems thinking abilities of 9 and 10 year old learners?, b) What were the systems thinking abilities of 9 and 10 year old learners after participation in systems-based citizen science research?, and c) Did productive interaction among learners influence systems thinking development over the course of their participation? The findings of this study may hold broad implications for science education, particularly for younger learners, as there no research on whether this population of learners can develop understandings of systems phenomena by engaging in citizen science research.

As previously discussed, systems thinking refers to our ability to recognize patterns of relationships and interactions between system components and then to synthesize these patterns into a unified view of the whole (Meadows, 2008; Senge, 1990). Ben-Zvi Assaraf and Orion (2005, 2010) tested and refined a model of systems thinking development that described the way learners come to understand complex systems as they operate over space and time, a model that is central to this work. Their research identified eight emergent characteristics of systems thinking and suggested that the ability to understand systems develops hierarchically, with learners sequentially engaging with and learning each new level, which then serves a foundation for learning the next level (Ben-Zvi Assaraf & Orion, 2005, 2010). Table 4.1 summarizes the emerging characteristics of systems thinking (see Table 1.2 for ecohydrologic examples as they relate to each characteristic).

Table 4.1
Eight Emerging Characteristics of Systems Thinking (Ben-Zvi Assaraf & Orion, 2010)

1. The ability to identify, describe, and explain observable components and common processes of the ecohydrological cycle
2. The ability to identify, describe, and explain the static relationships between or among systems components
3. The ability, to identify, describe, and explain the dynamic relationships within the system
4. The ability to organize system components, processes, and their interactions within a framework of system relationships
5. The ability to identify cycles of matter and energy within the system
6. The ability to identify, describe, and explain hidden dimensions of the system
7. The ability to generalize—to make hypotheses, propose explanations, and solve problems based on an understanding of systems' mechanisms
8. The ability to think temporally: retrospection and prediction

The purpose of this research was to study the extent to which participation in collaborative citizen science, designed around six steps of science research, might facilitate youths' development of systems thinking. I drafted the conceptual model, which was the theoretical guide for the design, by mapping the eight systems thinking characteristics to the six steps of citizen science (see Figure 4.1). Each step in the citizen science research afforded a particular type of task and participation structure, which in turn, afforded a particular way of thinking and knowing. Thus, as learners collaboratively engaged in the different steps of citizen science, I expected they would build knowledge and understanding of the ways in which complex systems operate.

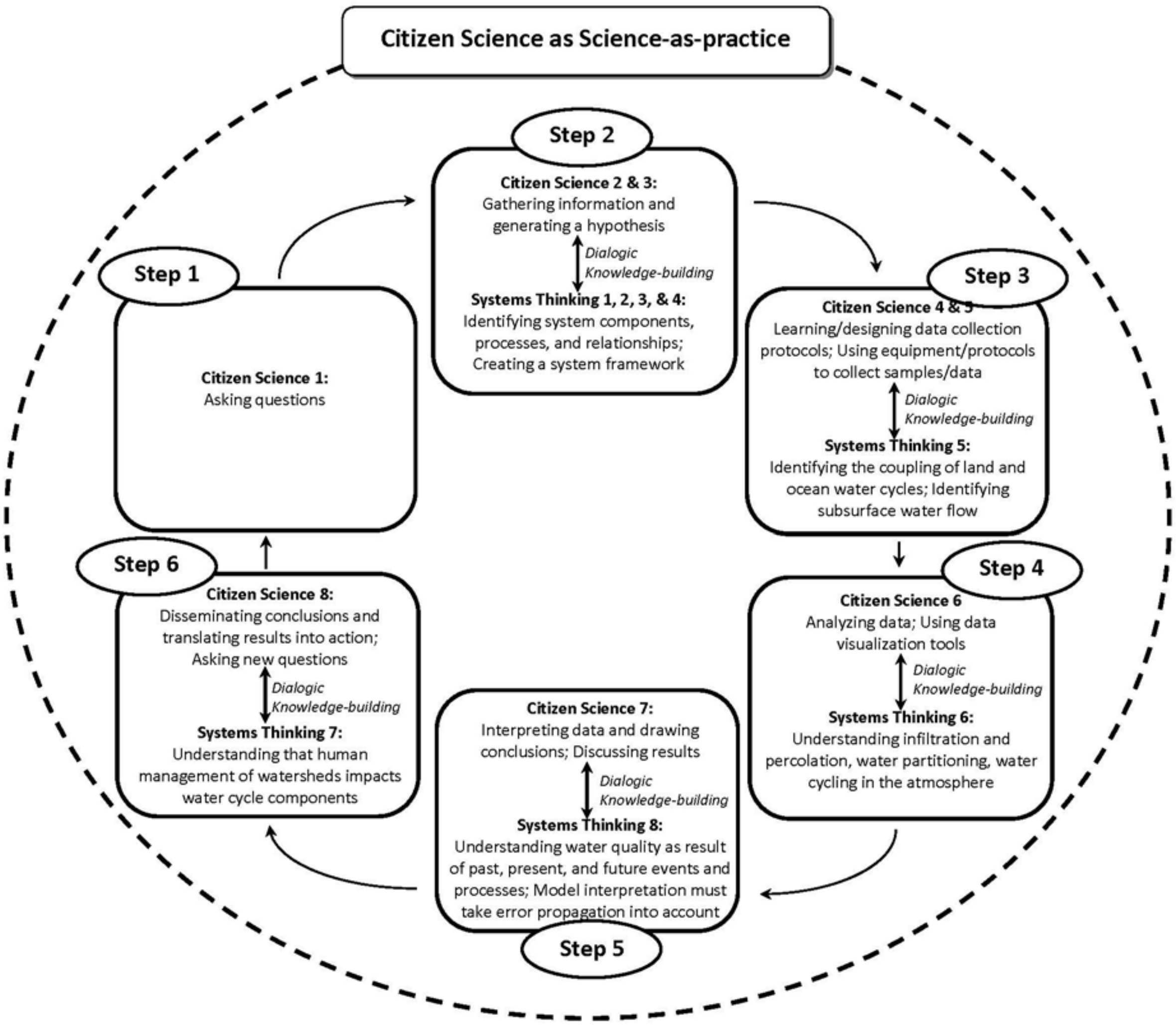


Figure 4.1 Conceptual Model of Citizen Science as Science-as-Practice: Citizen Science and Systems Thinking Characteristics Integration (see Table 1.2 for systems thinking characteristics)

Methodology

Research Context and Participants

The research context of this study was an after-school club that took place at a local elementary school and in a local State Park. The Citizen Scientists' After-school Club (the "Club") included 14 hours distributed in one after-school hour, twice each week, for an eight-week period. The participants spent nine of the 14 contact hours on the school campus, either in the classroom or outside on the campus, and the remaining five hours in the State Park, conducting background research on the ecohydrological system, gathering data related to our ecohydrological research question, or presenting their findings to the broader community.

Study participants included nine 9 and 10 year old learners, who were either in the 4th or in the 5th grade at their elementary school. These nine participants were divided into two citizen science research teams—the Green team and the Yellow team. Each team worked with a graduate or an undergraduate student facilitator who provided support as it engaged in the designed tasks. All of the facilitators had experience teaching in both formal (i.e., classrooms) and non-formal settings (i.e., after-school clubs). See Table 4.2 for the research teams by participants, age, grade, and facilitator. Although none of the 9-year-old learners had formal experiences with the water cycle, the two 10-year-olds began their in-class water unit around the fifth session of the Club. Evidence of this appears in the Yellow team transcripts.

Table 4.2
Research Teams by Participants, Age, and Grade

Team	Participant	Age	Grade	Facilitator
Green	Noah	9	4th	Joan
	Ethan	9	4th	
	Tim	9	4th	
	Sean	9	4th	
Yellow	Isabel	10	5th	Laura
	Nancy	10	5th	
	Abby	9	4th	
	Eric	9	4th	
	Fred	9	4th	

Research Structure

The development of this phase of the research included the following three tasks.

Task 1: Design of the outcome measures.

Addressing the research question required accounting for a large number of variables related to the eight characteristics of systems thinking, which required the use of a variety of research tools. First, to draw a general picture of learners' prior knowledge and their changing perception of the ecohydrological system, I identified four pencil-and-paper measures based on prior work by Ben-Zvi Assaraf and Orion (2005, 2010). Each measure was revised to be more closely aligned with the ecohydrological content that was the focus of the study and to the design conjectures discussed in Chapter 3. Second, to uncover how systems thinking developed over time through learner collaboration, I developed an analytic framework to code instances of learner talk captured by video. This multi tool approach—pencil-and-paper pre-/post tests and video-based analysis—enabled me to collect data on each learner's emerging systems thinking abilities and provided a method by which to triangulate findings. I will review each of the tools later in this chapter.

Phase 2: Design of the Learning Environment

Decisions related to the development of the learning environments were discussed in detail in Chapter 3, but it may be helpful to review several relevant aspects of the design. As discussed in Chapter 1, one way to help learners develop systems thinking may be to allow them to explore complex phenomena as active participants rather than as passive observers (Levy & Wilensky, 2004). Thus, the learning environment was designed to engage learners in authentic environmental research by providing them with a topic (i.e., Where does the water in Moro Canyon go?) related to an issue of interest (i.e., the restoration of State Park land) and a testable question (i.e., Does landscape type—degraded, under restoration, restored—influence where the water in Moro Canyon goes?) that served as an anchoring event for their citizen science research and for learning about complex systems. To conduct their research, learners investigated the ecohydrological components and processes and explored the dynamic and cyclic relationships among them by engaging in a mixture of knowledge and skill building experiences sequenced to reflect the process of science research. A critical aspect of any science research is gathering and working with data, so learners collected data as a means of working closely with the abstract aspects and hidden dimensions of the ecohydrological system. Thus, the sequence of tasks, the nature of individual activities, tools and materials available, and the participation structures were all designed to provide an authentic context for leaners to engage collaboratively in science research and with the eight characteristics of systems thinking.

Phase 3: Implementation and analysis of the learning environment.

Although I will discuss program implementation in detail in Chapter 5, it will be helpful to preview one element of program implementation at this point. I provided facilitators with session plans that included an overview of the task, the list of the tools and materials, the organization of the task structure, and an overview of the roles of the facilitator and the learners (i.e., the participant structures). We met as a team prior to each session to review details of the plan and discuss implementation. The purpose of this meeting was to ensure, as much as might be possible, consistency in implementation across all learner teams.

Research Measures

As previously discussed, I used five different tools to gather data related to the systems thinking outcomes. The four pencil-and-paper measures were administered at the beginning and again at the end of the club as pre- and post-tests. The fifth tool consisted of a systems thinking analytic framework that was used to code segments of learner interactions as they engaged with each other to complete designed tasks. Using multiple measures with targeted coding schemes allowed me to hone in on the specific systems thinking abilities of each learner and to document her or his changes in systems thinking as they occurred over the course of implementation. The following section includes a brief description of the research tools that were used and the specific systems thinking characteristic(s) they target, and Table 4.3 shows how each tool was aligned with specific systems thinking characteristics.

Word association.

The word association was given to measure individual learners' ability to identify system components and processes (characteristic #1). It is a direct probe of the associations a learner perceives for a particular concept (White & Gunstone, 1992). When administered, learners are given a word or idea and asked to freely associate ideas with this stimulus. The spontaneous ideas written by learners are subject to fewer constraints than are typically imposed in interviews or closed questionnaires (Ben-Zvi Assaraf & Orion, 2010; Wagner, Valencia, & Elejabarrieta, 1996; White & Gunstone, 1992).Thus, they allow for relatively unrestricted access to the mental representation of the stimulus idea (Hovardas & Korfiatis, 2006). To complete this task, we gave learners five minutes and asked them to list 12 words or ideas (elements) they naturally associated with the stimulus term: "Where does the water go?" If learners struggled with the measure or with the directions, we gave them the following prompt: "Imagine rain. Where does rain come from?" and "What happens to rain after it falls on the ground?"

Drawing analysis.

The Drawing Analysis was given to measure multiple system thinking characteristics (see Table 4.3), including a) components and processes (characteristic #1), b) dynamic relationships within a system (characteristic #3), c) a framework of relationships within the system (characteristic #4), d) the appearance of a cyclic perception of the system (characteristic #5), and e) hidden dimensions of the system (characteristic #6). There is evidence that drawings may serve as a useful tool for probing learner understandings of natural phenomena (Ben-Zvi Assaraf & Orion, 2010; Dove, Everett, & Preece, 1999) and for identifying the gap between learners' conceptions and the scientific view of a particular phenomenon (Novick & Nussbaum, 1978). Moreover, there are a number of studies that suggest that drawings provide opportunities for children to communicate ideas for which they do not have a concrete, visible object (see Rennie & Jarvis, 1995), which is important for measuring a learner's ability to recognize the hidden dimensions of a system. Thus, the drawing analysis allowed the learner to reveal, and me to see, qualities of understanding that may not have been as easily drawn out by other procedures (White & Gunstone, 1992). To complete this task, we gave learners 10 minutes and a list of words drawn from the main components and process of the ecohydrological system. We asked them to draw a picture of where the water goes using as many words from the list as possible. We assured them that we did not expect them to produce an artistic drawing, though several of the participants did express concern about their ability to draw.

Ecology System Inventory.

The Ecology System Inventory was administered to explore learners' ability to identify the hidden dimensions—both components and processes—of the ecohydrologic system (characteristic #6). Hidden dimensions refers to components and process that occur out of view and are thus more abstract and difficult to understand. We gave learners 10 minutes and a picture of an ecological system, adapted from Ben-Zvi Assaraf & Orion (2010) to a) make a list of the components of the ecosystem that they saw in the picture, b) add any components to the ecosystem that they thought were missing, c) show the relationship between the components of the picture, and d) give the picture a title. Again, we assured the learners that they were not expected to produce an artistic drawing.

Cyclic thinking questionnaire.

The Cyclic Thinking Questionnaire was administered to identify learners' understanding of the cyclic nature of the ecohydrological system (characteristic #5). When constructed well, Likert-type questionnaires can provide direct and reliable assessment of knowledge; however, they are also subject to inaccurate measurement as respondents can guess correctly without understanding underlying phenomena. Moreover, younger learners may have difficulties reading and understanding the meaning of the statements. To address these issues, we asked learners to circle their choice of answers and then write an explanation for their choice. The purpose of this was to a) identify learners who guessed correctly when they selected an answer but held an alternative understanding of the way that the ecohydrological system operates and b) to test whether wrong answers arose from a misinterpretation of the statement.

The questionnaire included four statements drawn from previous work done by Ben-Zvi Assaraf and Orion (2005) and from typical 4th and 5th grade textbooks: a) Clouds are the starting point of the water cycle, and the ocean is the ending point of the water cycle, b) The amount of water in the ocean grows each day because rivers are continually flowing into the ocean, c) Plants take up water from the soil through their roots and release water to the atmosphere from their leaves, and d) All the water that falls in a rainstorm runs off into the ocean. We gave learners 10 minutes to circle whether they agreed with, disagreed with, or were uncertain about the statement and then to write a short explanation of their answer. See Appendix D for the four pencil-and-paper measures.

Table 4.3
Research Tools Aligned with Systems Thinking Characteristics

Systems Thinking Characteristics	WA	DA	ESI	CTQ	VIDEO
1. System components and processes	✓	✓			✓
2. Static relationships among components					✓
3. Dynamic relationships within the system		✓			✓
4. Framework of relationships within system		✓			✓
5. Cycles of matter and energy within the system		✓		✓	✓
6. Hidden dimensions of the system		✓	✓		✓
7. Generalizations based on system relationships					✓
8. Think temporally; retrospection and prediction					✓

WA = Word Association; DA = Drawing Analysis; ESI = Ecology System Inventory; CTQ = Cyclic Thinking Questionnaire; VIDEO = Transcripts analyzed using the Systems Thinking Analytic Framework

Systems thinking analytic framework.

In addition to the pre- and post-test, I also generated data on teams' systems thinking through an analysis of video-based observations. Research indicates that individual assessments can lead to systematic under-measurement of learning because they fail to allow participants to draw on human resources in their environment (Schwartz, Bransford, & Sears, 2005). Thus, an important method for assessing learning over time is the analysis of participants' conversations as they occur in the course of the ongoing activity (National Research Council, 2009). To generate data on systems thinking as it emerged through learning interactions, I recorded the conversations that took place during whole group and small group work each session. To analyze the data, I developed a framework that included each level of systems thinking aligned with three dimensions of ability ranging from *Simplistic* to *Developing* to *Complex* as they related to each characteristic. Using this framework to code the interactions that took place over the course of the program allowed me to capture the way that learners' systems thinking evolved as they engaged in the designed sequences of learning activities.

Data Collection

The data was collected at the beginning, during, and at the end of the program. We administered the pre-tests on the second day of the program[2] and the post-tests on the last day of the program (Day 14). The learners completed each measure individually and one at a time in 35-minute sessions. With respect to the video, we began recording on the first day of implementation and then recorded all following days[3]. We used three cameras—one to collect

[2] I initially planned to administer the pre-tests on the first day of the program, but neither time nor interest permitted this. We spent the first day assenting the participants, building a community of learners/researchers, and discussing program logistics. We did briefly review our citizen science topic and question, but these topics were not addressed in depth until after learners had completed the pre-tests on Day 2.
[3] Due to a corrupted video file, I do not have a video record of the Green team's work on Day 3.

whole group interactions, and two to collect Green and Yellow research team interactions (Derry et al., 2010; Hall, 2000). We mounted all three cameras on tripods when we were working in the classroom and gathering ecohydrology data at our research plots in the State Park. There were occasions when activities required learners to hike in the Park. In these instances, the cameras were handheld. In addition, when teams were learning to use the ecohydrology equipment, the activity was structured in such a way that one learner from each team was asked to operate the camera. We did not record our hikes into or out of the Park. Although the cameras initially distracted learners, they appeared to lose interest in them over time (Heath, Hindmarsh, & Luff, 2011). Other than the days when learners operated the cameras, there were only four instances when learners either asked a question or made a comment about the cameras (Green Team, Day 7 and Day 9) or spoke directly to a camera (Green Team, Day 11 and Yellow Team, Day 12).

Data Analysis

In this section, I will discuss each measure separately, providing information on how I generated, applied, and quantified codes for each measure. With regard to the pencil-and-paper measures, only eight of the nine participants had matched word associations and Cyclic Thinking Questionnaires. In addition, I eliminated the drawing and Ecology System Inventory for one participant who did not complete the post-tests, leaving a total of seven matched drawings and Ecological Systems Inventories.

The overall analysis of the systems thinking measures and video transcripts involved qualitative coding and the quantification of the coded data. To increase consistency of the pencil-and-paper measure coding, the two coders—one of the implementation team members and I—independently coded the same four word associations, drawings, Ecology System Inventories, and Cyclic Thinking Questionnaires. These measures were blind coded; we did not know whose test we were coding or if we were coding a pre- or a post-test. After comparing and discussing the two separate analyses, we developed a standardized coding system for each measure and then recoded the initial four measures and coded the remaining measures. To determine consistency between the two coders, I calculated intercoder reliability analysis using the Kappa statistic, which I have included for each measure. Where appropriate, I also have included areas of disagreement as they related to the nature of the codes and the agreement that we reached through discussion (Hammer & Breland, 2014). For the pencil-and-paper measures, data analysis consisted of comparing the pre-tests to the post-tests and noting differences in the number and type of codes across the whole group, each team, and individual learners. This was done to account for differences in small team composition and facilitation as well as for outside influences (i.e., the two learners who were learning about the water cycle in their 5th grade class).

For the video transcripts, data analysis consisted of transcribing the video, isolating and coding segments of talk related to systems thinking, and then identifying patterns of talk that emerged over time. We used the initial analytic framework to individually code the transcripts from one session. After comparing and discussing the two separate analyses, we refined and tested the framework by coding transcripts from three additional sessions. After comparing and discussing our two separate analyses, we had the final framework, which I then used to code the remaining transcripts. See Appendix E for the coding schemes for each measure and for the systems thinking analytic framework.

Word association.

We coded the word associations first to establish the list of components and processes to code the remaining measures and to design the systems thinking analytic framework. To code this measure, we classified the words or ideas provided by learners as either a component or a process. For the initial round of coding, we used a list of both components and processes drawn from literature on the ecohydrological system (Brooks, Ffolliott, & Magner, 2013; Schlesinger, 1991) as well as from previous research on systems thinking (Ben-Zvi Assaraf & Orion, 2010). For the second round of coding, we added additional words/ideas that emerged from learner tests. Only categories agreed upon by both coders were included in the final coding.

Our initial coding disagreements were related to four areas: a) the grouping of similar components and processes (e.g., *pond* and *lake*, *river* and *stream*), b) the handling of duplicate ideas (e.g., a learner listed *evaporation* twice), c) the handling of unrelated ideas (e.g., a learner listed *trash*), and d) the scoring of statements that included both components and processes (e.g., "plants put out water through transpiration into the air"). Through discussion, we determined that both similar and duplicate words/ideas would be grouped and only counted once, that unrelated ideas would be eliminated from the analysis, and that all components and processes in a single statement, unless they were duplicate or unrelated ideas, would be counted in the final score. Interrater reliability was calculated separately for components and processes. For the components, final reliability was Kappa = .77, and for the processes it was Kappa = .85. Comparison of learners' pre- to post-word associations consisted of calculating change scores separately for the group as a whole, for each team, and finally for individual learners.

Learner Drawings.

Learners' responses to the drawing measure were initially coded using a scheme drawn from the literature (Ben-Zvi Assaraf & Orion, 2005; Rennie & Jarvis, 1995) and from the word association coding and then refined through discussion and a second round of coding. The drawings were analyzed separately for each of the systems thinking characteristics it was designed to measure. Our only coding disagreement across all analyses was related to what constituted a dynamic relationship between two elements. Through discussion, we determined that dynamic relationships were determined as components linked by a line or an arrow or drawn in close proximity with each other. See Figure 4.2 for an example of the way proximity and lines were used to code for dynamic relationships. In this drawing, water vapor and soil were linked through lines that indicate evaporation and transpiration lines were linked to plant by proximity. After establishing our final coding schemes, we coded the remaining pre- and post-tests. Overall, reliability across all five analyses was Kappa = .88, where the highest Kappa = 1.00 (processes

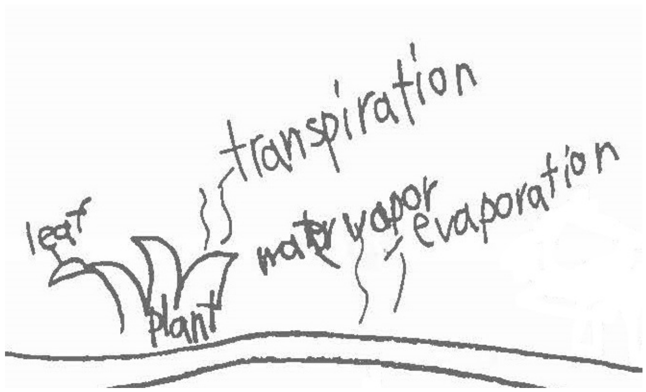


Figure 4.2 Example of a how dynamic relationships were coded

and cycles) and the lowest was .65 (dynamic relationships). Kappa for each aspect of the drawing analysis is reported separately in Appendix F.

Since the drawings were analyzed for multiple systems thinking components, I used several different methods to compare pre-test to post-test results. Because scores for components, processes, dynamic relationships, and hidden dimensions were based on counts, comparison of pre-test to post-test results consisted of calculating change scores separately for the group as a whole, for each of the teams, and finally for individual learners. Because the coding schemes used for framework of relationships and cycles of matter and energy involved using a rubric based on increasing complexity related to the particular characteristic to assign scores, comparison of the pre-test to the post-test results consisted of noting differences in scores for the group as a whole, for each team, and finally for individual learners.

Ecology System Inventory.

There were two phases in the analysis of the Ecology System Inventory. During the first phase, we examined each picture to identify components that were added to the picture. We then classified each component as either visible or hidden (e.g., components that are located beneath the Earth's surface or in the atmosphere that cannot be seen). During the second phase, we identified the nature of the hidden component (e.g., subsurface flow or transpiration from leaves into the atmosphere). Final reliability for the coders was found to be Kappa = 1.00. Comparison of pre- to post-test involved a review of the differences in the type of items added to the picture as indicated by the score applied.

Cyclic Thinking Questionnaire.

The questionnaires were analyzed in two phases. During the first phase, we coded each learner choice as *Correct*, *Incorrect*, or *Uncertain* for each statement. During the second phase, we conducted a content analysis of the learners' explanations. Each written explanation received a score ranging from 0 to 4 (0 = not scientifically correct, not relevant to the statement, "I don't know'" or blank; 1 = says that "the statement is true/untrue" without explanation; 2 = provides an intuitively correct answer ("I think that there is not a starting point or an ending point in the water cycle so I will disagree with that [statement]"), 3 = process based explanation ("There is not an end to the water cycle because water gets evaporated again."), and 4 = cycle-based explanation ("When it rains, water goes through the soil and the plants take it in; then they let it out through transpiration through their leaves."). Since I was primarily interested in learner reasoning, I coded the explanations independently of the circled answers. This meant that a learner could have circled the correct answer, but provided an explanation that was scientifically incorrect. For example, for the first statement regarding starting and ending points of the water cycle, Noah chose the correct answer, but he explained his choice by writing, "I disagree because the ocean is not [the starting point], it's in the clouds." Thus, incorrect explanations were given a score of 0 regardless of the circled answer, and all other explanations were given a score from 1 - 4 based on the level of reasoning displayed. This allowed me to identify those learners who held alternative understandings of the ecohydrological system. It also accounts for the differences in scores between the answers circled and the written explanations. Overall, final reliability across all four questions was Kappa = .79. Kappa for each question in the Cyclic Thinking Questionnaire is reported separately in Appendix F. Comparison of pre- to post-test results involved calculating the differences in correct and incorrect scores followed by noting the differences in reasoning for individual learners, across each team, and across the group as a whole.

Transcripts of video-based interactions.

Analysis of the transcripts involved three phases. The first phase involved transcribing video from each session, separating the transcripts into Whole Group, Yellow team, and Green team discussions, and then segmenting the transcripts based on when a different characteristic related to the levels of system thinking as it related to ecohydrology was raised in discussion (Jordan & Henderson, 1995). These segments were as short as one two-line question and answer sequence or included multiple turns of talk in which the focus of the interaction stayed the same.

The second phase of analysis consisted of testing and refining the initial framework by coding the segments of ecohydrology talk from four days of transcripts. The initial framework was developed using both the systems thinking literature (Ben-Zvi Asaraf & Orion, 2005, 2010) and the water cycle literature (Brooks, Ffolliott, & Magner, 2013; Schlesinger, 1991). To refine the framework, two coders—a member of the implementation team and I—independently coded transcripts from one session (Day 5: Building Models and Generating Hypotheses). After discussing and comparing the two separate analyses, we identified two areas of disagreement. First, according to the framework, segments in which the learner correctly identified an aspect of the characteristic of focus were coded as *Simplistic*; segments in which the learner correctly defined or described an aspect of the characteristic of focus was coded as *Developing*; and segments in which the learner correctly explained an aspect of the characteristic of focus was coded as *Complex*. We initially found it difficult to determine the difference between the *Simplistic* and *Developing* dimensions of complexity. Through discussion, we determined that if the facilitator defined and the learner identified an aspect, it was coded as *Simplistic*, and if the learner identified and defined or described an aspect, it was coded as *Developing*. To help elucidate the difference in these two codes, I have provided two examples. We coded Segment 1 as Characteristic 1 – *Components & Processes*; Dimension – *Simplistic*.

Segment 1

Facilitator: *So when [plants] give off water vapor into the atmosphere, what did we call that? Does anyone remember what we call that?*
Henry: *Transpiration*

We coded Segment 2 as Characteristic 1 – *Components & Processes*; Dimension – *Developing*.

Segment 2

Isabel: *[referring to runoff on their ecohydrologic model] That's water. That's [water on the ground]*
Fred: *oh, that's water?*
Isabel: *yeah, that's water that reaches the ocean*

A second area of disagreement focused on the issue of code co-occurrence. A number of segments included multiple characteristics—for example, in a discussion of the way that water moves through the ecological system (*Cycles of Matter & Energy*), learners identified the components and processes involved (*Components & Processes*). The following is an example of a segment that includes multiple characteristics:

Segment 3

1	Facilitator:	*Okay, so walk me through what can happen if it rains from this cloud* [points to drawing]
2	Sean:	*This cloud here?*
3	Ethan:	*So it rains*
4	Sean:	*So it rains*
5	Facilitator:	*So what happens to the water*
6	Ethan:	*and plants*
7	Noah:	*it runs off and then it goes into the hills where the plants are*
8	Sean:	*and then the plants suck it up into the roots*
9	Noah:	*and then they let it go*
10	Sean:	*and also[some] goes into the stream and some of it evaporates*
11	Noah:	*other goes underground*
12	Sean:	*and yeah and other goes to the ocean*
13	Ethan:	*one person talks at a time*
14	Facilitator:	*Do you want to add anything you think they missed, Ethan*
15	Ethan:	*Yeah the clouds get bigger from condensation*
16	Facilitator:	*which is from…*
17	Ethan:	*Evaporation*
18	Noah:	*Water vapor*
19	Sean:	*Water vapor*
20	Facilitator:	*Right, so you see how you go full circle. It rains*
21	Sean	*oh yeah and then it evaporates back*

Through discussion, we agreed that each segment would only receive one code and the highest characteristic represented in the segment would be the code used. Thus, the example was coded as *Cycles of Matter & Energy*. There was one exception to this, however, as we identified instances when learners recognized hidden dimensions of a system earlier than hypothesized. To address this issue, we agreed to assign multiple codes to a single segment only when hidden dimensions were identified as being part of a relationship, a framework, or a cycle (see line 8 of Segment 3). After we reached agreement on these issues, the other coder and I independently coded transcripts from an additional three days (Day 3, Day 7, and Day 11) until we reached a stable and reliable set of descriptors that seemed to span the eight characteristics and the three dimensions. At that point, I coded the remaining transcripts. During the coding, I also identified and extracted learner misconceptions for further analysis.

The third phase consisted of conducting code counts based on the transcript coding so that I could identify patterns of talk that emerged from the data. I created tables of the counts for all of the segments of talk that occurred across each day of program implementation, and then separately for the whole group and for each team to identify general patterns related to systems thinking as well as specific patterns related to design and implementation. To test the conceptual model as it related to dialogic knowledge building, I counted the total number of talk segments that occurred each day, and then I used these counts to identify the primary focus as well as level of complexity of all interactions that took place each day. To visualize the patterns, I created heat maps based on the relative number of talk segments related to each systems thinking characteristic that occurred on each day. I chose to use this method to gain a more holistic view of the way that the systems thinking evolved through collaborative engagement surrounding each task related to each research step. In other words, these characterizations served to highlight the extent to which the learners as a whole group as well as each team developed systems thinking as they worked and talked together. Moreover, the method allowed me to look at the effect of differences in implementation, which will be discussed in detail in the next chapter.

Results from the Ecohydrological Research

To provide context for the following sections (as well as for the findings in Chapter 5), I have provided details on our ecohydrological research. This text was adapted from the poster that the learners presented at the end of the Club. To create the poster, each team dictated text to the facilitators, who revised their dictation to fit into the final poster format.

Introduction

It is important to understand how water cycles in the oceans, in the atmosphere, and across the land surface because the water cycle is affected by the way that we manage the land surface (Wilcox et al., 2012). Evaporation and transpiration are both part of the water cycle. Together, they are called evapotranspiration (Villegas et al., 2010). More plants in an area might mean less evaporation, because plants can keep the soil cool. Plants can also block the wind. Alternatively, more plants in an area might mean more transpiration, because plants take water out of the soil (Wilcox et al., 2003; Huxman et al., 2005). Thus, it is important to find out how plants affect evapotranspiration, especially in areas where we want to conserve water.

Our study took place in Crystal Cove State Park, where we were studying where the water in Moro Canyon goes. Moro Canyon is an interesting site for this research because it is being restored by putting in native plants and taking out invasive species of plants. One way to understand if the restoration is working is to study water as it moves through the area. Thus, our question was: Does landscape type—Degraded, Under Restoration, and Restored—influence where the water in Moro Canyon goes?

We predicted that plants would transpire most in the Restored plot and the least in the Degraded plot, and we also predicted that it would be the opposite for soil moisture. Finally, we predicted that there would be the most soil moisture at the Restored plot and the least moisture at the Degraded plot.

Methods

To test our prediction, we gathered data on transpiration and soil moisture in one 1 meter x 1 meter plot from each landscape type every other day for two weeks. We also gathered data on air temperature, humidity, and wind speed and direction.

The Degraded plot was located up in a canyon. The soil was rocky, and plants covered 0% - 10% of the plot. The Under Restoration plot was located down canyon, just below the Degraded plot. The soil was rocky with some wood chips around the plants, and plants covered

10% - 20% of the plot. Finally, the Restored plot was located in a flat area. The soil was dry and rocky, and plants covered 90% - 100% of the plot.

Results

We expected to find the highest transpiration and little soil moisture in the Restored plot, and that is what we found (see Figure 4.3). We expected some transpiration and little water in the soil in the Under Restoration plot. Instead, we found a higher level of soil moisture and higher rate of transpiration than we expected. In fact, the Under Restoration plot had the highest amount of soil moisture, and the transpiration rate was almost the same as the restored site. This was the case even with less plant coverage. Finally, we expected the lowest transpiration rate and the least soil moisture in the Degraded plot. However, we found that soil moisture was higher than we expected. In fact, it was higher than soil moisture in the Restored site. However, the transpiration rate was the lowest of the three plots, which was what we expected. We also found that the Restored and Under Restoration plots had almost the same values for transpiration even though the Under Restoration plot had 10% - 20% plant coverage and the Restored plot had 90% - 100% plant coverage.

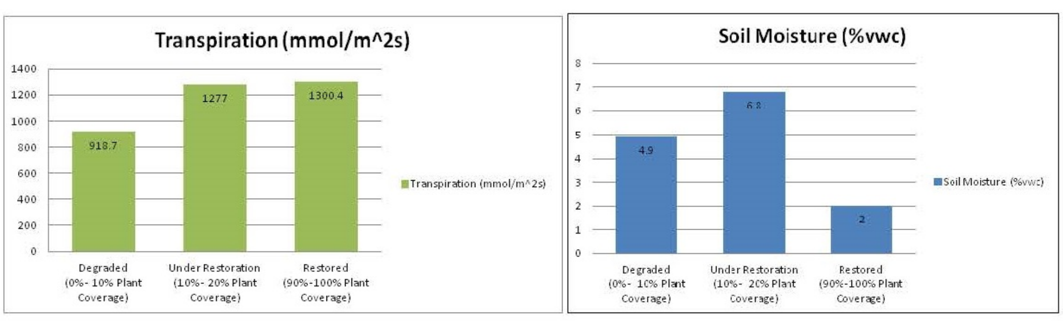


Figure 4.3 Transpiration and Soil Moisture Graphs

Discussion and Future Work

With respect to transpiration, we thought that the Restored plot had the highest rate of transpiration because there were more plants, and that there was less transpiration in the

Degraded plot because there were fewer plants. There was more transpiration in the Under Restoration plot than we expected. This is possibly because it was located in a canyon, which meant that there was more water in the plot, which led to a higher transpiration rate. With respect to soil moisture, we thought that the Restored plot had the lowest amount of soil moisture because there were more plants to take up the water. The Under Restoration and Degraded plots had higher soil moisture than we expected. We were not sure why, but we thought that we needed to study this more.

Thus, we thought that landscape type (Degraded, Under Restoration, or Restored) might affect where the water goes in Moro Canyon, but we did not have enough information to be sure. We also thought that the number of plants in an area affects where the water goes since plants increase transpiration. We also thought that one reason that we got results different from what we expected was related to the location of our plots (valley vs. flat area). Some areas might have been wetter or dryer than they looked (soil type affects how we can measure soil moisture, i.e., the hard soil in the restored plot made it difficult to measure soil moisture).

Our research led us to ask new questions related to where the water in Moro Canyon goes, including:

- How does weather effect transpiration and soil moisture in the three different plots?
- Do different plant species use different amounts of water?
- Do trees and plants have different transpiration rates?
- Why does it look so dry when there is water in Moro Canyon?
- Do animals affect where the water goes in Moro Canyon?

Results from the Systems Thinking Research

For the sake of clarity, I have organized the large amount of data by addressing each question related to learner development of systems thinking, first reviewing initial systems thinking abilities as measured by the pre-tests, then reviewing learners' systems thinking abilities following the learning process as measured by the post-tests, and finally reviewing learners' development of systems thinking as it occurred over the learning process as indicated by the coded transcripts. In each section, I will review learner outcomes related to each systems thinking characteristic, first discussing the outcomes of the group as a whole and then discussing the outcomes of each team.

Learners' Initial Systems Thinking Abilities

The analysis of the pre-tests indicated that, prior to participating in the Club, the learners possessed an incomplete and fragmented understanding of the ecohydrological system and held several common naïve conceptions related to the way the system operates. The word association and the drawing research tools were used to measure learner's ability to identify components and processes of the ecohydrological system. The pre-test word association analysis revealed that of all of the ideas presented across all of the participants, 75% were classified as components and 25% were classified as processes. Further analysis revealed that all of the components included in the word association pre-tests could be collapsed into four main categories: hydrosphere, atmosphere, biosphere, and geosphere. Of the components listed on the pre-test, the slight majority were either hydrosphere (e.g., *ocean*, *river*, or *lake*) or atmosphere components (e.g., *sun*, *cloud*, and *rain*), comprising 35% and 27% respectively. Of the processes, the most commonly listed were evaporation, precipitation, and use by humans. Thus, the components and processes that the learners listed were those that are the most familiar to most children, suggesting that the learners did have a basic knowledge of the commonly known components and processes associated with the water cycle. Interestingly, only three of the eight learners listed *plant* as a component and none of the learners listed *transpiration* as a process. To see if there were initial differences between the two teams, I analyzed the word associations by team and found similar patterns in both sets of pre-tests, suggesting that both teams had similar knowledge of components and processes prior to the beginning of the program.

The analysis of the learners' pre-test drawings for components and processes revealed a similar pattern. The majority of the ideas depicted were components (73% of all elements), and the majority of these components were classified as either atmosphere components (33%) or hydrosphere components (28%). Again, these components are those that are most familiar to children. Eric's drawing (Figure 4.4) provides an illustration of how children commonly depict the water cycle using atmosphere (i.e., *cloud*, *rain*, and *fog*) and hydrosphere components (i.e., *ocean*, *river*, *spring*, and *puddle*). Interestingly, Eric's drawing does not include the sun.

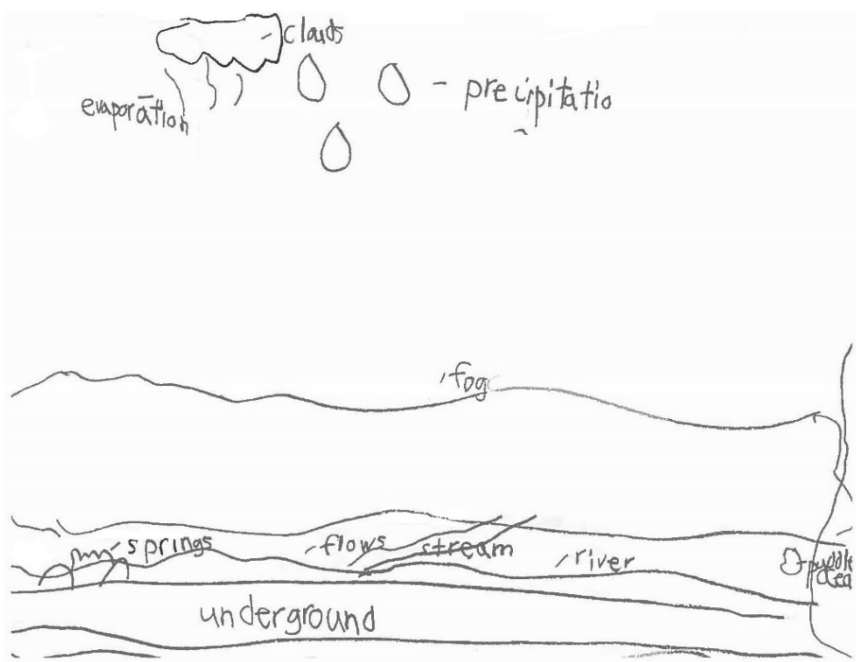


Figure 4.4 Eric's pre-test drawing, including mainly atmosphere and hydrosphere components, reflecting a simplistic perception of the ecohydrologic system

The drawings also indicated that learners held naïve conceptions of the system components and processes, drawing infiltration as a sewage plant, groundwater as an underground lake, and underground flow as an underground river. The following question (Segment 4) from the first day of the Club illustrates the depth of the last two misconceptions listed:

Segment 4:

1	Facilitator:	*Nancy, what did you want to add?*
2	Nancy:	*I had a question about, if the water, if it does go through the soil and goes down, if it goes too deep, like the center, not the center, but like sort of around the center of the Earth, it's really hot, so if it went too deep, wouldn't it evaporate then when it hits something [cold]it would turn back into water and keep evaporating, so it just keeps going like this?*

(As a note, Nancy's idea that groundwater could be found close to the center of the Earth stayed with her throughout the program, appearing in transcripts from Day 1, Day 3, Day 5, and finally, Day 12. Interestingly, Nancy's post-test drawing indicated a shift in her thinking as she correctly represented both groundwater and underground flow (see Figure 4.13).) The drawings also suggested that the learners related the components and processes most closely to the human aspects of the system. For example, Isabel depicted *evaporation* as a process that occurs from a container—even having drawn a plant in soil next to the container (see Figure 4.5), a common example given to students who are studying the water cycle. Finally, similar to the word association responses, none of the learners depicted *transpiration* on the pre-test drawing (although five of the seven learners drew a plant, which was listed among the words given to learners as part of the pre-test). Table 4.4 includes a list of the components and Table 4.5 includes a list of the processes that learners depicted in their drawings.

Figure 4.5 Section of Isabel's pre-test drawing showing her naïve conception of evaporation

The drawings were also used to measure learners' ability to identify dynamic relationships among system components and to organize these relationships in a coherent framework. Analysis of the drawings related to dynamic relationships suggested that learners had a very simplistic view of the ecohydrological system prior to beginning the program. Although all of the learners correctly depicted at least one dynamic relationship on their drawings, these relationships were limited to evaporation and precipitation. There were no illustrations of relationships involving *transpiration*, *water uptake by plants, runoff, percolation,* or *underground flow* (see Table 4.6 for Dynamic Relationships appearing in learners' drawings). Moreover, three of the learner's drawings did not represent an organized framework of relationships at all, with only one drawing representing more than two of the ecohydrologic relationships. In general, the drawings depicted a fragmented view of the system, with components and processes separate and distinct from each other, reflecting a gap between learners' knowledge of the system components and their ability to incorporate them correctly within a coherent framework of the system. Isabel's drawing (Figure 4.6) provides an example of this fragmented view. As with the word association analysis, the drawing analysis revealed similar patterns for both teams, again indicating that they possessed similar background knowledge prior to beginning the program.

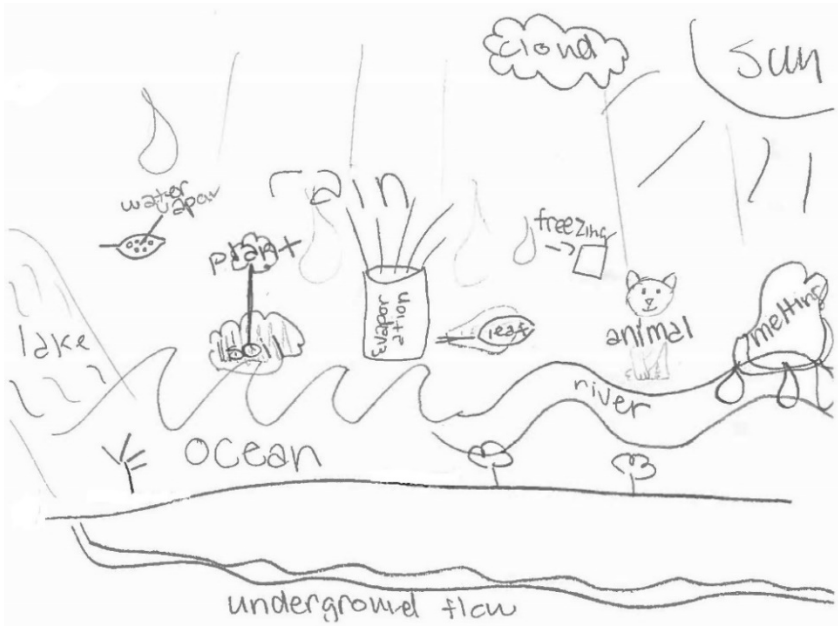


Figure 4.6 Isabel's pre-test drawing illustrating her fragmented view of the ecohydrological system

The drawings and the Cyclic Thinking Questionnaire were used to measure learners' knowledge of cycles within the system. Understanding the ecohydrologic system includes understanding the idea that we live in a cycling world that is built upon a series of subsystems (atmosphere, hydrosphere, biosphere, and geosphere) that interact through an exchange of energy and matter. The drawing analysis revealed that learners lacked an understanding of these subsystems as they connect to each other through system components and processes and the cycling of energy and matter. Five of the seven pre-test drawings did not include any cycles, and only one learner could connect the land cycle to the ocean cycle via river flow. Nancy's drawing illustrates a simplistic perception of the way that matter and energy cycle through the system, depicting only the sun's role in evaporation from the soil (Figure 4.7).

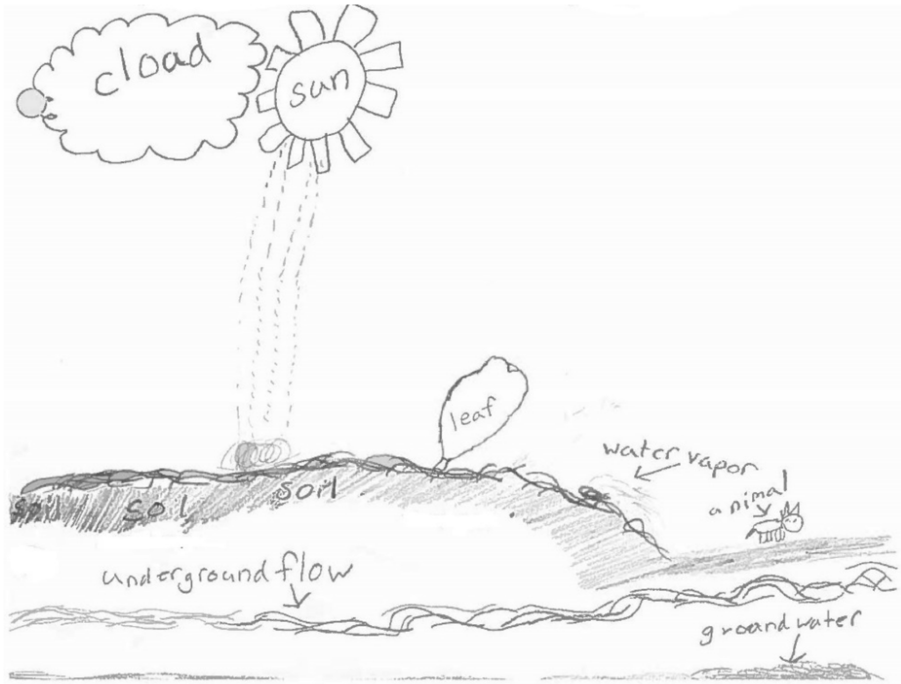


Figure 4.7 Nancy's pre-test drawing, reflecting a lack of knowledge that water cycles through the ecohydrological system

The Cyclic Thinking Questionnaire revealed a similar pattern. Although all the learners indicated that they understood that cycles have no starting or ending point, an analysis of their reasoning reveals either scientifically incorrect ("I disagree because it [water] is originally made from H_2O") or intuitive reasoning ("The water cycle never ends. It keeps going on and on") rather than cycle-based reasoning. When asked if they agreed with the statement that the amount of water in the ocean grows each day because rivers are continually flowing into the ocean, five of the eight learners chose the incorrect answer, again supporting their choices with scientifically incorrect or intuitive reasoning, including "I agree because there is constantly rain," "Rivers don't just stop somewhere. Rivers have to flow into something, so the river flows into the ocean," and "Because it's true." Although the pattern of correct and incorrect answers is similar for both teams, the Yellow team did exhibit a higher level of reasoning in the pre-test, providing fewer intuitive and more process-based explanations. Two of the four learners on the Yellow team were in the 5th grade and may have had more experience with this type of pencil-and-paper test.

Finally, both the drawings and the Ecology System Inventory were analyzed to measure learners' pre-knowledge of hidden dimensions of the ecohydrological system. Both measures indicated a similar pattern of ability across all learners. Learners did depict hidden dimensions in their drawings and did add hidden processes to their Ecology System Inventory. In fact, all of the learners added water vapor in the atmosphere and underground water flow to both their drawings and Ecology System Inventories, which were both discussed during the Club. However, since both of these processes were listed in the word bank associated with the drawing measure, it makes sense that learners added them to their drawings. More telling than the appearance of underground flow, for example, is its incorrect depiction. Thus, the drawings served to elicit learners' naïve conceptions of this hidden dimension. Eric, Isabel, and Nancy's pre-test drawings (Figures 4.3, 4.5, and 4.6) depicted the understanding of underground flow as an underground river that was held by all seven learners. Similarly, although all seven leaners added evaporation/water vapor in the atmosphere to their drawings, only one added it to his Ecology System Inventory, even with the sun drawn directly above a puddle of water in the picture they were given. This suggested that the learners may have held a very general view of evaporation, perhaps considering it a process that occurs only with select bodies of water, including the ocean, lakes, and streams (or cans). Finally, none of the learners included transpiration as part of her or his drawing or Ecology System Inventory. As with the other analyses, a comparison of the two learner teams suggests a similar level of knowledge about the hidden dimensions of the ecohydrological system.

In summarizing the pre-test findings, the learners' initial systems thinking abilities can be characterized by a general level of understanding of system components and processes and a fragmented and partial perception of the ways in which these components and processes interact over space and time, which is similar to findings from Ben-Zvi Assaraf and Orion's (2010) work with elementary school students. Further, none of the learners exhibited an understanding of the role that plants and transpiration play in the ecohydrological system. With the exception of two learners, their reasoning about the system as measured by the Cyclic Thinking Questionnaire was based on intuition rather than on an understanding of the ways that system components and processes are dynamically related and that cycles of matter and energy connect across different scales.

Learners' Systems Thinking Abilities Following the Learning Process

The distribution of the post-test word association ideas revealed some interesting differences from the pre-test results. Five of the eight leaners listed fewer components on their post-tests, and while a different set of five listed more processes. Across the whole group, the total number of components listed by all learners decreased from 54 to 51 (6% decrease), while the total number of processes increased from 18 to 26 (44% increase). With respect to the components, the biggest decrease was in the words classified as biosphere components (from 15 to 10 overall). The elements that were included on the pre-test but not on the post-test were those related to the human aspect of the system (e.g., *house* and *sewer*). This was likely an effect of our research topic, which focused primarily on where water in nature goes. However, our environmental research was related to restoration—an inherently human activity. In the review of the transcripts, which I will discuss in depth in the next section, the learners did consider the human aspect of the system when they discussed the effects of the restoration on where the water goes in Moro Canyon and the decisions land managers make regarding restoration. With respect to processes, none of the learners listed transpiration on the pre-test, but six of the eight learners included in on the post-test. In addition, only one participant listed runoff on the pre-test, but five included it on the post-test. Interestingly, none of the learners listed any form of *use by plants* on their post-test, but it may be that they considered transpiration as *use by plants* and did not want to duplicate their answers.

A comparison of the Green team and the Yellow team word associations revealed that the Yellow team demonstrated greater changes in their knowledge of components and processes, increasing the number of processes listed by 100% as compared to the Green team's decrease by 11%; however, the difference between overall pre- to post-test scores could be attributed to one learner's scores. Nancy, a member of the Yellow team, included 15 rather than 12 responses on her post-test, and each response contained multiple elements. In contrast, neither Tim nor Sean, both members of the Green Team, completed the word association, each leaving lines blank. This may have been due to their lack of interest in completing the post-tests, which was evident in the unrelated drawings on both post-tests and will be discussed later in this chapter.

The drawing analysis revealed a difference in the number of both components and processes, with a 16% increase in the total number of components (from 69 to 81) and a 65% increase in the total number of processes depicted (from 26 to 43) across all learners (see Table 4.4). Individually, four of the seven learners had an increase in the number of components depicted in their drawings, and six of the seven had an increase of processes. Notably, the drawings indicated a change in learners' perception of plants and transpiration as important elements of the ecohydrological system. All seven of the post-test drawings included plants and leaves, with one depicting roots taking up water from the soil. The same drawing also showed the infiltration of water into the soil. With respect to processes, six of the seven learners included transpiration on their post-tests, which was not depicted on any of the pre-tests. However, several interesting misconceptions related to transpiration appeared in the post-test drawings. Fred, a member of the Yellow team, depicted transpiration as liquid water coming up through the plant's stem (Figure 4.8), while Sean, a member of the Green team, drew transpiration as liquid water falling out of the leaf (Figure 4.9).

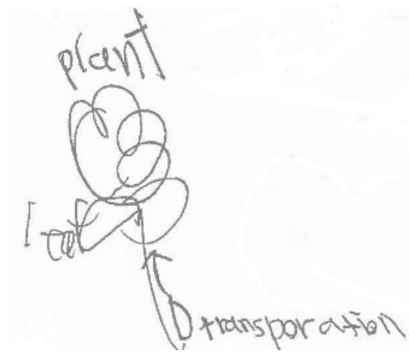


Figure 4.8 Fred's depiction of transpiration in his post-test drawing

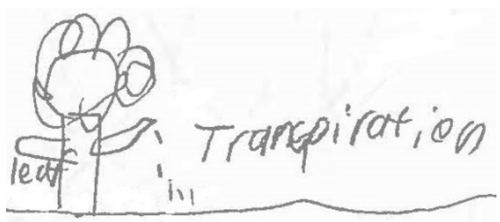


Figure 4.9 Sean's depiction of transpiration in his post-test drawing

Although the drawing analysis revealed an increase in the number of processes depicted across all learners, the Yellow team exhibited a greater increase (86%) than the Green team (42%). Moreover, the Yellow team also increased in the number of components depicted (48%), whereas the number of components present in the Green team's post-test drawings decreased. Thus, it is clear that, similar to the results from the pre-/post-test word association analysis, the changes in the drawings were driven by the Yellow team's scores, specifically Eric, Nancy, and Isabel's scores (see Tables 4.4 and 4.5)

Table 4.4

Pre/Post Comparison of System Components Appearing in Learners' Drawings

Team	Yellow (N = 4)				Green (N = 3)			
	Pre (#)	Post (#)	Change (#)	Change (%)	Pre (#)	Post (#)	Change (#)	Change (%)
A. Components								
Hydrosphere								
1. Ocean	3	4	1		3	3	0	
2. River/Stream	3	4	1		3	3	0	
3. Lake/pond/spring	3	4	1		3	2	-1	
4. Puddle	0	0	0		1	0	-1	
Total Hydrosphere	**9**	**12**	**3**		**10**	**8**	**-2**	
Atmosphere								
5. Sun	3	4	1		3	3	0	
6. Cloud	4	4	0		3	3	0	
7. Rain	2	4	2		3	3	0	
8. Water vapor	2	4	2		2	2	0	
9. Fog	0	0	0		1	0	-1	
Total Atmosphere	**11**	**16**	**5**		**12**	**11**	**-1**	
Biosphere								
10. Plant	2	4	2		3	3	0	
11. Roots	0	1	1		0	0	0	
12. Leaf	3	4	1		3	3	0	
13. Animal	3	4	1		3	3	0	
Total Biosphere	**8**	**13**	**5**		**9**	**9**	**0**	
Geosphere								
14. Soil	3	4	1		3	3	0	
15. Groundwater/aquifer	2	4	2		2	1	-1	
Total Geosphere	**5**	**8**	**3**		**5**	**4**	**-1**	
Total Components	**33**	**49**	**16**	**48**	**36**	**32**	**-4**	**-11**

Table 4.5

Pre/Post Comparison of System Processes Appearing in Learners' Drawings

B. Processes								
1. Evaporation	4	4	0		3	3	0	
2. Transpiration	0	3	3		0	3	3	
3. Precipitation	2	4	2		1	3	2	
4. Condensation	0	2	2		0	2	2	
5. Percolation	0	0	0		0	0	0	
6. Infiltration	0	1	1		0	0	0	
7. Underground flow	4	3	-1		3	2	-1	
8. Melting	2	3	1		1	1	0	
9. Freezing	1	3	2		1	0	-1	
10. Surface flow/runoff	1	3	2		3	3	0	
Total Processes	**14**	**26**	**12**	**86**	**12**	**17**	**5**	**42**

The analysis of the drawings also highlighted changes between the pre- and the post-tests with respect to dynamic relationships. Prior to participating in the Club, learners identified eight distinct dynamic relationships within the ecohydrologic system. However, in the post-test, they identified 13 distinct dynamic relationships (Table 4.6). This pattern was similar across both teams, with the Yellow team identifying six relationships on their pre-tests and 12 relationships on their post-tests, and the Green team identifying seven relationships on their pre-tests and 11 on their post-tests. The most important change from pre- to post-test is the inclusion of transpiration in dynamic relationships, with all seven learners depicting plants transpiring water to the atmosphere, and two depicting roots taking up water from the soil. Thus, all of the learners improved their understanding of the role that plants play in the ecohydrological system. However, as was previously mentioned, the drawings did reveal misconceptions regarding the process of transpiration. Also notable was the increase in the number of learners who drew evaporation of water from soil to the atmosphere (an increase from two to five learners). It is apparent from the increase in transpiration from plants and evaporation from soil that the learners made connections between the activities in which they engaged and the dynamic relationships among system components.

Table 4.6
Pre/Post Comparison of the Number of Learners who included Dynamic Relationships in their Drawings (N=7)

	Pre	Post	Change
1. Sun causes water to evaporate	5	4	-1
2. Evaporated water forms clouds	2	4	2
3. Cloud formation and precipitation	6	6	0
4. Rain runs off into rivers/oceans	0	3	3
5. Rivers flow into oceans/lakes	3	4	1
6. Water evaporates from freshwater	3	5	2
7. Water evaporates from the ocean	2	3	1
8. Water evaporates from the soil	2	5	3
9. Water infiltrates into the soil	2	3	1
10. Roots take up water from the soil	0	2	2
11. Leaves transpire water to the atmosphere	0	7	7
12. Water percolates into deep storage	0	3	3
13. Underground flow comes from groundwater	0	1	1

The drawings were also used to measure learners' ability to organize relationships into a framework that correctly represented the dynamic relationships between different components. A comparison of the pre-test to the post-test drawings indicated that overall, five of the seven learners did increase their ability to organize components, processes, and their relationships in a coherent way. Neither Isabel nor Nancy's initial drawings represented an organized framework, but their final drawings indicated a more complex understanding of the system as both learners represented and connected multiple relationships. A comparison of Isabel's pre- and post-test drawings illustrates this change (Figure 4.10 and Figure 4.11). She did not include any connections in her pre-test drawing, but in her post-test drawing, she incorporated and connected *evaporation*, *transpiration*, *precipitation*, *surface flow*, and *underground flow* and their related components in a coherent way; however, she did not correctly incorporate *freezing* or *melting* within the framework (although both processes were correctly depicted). This is interesting in that we did not explicitly investigate either of these processes during the Club; thus, they served as somewhat of a control for this particular analysis.

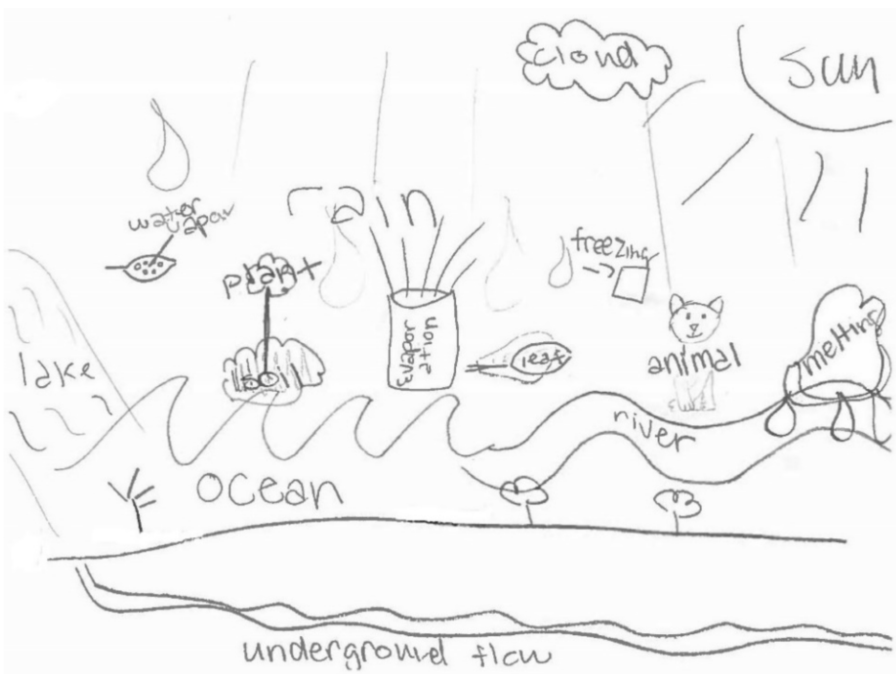


Figure 4.10 Isabel's pre-test drawing illustrating her fragmented view of the ecohydrological system

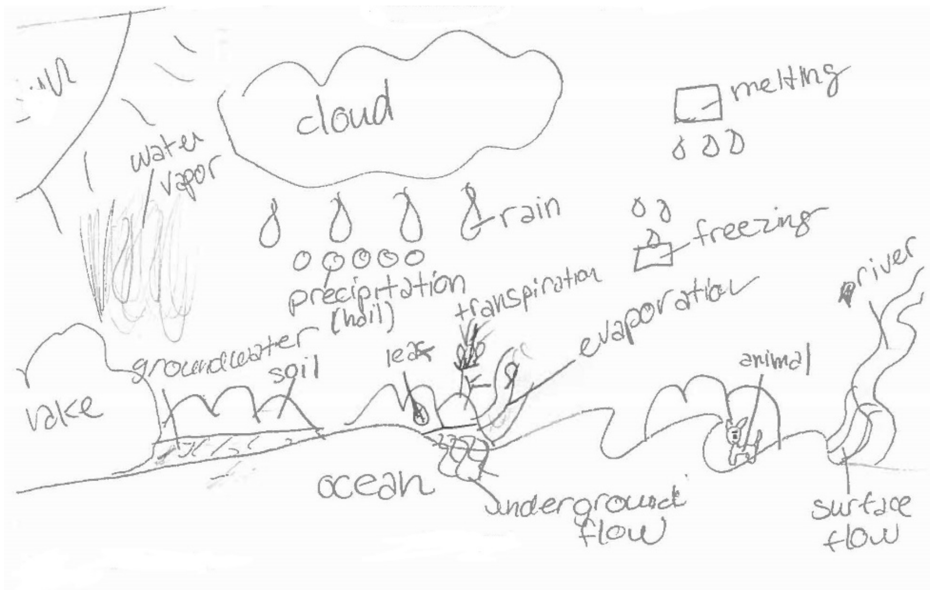


Figure 4.11 Isabel's post-test drawing, demonstrating a more complex framework of dynamic relationships

Two learners, Fred and Noah, did not increase in their ability to organize their understandings into a coherent framework. Neither of Fred's drawings represented an organized framework. In fact, his post-test was remarkably similar to his pre-test, showing relationships as isolated and distinct from each other. Similarly, Noah's score went down from *Developin*g on his pre-test drawing to *Simplistic* on his post-test. These scores may be more of a reflection of their disinterest in taking the post-test than in their knowledge of the ecohydrological system, which I will address later.

With respect to cycles of matter and energy, the drawing analysis indicated that six of the seven learners experienced a shift from a fragmented perception of the system that did not include cycling between subsystems to a more holistic view of the system that included some level of connection between atmosphere, hydrosphere, biosphere, and geosphere subsystems. In fact, four of the learners drew pictures that represented and connected all four subsystems, demonstrating an increased understanding of the cycles that constitute the ecohydrologic system. Nancy's drawing (Figure 4.12) is a particularly complex example of the ways in which all four subsystems interact, especially when compared to her pre-test drawing (Figure 4.13).

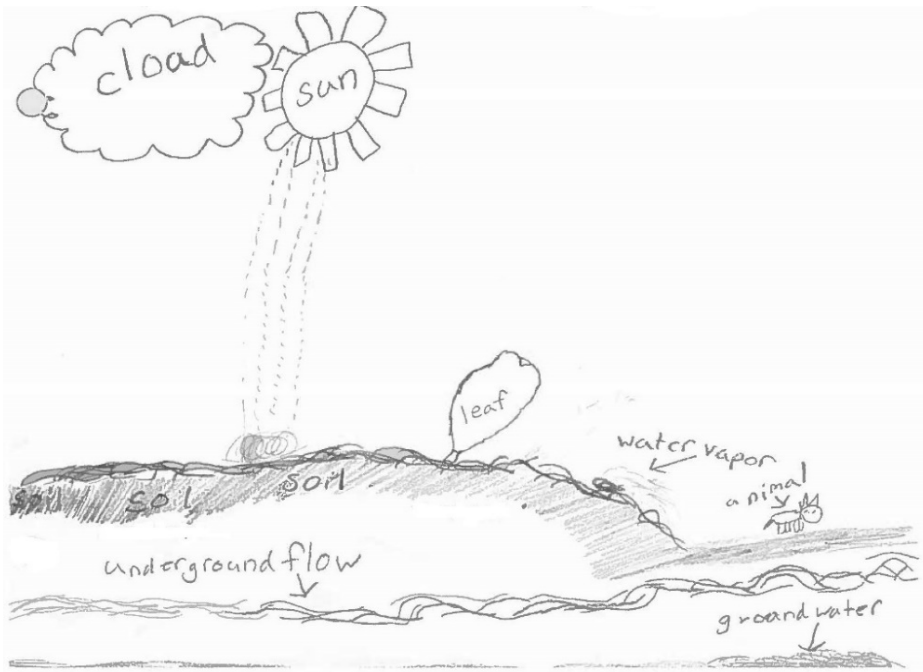


Figure 4.12 Nancy's pre-test drawing, reflecting a lack of knowledge that water cycles through the ecohydrological system

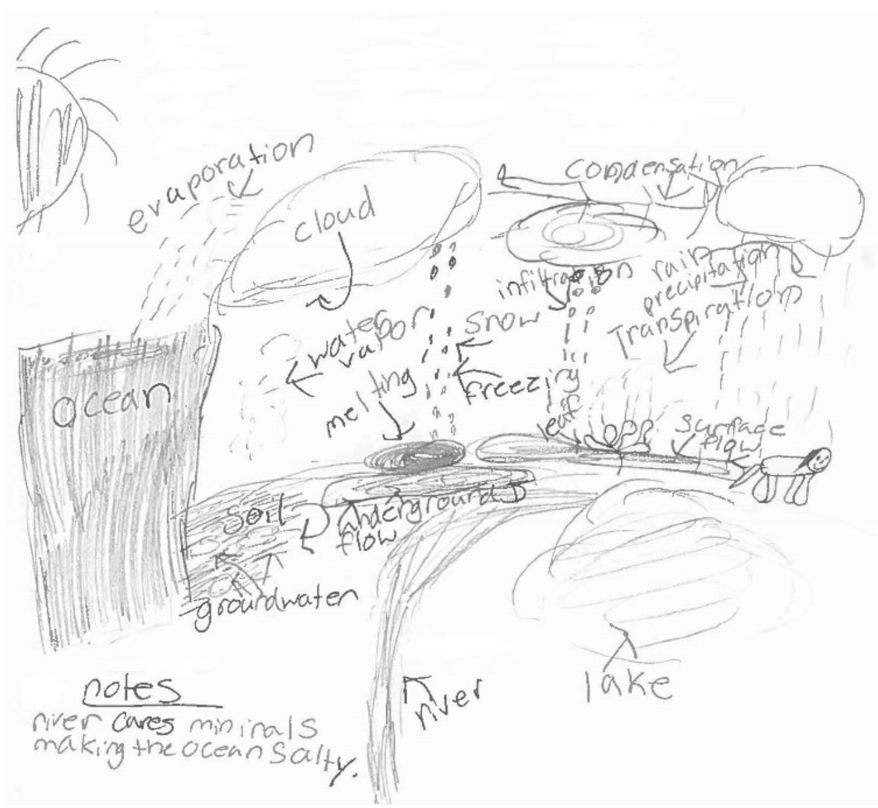


Figure 4.13 Nancy's post-test drawing indicating a more cyclic perception of the ecohydrologic system

When comparing the Yellow team to the Green team, a similar pattern emerged. In their initial drawings, only one member of the Green team and one member of the Yellow team included any cycles. By the post-test, all of the Green team members and all but one of the Yellow team members depicted some level of cycling.

The Cyclic Thinking Questionnaire revealed a different pattern. Although there was a general shift from scientifically incorrect toward cycle-based reasoning, the majority of the learners' post-test explanations were based on either intuition or processes rather than on an understanding of cycles. For example, although all of the learners indicated they understood that cycles do not have a starting or ending point, the analysis of the post-test reasoning indicated that their ability to reason cyclically decreased from pre- to post-test (see Table 4.7). None of the explanations given across all of the learners were cyclic in nature. Moreover, the majority of the explanations were intuitively-based, including "I think that there is not a starting point or an ending point in the water cycle, so I will disagree with that answer" and "It's a cycle, it goes on." Interestingly, when asked if they agreed with the statement that plants take up water through their roots and release water through their leaves, five of the eight learners answered correctly (an increase from four on the pre-test), but their reasoning was predominantly process-based, writing, for example, that "leaves transpire water vapor when they open their little holes [stomata]." Only one learner provided a cycle-based answer, writing "when water goes through the soil, the plants take it in, then they let it out through transpiration through their leaves."

Table 4.7
All learners' perceptions of cycles as show in the questionnaire (N=8)

Number of Correct Answers Circled						
		Pre			Post	
Item	Incorrect	Uncertain	Correct	Incorrect	Uncertain	Correct
1			8			8
2	5	1	2	3	2	3
3	2	2	4	1	2	5
4		2	6		1	7

Level of Reasoning										
			Pre					Post		
Item	NC	NE	IN	PB	CB	NC	NE	IN	PB	CB
1	2		3	1	2	3		5		
2	6		1	1		4		1	2	1
3	2	2		3	1	2		1	4	1
4			1	7				2	5	1

NC = Not Correct; NE = No Explanation; IN = Intuitive Answer; PB = Process-based Answer; CB = Cycle-based Answer

The analysis of the questionnaires by teams revealed that both teams exhibited a shift in thinking from scientifically incorrect to scientifically correct reasoning. However, the Yellow team's reasoning was in general more process (38% of total explanations) and cycle based (19% of total explanations), while the Green team's reasoning was more intuitive (25% of total explanations) and process-based (38% of total explanations).

This learners' performance on the Cyclic Thinking Questionnaire may have been related to several factors that were unconnected to their knowledge and understanding of cycles. First, the questionnaire, more than any of the measures, more closely resembled a school-based test, which means that there may have been a perceived mismatch between the structure of the learning and the structure of the test. Second, this was the last post-test administered, and the learners were noticeably suffering from test taking fatigue. The effects of both of these factors can be seen on both the pre-test and the post-test as a majority of the learners wrote short, incomplete answers on both tests. Third, the post-tests were administered on the last day of the program, and a number of the learners indicated, verbally and through the unrelated pictures they drew on the forms, that they were not interested in taking the test.

Finally, both the drawings and the Ecology System Inventories were used to measure learner ability to identify hidden dimensions of the system. A comparison of the pre- to the post-test drawings suggested that learners increased in their understanding of plants and transpiration as important elements in the ecohydrological system. Overall, six of the seven learners depicted transpiration from plant leaves on their post-test drawings, and two of the seven included plant roots taking up water from the soil. None of the learners included transpiration or water uptake on her or his pre-test drawings. With respect to underground flow, seven of seven learners drew this process on their post-test drawings. Of these seven, three drawings had correct depictions, which is an improvement from the seven learners who drew incorrect depictions of underground flow on their pre-test drawings.

Analysis of the Ecology System Inventory revealed that six of the seven learners added hidden components to their post-test inventories, which is an increase from the two who added hidden components to their pre-test inventories. Of these six, three added plant transpiration and water uptake by plans as hidden dimensions to their post-test inventories. Notably, all three of these learners were members of the Yellow team. The fourth member of the Yellow team did not add any components to his post-test, receiving a score of 0. Finally, five of the six learners who added hidden dimensions included evaporation on their post-test inventories, an increase from the one learner who included it on his pre-test. This change suggested that the learners were able to transfer their more general understanding of evaporation to a specific setting more reflective of the ecohydrological system. Figure 4.14 presents Nancy's pre-test inventory in which she added to already existing components (e.g., a *tree*).

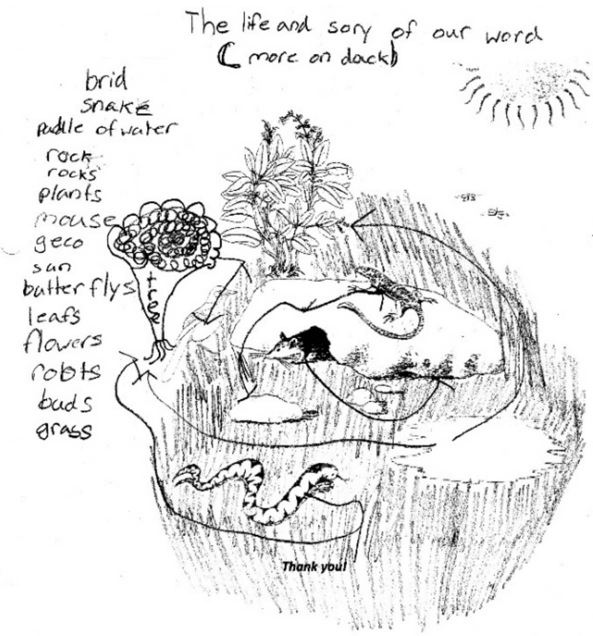


Figure 4.14 Nancy's pre-test Ecology System Inventory

Figure 4.15 presents Nancy’s post-test inventory in which she added hidden dimensions (e.g., *evaporation*, *transpiration*, *runoff*, *roots*, *water in the soil*, and *groundwater*).

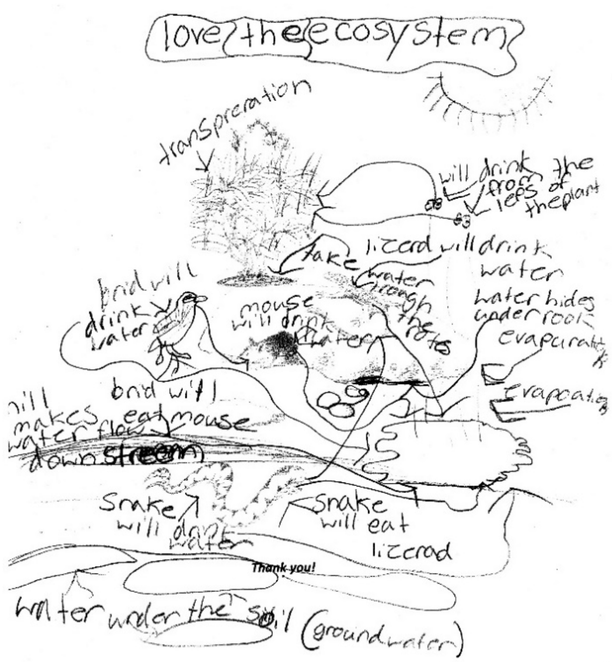


Figure 4.15 Nancy's post-test Ecology System Inventory

It is important to note that we administered the post-tests on the last day of the program, which appeared to have an impact on learner outcomes. Since the learners had already presented the results of their research to the broader community, they felt that "their work was done" and that the Club was over. Because of this, four of the learners—Ethan, Fred, Sean, and Noah—expressed disinterest with and frustration in completing their post-tests, finishing them in substantially less time than was given and with little attention to detail. This lack of interest may have led to the systematic under-measurement of the understandings and abilities of these four learners.

Learners' Systems Thinking Development over the Course of Program Participation

The comparison of the pre-tests to the post-tests did yield important information on differences in learners' systems thinking abilities after participating in the Club; however, individual assessments can often result in the systematic under-measurement of learning because they do not allow participants to draw on the human and material resources available in their environment (Schwartz, Bransford, & Sears, 2005). Moreover, results from pre- and post-tests cannot account for learning as it progresses though participation in activity and collaboration with others over time. Thus, analysis of the video was essential to understand if and how the learners' systems thinking developed through ongoing social interaction. In this section, I will discuss the overall pattern of talk as it emerged by each day and by citizen science step. I will also compare the analyses of the transcripts of the two research team's interactions to identify any differences that emerged between teams as well as compare the pre- and post-test analyses to the transcript analysis to triangulate results across different data collection methods and measures.

The conceptual model that supported this research was constructed through the mapping of the eight systems thinking characteristics to the six steps of citizen science (see Figure 4.1). This mapping suggests that systems thinking develops hierarchically through engagement with the steps of citizen science. Each step allows learners to engage with a cluster of characteristics, which then serves as a foundation for engaging with the next cluster of characteristics. Accordingly, each programmatic step was designed to afford learners with opportunities to engage collaboratively in particular tasks that supported specific science-related processes and systems thinking abilities. For example, during the first five days of the Club, learners developed an understanding of components, processes, and relationships that would become the foundation for understanding cycles of energy and matter, which, in turn, would become the foundation for making and testing hypotheses based on their understanding of complex systems. Thus, when analyzing the transcripts, I expected to find increasingly complex systems thinking talk as learners moved from one citizen science step to the next. I also expected to find a similar pattern with respect to complexity of talk as learners could first identify, then define and describe and finally explain in context elements of each systems thinking characteristic.

For the purposes of analysis, I sorted the transcripts in to whole group, Green team, and Yellow team transcripts. I analyzed each set separately and then added all the segments together. A holistic review of the transcripts suggest that that this was generally the case as the overall pattern of talk shifted toward higher levels of systems thinking. The heat maps below reveal this pattern as they show the distribution of segments across each day. Figure 4.16 presents a map of all systems thinking segments by day (the Green team, and Yellow team, and Whole group segments combined), Figures 4.17 and 4.18 respectively present the Green and Yellow team's systems thinking segments, and Figure 4.19 presents the Whole group segments. The red and orange colors indicate more instances of systems thinking talk, the pale green and dark green colors indicate fewer instances, and the dashed lines represent what I expected to see as each thinking characteristic was introduced to and considered by the learners. Table 4.8 provides a list of the systems thinking characteristics. With regard to the maps of each team, it is important to note that both teams, with the exception of Days 5 and 12, had roughly the same number of talk segments (see Appendix G for the data tables from which the heat maps were constructed). Due to a technology error, there was no video for the Green team for Day 3. The difference in the number of segments on Day 12 is likely an artifact of the different tasks assigned to the teams, which I will address later.

Reviewed together, these maps reveal the number of interactions relative to the type of work—either whole group or research team. The heat maps suggest that as learners collaboratively engaged in tasks related to citizen science, they did engage in interactions related to complex systems; however, there were several unexpected findings with regard to systems thinking as it emerged over each citizen science step. The heat maps also suggest that, to some extent, learners did engage in increasingly complex talk as they engaged with each characteristic. In general, there appeared to be more talk at a lower level as learners developed the ability to identify aspects of each characteristic (*Simplistic*), but they became increasingly able to describe (*Developing*) and to explain (*Complex*) ecohydrologic system phenomena in context. An example of this pattern of talk is apparent on Day 5 related to Characteristic 1. Interestingly, this pattern is not consistent across all characteristics, and a review of the transcripts for the scaffolds and supports offered during implementation may shed light on this phenomenon. In the following section, I will discuss systems thinking talk as it occurred during each citizen science step.

Table 4.8

Eight Emerging Characteristics of Systems Thinking (Ben-Zvi Assaraf & Orion, 2010)

1. The ability to identify, describe, and explain observable components and common processes of the ecohydrological cycle
2. The ability to identify, describe, and explain the static relationships between or among systems components
3. The ability, to identify, describe, and explain the dynamic relationships within the system
4. The ability to organize system components, processes, and their interactions within a framework of system relationships
5. The ability to identify cycles of matter and energy within the system
6. The ability to identify, describe, and explain hidden dimensions of the system
7. The ability to generalize—to make hypotheses, propose explanations, and solve problems based on an understanding of systems' mechanisms
8. The ability to think temporally: retrospection and prediction

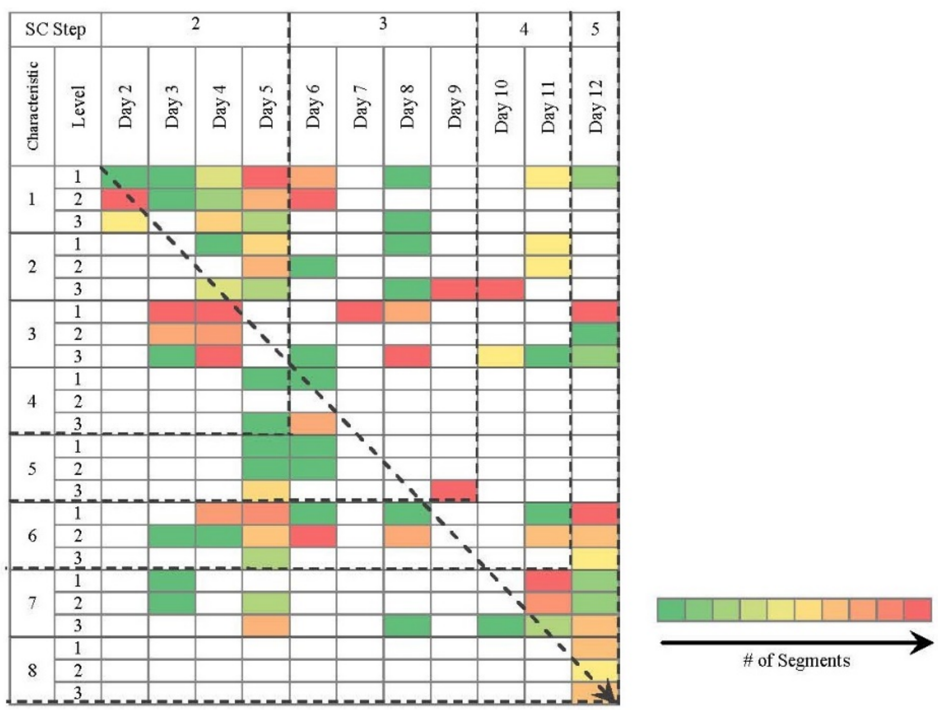


Figure 4.16 Heat map of the all systems thinking talk segments (Whole group, Green team, and Yellow team) across all days. Each column represents a day, and each row represents a systems thinking characteristic (1 – 8) across three levels of complexity (1 = *Simplistic*, 2 = *Developing*, 3 = *Complex*).

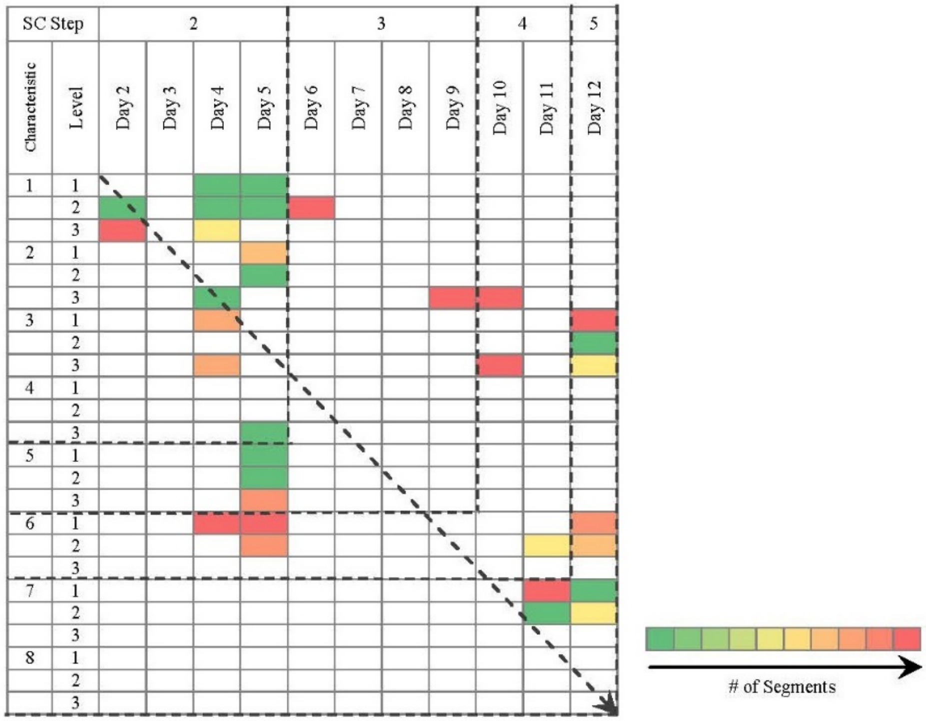


Figure 4.17 Heat map of the number of the Green team's systems thinking talk segments across all days. Each column represents a day, and each row represents a systems thinking characteristic (1 – 8) across three levels of complexity (1 = *Simplistic*, 2 = *Developing*, 3 = *Complex*). Note – there is no video data for the Green team on Day 3.

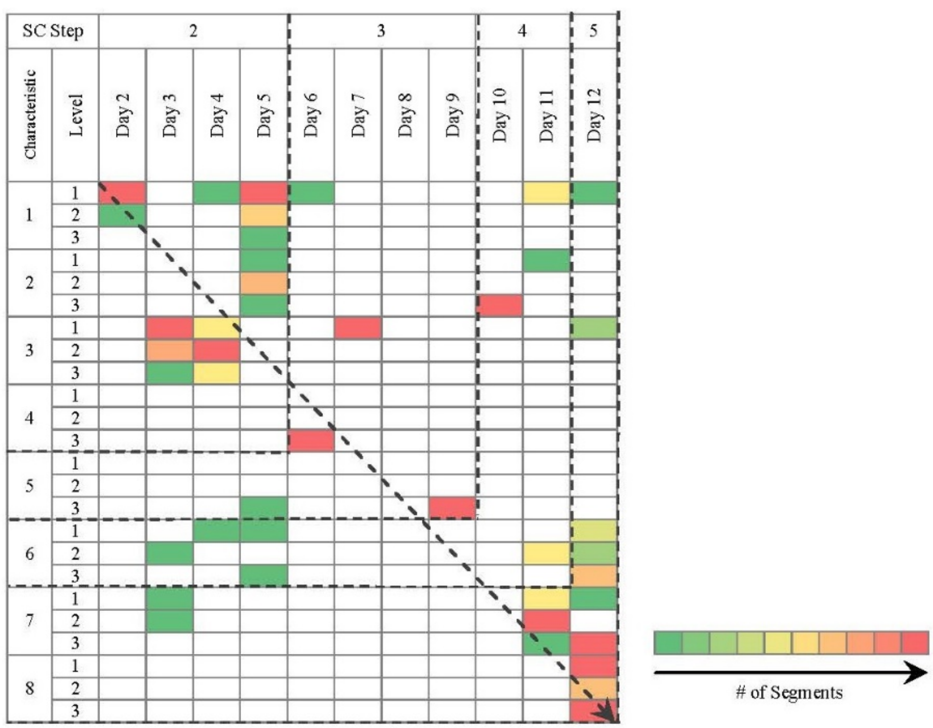


Figure 4.18 Heat map of the number of the Yellow team's systems thinking talk segments across all days. Each column represents a day, and each row represents a systems thinking characteristic (1 – 8) across three levels of complexity (1 = *Simplistic*, 2 = *Developing*, 3 = *Complex*).

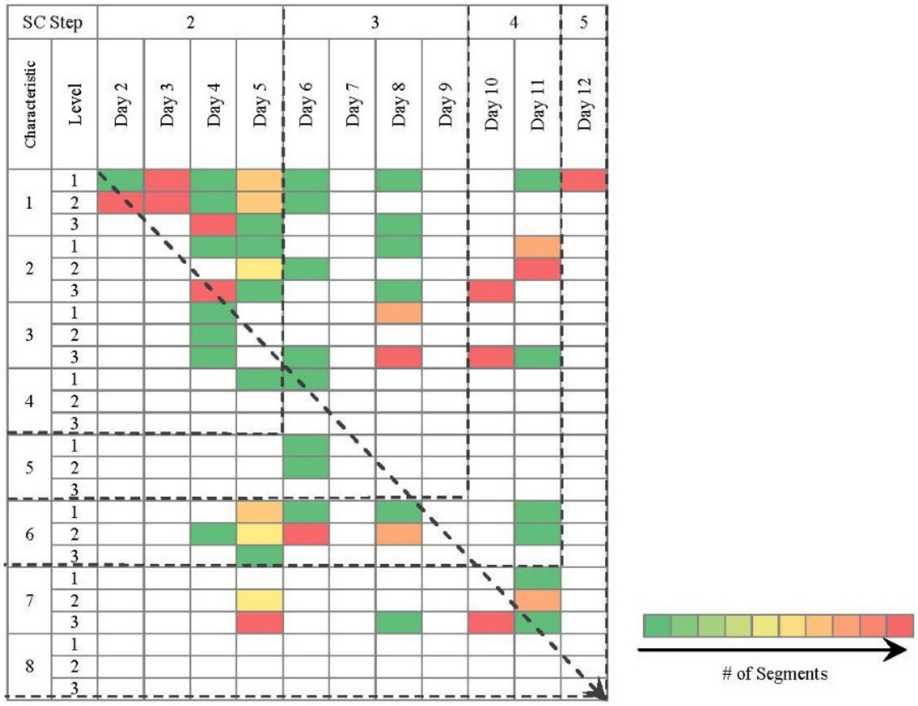


Figure 4.19 Heat map of the number of whole group systems thinking talk segments across all days. Each column represents a day, and each row represents a systems thinking characteristic (1 – 8) across three levels of complexity (1 = *Simplistic*, 2 = *Developing*, 3 = *Complex*).

Analysis of transcripts by day and citizen science step.

Days 2 through 5 (citizen science step 2).

The learning focus of Days 2 through 5 (Citizen Science Step 2) included gathering background knowledge about the ecohydrological system, using our background knowledge to build representations of water movement through Moro Canyon, and then using our representations to generate hypotheses related to our research question. Overall, the majority of the interactions for both the group as a whole and for each of the teams focused on components and processes, and static and dynamic relationships. (It is important to note that the Green team did have a relatively high number of talk segments related to hidden dimensions on both Day 4 and Day 5, but hidden dimensions was the only code that could co-occur with other codes.)

With regard to levels of complexity, the transcripts from Day 3 provided an interesting example of the way that teams' thinking rapidly progressed along the three dimensions of complexity as they identified different components, described what they saw as the two components interacted with each other, and explained why the interaction occurred as it did. The three segments below illustrate this progression. They were drawn from the Yellow team's investigation of soil percolation rates, during which they poured measured amounts of water into three different soils types and observed and noted any differences between the three. Segment 5 was coded as *Dynamic Relationships; Simplistic* as learners identified the relationship between the water and the different types of soil.

Segment 5

Facilitator: *So what did you guys observe?*
Fred: *We observed that*
Nancy: *Oh and the sand became all mushy!*
Isabel: *It became all dirty and stuff*
Eric: *I'm letting it all seep in*
Isabel: *The sand became all mushy. The sand got wet and became mushy*

Segment 6 was coded as *Dynamic Relationships; Developing* as Eric was describing what happened to the three soil types when the water was added.

Segment 6

Eric: *Wait, but the water stays up here! The sand soaked in, the water in the soil soaked in*
Facilitator: *That was a really good observation, Eric. Did the rest of you hear?*
All: *No*
Facilitator: *Want to repeat yourself?*
Eric: *The water got stuck inside of the soil instead of going through. Maybe it would have, it got stuck, leaving like a drop or two*

Segment 7 was coded as *Dynamic Relationships; Complex* as Eric explained why the sand and the water interacted as they did, saying that "the sand was able to absorb" (line 4).

Segment 7

Eric: *For this one, the water went straight through*
Isabel: *And it made the sand become mushy*
Facilitator: *Oh, all right*
Eric: *And the sand was able to absorb some of it and not let all the water just go right through*

In general, it appeared that the learners came into the program being able to identify both components and processes as there were more instances of *Developing* and *Complex* talk segments than there were *Simplistic* on Days 2, 3, and 4. Analysis of the pre-test word associations and drawings revealed a similar pattern as learners both listed and drew components and processes that are commonly associated with the water cycle prior to beginning the program.

There were two unexpected findings during this initial stage. First, both teams began to identify and describe hidden dimensions of the ecohydrological system, which was much earlier than predicted—recognizing hidden dimensions is a higher-level skill because these dimensions are abstract in nature. Interestingly, for both teams, the interactions that took place at this level occurred during their investigations into evaporation (Day 3) and transpiration (Day 4) and their representation building (Day 5). Thus, the more abstract hidden dimensions of the system were made concrete through the designed tasks.

Similarly, on Day 5, team interactions ranged in focus from identifying systems and components to generalizing about system interactions. A close review of the transcripts from this day suggested that this was an artifact of both the tasks in which the teams were engaged and the ways in which the tasks were organized. In a whole group discussion on Day 5, learners first reviewed their investigations on the water cycle (Day 2), evaporation (Day 3), and transpiration (Day 4). Then, they met in teams to build a representation of where the water in Moro Canyon goes, and finally, they regrouped to generate hypotheses related to their research question and based on their representation. Thus, the conversation moved along the seven of the eight systems thinking characteristics because each of the tasks required a specific type of thinking. The following four segments, drawn from the Day 5 transcripts, illustrate the way the interactions evolved over the course of the day. Segment 8, which was coded as *Components & Processes; Simplistic*, was taken from the whole group discussion at the beginning of the day when the learners were reviewing components and processes as a way to activate prior knowledge before working on their representations.

Segment 8

Facilitator: *So when they* [plants] *give off water vapor into the atmosphere, what did we call that? Does anyone remember?*
Henry: *Transpiration*

Once learners began working in their research teams, the focus of the conversations shifted toward higher levels of systems thinking. Segment 9, taken from the Green team's small group work, was coded as *Cycles of Matter and Energy; Developing* as the team was connecting the ocean and land dimensions of the cycles on their representation.

Segment 9

Facilitator: *What do those arrows mean?*
Noah: *Um, where the water goes.*
Sean: *This is where, this is where…*
Facilitator: *But what exactly is happening to them?*
Noah: *It's either evaporating up, which I'm going to* [draw]
Sean: *it runs into the stream here*
Noah: *Or it would either go to the ocean*
Ethan: *I think we should write what it's doing.*
Facilitator: *You can add that if you want, Ethan. So the up arrows are…*
Noah: *Going up to evaporation. And the down ones are going in underground.*
Facilitator: *And then the ones that are going with the river are just flowing?*
Sean: *They're going to the ocean.*
Facilitator: *Hmm, I like that*

Segment 10, taken from the Yellow team's small group work, was coded *Cycles of Matter and Energy; Complex* as Nancy used the representation that was drawn by the team to describe connections between the ocean, land, and hidden dimensions depicted on their representation.

Segment 10

Facilitator: *Show me what happens in the water cycle. Where do you think the water in Moro Canyon goes? When it rains, what happens to it?*
Nancy: *I think that when it rains, it goes into the… some of it doesn't go into the trees right away or like the plants. It goes into the ground. And then the soil keeps it so it can give it to the plants maybe later in their life but when the water comes and the plants collect it and some of it can go out through the leaves and evaporate and some of it the plants and trees store. I also think that some of it goes down into the ocean.*

Finally, the teams gathered as a whole group to generate a hypothesis related to their research question. Segment 11 was coded as *Generalizing (Hypothesis); Complex* as Nancy was explaining her hypothesis regarding the partitioning of water related to different landscape type.

Segment 11

Nancy: *Well, I was going to say for the restored one, I think that um, I don't exactly agree with that because I think when it's restored, it [water] goes into the soil and through the plants and it evaporates so I think the water has a majority of more ways to go since it has a better landscape to choose from*

Student: *Oh, that's true*

Nancy: *Well, it doesn't choose, like it has a better landscape to do stuff that it does*

Day 5 also showed a different pattern with regard to the complexity of talk. The highest relative number of talk segments was related to *Simplistic* interactions regarding components and processes, which is interesting in that the tasks included building a representation of the system and generating a hypothesis, which are both cognitively complex. Again, a review of the transcripts revealed that the majority of the lower level, simplistic talk segments occurred during the introductions to the tasks and as a way to refocus learner attention on salient elements of the ecohydrological system.

Days 6 through 9 (Citizen Science step 3).

Days 6 through 9 involved data collection (Citizen Science Step 3). On Day 6, teams learned how to use the leaf porometer, soil moisture meter, weather station, and iPad and how to follow the data collection protocols to gather and record data. On Days 7 and 9, research teams went into the field to gather transpiration, soil moisture, and weather at their research plots. We originally scheduled three days in the field, but it rained on Day 8, so we stayed on campus and engaged in a whole group discussion about our experiences to that point.

Overall, Days 6 through 9 yielded unexpected findings. First, there were significantly fewer talk segments related to systems thinking overall across these days, with the majority of the interactions occurring on Day 6 and Day 8. With respect to Day 6, very little of the systems thinking talk took place when the teams were practicing with the equipment (see Figure 4.14 and 4.15). The bulk of the interactions occurred during the introduction to the day as the whole group was reviewing the tasks and findings of the previous days' investigations (Figure 4.16). Moreover, there was only one systems thinking segment on Day 7 and two systems thinking segments on Day 9. Interestingly, these were days when the teams were in the field gathering data. A review of the transcripts revealed that teams were focused on using the equipment correctly, which left little attention for making connections between the equipment used, the data collected, and the way the system operated. The pre- and post-test analyses suggested that the learners did make connections between the equipment, data, components and processes, and dynamic relationship. This may be because the unplanned discussion on Day 8 helped the learners to clarify misunderstandings about the ecohydrological system and about the research. This is reflected in the heat map (Figure 4.13), which indicates talk on Day 8 clustered around components, processes, relationships, and hidden dimensions. However, the implications of the lack of systems thinking talk during the field work as it relates to program design is interesting and will be discussed further in the next chapter.

A review of the transcripts from Day 8 revealed some additional interesting and unexpected talk. The unplanned discussion allowed us to elicit learner understandings and to uncover and address naïve understandings and misconceptions about the ecohydrologic system and their environmental research. It appeared that at least three learners believed that plants release liquid water during transpiration. Segment 12 illustrates this misconception.

Segment 12

Facilitator: *so plants need carbon dioxide so they can get food, and they do that through the process of photosynthesis. And so they open their stomata so they can get that carbon dioxide inside the leaf to make plant food, like sugars and things like that. But when they open up their stomata, what do they also release?*

Learners: *[chorus] water. They release water. Yeah*

This misconception echoed one that appeared in the transcripts from Day 5 (see Segment 13) and again in two of the post-test drawings (see Figures 4.7 and 4.8).

Segment 13

Facilitator: *So we might also get some runoff, some surface runoff into the stream.*
Noah: *And also, um, transpiration*
Facilitator: *What do you mean by transpiration?*
Noah: *From the plant*
Facilitator: *What's happening with that?*
Noah: *The water from the plant will fall out*
Facilitator: *Okay, okay. No, that's an interesting idea. So if I were going to draw an arrow, what would that arrow look like?*
Noah: *Um, the plants leaves, like an arrow down from the leaf*

Related to this misconception was the notion that the leaf porometer was squeezing and then measuring liquid water from plant leaves. Segment 14 illustrates this idea.

Segment 14

Isabel: *and if there is that little desiccant thing inside of the porometer*
Facilitator: *it's called a sensor head*
Isabel: *oh the sensor head… then it can take all the water of the plant fast and measure that amount?*
Facilitator: *it doesn't take the water out of the plant*
Isabel: *oh*
Facilitator: *it just measures how much is released*

Thus, Day 8 provided an opportunity to consider immediate programmatic changes that needed to be made as we related naïve understandings to aspects of program design. The relevant point here is that there was a great deal of talk related to multiple systems thinking characteristics along all dimensions of complexity as learners asked questions and provided each other with explanations related to questions. Segment 15, which was coded as both *Dynamic Processes; Complex* and *Hidden Dimensions; Complex,* illustrates the nature of the talk that occurred on Day 8:

Segment 15

Isabel: *How could the plant transpire so quickly?*
Facilitator: *Oh my gosh, this is an excellent question. How does a plant transpire so quickly? Does anybody know the answer to that?*
Ethan: *It doesn't*
Facilitator: *let's think about it for just a second. Let's see if we can get some explanations for that.*

Okay, so the question that we have before us, scientists, is how does the plant transpire so quickly? [to Isabel] Is that what you would like to know?

Nancy: *okay, so I think when you guys drew the straw up, it's always going in the water cycle so so there is always water going out [of the plant] for the new water to come in, so it's always in the water cycle because you said there's like different stages so it's always be in a stage and there's the water keeps going out so new water comes in*

Facilitator: *Okay, so what do we think about that explanation?*

Students: *no*

Facilitator: *Now, if you disagree, what I need you to say is, "I disagree with that…"*

Sean: *"I disagree strongly…*

Facilitator: *Why do you disagree?*

Sean: *I disagree with that because that doesn't really explain how it goes so fast*

Students: *yeah*

Facilitator2: *but it does explain what?*

Student: *the water cycle*

Facilitator2: *how water is coming out of the plant*

Facilitator: *It does, but [to Sean] can you clarify a little bit when you say it doesn't explain why it goes so fast*

Sean: *Well our question is like why is… how does water transpire so quickly*

Nancy: *because it's always in the circle motion, always coming out*

It is likely that the unexpected change in Day 8 plans allowed for interactions that would not have otherwise taken place. Given the few segments related to systems thinking that occurred on Days 7 and 9, it may be that these unplanned interactions played an important role in the development of learners' systems thinking.

Days 10 and 11 (Citizen Science step 4).

Days 10 and 11 involved data analysis and drawing conclusions. On Day 10, teams built bar graphs of their data, and on Day 11, they drew conclusions from on their graphs. Overall, a total of six systems thinking interactions took place on Day 10, which was unexpectedly low. A review of the transcripts from Day 10 revealed that the activity and, as a consequence, the interactions, took a procedural turn, as teams focused on identifying the different variables related to their question, the type of graph—line, pie, or bar—to best represent their data, and then constructing the graph of their data. The few systems thinking interactions that did occur were related to explaining static and dynamic relationships. Interestingly, these interactions all took place at a higher level of complexity as learners explained their ideas rather than merely identified or described the relationships under discussion. Segment 16, which was coded as *Static Relationships; Complex*, illustrates the Whole group's systems thinking talk that occurred on Day 10:

Segment 16

Isabel: *The landscape type is the independent because it'll stay the same whether it's like soil or like rocky because then the water loss to transpiration depends on different soil types.*
Facilitator: *I think what Elizabeth said is the same thing that Isabel said, that the plot, which we're also calling the landscape type, that stays the same, right? How many of you agree with that?*
Learners: *[raise hands]*
Facilitator: *Right, so we're going to call this [independent variable] landscape type. So what does that make the dependent variables? Yes?*
Tim: *The landscape and both ways… Oh, the landscape, no the dependent is the transpiration and evaporation*
Facilitator : *Okay, so why do you think it's transpiration and evaporation?*
Tim: *Because it depends on the landscape, so it depends like which kind of landscape it is*

Analysis of the Day 11 transcripts revealed a markedly different pattern of interactions from those that took place on Day 10. Although there were a number of systems thinking segments related to components, processes, and static relationships, the vast majority of the segments (18 of the 31 total segments) were classified as *Generalizing*, as teams compared their hypothesis to their data and proposed explanations for their findings. Segment 17, drawn from the Yellow team, was coded as *Generalizing (Proposing Explanations); Complex*, and illustrates both the level of talk and the complexity of thinking that emerged through the Yellow team's interactions.

Segment 17

Facilitator: [to Fred] *So, now, what's your question? You had a question.*
Fred: *Um, is this lower?*[pointing to the bar chart]
Facilitator: *What do you think? What do you guys think about that?*
Fred: *Yeah.*
Facilitator: *Think about that. So talk about these. Which one of these, in terms of transpiration, had more, the higher the bar the more water lost through transpiration. So which one of those plots lost more water through transpiration?*
All: *Restored*
Isabel: *Because there's more plants. More plants.*
Fred: *We have to restore everything and we have to restore life and it looks better.*

Facilitator: *So, you think that the restored plot had more water lost, but make sure you relate it back to the data first, right?*

Isabel: *It had more plants!*

Nancy: *Well, I think it had more water lost since it has more plants and that shows that there is going to be more water lost because of the plants and all they need. If it was one plant, it would need a certain amount to survive, so they need a certain amount of water and every plant needs a certain amount of water times the amount of plants that is there, and with degraded it doesn't have as much plants so with restored it has a lot of plants so what everyone's going to say is it's complicated.*

Fred: *If there's more water, oh, I keep thinking about saving water, just wanted to say. Okay, so here's what I meant.*

Facilitator: *So let's listen to Fred because he's got some interesting things to say.*

Fred: *Well, I was, I got confused. This one* [under restoration] *has probably the better, has better conditions because they have, they lost less*

Facilitator: *Condition? I don't…*

Isabel: *He's saying the plants will be able to take in more.*

Nancy: *But if I was, if I was stating this too, I would say but it's* [more] *degraded so it's not going to have a good place to actually live, the plants.*

Day 12 (Citizen Science steps 5 & 6).

Day 12 (Citizen Science steps 5 & 6) involved creating a poster to disseminate our findings to the broader community. Learners were divided into their research teams, and each team was given a section of the poster to design. Overall, the analysis of the Day 12 transcripts revealed that the vast majority of talk focused on dynamic relationships, hidden dimensions, generalizations, and thinking temporally. The review of the transcripts suggested that, similar to all of the days except the field days (Day 7 and Day 9), the components and processes were discussed during the whole group and small team introductions as a way of activating prior knowledge. There were two interesting findings drawn from the transcripts. First, the systems thinking level at which the interactions took place was directly related to each team's assigned task. The Green team was assigned the Results section of the poster, which meant that they were primarily responsible for comparing our results to our hypothesis and proposing explanations for our findings; thus, their talk focused primarily on dynamic relationships as they related to hidden dimensions of the ecohydrological system (when removing the double coded hidden dimensions, 8 of 11 of their segments were coded as *Dynamic Relationships*). Segment 18, which was coded

Dynamic Relationships; Developing, illustrates the type of interactions that occurred in the Green team as they worked together to complete their section of the poster.

Segment 18

Facilitator: *…so our findings for the restored landscape*
Sean: *so we got that* [point to the graph]
Tim: *there was actually a tiny bit less than we thought going in, less going down then we thought and that's less water than we thought there would be. And there was more going up than we thought*
Sean: *What?*
Tim: [pointing to the graph] *see, there was more going up than we thought*
Facilitator: *what do you mean, going up?*
Tim: *transpiration, water going up*

To prepare for their poster presentation, the Green team also proposed explanations for their findings, as illustrated in Segment 19, which was coded as *Generalizing: Complex*.

Segment 19

Tim: *They* [plants] *leave more water in the soil*
Sean: *How would they suck up less? They should suck up more…oh yeah, that actually does make sense*
Facilitator: *No, what were you going to say?*
Sean: *Nothing*
Tim: *He got my standing* [he understands me] *because like, there's less plants in this one*
Sean: *Because there's more plants so they would suck up more water*
Tim: *Yeah, they would suck up more water and there's less plants in there. Well, there will be more water*
Facilitator: *So you think that because there's more plants, that they'd use more water?*
Tim: *Yes*
Sean: *Well, look at the degraded, though*
Facilitator: *Look at this though, they're releasing as much water as they take up*
Tim: *Well, because those plants were littler and I think you need like less water when they're little than when they're big*
Facilitator: *That could be possible*
Sean: *If they have less, if they have less, do, does, um, transpiration happen at the same speed? Like does it depend on which plant it is?*
Facilitator: *It depends on the number of leaves*
Tim: *Yeah, so if it's enough tiny…*
Facilitator: *So think about how many leaves there were in 90-100% plant coverage. Do you remember that plot?*
Sean: *Well, if it's really tiny, how is there almost the same as that?*
Tim: *Because they're tiny but if there's a lot of tinies, it equals like little…*
Sean: *But she said the more leaves…*
Facilitator: *So which one had more leaves?*
Sean: *That one obviously* [points to restored plot]
Tim: *Well, maybe not.*
Facilitator: *Like how many more leaves?*
Sean: *Yes, it did though. Because there's like 40 different plants in one.*

The Yellow team, on the other hand, was assigned the Discussion and Future Work sections of the poster, which meant that they were primarily responsible for proposing explanations regarding our findings and thinking temporally as the research findings had implications for both further research and for Park management; thus, their talk focused primarily on generalizations and predictions as they proposed explanations for their findings and considered future research questions. Segment 20, which was coded *Generalizations (Explanation); Complex*, illustrates the type of interactions that occurred in the Yellow team as they worked together to complete their section of the poster.

Segment 20

Facilitator: *so, we'll go through each of the different things we studied and through each of the landscapes and figure out what we found out from each of those datasets, okay? So, what do we know about transpiration from the degraded landscape? So, did we have high or low amount of transpiration from the degraded landscape?*
Nancy: *um, I think that we…*
Facilitator: *okay, so let's think about degraded. So, was there a lot of plants in degraded?*
Abby: *no*
Nancy: *I think that there was not a lot of plants*
Isabel: *there was less transpiration*
Facilitator: *okay, so less transpiration. Why did we have less transpiration?*
Fred: *less plants*
Facilitator: *because we had less plants*
Nancy: *I have a question If there's less plants in like the area, then there would be a lot more water in the ground because the plants aren't sort of absorbing it through their roots*
Eric: *and we didn't measure evaporation*
Facilitator: *not necessarily, it depends*
Eric: *we never learned the evaporation*
Nancy: *that's why we put a question mark*
Facilitator: *right. And we don't know how much water is actually going to depth to ground water. We don't know how much is getting lost to run off, we don't know getting like going into the streams. Things like that, so potentially, but it also depends on the soil type. There's a lot of factors, but that would be an interesting maybe for future work. So we could see, like that could be another question, is there more water in the soil if there is less plants. That's an interesting question. Okay, so let's move on. So, what about under restoration, how was our transpiration in under restoration?*
Abby: *medium*
Isabel: *it was sort of, yeah, it was sort of in the middle. Like at times there can be more and at times there can be less based on the plants*
Eric: *because it depends*
Isabel: *there it's still being restored*
Facilitator: *right*

Nancy: *I noticed that when it was being restored there was only a 27 difference* [in porometer readings] *in transpiration from when it was being restored and when it was restored, and then in the soil moisture there was…when it was being restored there was a lot more of the water in the ground and then when it was restored there was a lot less and so I was wondering why that was happening because there was… I thought that it was better when it was being restored verses when it was not*

Facilitator: *so that's actually a very good point, Nancy. So you noticed that there was a smaller difference between the restored and the under restoration*

Nancy: *in transpiration and soil moisture went down a lot when it was restored and it was like really high, the highest it was when it was under restoration*

Facilitator: *right, so you think that maybe there was a lot more water in the area where the under restoration plots were, which might have increased the transpiration rate?*

Nancy: *yes. Do you know why that is?*

Facilitator: *ah, the location*

Nancy: *okay*

Facilitator: *so the under restoration plot was in a little valley, so all of the water was kind of collecting there, whereas the restored plot was out on a flat plain. Okay, so let's go back to restored. So, transpiration, so we already said it was the highest, right? But you think that maybe it could have been higher if it was in an area with more soil moisture? Is that what we think, or…*

Nancy: *I think, well, I'm just… I guess it could if there was more soil moisture because that means that it* [a plant] *would collect more water because as you said the um what is it called in the leaf that opens up the*

Facilitator: *Stomatas*

Nancy: *Stomatas, yeah, those and you said when they open they are losing water so if there is more water in the area they would probably like suck more up because they would be able to open them more freely so that when they have more water [available] they [lose more water]*

The Yellow team also identified related research questions that might help explain some of our findings as well as help the land managers understand how the restoration might influence water as it flows through the Park. Segment 21, which was coded as *Thinking Temporally; Complex*, illustrates this type and level of interaction.

Segment 21

Facilitator: *what other questions do we have about Moro Canyon? …so, Eric, what's your question?*

Eric: *what type of species of plants stay there and how much, honestly does this relate to water? And how much water does each kind, does one specifically take more than the others?*

Facilitator: *that's a really good question. Do different plant species use different amounts of water?*

Finally, the Yellow group did consider the research as it related to park management, illustrated by Segment 22, which was coded *Generalizing (Solutions); Developing*.

Segment 22

Nancy: *I have a question. So, when I'm looking at these charts, I can see that in the transpiration it has…not much more than it does in under restoration, and it has a lot less in restored and I'm thinking, well, in restored it's supposed to be a lot better, but it's not that much better if I look at it now because this only has a little bit more but this has a lot less. Why don't you keep it under restoration?*

Discussion

This study investigated whether and to what extent 9 and 10 year old learners could develop systems thinking in the context of citizen science. The conceptual model reflected the integration of the steps of science research with the characteristics of systems thinking. The model served as the basis for the design of the Citizen Science After-school Club, which focused on the environmental research and provided direct interaction with the components and processes and the dynamic relationships of the ecohydrologic system. I analyzed data from individual pre- and post-tests and from whole group and team transcripts to study the systems thinking outcomes associated with the model.

The triangulation of paper-and-pencil research tools suggested that, over the course of the Club and to a varying degree, the learners replaced their simplistic view of the system with a more complex understanding of the ways that coherent systems operate over space and time. Table 4.9 presents differences in learner achievement between the pre-test and the post-test. Analyses indicated that six of the learners showed improvement across the systems thinking characteristics measured, while one learner stayed at the same level. A finer-grained analysis revealed that individual learners could be characterized by the nature and degree of their improvements on each measure and suggested three categories of learners: *Complex*, *Developing*, and *Simplistic*. The first category included Nancy and Isabel, who I characterized as having a more complex perception of the ecohydrological system at the end of the learning process. For Nancy and Isabel, their view of the system evolved such that they perceived the system components and processes as dynamic, integrated, and cyclic at the end of their participation in the Club. However, both Nancy and Isabel were 5th graders, who started their in-class water cycle unit around the 5th session of the Club. Thus, it is impossible to disentangle what they learned in class from what they learned in the Club. It may very well be that the double dose of content acted synergistically as they brought knowledge and understandings across the boundary between their in-school and after-school contexts. There were two days when information and experiences from their school day appeared in the transcripts. On Day 5, Nancy explained, "there's only 3% fresh water in the world and 97% salt water in the world, that's what we learned yesterday," and on Day 11, Isabel defined transpiration as "the passage of water through plants," which she identified as "the definition from school."

The second category included Eric, Tim, Sean, and Noah, who I characterized as having a *developing* perception of the system. Eric and Tim both improved on all of their post-test scores, listing more processes, identifying a greater number of dynamic relationships, and improving their ability to organize the relationships in a coherent framework. Moreover, both improved in their knowledge of the ways that cycles operate, drawing more connections between different subsystems. However, their level of improvement was not as dramatic as that of Isabel and Nancy. Sean and Noah demonstrated similar improvements on their pre-tests as Eric and Tim, except in the category of dynamic relationships, where their scores did not change from pre- to post-test. With regard to the Cyclic Thinking Questionnaire, all four improved in their ability to reason; however, at the end of the learning process, they all perceived the system as a series of less connected processes rather than collection of more connected cycles and could be classified as process rather than cyclic thinkers.

The third category included Fred, who I characterized as having a *simplistic* view of the system. Fred, a member of the Yellow team, showed no evolution in his view of complex systems in that his post-test scores matched his pre-test scores—there were no changes. Although on his pre-tests, he could identify components and processes and organize them into a few dynamic relationships, his post-tests reveal that he did not increase in his ability to organize components and processes into a coherent framework, connect subsystems through the flow of energy and matter, or identify hidden dimensions of the system. Finally, although Ethan did take the pre-tests and two of the post-tests (word association and Cyclic Thinking Questionnaire), he did not complete either the drawing or the Ecology System Inventory. Thus, it was impossible to draw conclusions about Ethan's learning from the pre-/post-test analysis.

Table 4.9
Development of Systems Thinking Abilities as Measured by Pre-/Post Tests

ST Characteristic	Ability	Measured by	Pretest- to Post-test
Time (prediction or retrospection)	The ability to explain relationships that involve time (restoration)	Not measured through pre-/post-tests	
Generalizations	The ability to make generalizations	Not measured through pre-/post-tests	
Hidden Dimensions	The ability to add processes that take place under the surface of the system	Drawings Ecology System Inventory	Isabel – *Increase* Nancy – *Increase* Eric – *Increase* Sean – *Increase* Tim – *Increase* Noah – *Increase* Fred – *Decrease*
Cyclic Thinking	The ability to connect subsystems through the flow of energy and matter	Drawings Cyclic Thinking Questionnaire	Isabel – *0* to *4; Process* to *Cycle* Nancy – *0* to *4; Process* to *Cycle* Eric – *0* to *2; Process* to *Process* Tim – *0* to *4; Intuitive* to *Process* Noah – *3* to *4; Unscientific* to *Process* Sean – *2* to *3; Unscientific* to *Process* Fred – *0* to *0*; *Unscientific* to *Unscientific* Ethan – *N/A; Unscientific* to *Unscientific*[1]
Organized Framework	The ability to organize system components and processes within a framework of relationship	Drawings	Isabel – *No Framework* to *Complex* Nancy – *No Framework* to *Complex* Eric – *Simplistic* to *Developing* Tim – *Simplistic* to *Developing* Noah – *Developing* to *Developing* Sean – *Simplistic* to *Simplistic* Fred – *No Framework* to *No Framework*

Relationships within the system	The ability to identify dynamic relationships within the system The ability to identify relationships between two components	Drawings	Isabel – *Increase* Nancy – *Increase* Eric – *Increase* Tim – *Increase* Noah – *Increase* Fred – *Increase* Sean – *No Change*
System Components	The ability to identify processes The ability to identify components	Word Association Drawings	Isabel – *Increase* Nancy – *Increase* Eric – *Increase* Tim – *Increase* Noah – *Increase* Sean – *Increase* Fred – *Decrease* Ethan – *Decrease*

[1]Based on only Cyclic Thinking Questionnaire

The results from pre- and post-tests provided an overview of individual learners, but they could not account for learning as it progressed though participation in activity and collaboration with others over time. Thus, the video analysis was essential to understand if and how the whole group and each teams' systems thinking abilities developed through ongoing social interaction. It is important to note that I did not conduct an analysis of the transcripts at the individual learner level. Such an analysis may have revealed interesting differences in the level and nature of individual interaction and learning; however, at the team level, the analysis indicated that both the Green team and the Yellow team engaged in increasingly complex systems thinking conversations over time.

Overall, the analysis of the transcripts suggested that teams did engage in the type of systems thinking interactions predicted by the conceptual model. During the initial days of the Club, teams built an understanding of components, processes, and relationships, which then provided a foundation for understanding cycles of energy and matter, which, in turn, provided the foundation for hypothesizing, explaining, and solving problems based on their understanding of complex systems. Moreover, I found a similar pattern with respect to complexity of talk as learners could first identify, then define and describe and finally explain in context elements of each systems thinking characteristic.

Interestingly, the analysis by day suggested that teams engaged in higher levels of systems thinking earlier than predicted by the conceptual model. For example, the model mapped citizen science step 2 (gathering information and generating a hypothesis) with systems thinking characteristics 1 through 4. However, the transcripts revealed that learners engaged in interactions that focused on cycles of matter and energy (systems thinking characteristic 5), hidden dimensions (systems thinking characteristic 6) and to some extent, generalizations (systems thinking characteristic 7). This appeared to be closely related to the nature of the task in which they were engaged, as building representations of the ecohydrological system help learners to understand cycles of matter and energy as well as hidden dimensions, and generating hypothesis helped learners to generalize about the movement of water through landscape type.

These findings are similar to Ben-Zvi Assaraf and Orion's (2010) findings, which suggested that, with support, learners as young as 10 could begin to understand important concepts and perspectives related to systems and that focusing on characteristics in a specific sequence provides foundational support for higher levels of systems thinking. Support for this hierarchical model of systems thinking comes from earlier studies that were related to science learning in general (Wilensky & Resnick, 1999) and to Earth Systems specifically (Ben-Zvi Assaraf, 2005, 2010; Kali, Orion, & Eylon, 2003).

The outcomes of this study also support researchers who found that young children are capable of abstract thinking, especially when engaged in collaborative inquiry (Thompson & Reimann, 2007) conducted in an authentic context (e.g., Bevan et al., 2009; Cuevas, P., Lee, O., Hart, J., Y Deaktor, 2005; Edelson, 1998; National Research Council, 2000; Resnick, 1987).

Analysis of the transcripts suggested that learners could better identify relationships between systems and components when they engaged in learning activities that provided real world, outdoor contact with the more abstract processes and hidden dimensions of the system because these activities enabled learners to interact with abstract phenomena in a more concrete way. Indeed, one way to help learners, especially younger learners, to develop systems thinking may be to situate the exploration of complex phenomena in ordinary everyday contexts that place learners in the role of actual participants (Jacobson & Wilensky, 2006). Thus, this study joins several studies that highlight the potential of outdoor learning environments (DeWitt & Osborne, 2007; Dillon, Rickinson, Teamey, Morris, Choi, Sanders, & Benefield, 2006; Orion, 2002), suggesting that situating learning of complex topics in outdoor environments allows learners to directly experience concrete phenomena and materials as they appear in the real world. This may be even more critical for younger learners, whose abstract thinking abilities are still relatively undeveloped (Orion, 2002).

There were several limitations to this study that highlight the need for future work. First, this study was conducted with a small, homogeneous sample. The participants were drawn from the same school and the same classes. The design of this study and the data that was collected cannot account for the degree to which this influenced the collaboration among team members. It is possible that participants drawn from different backgrounds would have a very different collaborative learning experience that might result in different learning outcomes. Second, as previously mention, there were two 5th grade students who participated in the study. Both of these students, who were in different classes, were learning about the water cycle in school. The nature and scope of the study made it impossible to a) disentangle what they were learning in the Club from what they were learning in school, and b) determine if the results of their pre-/post-test and the study of their interactions were the result of this double-dose of content or related to developmental differences from the 4th grade participants. Third, with respect to the analysis of the drawing and the Ecology System Inventory, all analyses are open to interpretation by the researcher, which means that the findings should be approached with a certain degree of skepticism. Fourth, the approach taken focused on the progress that groups of learners made in systems thinking. The scope did not allow for the tracking of individual learners' progress over time. A case-study method that includes an analysis of interactions at the individual level would uncover changes in individual learners that would yield valuable information on systems thinking development. Fifth, aspects and situations from different science fields and disciplines are often governed by the same systems principles. Thus, understanding how to promote knowledge transfer across fields and disciplines is an important goal of systems thinking research. Again, the scope of this work did not allow for the study of whether this locally learned knowledge would transfer to other contexts, topics, fields, or disciplines. Such research would be invaluable to this field of study. Finally, just as this study was limited in scope, it was also limited in time. Longitudinal studies would allow us to determine whether the systems thinking abilities gained through participation in designed interventions persist through time.

CHAPTER 5

Understanding the Design of the Learning Environment

Nancy: *I think that's where it's best in like where all the plants are and everything, even though we don't know the evaporation, which is a very important part, but which we don't know. When it's under restoration, it's best but, when it's restored, I say it goes down a lot*
Abby: *I don't know if that's what it means*
Eric: *My mind is officially blown!*
Facilitator: *So let's think about this for just a second*
Isabel: *I like this whole thing*

During the last two decades, the main goal of science education has shifted from preparing future scientists to educating future citizens, citizens who are capable of navigating complex scientific concerns and environmental issues. This shift is nowhere more evident than in the calls to develop science programming that allows learners to build understandings of concepts that cut across multiple science disciplines, including systems and systems models (National Research Council, 2012). Current research on science learning suggests that learners may learn these cross-cutting concepts by engaging in the key practices of science—asking questions, developing and using models, and engaging in argument from evidence (Lehrer & Schauble, 2006; National Research Council, 2012). This particular area of study focuses on what learners need to do to learn science, a view that embodies the dialogic knowledge-building processes that involve developing predictions and explanations that represent our understandings about the natural world (Duschl, 2008). This notion of science-as-practice involves complex design and ambitious implementation and leads to a number of interesting questions. What does science learning as science-as-practice look like, and what designs and which forms of practice provide the greatest educational leverage for developing systems thinking?

The purpose of this research was to study the extent to which the design of the Citizen Scientists' After-school Club ("Club"), a citizen science approach to developing systems thinking, influenced participants' learning of systems. This chapter tells the story of the design of the Club, pointing out the theoretical underpinnings of the design, the challenges that arose from implementation, the ways I addressed those challenges—both in the moment and in the revised program, and the lessons I learned about the design and implementation and about taking a theory-based approach to studying learning environments. All learning environment designs begin with a high-level conceptual model about how learning occurs within a particular design. This model drives the identification of theoretical design principles, which leads to the formulation of testable learning conjectures and to decisions about the ways these conjectures are embodied in specific features of the design. When arranged together in a conjecture map, these elements provide the foundation for both the design and the study of the learning environment. Thus, both the intervention and the study design arose from the mapping of the theoretically derived conjectures about learning to specific features of the intervention design to learning outcomes. The questions, then, were related to the ways in which the embodied conjectures mediated interactions that brought about learning. To understand the relationship between the designed environment and the learning outcomes, I asked a) Were the design elements identified in the conjecture map evident in the implementation of the environment?; b) What was the relationship between design elements and systems thinking outcomes?; and c) What were the challenges associated with designing and implementing such an intervention?

This study contributes to the field in three fundamental ways: a) it advances our knowledge of the ways authentic citizen science experiences might facilitate the development of systems thinking, b) it increases our understanding of the learning outcomes, implementation and design challenges, and design principles associated with collaborative involvement in citizen science research, and c) it illustrates a design-based methodology for studying the explicit links between the multiple elements that make up the design and that mediate learning. The findings reported here may have implications for environmental science researchers, who are interested in innovative and effective outreach models; for science educators, who are interested in innovative and effective science learning methods; and for science learning researchers, who are interested in ways to facilitate systems thinking development and in ways to systematically study designed interventions.

Since the purpose of this research was to study the extent to which the design of the Club influenced participants' learning, it might be helpful to revisit the conjecture map. This map illustrates the links between design principles, learning conjectures, embodiments, and anticipated learning outcomes (Figure 5.1), thus providing a detailed view of my ideas about how learning might be made to happen. By tracing the observed effects back to specific conjectures and to interactions among specific conjectures, I uncovered theoretical knowledge about systems thinking development by identifying specific aspects of the instructional design that led to the mediating processes—in this case, the learning interactions—that influenced both learning and instruction. The conjecture map led to empirical predictions that were tested, and the results led to both refinements of the design as well as refinements of the conceptual model (which I will discuss in Chapter 6).

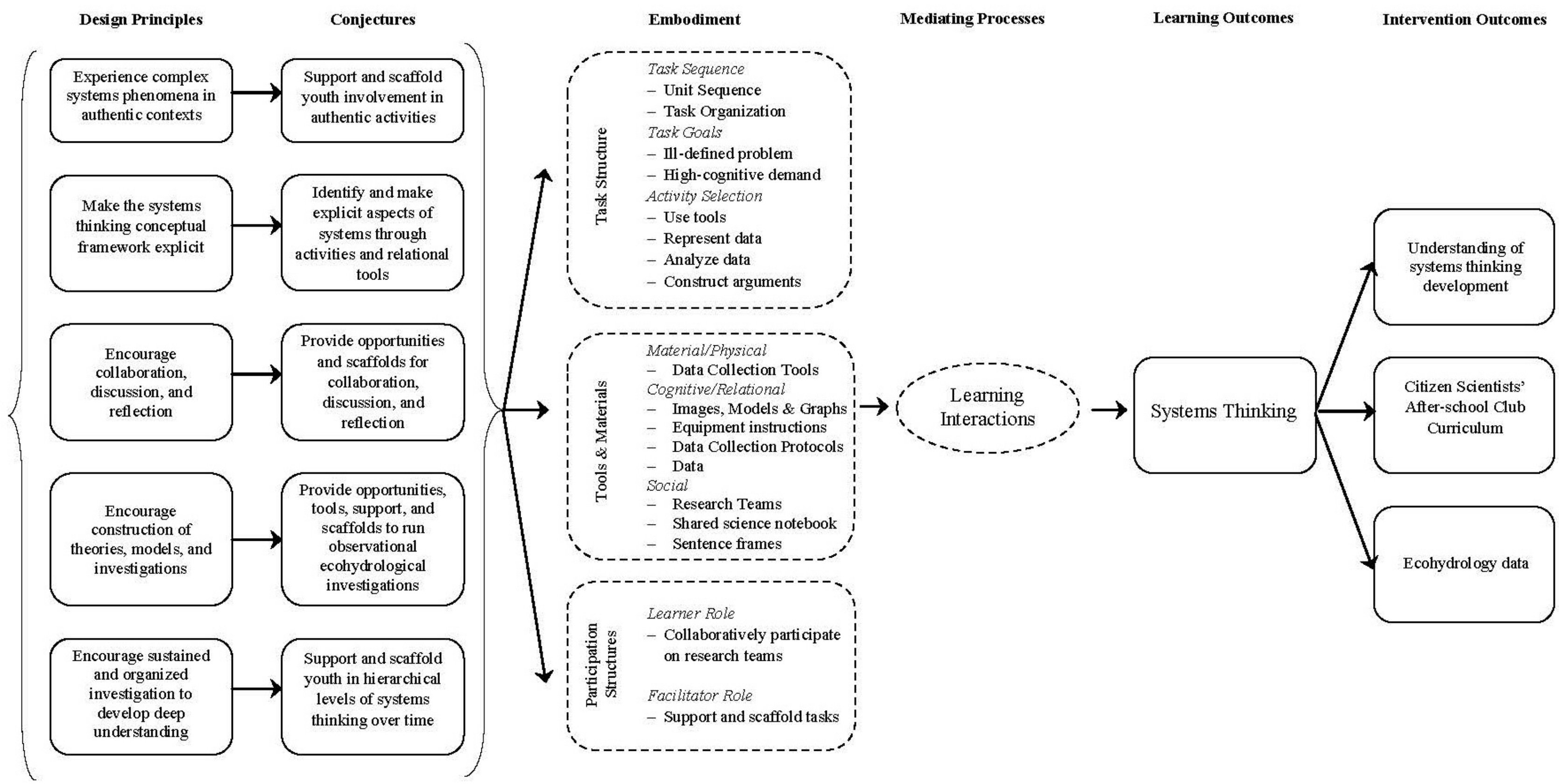


Figure 5.1 Citizen Scientists' After-school Club Conjecture Map derived from the theory that authentic experiences (i.e., collaborative citizen science) engage learners in collaborative knowledge building processes that support the development of systems thinking characteristics

Methodology

In this section, I re-introduce the design and implementation team, review the design and research structure, and discuss the sources from which I collected the data and the methods I used to analyze the data.

Design and Implementation Team

There were four members of the design team: me as the lead researcher and designer, Alice, a graduate student in biological sciences, and Laura and Katie, undergraduate students each working on a degree in science and a teaching credential. Alice served as a content reviewer, and Laura and Katie provided education and design support. The design team met weekly over the course of three months to discuss, review, and revise the overall design of the unit, including the sequence and organization, and the specific tasks, tools, and participation structures reified in the design.

The implementation team consisted of four members, three of whom were on the design team. The fourth member—Jacque—was added to replace Katie, who could not participate in the implementation. Jacque was an undergraduate student working on a degree in science and a teaching credential. During program implementation, I served as the primary facilitator, providing both whole group instruction and small research team facilitation. The other members of the implementation team worked with small research teams and served as program aids.

Design and Research Structure

This aspect of the research consisted of two phases, with each phase consisting of different tasks:

Phase 1: Informed exploration.

The first phase consisted of informed exploration. During this phase, I identified and defined the problem (i.e., systems thinking), conducted a comprehensive review of the literature related to the problem, used the literature to draft the conceptual model, and developed the conjecture map. It was also during this phase that I identified the target audience, the study context, and the design and implementation team.

Phase 2: Design, Implementation, and Revision.

The second phase of the design and research structure consisted of design, implementation, and revision, during which I refined the learning research plan and worked with design team members to develop the ecohydrological citizen science research, which was the foundation for the design of the learning environment. The design team conducted background research; identified the specific research question; developed, tested, and refined protocols and data forms; and addressed data quality issues.

As we developed the ecohydrological research, we worked to translate the citizen science research into a curriculum for the Club. The process of translation included developing the overall structure and sequence of the program and identifying the ways that each specific conjecture was embodied in the tasks structures, tools and materials, and participation structures. Finally, we implemented the intervention with our youth participants, collecting data throughout the implementation to create a comprehensive record of the ongoing design and implementation processes and challenges.

The goal of this phase was to improve the initial design by testing and revising the foundational conjectures that made up the design. I did this through an analysis of the embodied conjectures that made up the design. The outcome of this phase was a comprehensive set of tested design principles and lessons learned that could be used locally to redesign the intervention and globally to guide the design of similar interventions for similar contexts. The findings related to the design, including the challenges and lessons learned, are addressed in this chapter.

Data Sources

I used multiple sources of data to document the implementation and the evolving challenges, anomalies, interpretations, and understandings of the designed intervention. Sources included: a) the overall unit plan and each daily session plan, b) audio recorded field notes taken during team meetings before and after most implementation sessions, c) two semi-structured interviews with design and implementation team members conducted after implementation, d) transcripts of video-recorded learner interactions as they engaged in intervention activities, and e) ecohydrology data collected by participants.

This type of work requires an extensive data set—the more relevant and extensive the document, the greater potential to effectively revise both the conceptual model and the intervention design, and the more persuasive my descriptions of the intervention and findings (Wang & Hannafin, 2005). Because I was primarily interested in understanding the learning interactions as mediated through the evolving embodied conjectures (i.e., task structures, tools and materials, and participation structures), qualitative data collection efforts targeted the elements of the conjecture map as they related to the design and implementation of the intervention and the learning outcomes associated with participation. As such, the study of these embodied conjectures and the learning interactions were not treated separately. Instead, I used the detailed conjecture map and the related design decisions in the form of lesson plans, participant observations in the form of field notes, learning interactions in the form of transcripts, and interviews with the implementation team members to better understand if and how the project elements afforded interactions among conjectures, if these interactions mediated social interactions, and if these interactions led to systems thinking outcomes (Barab et al., 2005).

Data Collection

The data was collected before, during, and after the end of the program. With respect to the unit and session plans, I provided the facilitators with the overall unit plan that detailed design decisions regarding sequence, organization, and timing, and daily session plans that included an overview of the task, the list of tools and materials required, the way the task was organized, and the roles of both facilitators and the learners. At the end of the program, I gathered the final copies of each session plan as well as the overall unit plan. With respect to the implementation field notes, we met as a team just prior to each session to review the details of the session plan and to discuss implementation. The purpose of the meeting was to ensure, as much as might be possible, consistency in implementation across all teams. We also met immediately following each session to review the successes and challenges of the implementation. The purpose of this meeting was to capture our immediate and unfiltered impressions of the session, to discuss issues related to the next session(s), and to consider changes for the next round of implementation. I recorded these meetings and then later took notes on our discussions. With respect to the implementation team interviews, we met immediately following the end of the Club and then two months later to review each session, identify implementation challenges and potential design solutions, and discuss possible revisions to the intervention. With respect to the video, we began recording on the first day of implementation and then recorded all of the following days. We used three cameras—one to collect whole group interactions, and one each to collect Green team and Yellow team interactions. The cameras were mounted on tripods during the majority of the sessions. Finally, I gathered all learner collected transpiration, soil moisture, and weather data in one data set to assess the quality and the trustworthiness of their work.

Data Analysis

Analysis of the unit plan, session plans, and learner interaction transcripts consisted of four phases. The first phase involved sorting the session plans, field notes, and transcripts by day so that, with common codes, I could link design to implementation. The second phase involved developing and testing a coding framework based on the conjectures and embodiments identified by the conjecture map (see Figure 5.1). Because I was interested in capturing how each conjecture worked through specific embodiments, I created individual maps for each conjecture (see Figure 5.2 for an example of the map for Conjecture #1: *Support and scaffold involvement in authentic activities*). Each map is different for each conjecture because the individual conjectures were embodied in different ways. For example, Conjecture 4: *Make systems thinking explicit* was not embodied in the task goals, so the conjecture map does not reflect this pathway.

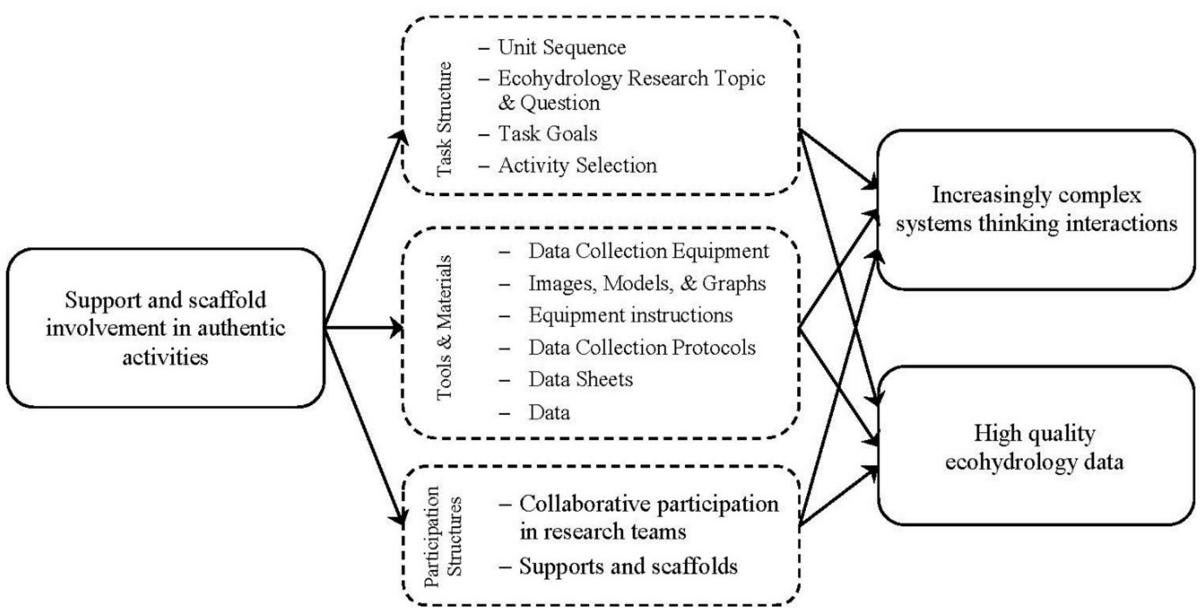


Figure 5.2 The coding pathways of conjecture #1.

These maps specified pathways from conjecture through embodiments to specific outcomes (see Figures 5.7 through 5.7 for the remaining individual maps). The specified pathways then became the coding pathway for each conjecture, with the first code describing the conjecture (see Table 3.4), the second code describing the embodiment (*task structure, tools & materials,* or *participation structure*), and the third code describing the specific way the embodiment took shape in the design and implementation (see Saldaña, 2009). These, then, were descriptive codes used to identify the topic of particular segments of the session plans, field notes, interviews, or transcripts. Table 5.1 provides an example of three possible pathways of the coding scheme for conjecture #1, which is shown in Figure 5.2.

Table 5.1
Example Coding Pathways for Conjecture #1: Authentic Activity

Authentic activity	Task Structure	Task Goals
Authentic activity	Tools & Materials	Images, models, & graphs
Authentic activity	Participation Structures	Supports & Scaffolds

To test the framework, I coded the lesson plans, field notes, and transcripts from three days (Day 2, Day 7, and Day 11). I randomly chose one day from Days 1 – 5, when the learners conducted background investigations; one day from Days 6 – 9 when the learners focused on equipment use and data collection; and one day from Days 10 – 12, when the learners analyzed data and prepared to communicate their findings. I did this to make sure that I tested each conjecture of the framework.

I found, however, that this did not provide the detail that I needed to link the specific embodiments as they were designed in the lesson plans or enacted in the implementation to outcomes. To examine the specific way that tasks structures (e.g., task goals) and participation structures (e.g., supports and scaffolds) were enacted in the moment of facilitating and learning, I added additional codes to the pathways for *Task structure, Images, models, & graphs*, and *Participation structure* (because of space constraints, these additional codes are not illustrated on the individual conjecture maps). For example, Task Structure was coded as one of the following: *Task sequence*; *Task goals*; *Topic & question*; or *Activity selection*. The segments that were coded as *Task goals* were then coded as one of the following: *Processing ideas*, *Connecting activity with ideas*, or *Seeking "why" explanations* (see Table 2.6 on page 65 for characteristics of high-cognitive demand tasks). Similarly, Participation Structure was coded as *Learners – Collaborative Participation* or as *Facilitators – Supports & Scaffolds*. The segments that were coded as *Facilitators – Supports & Scaffolds* were then coded as one of the following: *Coaching & modeling* or *Questioning.* If the segment was coded as *Questioning*, it was further coded as one of the following: *Sharing, expanding, or clarifying thinking*; *Deepening reasoning*; *Listening to others*; or *Thinking with others* (see Table 3.8 on page 64 for examples of question types used to scaffold learning). This allowed me to identify the specific task goals or the specific type of questions that facilitators asked to scaffold learning, and it had the added benefit of allowing me to determine whether specific embodiments interacted with each other. For example, I could identify which type of questioning (e.g., *Thinking with others*) interacted with which set of task goals (e.g., *Seeking "why" explanations*). It is important to note that some of the pathways extended further than others did. For example, there were four different types of questions that could have been used as scaffolds, so the pathway for *Supports & scaffolds* (seen below) extended further than the pathway for *Task goals* did because the specific type of questions was included. Figure 5.3 shows an example of the coding pathways for *Task goals* and *Facilitators – Supports & Scaffolds*, and Figure 5.4 and Table 5.2 provide an example of the way that coding pathways were used to describe segments of talk.

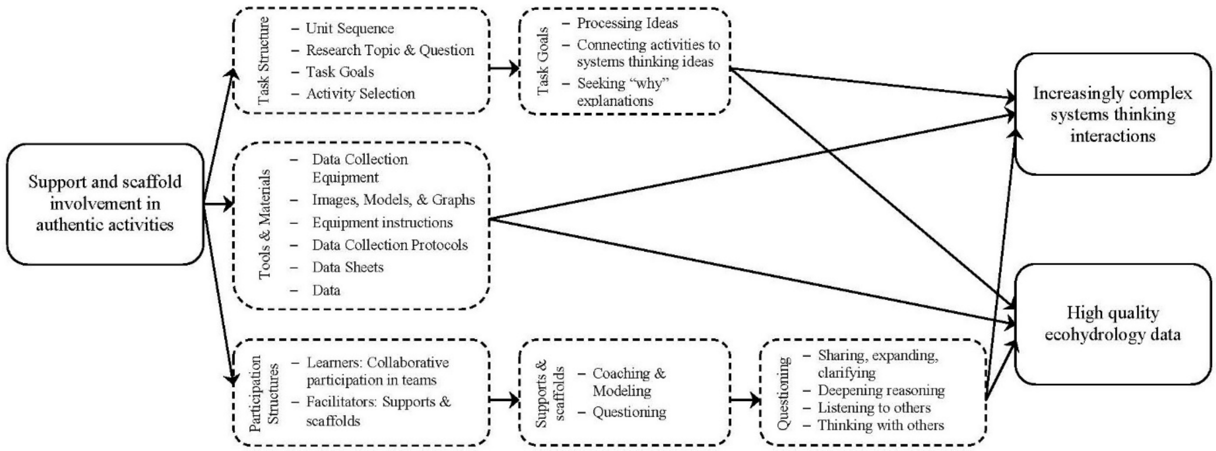
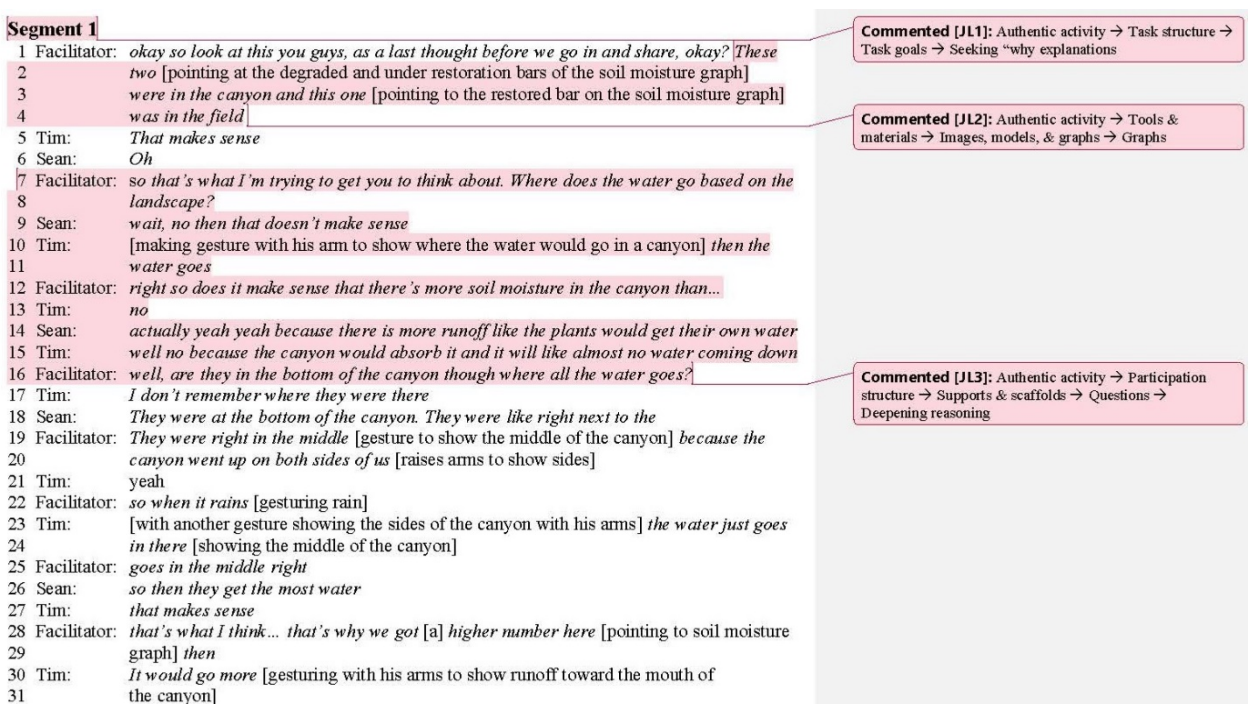


Figure 5.3 Example of the coding pathways for *Task goals* and *Facilitator – Supports & Scaffolds*



Segment 1

1 Facilitator: *okay so look at this you guys, as a last thought before we go in and share, okay? These*
2 *two* [pointing at the degraded and under restoration bars of the soil moisture graph]
3 *were in the canyon and this one* [pointing to the restored bar on the soil moisture graph]
4 *was in the field*
5 Tim: *That makes sense*
6 Sean: *Oh*
7 Facilitator: *so that's what I'm trying to get you to think about. Where does the water go based on the*
8 *landscape?*
9 Sean: *wait, no then that doesn't make sense*
10 Tim: [making gesture with his arm to show where the water would go in a canyon] *then the*
11 *water goes*
12 Facilitator: *right so does it make sense that there's more soil moisture in the canyon than...*
13 Tim: *no*
14 Sean: *actually yeah yeah because there is more runoff like the plants would get their own water*
15 Tim: *well no because the canyon would absorb it and it will like almost no water coming down*
16 Facilitator: *well, are they in the bottom of the canyon though where all the water goes?*
17 Tim: *I don't remember where they were there*
18 Sean: *They were at the bottom of the canyon. They were like right next to the*
19 Facilitator: *They were right in the middle* [gesture to show the middle of the canyon] *because the*
20 *canyon went up on both sides of us* [raises arms to show sides]
21 Tim: yeah
22 Facilitator: *so when it rains* [gesturing rain]
23 Tim: [with another gesture showing the sides of the canyon with his arms] *the water just goes*
24 *in there* [showing the middle of the canyon]
25 Facilitator: *goes in the middle right*
26 Sean: *so then they get the most water*
27 Tim: *that makes sense*
28 Facilitator: *that's what I think... that's why we got* [a] *higher number here* [pointing to soil moisture
29 graph] *then*
30 Tim: *It would go more* [gesturing with his arms to show runoff toward the mouth of
31 the canyon]

Commented [JL1]: Authentic activity → Task structure → Task goals → Seeking "why explanations

Commented [JL2]: Authentic activity → Tools & materials → Images, models, & graphs → Graphs

Commented [JL3]: Authentic activity → Participation structure → Supports & scaffolds → Questions → Deepening reasoning

Figure 5.4 Example of a Segment of Talk with Coding Pathways

Table 5.2
Segment 1 Coding Pathways

Authentic activity	Task Structure	Task Goals	Seeking "why" explanations	
Authentic activity	Tools & Materials	Images, models, & graphs		
Authentic activity	Participation Structures	Supports & Scaffolds	Questions	Deepening reasoning

I tested the revised framework on the same three days and found that I had reached a stable set of descriptors (see Appendix H for the coding framework). I have provided simplified individual maps detailing possible pathways for conjectures 2 – 5 below (see Figures 5.5 through 5.8).

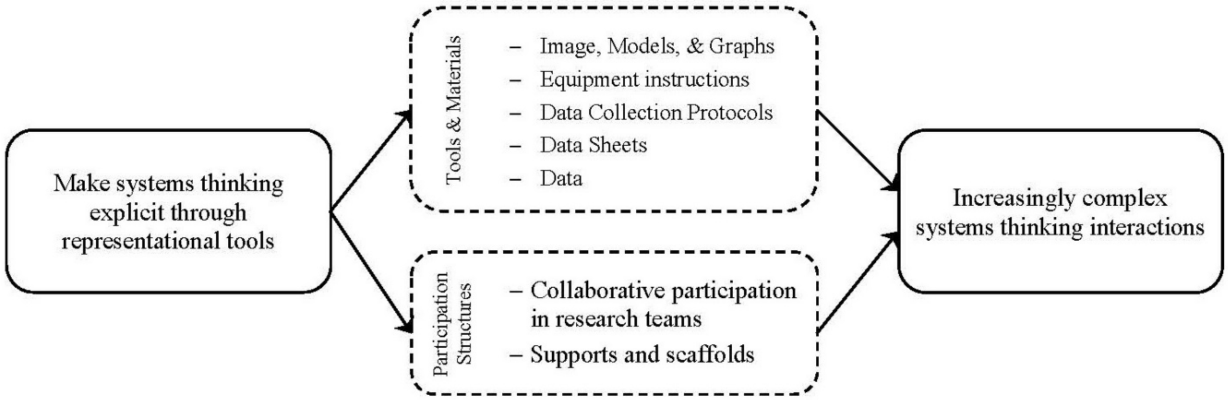


Figure 5.5 The coding pathways of Conjecture #2.

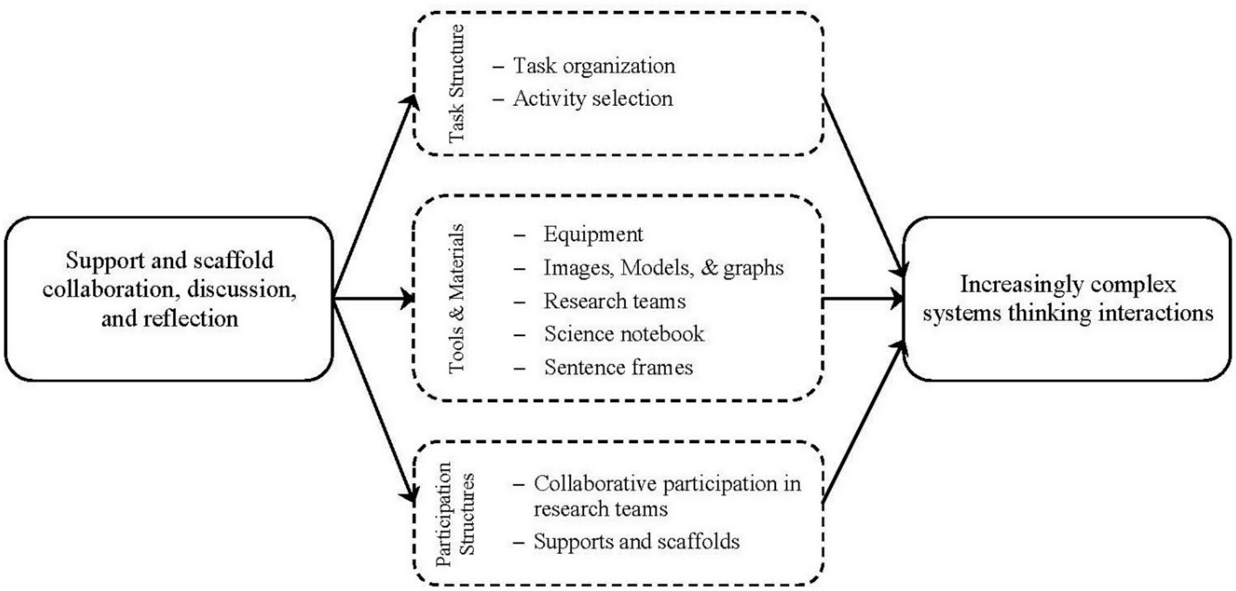


Figure 5.6 The coding pathways of Conjecture #3

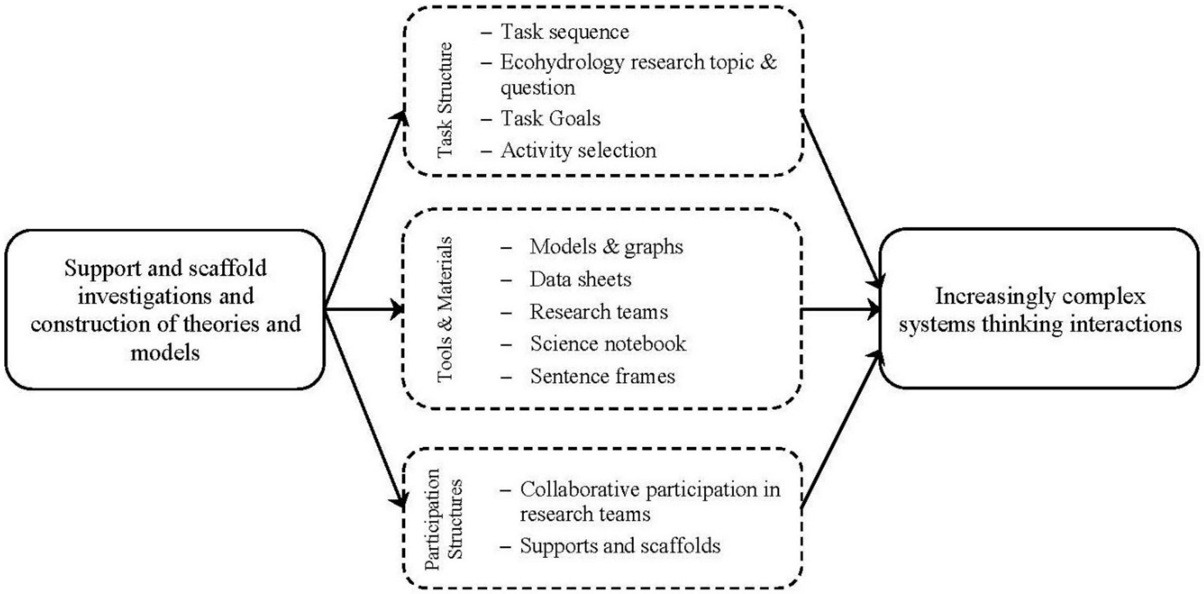


Figure 5.7 The coding pathways of Conjecture #4.

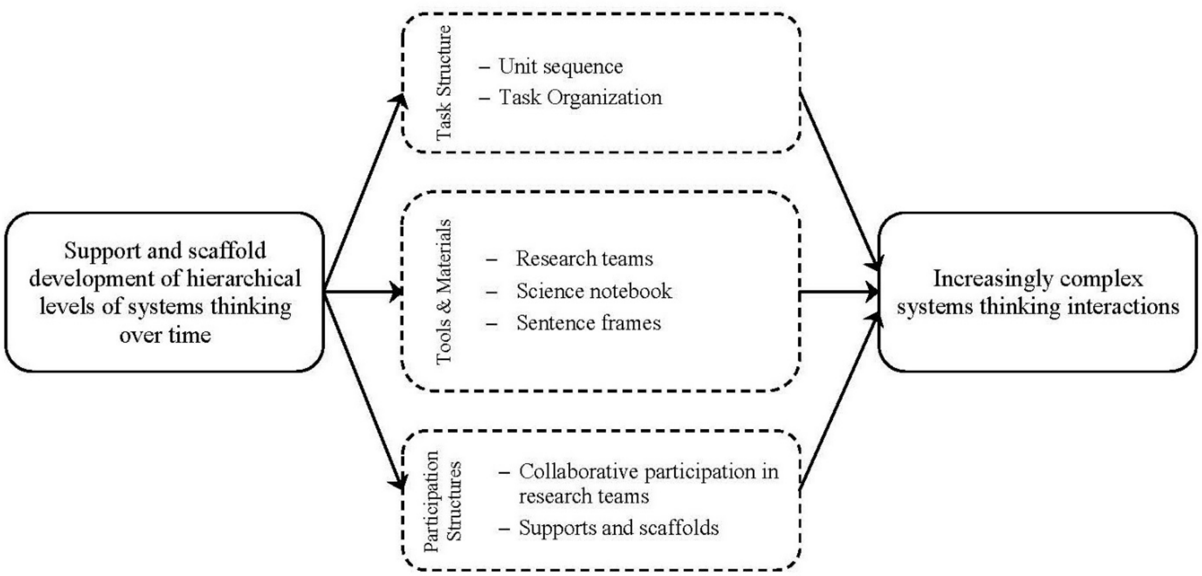


Figure 5.8 The coding pathways of Conjecture #5.

At that point, I coded all of the remaining session plans, field notes, transcripts as well as the unit plan and the interviews. To ensure a level of credibility, I coded the session plans and preparation field notes first. Then, I coded the transcripts and the debrief field notes. To identify the way different embodiments interacted, segments of the transcripts could have multiple or overlapping codes. See Figure 5.3, drawn from the Green team transcripts on Day 12, for an example of code co-occurrence. In this way, I could identify patterns of code occurrence and co-occurrence.

After coding all of the data for conjectures, I merged the conjecture codes with the systems thinking codes in the transcripts (see pages 83-86 in Chapter 4 for a discussion of how the transcripts were analyzed for systems thinking outcomes). For example, Segment 1, seen above in Figure 5.3, was coded as *Generalizing (Proposing Explanations); Complex*. From this, I created a table for each data source (e.g., session plan or transcripts) from each day that linked either single or clusters of embodied conjectures to levels and dimensions of systems thinking. See Table 5.3 for an example of these tables. The different colors were used to indicate code co-occurrence as it related to systems thinking level and dimension. The codes without colors were not linked to systems thinking segments. Thus, the Conjectures/Embodiments on the first three lines appeared in the same coded segment as the Systems Thinking Level and Dimensions on the first two lines. The last four lines of Table 5.3 represent the interaction in Segment 1 (Figure 5.3).

Table 5.3

Example of Conjectures/Embodiments linked to Systems Thinking Levels/Dimensions (drawn from Day 12, Green team transcripts)

Conjectures/Embodiments	**ST Level/Dimension**
TASK GOAL: Authentic activity (task structure (task goals (seeking “why” explanations	
Authentic activity (tools & materials (images, models, and graphs	Level 6, Dimension 2
Authentic activity (participation structures (support & scaffold (questions (deepening thinking	Level 7, Dimension 3
Authentic activity (participation structures (collaborative participation (productive	
Authentic activity (tools & materials (images, models, and graphs	
Authentic activity (task structure (task goals (seeking “why” explanations	Level 7, Dimension 1
Authentic activity (participation structures (support & scaffold (questions (deepening thinking	
Authentic activity (participation structures (collaborative participation (productive	
Authentic activity (participation structures (support & scaffold (questions (share, expand, clarify thinking	
Authentic activity (tools & materials (images, models, and graphs	
Authentic activity (participation structures (support & scaffold (questions (deepen reasoning	Level 3, Dimension 1
Authentic activity (participation structures (support & scaffold (questions (deepen reasoning	Level 3, Dimension 1
Authentic activity (participation structures (collaborative participation (productive	
Authentic activity (tools & materials (images, models, and graphs	Level 3, Dimension 1
Authentic activity (participation structures (support & scaffold (questions (deepen reasoning	Level 3, Dimension 2
Authentic activity (participation structures (collaborative participation (productive	Level 7, Dimension 1
Authentic activity (tools & materials (images, models, and graphs	Level 3, Dimension 1
Authentic activity (tools & materials (images, models, and graphs	Level 3, Dimension 1
Authentic activity (participation structures (support & scaffold (questions (share, expand, clarify thinking	
Authentic activity (tools & materials (images, models, and graphs	Level 6, Dimension 2
Authentic activity (participation structures (support & scaffold (questions (share, expand, clarify thinking	Level 3, Dimension 1
Authentic activity (task structure (task goals (seeking “why” explanations	Level 7, Dimension 3
Authentic activity (tools & materials (images, models, and graphs	
Authentic activity (participation structures (support & scaffold (questions (deepen reasoning	
Authentic activity (participation structures (collaborative participation (productive	

The third phase consisted of several steps. First, to determine if the implementation reflected the design, I examined the session plan, field notes, and transcripts from each day to look for presence or absence of each conjecture. Second, to link conjectures to outcomes, I examined the tables for each day to identify any patterns in the conjectures as they were related to the systems thinking outcomes. To do this, I counted the number of embodiment types related to a) each systems thinking characteristic, and b) each level of reasoning (*Simplistic*, *Developing*, or *Complex*). This allowed me to see if and how specific aspects of the design were related to specific systems thinking outcomes. Third, to detect interactions between conjectures, I created a matrix of co-occurring codes, which I considered to be interacting, and then calculated the percentage of each co-occurrence as it related to the learners' level of reasoning. I also examined the Conjecture/Embodiment tables from each day to identify any patterns of multiple (three or more codes) code co-occurrence as they were related to systems thinking outcomes. This method allowed me to see if specific interactions among conjectures may have mediated learning interactions that were linked to specific systems thinking outcomes, particularly to levels of reasoning. Finally, I extracted all of the challenges identified in the field notes, the transcripts, and the interviews to identify any patterns of challenges that related to design and implementation. Understanding these challenges was critical to revising the design and to understanding implementation.

With respect to data quality, I compared the data gathered by the learner research teams to data in the same dataset gathered by the implementation team and to data in a different, but comparable data set gathered by undergraduate students working with the same equipment.

Results

For the sake of clarity, I have organized the large amount of data by addressing three questions related to implementation and to systems thinking development. First, I review the relationship between implementation and design, discussing whether the design elements identified in the conjecture map were indeed evident in the implementation. Next, I review the relationship between design elements and systems thinking outcomes, identifying which design elements were associated with which outcomes and how the design elements appeared to interact with each other. Finally, I review the challenges that were identified in the field notes, transcripts, and interviews.

The Relationship between Design and Implementation

The first question I asked was whether the design elements identified in the conjecture map were evident in the implementation. Overall, the analysis of conjectures as they related to design suggested that there was a relationship between the conjectures and the unit sequence, but the analysis of the conjectures as they related to the transcripts revealed inconsistency in implementation. First, analysis of the lesson plans and field notes from the preparation meetings uncovered a clear relationship between conjectures, task goals, and unit sequence (see Table 5.4). On the first four days, when the learners were building background information related to the citizen science topic and question, the activities focused on the construction of theories, representations, and investigations (Conjecture #4), and the task goals included having the learners process ideas that emerged from their investigations and begin connecting the activities to systems thinking ideas. Day 5, when learners built representations of the ecohydrologic system and then used their representations to generate hypotheses related to the citizen science question, served to bridge the first half and the second half of the program as learners used representational tools to highlight specific and multiple aspects of the ecohydrological system. The primary goal of Day 5 was to help learners connect the activities in which they engaged to citizen science and systems thinking ideas. The last six days of the program (Days 6 through 12) focused on learner involvement in authentic activities, including learning to use the equipment, gathering and analyzing data, and designing a poster to share their findings. Over the course of these six days, the task goals included both connecting activities to citizen science and systems thinking ideas and seeking "why" explanations.

Table 5.4
Sequencing: Relationship between Days, Conjectures, and Task Goals

Day(s)	Conjecture	Primary/Secondary Task Goals
2 - 4	Provide opportunities, tools, and scaffolds to run observational ecohydrological investigations	1) Processing ideas 2) Connecting activities to systems thinking ideas
5	Identify and make explicit aspects of systems through representational tools	1) Connecting activities to citizen science and systems thinking ideas 2) Seeking "Why" explanations
6 - 12	Support and scaffold learner involvement in authentic activities	1) Connecting activities to citizen science and systems thinking ideas 2) Seeking "why" explanations

However, the analysis of the session plans related to the transcripts revealed inconsistency in implementation with respect to systems thinking (see Appendix I for an example of the connections between task design, preparation, implementation, and debrief). Table 5.5 shows the relationship between design and implementation by tracking the appearance of conjectures and task goals across the learning sequence. The pattern suggests that although the tasks goals were explicit in the session plans for all of the days, they were not always apparent in the transcripts.

Table 5.5
Relationship between Design and Implementation: Appearance of Conjectures and Task Goals Across the Learning Sequence

Conjecture	Goals	Day	Design (Lesson Plan)	Preparation (Field Notes)	Transcripts			Debrief (Field Notes)
					W	Y	G	
Investigations	Process ideas & Connecting activity to ST ideas	2	✓	✓	✓	✓	✓	✓
		3	✓	n/a	✓	✓	n/a	✓
		4	✓	✓	✓	✓	✓	✓
ST Explicit	Connect activity to ST ideas & Seeking "why" explanations	5	✓		✓	✓	✓	✓
Authentic Activity	Connecting activity to ST ideas & Seeking "why" explanations	6	✓		✓			
		7	✓		n/a			
		8[1]	✓		✓	n/a	n/a	✓
		9	✓		n/a			n/a
		10	✓	✓	✓			
		11	✓	✓	✓	✓	✓	✓
		12	✓	n/a		✓	✓	✓

W = Whole Group; Y = Yellow team; G = Green Team; n/a = no data available
[1]Rainy day

This absence was most noticeable on Days 7 and 9, when the learners gathered data in the park. A closer look at the transcripts revealed that the majority of the interactions that took place on these two days focused primarily on gathering high quality data and, as such, they contained few instances of talk related to connecting the activity (using equipment to gather data) to systems thinking. For example, on Day 7, the Yellow team had one systems thinking segment, while the Green team did not have any, and on Day 9, each team had one segment. This may have been related to the procedural rather than the conceptual way the tasks were implemented as the facilitators and learners were focused on using the equipment correctly to gather high quality data rather than spending time making conceptual links between the data collected and different aspects of the ecohydrological system. This suggests that it may be necessary to explicitly scaffold authentic practices if these practices are to be a means of building conceptual knowledge. Segment 2, drawn from the Green team transcripts, illustrates the type of interaction that occurred on both days. In this segment, the facilitator was helping Tim use the leaf porometer to gather transpiration data.

Segment 2

1 Facilitator: *so, who wants to do this?* [enter transpiration into the data sheet on the iPad]
2 Sean: *me*
3 Tim: *Will you hold this please?* [hands porometer display to Facilitator]
4 Sean: *is this the porometer?*
5 Facilitator: *yeah, it's ready. So okay*
6 Sean: *The leaves are really small*
7 Facilitator: *you want to quickly clamp it…*
8 Sean: *on a big one*
9 Facilitator: *on these, that's good*
10 Tim: *I'll hold… um*
11 Facilitator: *here, open it up and place them right here* [helping Tim] *and then close them*
12 Tim: *okay*
13 Facilitator: *and then hold it right there*
14 Sean: *What did we get? What are our readings?*
15 Tim: *got to wait*
16 Sean: *Oh, I think we got it. Oh…*
17 Tim: *no*
18 Sean: *oh, it's still going on*
19 Facilitator: [to Tim] *now you have to take it off*

There was a similar pattern on Day 6, when the learners practiced using the equipment and on Day 10, when the learners graphed their data. Although the task goals, which were related to connecting the activity to systems thinking ideas, appeared in the session plan and the whole group discussion on both days, there were no instances in either of the research team transcripts. A review of the transcripts and the field notes from these days suggested an interesting reason for this pattern. Similar to the data collection days, these tasks were implemented in a procedural rather than conceptual manner, with the facilitators and the learners focusing on following the steps of a procedure rather than on how each of the steps might lead to an overall understanding of the particular task. However, the reason for this more procedural approach appeared to be related to a lack of time and the need to "get the job done." Segment 3, drawn from the Yellow team transcripts from Day 10, illustrates the way the lack of time can influence task implementation. In this segment, the facilitator closely directed the details of learner activity, and, in one instance, focused on the unimportant detail of color (lines 5 – 7) rather than on what the graphs were communicating through their design and construction (lines 16 – 18). As a note, the lack of time was a frequently identified challenge, one that I will address it in more detail later in the chapter.

Segment 3

Facilitator: *You're just about out of time, you're not going to get your other graph built*
Fred: *Noooo*
Nancy: *We only have two minutes*
Facilitator: *Okay, what I'm going to have you guys do, is you're just going to finish the top graph. You guys need to get it colored*
Fred: *So should I color with this?*
Facilitator: *Go ahead, just color it in, doesn't matter what color it is*
Fred: *Like this for this?*
Facilitator: *No, that's good, keep going. Now as you're coloring these things in think about this, you need to label this, what are you going to label this?*
Nancy: *I don't know*
Facilitator: *Look at the chart and think about it*
Eric: *Volume water content*
Facilitator: *We've got to finish this. We need to think now, about what goes here* [points at the y-axis] *Okay gentlemen, I want you to think right here, this is the question. If you're going to label this y-axis, what is going to go right on that y-axis?*
Isabel: *This is water lost to transpiration*
Facilitator: *Okay, put it on there then, good. And then what is this whole graph, chart telling us? So, what is the name, what is your plot telling you there?*
Nancy: *It's telling us about how much water is lost through transpiration.*
Facilitator: *So, give your bar chart, your bar graph, a title. Just one big word. What is that word?*
Nancy: *Transpiration*
Isabel: *Transpiration!*
Facilitator: *Okay, write that at the top*
Nancy: *We should do it in a color*
Facilitator: *Okay, let's get everybody back to their tables*

The Relationship between Design Elements and Systems Thinking Outcomes

The second question that I asked explored the relationship between design elements and systems thinking outcomes. It is important to note that the corpus of data was extensive, so I limited my analysis to a consideration of *Task Goals*, *Relational Tools*, and *Scaffolds*. I chose these specific design elements, or embodiments, because they were the most commonly coded aspects of the design. In this section, I present the results related to two dimensions of this analysis. First, I examined the relationship between individual conjectures as they were embodied in the task structures (i.e., task goals), tools and materials (i.e., relational tools), and participation structures (i.e., scaffolds) and the systems thinking outcomes (i.e., characteristic and level of reasoning) (see Table 5.6 for the systems thinking characteristics). Second, I examined the relationship among clusters of embodiments as they related to systems thinking outcomes. An initial exploration of each team's transcripts revealed that the pattern of embodiment and interactions was similar across all days of implementation for both the Green team and the Yellow team, so the findings reported here are those for all systems thinking segments over all of the days.

Table 5.6
Eight Emerging Characteristics of Systems Thinking (Ben-Zvi Assaraf & Orion, 2010)

1. The ability to identify, describe, and explain observable components and common processes of the ecohydrological cycle
2. The ability to identify, describe, and explain the static relationships between or among systems components
3. The ability, to identify, describe, and explain the dynamic relationships within the system
4. The ability to organize system components, processes, and their interactions within a framework of system relationships
5. The ability to identify cycles of matter and energy within the system
6. The ability to identify, describe, and explain hidden dimensions of the system
7. The ability to generalize—to make hypotheses, propose explanations, and solve problems based on an understanding of systems' mechanisms
8. The ability to think temporally: retrospection and prediction

The relationship between embodiment and systems thinking.

In this section, I first detail the results regarding the relationship between the embodied conjectures and the systems thinking outcomes, and then I present the results regarding the relationship between the embodied conjectures and the level of reasoning. I examined the systems thinking characteristics and levels separately to hone in on the targeted relationships.

Embodiment and systems thinking characteristics.

Task goals. With respect to task goals, analysis of the transcripts revealed that the *Processing ideas* code was primarily associated with systems thinking characteristics 1 through 3, that *Connecting activities to systems thinking ideas* was associated with characteristics 1, 2, 6, and 7, and that *Seeking "why" explanations*, though having a much broader distribution, was primarily associated with systems thinking characteristics 6 through 8 (see Table 5.7).

Table 5.7
Number of Systems Thinking Segments Related to Conjecture Embodiment and Systems Thinking Characteristics

Embodiment	Systems Thinking Characteristics							
	1	2	3	4	5	6	7	8
Task Goals								
Processing ideas	20	5	14	4			2	
Connecting activities to ideas	20	2				4	28	
Seeking "why" explanations	8	6	19	1	2	25	31	11
Relational Tools								
Images, Models, Graphs	23	9	6	2	6	24	8	
Scaffolds								
Coaching and modeling	7	2	2					
"Share, expand, or clarify" questions	15	10	11	1	2	17	18	8
" Deepening reasoning" questions	15	5	16	1	5	17	19	3
"Listen to others" questions	3		2					
"Thinking with others" questions	8	7	5	1	1	4	27	

When taken with the designed sequence (Table 5.4) and the appearance of learning goals across the sequence (Table 5.5), these findings were what I expected to see, and they offer support for the conceptual model on which the design is based. For example, I designed the tasks for Days 1 – 4 to engage learners in investigations that offered opportunities to process ideas related to systems thinking characteristics 1 – 4, and these tasks were implemented as they were designed. Thus, I expected to see a clear relationship between task goals and systems thinking outcomes. Perhaps the most interesting outcome of this analysis is that it highlighted the importance of the relationship between the design and the implementation. This was most apparent when looking at the *Connecting activities to systems thinking ideas* and systems thinking characteristics. The activities associated with *Connecting activities to systems thinking ideas* goals were designed to bridge between *Processing ideas* related to lower level characteristics and *Seeking "why" explanations* related to higher level characteristics; however, they did not serve this function. When looking at Table 5.6, it appeared that this might have been related to implementation; the activities in which the learners engaged on these days were not implemented as designed.

Scaffolds. The analysis of the transcripts related to scaffolds revealed that different scaffolds were used as increasingly complex systems thinking characteristics were introduced (Table 5.7). Several interesting patterns emerged. First, although the lower level characteristics (e.g., characteristics 1 – 3) were scaffolded in multiple ways, *Coaching and modeling* were only used to support systems thinking at these lower levels. It may be that as learners begin to grapple with increasingly complex ideas, they need support that ranged beyond demonstrating tasks, offering hints, giving feedback, and providing reminders. Instead, they need support structures that ask them to clarify their thinking, to provide evidence or reasoning, and to respond to the ideas, evidence, or reasoning of others. The pattern of associations between instances of *Share, expand, or clarify* questions and *Deepening reasoning* questions and increasingly complex levels of systems thinking also supported this finding. Perhaps the most interesting association was that between instances of *Thinking with others* and the ability to generalize (characteristic #7), which suggested that, as learners tackled increasingly complex concepts and ideas, the type of questions asked allowed them to leverage the thinking of others to build a more coherent understanding of the ecohydrological system.

Relational Tools. Finally, the analysis of the transcripts related to relational tools, coded as *Images, models, and graphs*, showed a pattern similar to that seen with the task goal of *Seeking "why" explanations* as well as the scaffolds of *Share, expand, or clarify* and *Deepening* *reasoning* in that it was associated with multiple characteristics of systems thinking. This suggested that these tools were used across the intervention to support task goals and act as scaffolds for learning. Thus, these tools may have been used in concert with other embodiments to provide a concrete view of abstract ideas. In doing so, they offered a focal point around which the task goals were achieved and the support for learning was provided. In a later section, I discuss the interactions between the task goals, relational tools, and embodied conjectures as they were related to systems thinking outcomes.

Embodiment and level of reasoning.

Analysis of the relationship between embodiment and level of reasoning (*Simplistic*, *Developing*, and *Complex*) revealed that task goals, relational tools, and scaffolds were associated with all levels of reasoning, and no distinctive pattern emerged that suggested one type of task goal or scaffold provided greater leverage for increasing complexity of reasoning (Table 5.8). Perhaps the only finding of interest is that, similar to the findings related to systems thinking characteristics, *Coaching and modeling* shows a stronger association with *Simplistic* and *Developing* than with *Complex* reasoning. Findings from the study of systems thinking outcomes (see pages 106 – 107 in Chapter 4) suggested that, to some extent learners did engage in increasingly complex talk. Thus, with respect to reasoning, it may be that higher levels of reasoning were associated with interactions among different embodiments.

Table 5.8
Number and Percentage of Systems Thinking Segments Related to Conjecture Embodiment and Level of Reasoning

Embodiment	Level of Reasoning			
	1 – Simplistic	2 – Developing	3 - Complex	Total #/ (%)
Task Goals				
Processing ideas	16 (35)	12 (27)	17 (38)	45 (100)
Connecting activities to ideas	8 (31)	10 (38)	8 (31)	26 (100)
Seeking "why" explanations	48 (47)	28 (27)	27 (26)	103 (100)
Relational Tools				
Images, Models, Graphs	41 (39)	36 (34)	29 (27)	106 (100)
Scaffolds				
Coach and modeling	3 (27)	7 (64)	1 (9)	11 (100)
Share, expand, or clarify questions	29 (43)	26 (38)	13 (19)	68 (100)
Deepening reasoning questions	28 (34)	21 (25)	34 (41)	83 (100)
Listen to others questions	0 (0)	5 (71)	2 (29)	7 (100)
Thinking with others questions	20 (32)	19 (30)	24 (38)	63 (100)

Interactions among embodiments related to levels of reasoning.

In this section, I present the results regarding the relationship between embodied conjectures as they interacted and systems thinking outcomes, specifically levels of reasoning. Analysis of the transcripts revealed that, in general, there was more talk at a lower level as learners developed the ability to identify aspects of each systems thinking characteristic (*Simplistic*), but they did become increasingly able to describe (*Developing*) and to explain (*Complex*) ecohydrological system phenomenon in context. This pattern was not consistent across all characteristics, and the analysis by embodiment did little to shed light on this finding. However, a more detailed review of the transcripts revealed that increasingly complex levels of reasoning were related to interacting aspects of the design that appeared to be acting in concert to support reasoning. With respect to the talk segments coded as *Complex* reasoning, 52 of the 60 total segments were associated with the co-occurrence of the target codes (see Table 5.9).

Table 5.9
Embodiment Interactions: Percentage of Total Complex Segments by Interaction (N=52)

	Processing ideas	Connecting activities to ideas	Seeking "why" explanations	Images, Models, Graphs	Coaching and modeling	Share, expand, or clarify	Deepening reasoning	Listen to others	Thinking with others	**Total**
Processing ideas										
Connecting activities to ideas	2%									
Seeking "why" explanations	--	--								
Images, Models, Graphs	--	--	2%							
Coaching and modeling	--	--	2%	--						
Share, expand, or clarify	--	2%	10%	2%	--					
Deepening reasoning	15%	--	12%	21%	--	--				
Listen to others	--	2%	--	--	--	--	--			
Thinking with others	--	--	12%	12%	--	2%	6%	--		
Total	17%	4%	37%	35%	--	2%	6%	--		100%

An analysis of these talk segments revealed that the majority of the segments at this level were associated with the co-occurrence of *Deepening reasoning* and *Images, models, graphs* (see Table 5.9). Thus, when facilitators combined questions that asked for evidence or reasoning ("What is your evidence?", "What patterns do you see in these data?", "Do you think that data/answer/argument is reasonable?", and "How did you come to that conclusion?") and that challenged their thinking ("Does it always work this way?", "How are these two ideas related?" and "How does this idea compare to her idea?") with the use of relational tools, learners were able to visualize systems and data, create connections between multiple aspects of the system, and build increasingly complex explanations. Other promising interactions include tasks that require learners to produce "why" explanations that are supported by questions that deepen their reasoning and intellectual collaboration and the use of relational tools. Segment 4, drawn from the Yellow team's transcript on Day 11, illustrates this level of reasoning as it related to an interaction among different embodiments. In this conversation, the Yellow team was reviewing their graphs to draw arrows to represent the relative amount of water lost through transpiration for each landscape type.

Segment 4

Abby: *With the transpiration, I think there'd be less water in it because it's less plants.*
Facilitator: *Does that reflect what you see here?*
Isabel: *Question mark*
Facilitator: *That there's less water being transpired? Because remember, what you're saying has got to be based on the data. It can't be based on what you guess.*
Abby: *Yeah, because there's less than all the other ones*
Facilitator: *So what would our arrow look like?*
Nancy: *I think…*
Isabel: *I think it'll look like this*
Abby: *I think it'll be thinner and not fatter because then it represents less water*
Isabel: *But I think it should go from this to this to this for transpiration*
Facilitator: *Is this, like this one is what you think?*
Abby: *Um, yeah, that one*
Facilitator: *Do you all agree?*
Isabel: *Can I draw it?*
Facilitator: *Wait, we don't have agreement yet, we don't have a consensus*
Abby: *Like, I think it would be between that one and that one*
Isabel: *Oh, I was thinking this one and this one. Because this is sort of-ish close to that. Now, I'm not sure*
Facilitator: *Between that one and that one? Now, look at your data*
Isabel: *Because this is sort-of-ish close to that*
Facilitator: *What do you guys think? Fred, what do you think?*
Fred: *I don't know*
Facilitator: *Why not?*
Fred: *I said I don't know*
Facilitator: *Well, what do you think?*
Isabel: *Why don't you know?*
Facilitator: *Because they're talking about drawing the arrow here and there's one group that's saying between this one and this one and one group that's saying between this one and this one. So look at the three different the three different things and think about how close they are. And one argument is that they're all pretty close, all the numbers are pretty close to each other*
Fred: *I would say in the middle since they're both saying the middle. Okay, so this one is 23 off, this one is like, oh wait*
Nancy: *I have a question. So, when I'm looking at these charts, I can see that in the transpiration, it has just like not much more than it does in under restoration and it has a lot less in restored, and I'm thinking well in restored, it's supposed to be a lot better, but it's not that much better if I look at it now because this only has a little bit more but this has a lot less, why don't you keep it under restoration?*
Eric: *But maybe, but maybe…*
Isabel: *You are so smart.*
Facilitator: *Wait, wait, wait, let's listen to what Eric has to say*
Eric: *But maybe it's almost done being restored*

With respect to the systems thinking segments coded as *Developing*, 50 of the total 76 segments were associated with the co-occurrence of the target codes. Although the pattern is less clear, there appeared to be some similarities to the *Complex* segments. The *Seeking "why" explanation*s, the *Images, models, graphs*, the *Deepening reasoning*, and the *Think with others* codes combined in various ways to support increasingly complex reasoning (see Table 5.10). The majority of the talk segments were associated with tasks that focused on explanations combined with scaffolds that supported community knowledge building. As with *Complex* reasoning, the use of images, models, or graphs may have helped to make abstract concepts more concrete. The use of relational tools combined with questions that asked learners to expand or clarify their thinking ("Can you say more about that?" and "What do you mean by that?") may have had the effect of making learner ideas public and available for team consideration.

Table 5.10
Embodiment Interactions: Percentage of Total Developing Segments by Interaction (N=50)

	Processing ideas	Connecting activities to ideas	Seeking "why" explanations	Images, Models, Graphs	Coaching and modeling	Share, expand, or clarify	Deepening reasoning	Listen to others	Thinking with others	**Total**
Processing ideas										
Connecting activities to ideas	--									
Seeking "why" explanations	--	--								
Images, Models, Graphs	--	2%	--							
Coaching and modeling	2%	--	4%							
Share, expand, or clarify	2%	4%	2%	14%	--					
Deepening reasoning	2%	--	12%	14%	--	--				
Listen to others	2%	4%	--	--	--	--	--			
Thinking with others	--	2%	18%	8%	--	2%	6%	--		
Total	8%	12%	36%	36%	--	2%	6%	--		100%

Segment 5, drawn from the Green team's transcript of Day 5, illustrates the interaction between *Seeking "why" explanations* and *Thinking with others* as the learners briefly discuss whether plants get water through their roots or their leaves (Lines 9 – 38).

Segment 5

1	Facilitator:	*Okay, I think there's one more arrow that you guys could draw that'd be really helpful*
2		*It happens before transpiration. How do those plants get the water in the first place?*
3	Sean:	*The rain, rain, no the…*
4	Noah:	*Yeah the rain*
5	Sean:	*Water going to it*
6	Ethan:	*The ground water*
7	Facilitator:	*So what do they use to get water?*
8	Sean:	*Rain*
9	Facilitator:	*How do plants get water?*
10	Ethan:	*roots*
11	Noah:	[yelling] *Leaves! Leaves! Leaves!*
12	Ethan:	*roots*
13	Facilitator:	*Ethan just had a good idea*
14	Sean:	*Oh yeah the roots*
15	Facilitator:	*So they get their water from the soil*
16	Noah:	*Also they could get it from leaves because leaves basically are a root*
17	Ethan:	*[Roots] collect it but then it goes in the plant*
18	Facilitator:	*Do you guys agree with that?*
19	Sean:	*Yeah, I agree with Ethan*
20	Facilitator:	*Who do you agree with, Sean?*
21	Sean:	*Ethan*
22	Facilitator:	*What do you think of Noah's statement?*
23	Sean:	*What did you say?*
24	Noah:	*That basically the leaves collect it but then they like…*
25	Sean:	*Well, the plant… I disagree because the…*
26	Facilitator:	*Good job, Sean*
27	Sean:	*The plants need the water in the first place to have the leaves. The leaves*
28		*wouldn't grow without the water.*
29	Noah:	*Well, true, but how about a seed? You plant a seed, it gets water but how does it get*
30		*water? It doesn't burst.*
31	Facilitator:	*Well, what's the, have you guys ever done an experiment where you have a seed in class,*
32		*what's the first thing that happens to a seed?*
33	Noah:	*Roots, grows roots*
34	Sean:	*roots*
35	Facilitator:	*Roots… It needs water*
36	Sean:	*So roots*
37	Ethan:	*The water breaks it open and then there's roots*

With respect to the systems thinking segments coded as *Simplistic*, 77 of the total 97 segments were associated with the co-occurrence of the target codes. Again, analysis revealed a similar pattern with *Seeking "why" explanations* interacting with *Share*, *Expand, or Clarify* and *Deepening reasoning* and *Images*, *Models*, *Graphs* interacting with *Deepening Reasoning* (see Table 5.11).

Table 5.11
Embodiment Interactions: Percentage of Total Simplistic Segments by Interaction (N=77)

	Processing ideas	Connecting activities to ideas	Seeking "why" explanations	Images, Models, Graphs	Coaching and modeling	Share, expand, or clarify	Deepening reasoning	Listen to others	Thinking with others	**Total**
Processing ideas										
Connecting activities to ideas	--									
Seeking "why" explanations	--	--								
Images, Models, Graphs	1%	4%	3%							
Coaching and modeling	1%	--	1%	--						
Share, expand, or clarify	1%	1%	17%	6%	--					
Deepening reasoning	12%	--	17%	17%	--	--				
Listen to others	--	--	--	--	--	--	--			
Thinking with others	--	--	9%	4%	--	3%	3%	--		
Total	15%	5%	47%	27%	0%	3%	3%	0%		100%

Overall, this analysis suggested that interactions among the various embodiments worked together to support increasingly complex thinking. Moreover, there were additional instances of code co-occurrence that are of interest. For example, a review of the Conjecture/Embodiment tables revealed that the *Thinking with others* code regularly occurred with the *Productive collaboration* code, both of which were related to Participation Structures. There were also instances when three codes would co-occur. For example, on the day when learners developed their representations of where water goes (Day 5), *Connecting ideas to systems thinking ideas*, *Share, expand, or clarify*, and *Images, models, graphs* were related to higher levels of complexity in learner reasoning. On Day 11, when learners used their graphs to make a representation of their data to compare to their hypothesis, *Seeking "why" explanations* appeared with *Think with others, Deepening thinking*, and *Images, models, and graphs*. The systems thinking segments associated with this co-occurrence demonstrate complex reasoning at a high systems thinking level. Segment 6 is the interaction associated with these multiple codes.

Segment 6

Facilitator: *Okay, let's think about that. Our last thing we want to think about is why? Why might that be the case? What might be some reasons or explanations for why that's the case? In my group, we came back to one thing a lot. We kept coming back to it.*
Sean: *So did we.*
Facilitator: *So the yellow group, what did we talk about a lot in our group? Yes, Nancy?*
Nancy: *I thought that we talked about like, the questions or…*
Facilitator: *Yes, well, when we were thinking about why, yes a lot of questions, why our data didn't seem to match our hypothesis, and Eric actually brought up a really interesting question.*
Eric: *Some restored plots could be more restored than others*
Facilitator: *So he came up with this idea of the plots. It could be that the plots are really different*
Isabel: *It's true*
Facilitator: *The differences in plots and not only the differences in plots, but we also talked about…did anyone else talk about plots?*
Facilitator2: [to green team] *You guys did*
Sean: *Yeah, we did*
Facilitator: *What did you guys say?*
Sean: *Well, we, well our data was really weird*
Facilitator: *It was really weird, huh?*
Sean: *Yes*
Facilitator2: *So what were the reasons you thought that, remembering, we talked about locations of the plots*
Sean: [begins shuffling papers around] *Yes, so, for our transpiration, for under restoration and restored, restored had 90% to 100% plant coverage and under restoration has 10% to 20%, but they like almost the same*
Facilitator: *But that's really weird and you wouldn't expect that. So why might that be?*
Sean: *I'm uncertain*
Facilitator: *Noah, what did you want to say?*
Noah: *And also there could be um, different spots and the hills could be trapping, keeping the wind down and also it could be like next to be like down ways so when it rains, all the rain will pour down in that spot…*
Facilitator2: *Do you mean the canyon?*
Noah: *Yeah and also it could be right next to a river*
Facilitator: *Okay, so….*
Sean: *And also it was weird for the soil moisture because for the restored, we, restored was less than degraded for us*
Facilitator2: *Did anyone else encounter hard soil?*
[learners start yelling yes]
Facilitator2: *Where was it?*
Sean: *At the plots*
Noah: *Maybe…*
Facilitator: *Wait, you're all talking at one time and we can't hear. So where was the soil the hardest when you were putting in the soil moisture meter, for those of you who used it, where did*

you think that it was the hardest?
Noah: *In the ah place.*
Sean: *We didn't go to the degraded though, did we?*
Facilitator: *Henry, did you want to answer? Yeah, where?*
Henry: *Uh, the degraded*
Facilitator3: *Just think about, where, what was the one that was different?*
Henry: *Ohhh, the restored*
Sean: *Yeah*
Isabel: *That was completely different.*
Facilitator: *So…*
Ethan: *Oh, I have…*
Facilitator: *So, this harder soil, so maybe that affected the readings of soil moisture that we got*
Sean: *That shouldn't matter*
Isabel: *That's smart, I see your point*
Facilitator3: *What was, I think you mentioned it, Mark*
Sean: *I agree with you*
Facilitator: *Wait, wait*
Facilitator3: *So if we put it in the soil and it's hard, can we go very deep?*
Sean: *No. I disagree*
Facilitator3: *Where is a lot of the water?*
Mark: *It's affects the readings*
Sean: *Well, it shouldn't matter. Should it?*
Isabel: *Yeah, it should*
Facilitator: *Okay, there's an interesting question, we're going to have to wrap it up on this one. Should the hardness of the soil matter for the soil moisture reading?*
Mark: *Yes*
Facilitator: *I want you to listen closely* [Sean starts to talk] *Wait. They have an explanation for it. You can't actually respond to an explanation they haven't given. Mark, what's your explanation?*
Mark: *Uh, so if the soil is hard, you can't go deep enough to find the water in the ground.*

Another common code interaction, one that was unrelated to systems thinking, occurred on the days when the teams learned to use the equipment (Day 6) and then collected data in the park (Days 7 and 9). In these instances, *Coaching and modeling*, a form of scaffolding, occurred with *Data Collection Equipment, Data Collection Protocols, or Data.* Interestingly, there were few systems thinking segments on these days—rarely were the learners asked to make connections between the data they collected and systems thinking ideas. This suggested that these tools, which could have been used as relational tools in support of systems thinking, were used instead as physical/material tools in support of the collection of high quality data.

Before addressing implementation challenges, it is important to make note of the quality of the data collected by both the teams. Analysis of the data suggested that the learners were capable of using the equipment to gather and record high quality transpiration, soil moisture, and weather data. They were also capable of recognizing when the data they collected did not make sense. However, the data was ultimately not usable by environmental researchers. The issue of unusable data is one of the challenges that was identified and will be discussed at length in the next section.

Implementation Challenges

The third question that I asked related to the challenges associated with designing and implementing collaborative citizen science with specific learning outcomes—systems thinking—with 9 and 10 year old learners. Analysis of the field notes, the transcripts, and the focus group interviews revealed a number of challenges. I sorted these challenges into the following categories: a) Issues related to the Citizen Science research, b) issues related to the tools and materials that we used, c) issues related to connecting the investigations/authentic activities to systems thinking ideas, d) issues related to building and maintaining a collaborative community, and e) issues with time. Interestingly, these challenges mapped very clearly to the design principles and conjecture for learning, and each will be discussed in depth in the next section.

Challenges Encountered and Lessons Learned

For the sake of clarity, I have organized the discussion of challenges and lessons learned by the related design principle. It is important to note that there are areas of overlap between each category, so some of the concerns may be discussed in several areas. First, I review challenges related to designing and implementing citizen science research, focusing on design decisions as they related to the topic, question, data collection, and data analysis; trade-off points between research and education, both in the design and in the implementation; and data collection and data quality. Second, I discuss challenges related to tools, focusing particularly on the way that tool use was not, but could be, designed to support learning. Third, I review challenges related to connecting the activities to systems thinking ideas, addressing issues with scaffolding as it related to either citizen science or systems thinking outcomes. Fourth, I discuss challenges related to time, focusing primarily on time as it related to building new conceptions and addressing misconceptions. Finally, I discuss challenges related to building and maintaining a collaborative community, providing insight into the way this community developed over time and discussing design decisions as they related to maintaining this community.

The Challenge of Citizen Science

The consensus among both the facilitators and the learners was that the citizen science context was an integral part of the design. Both Alice and Laura felt that it situated the learning in an authentic context that provided concrete examples of abstract concepts and allowed learners to build knowledge and make generalizations about the real world. Segments 7 and 8, drawn from the focus group interview with the designers/facilitators, illustrate these points.

Segment 7

Alice: *I was very, very impressed with the intervention's effects on the students. Coming in, a lot of the students seemed like they had a vague idea of a lot of the topics we were covering, but there was a lot of misconceptions that appeared, and through the structure of the citizen science component, so actually having to do research, the structuring that we did through scaffolding, and the way the information was presented, I could really see the information sort of clicking with the students, and the way that they were sort of able to grasp these concepts that even some college students don't really understand was really impressive…*

Joan: *When you say structure of the program, are you referring to the citizen science or to the way we designed it? Do you think it would have been as effective had we pulled the citizen science component out and just…*

Alice: *I do think that it wouldn't have been as effective without the citizen science. I think that for the students, that was their favorite part. I mean, it is important, you need to have classroom time to introduce the concepts, but without the real world application, I don't think it would have been as effective*

Laura echoed these sentiments later in the interview.

Segment 8

Laura: *I agree with Alice on the fact that citizen science was an essential component of the program. I think it gives students a way to really feel important and involved and a meaningful part of the actual science going on—make their own generalizations and pool their knowledge to be a part of that. And to be a major component, not just a minor student component like they usually are*

When the learners were asked about citizen science, they responded in a similar fashion. Segments 9 – 11 were drawn from an informal discussion with the learners at the end of the program.

Segment 9

Isabel: *I felt beautiful when I was here. I sort of felt that I had a great responsibility in my hands because I was being a scientist*

Segment 10

Nancy: *I thought it was really fun and it was really interesting because we never did this kind of stuff in class, so it was fun to do something different*

Segment 11

Learner: *I liked working with everybody*

Although there was general agreement that the citizen science context added to the learning environment, there were several challenges that need to be addressed. The first of these challenges relates to the design of the research that serves as the foundation for the learning intervention. In their work on designing citizen science as a space for developing science literacy, Bonney and colleagues (2009) presented a sequence for designing and implementing a citizen science project, detailing the steps involved in developing a project (see Table 5.12).

Table 5.12

Sequence for Developing a Citizen Science Project (Bonney et al., 2009)

1. Choose a scientific question.
2. Form a scientist/educator/technologist/evaluator team.
3. Develop, test, and refine protocols, data forms, and educational support materials.
4. Recruit participants.
5. Train participants.

6. Accept, edit, and display data.
7. Analyze and interpret data.
8. Disseminate results.
9. Measure outcomes.

This sequence proved quite useful during the initial design phase of this research, guiding the decisions that needed to be made at each step. The sequence, however, proved to be too linear once we began implementing the program, and, as such, did not represent the need for iteration that characterized our collaborative citizen science. For example, the details of step 2 clearly delineate roles and responsibilities of each team member. In the Bonney et al. sequence, the researcher is required to ensure the project's integrity, to develop protocols that will lead to the collection of high quality data, and to analyze and publish data after they are collected; and the educator is required to explain the project's importance and significance to participants, to field-test the protocols, to develop clear and comprehensive project support materials, and to provide appropriate feedback to the participants (2009). We found, however, that such a clear delineation of responsibilities could not adequately characterize our need for ongoing interactions between researchers, designers, and educators, especially since this project had the dual goals of collecting high quality data and meeting clearly defined learning outcomes. For example, the data collected by the participant research teams was neither usable by the researcher nor used effectively as a tool for developing systems thinking by the educators. There were a number of reasons for this, including the lack of a comprehensive data management plan (which serves to make the data more trustworthy), the design of the data collection protocols and the data sheets, and the determination of plot locations. Although the numbers that were recorded accurately reflected the transpiration rates and soil moisture amounts, the data was collected in plots that were not representative of the landscape types. Moreover, we only collected data at one plot per landscape. As a note, plot location may have been the major contributor to our questionable data and unexpected findings—the plots were chosen for logistical rather than research reasons (two teams had to share equipment, so the plots had to be close together), and two of the plots—degraded and under restoration—were located in a canyon that funneled water down to the sites. Thus, it seems clear that had the educators worked more closely and iteratively with the researchers on all aspects related to data collection and management, the data may have been more usable for both research and learning purposes. Thus, this suggest that both researchers and educators would benefit from closer collaboration, especially when designing and implementing collaborative citizen science projects, where one goal is to involve participants more deeply in the processes of science (Bonney et al., 2009). This also suggests that collaborative citizen science is a more costly endeavor than contributory citizen science because, as participants take on a larger role, both researchers and educators need to be more deeply engaged in the project.

Similarly, I found that step 6 from the sequence (accept, edit, and display data) and step 7 (analyze and interpret data) were closely and iteratively connected with step 3 (develop, test, and refine protocols, data forms, and educational support materials). The data sheets, in particular, were revised multiple times over the course of the implementation as we sought to meet the researcher's need for high quality data and the learners' need for learning support. We were never fully successful in our redesign efforts, as data collection remained isolated from systems thinking and data was not usable. This was evident in the transcripts from Days 7 and 9—both data collection days, when there were very few systems thinking talk segments. Moreover, once we had our data, we were unsure of how to have the learners analyze it and once again made decisions that were ineffective for both the learning and the research. This was especially apparent on Day 10, when the learners graphed their data. Rather than developing a conceptual view of the ecohydrological system, learners gained knowledge of graphing—which, though important, was unconnected to the learning goals of the program.

These findings raised questions about the different types of knowledge that researchers, designers, and educators have and the ways in which their knowledge can be leveraged in the design and implementation of collaborative citizen science. Because we define citizen science as generating usable and trustworthy data, the science research must drive the design of the intervention. However, when there are learning outcomes to consider, one of the key challenges of citizen science is to identify and then design and implement around both research and education needs so that the learners achieve the learning outcomes while maintaining the rigor of the science research, the quality of the data, and the authenticity of the experience (Dickenson & Bonney, 2012; Shirk et al., 2008).

Thus, I suspect that taking a systems rather than a linear approach to the design and implementation of collaborative citizen science may yield both higher quality data and better learning outcomes. Such an approach requires both identifying trade-off points in the design and implementation and increasing the ongoing researcher, designer, and educator interaction to navigate both the initial and the in-the-moment decisions that must be made. For us, these trade-off points included decisions about aspects of the curriculum related to developing background knowledge and analyzing data, aspects of the research related to collecting and analyzing data, and aspects of time, which will be discussed later. For example, how much background knowledge do the learners need to a) collect high quality data, and b) connect the activity of data collection to systems thinking ideas? With respect to data collection, a) how much data did we need to collect for the researcher, and b) how did we balance the researcher's need for data with our need to achieve our specified learning outcomes? These questions, and others like them, relate to the ways in which the research and education resources were leveraged in both the design and the implementation.

The Challenge of Tools

The use of tools both supported the authenticity of the Club and constrained the opportunities to learn. Although the learners very much enjoyed working with the tools (see Segment 12, drawn from an informal discussion with the learners at the end of the program), the facilitators recognized the ways in which the tools, especially combined with our lack of time, limited the amount of work we could do (see Segment 13, drawn from the focus group interview with the facilitators).

Segment 12

Tim: *It was fun because when I first used the equipment, it was fun because I didn't know what I was doing. Sometimes you can break it*

Segment 13

Alice: *I think definitely the citizen science component was beneficial. Of course, there were some drawbacks. It was hard to organize all of the data collection, and we only had a limited amount of data collecting tools. Time was also an issue. I wonder in the future, if this is going to be something that is [sustained], if having that equipment and having it available might [be possible]*

We used a number of different tools in the design and implementation of the Club. The data collection equipment, protocols, and data sheets are all material/physical tools that allowed us to do the real work of science research. We used these tools to gather data on transpiration, soil moisture, and weather—all related to important ecohydrological processes. We also used relational tools, which are intellectual devices that our learners used to visualize the task they were performing (e.g., representations and graphs) (Ambitious Science Teaching, 2015; Quintana, Reiser, Davis, Krajcik, Fretz, Duncan, Kyza, Edelson, & Soloway, 2004), to organize the data and information they were gathering (e.g., science notebooks), and, in some instances, to supplant their thinking as it related to more procedural tasks (e.g., data collection protocols) (Pea, 2004). Finally, we used social tools to help learners collaboratively construct socially shared knowledge, providing access to shared information and shared knowledge-building relational tools.

Over the course of the design and implementation, it became apparent that a single object could take on the characteristics of different tool types, depending on how it was used in a particular context. For example, the science notebook was used as a relational tool on Day 11, when learners were comparing their data to their hypothesis. They often referred back to the representation of water flow they constructed on Day 5 to the graphs they made on Day 10. In general, it was also designed as a device to afford collaboration—each team shared a notebook and shared the task of recording their observations in the notebook. This allowed learners to construct knowledge as they engaged in the ongoing processes of comparing and checking their understandings with the ideas that were being rehearsed by and with others (Edelson, 1998; Mortimer & Scott, 2003).

Although a number of tools served multiple purposes, there were several tools that were under-designed. Through the transcript analysis, it became clear that learners did not connect the activity of data collection to systems thinking ideas. The learners used leaf porometers, soil moisture meters, and weather stations to gather and record data on important ecohydrological processes; however, the information they provided was conceptually meaningless. Had they used these physical tools in conjunction with relational tools, the activity could have been leveraged to help learners see the connections between equipment, data, and systems thinking characteristics. Both the data collection protocols and the data sheets are tools that, with revision, may afford this type of intellectual work. These objects could be redesigned such that they take on the dual role of a physical/material tool and a relational tool. Their use as supports for learning, along with facilitator scaffolding that extends beyond coaching and modeling (which were used to the exclusion of other types of scaffolding on Days 7 and 9) (Collins, 2006), would help learners forge stronger links between the data collection activity and systems thinking components, processes, and relationships (Ambitious Science Teaching, 2015; Tabak, 2004).

The Challenge of Connecting Activities to Systems Thinking Outcomes

Although it has been discussed in the two previous sections, this particular challenge deserves a section of its own. In Chapter 4, we saw that there were differential systems thinking outcomes. The two 5th graders had a more complex perception of the ecohydrological system at the end of the learning process compared to the 4th graders. As was discussed, this could be attributed to age-related developmental ability, to the fact that they were learning about the water cycle in school at the same time they were participating in the Club, or—and I think this most likely (though impossible to disentangle with these data)—to a combination of both. Thus, it is important to consider how the design afforded a higher level of learning for some and a lower level of learning for others. Segment 14, drawn from the focus group interview, addressed this challenge.

Segment 14

Jacque: *I agree with the idea that systems thinking was one of the important goals. I feel like that goal was accomplished in some of the students… But the interview that I did with the student—I'm not sure he was quite there yet. He was one of the younger students in the group, and it was like he knew all of the pieces, but he didn't know how they all fit together. So, I don't know how it is in the whole group, but the one student who I really talked to in depth, I wasn't really sure that he understood that this is a system.*

One possible explanation for the differences in learning across the Club participants is that program implementation did not provide robust opportunities for learners to make connections between what they were doing and what they were supposed to be learning. There are two instances when this lack of connection as it related to program design were apparent. First, on the days when the learners learned to use the equipment (Day 6) and then went into the field to gather data (Day 7 and Day 9), learners were engaged in activities that were designed to help them make the connections between the task and the systems thinking ideas. However, the execution of activities was more procedural than conceptual in nature, primarily because facilitation involved scaffolding the learning through coaching and modeling rather than questioning for depth and collaboration. This is likely related to the notion of trade-off moments—facilitators had to choose between making sure that the learners are competent to safely and correctly use the equipment to gather high quality data or helping the learners develop conceptual understanding components, processes, and relationships that define the ecohydrological system.

One possible solution to this challenge lies in the literature on scaffolding and in findings related to embodied conjectures and systems thinking outcomes and in the literature on scaffolding. First, there is an open problem in the learning sciences related to the nature and amount of learner support structures that we design into and provide during the implementation of the designed experiences. Although we have identified multiple ways that learning can be scaffolded (Hmelo-Silver & Barrows, 2008; Jonassen, 1999; Pea, 2004; Quintana et al., 2004; Reiser; 2004; Wood et al., 1976), questions remain about how much and what types of supports should be available. Current research in this area aims to uncover the nuances of scaffolding by asking if the type of support should vary depending on the specific learning outcomes (Koedinger & Aleven, 2007; Koedinger, Pavlik, McLaren, & Aleven, 2008). Tabak (2004) examined distributed scaffolding, which incorporates multiple forms of support through different means to address the complex and diverse learning needs that arise in the learning environment.

She also introduced the notion of *synergy* as a pattern of scaffolded interactions that address the same learning need and interact with each other to produce a more robust form of support. This is supported by our findings related to interactions among different conjectures that were associated with systems thinking outcomes.

As discussed in the previous section, the different types of scaffolding we used during implementation led to different kinds of work, and interacting scaffolds seemed to lead to increasingly complex levels of reasoning. For example, facilitators effectively used a sequence of coaching and modeling to support the teams as they learned to use and then deployed the equipment to gather data and as they built their graphs to analyze their data. They also effectively used questions related to deepening reasoning to support teams as they developed explanations for their data. This suggests that it may be possible to differentiate scaffolding based on desired learning outcomes. Similar to the notion of differentiating learning based on learner needs, this type of work requires identifying the nature of the learning outcomes—procedural or conceptual, and then designing and implementing scaffolds to support the different type of outcomes. It is also possible to explicitly design multiple scaffolds into each activity to provide synergistic support for learning outcomes (Tabak, 2004). For example, a session plan with outcomes related to connecting data to ecohydrological system components, processes, and dynamic relationships might include coaching, modeling, and questions as scaffolds. These three scaffolding types work together such that learners are supported both in using the equipment and in deepening their thinking about how the concrete number they collect relates to the abstract concept of transpiration, for example. To test this idea, the session plan for the data collection could be revised to include specific types of scaffolding for specific outcomes in the hopes that learners would both develop facility with the equipment as well as link the equipment use, data collection, and the resulting data to aspects of the system they are studying.

The Challenge of Time

The lack of time, both in the day and over the course of the implementation, was the most frequently identified challenge. There were multiple issues related to time, including lack of time for learners to grapple with complex tasks and abstract concepts and to surface, understand, and address learner misconceptions. Segment 15, drawn from the focus group interview, addresses several aspects of the time limits we faced.

Segment 15

Jacque: *I think that the curriculum was really strong. I think that the sequencing wasn't the best that it could be, but I think that the actual activities that were planned were really effective. They were really engaging for the students, and made them want to come back the next week*

Joan: *Can you give me more information about sequencing?*

Jacque: *I feel like in the beginning we spent too much time in the classroom and one of the cool things about the program is that we got to go down into the Park, and I think that doing that earlier might have engaged the students a little more in writing their hypothesis and thinking about what landscapes they were actually looking at. So, I think more time earlier on actually going into the field…*

Alice: *Yeah. And also, I agree with Jacque that the curriculum was great, but I feel like it wasn't really done well in the sense that we didn't really get into a lot of the concepts because we were really rushed for time. Doing an activity without having student actually think about it…"pour this water in here"*

Laura: *Yeah*

Jacque: *Yeah, there was no unpacking time*

The theoretical model for designing constructivist learning environments conceives of a meaningful and ill-defined question as the focus of the experience. The goal of the learner working in this type of environment is to interpret the question and then to work through the scientific process to arrive at an answer (Jonassen, 1999). Tasks that are problematized in such a way provoke learners to devote resources, including time, to answering the question (Reiser, 2004). The tasks that were designed as part of the Club engaged learners conducting investigations to build background information, construct representations of the ecohydrological system based on their background knowledge, generate hypotheses based on their representation, and then gather and analyze data all as a means of answering their question. Well-crafted tasks have real-world relevance, accessibility, feasibility, and high-cognitive demand. This type of task requires learners to spend time grappling with the complexity of the task and the abstractness of the concepts arising from task engagement.

There are several examples of interactions that illustrate the importance of time and the influence of a lack of time on learning. First, as previously mentioned, the data we collected was not usable, and it led to unexpected outcomes. Although this was unfortunate for the researcher, it provided fertile ground for discussion; however, the learners needed additional time to struggle with possible explanations for our findings, time that we did not have. Thus, our limited time led to confusion and, in some instances, frustration as learners could not work through the problem in the time available. Segment 16 illustrates the confusion that resulted from our unexpected outcomes and the lack of time to engage fully in a discussion to understand them.

Segment 16

Facilitator: *So this was the least, a little more, and then more. And then this, is that what happened?*
Sean: *But how is there more water in the soil?*
Facilitator: S*ee, we thought that there was like a medium, average amount in here, and a tiny bit in here*
Sean: *We must have messed up or something! Because this has…*
Facilitator: *You think we messed up?*
Ethan: *No.*
Sean: *Yes, because that's not possible, well it is possible but that doesn't look right to me.*
Facilitator: *Hmm. Why do you think that is?*
Sean: *This is less than degraded, like, I don't think that would be true.*

Second, it takes time to surface, understand, and address misconceptions. A review of the transcripts from Day 8 revealed some interesting and unexpected talk. The day was originally scheduled as a data collection day, but due to rain, we stayed on campus and, as a whole group, reviewed our work to date. This allowed us to elicit learner understandings and uncover and address naïve understandings related to their research. For example, as we designed the program, we knew that we would be constrained by a lack of time. For this reason, we did not explicitly address the processes of photosynthesis and transpiration. The implications of this decision are clear in the following segment, Segment 17, in which Isabel expressed disbelief that plants transpire constantly.

Segment 17

1	Isabel:	*when we were talking about the reading and we put the clamp on the leaf for like a*
2		*minute or so and then we can tell the reading, but how can the water already be*
3		*transpire[ing] in one minute while we're taking the reading*
4	Facilitator:	*so are you saying that you think that plants transpire a lot slower, or*
5	Isabel:	*well, I don't know because I can't really believe that water can transpire…*
6	Facilitator:	*…constantly?*

From a design perspective, two things about this are interesting. First, one wonders if Isabel's idea resulted from a lack of time for her to elaborate on and evaluate her knowledge and understanding. The investigations in which the learners engage during the first four days were designed to concretize abstract processes. They were given time to make observations, but little time to verbalize their understandings and then to evaluate their own explanations. Thus, they did not grapple with conceptions, only with observations. Second, this understanding was elicited through an unplanned discussion. Taken together, these two points suggest that a) more time needs to be added to each activity so that learners have time to talk about and evaluate their ideas, understandings, and explanations, and b) more time needs to be added to the unit sequence so that we can more fully explore systems thinking concepts (e.g., plants and transpiration) and more fully check learners' developing understandings of the ecohydrological system.

The Challenge of Collaboration

The final challenge is related to creating and maintaining a safe collaborative environment. It was evident that, for both the facilitators and the learners, collaboration was an essential and successful aspect of the Club. The following segments, Segment 18, drawn from the focus group interview, and Segment 19, drawn from an informal discussion with the learners at the end of the program, illustrate our success in building a collaborative environment.

Segment 18

Laura: *Something else that I wanted to mention was the student talk that we facilitated. I want to say that by the end of the program, we didn't really have any quiet students because we pushed them to articulate and explain their thinking about what we were showing them and they were willing to share their thoughts at the end and respectfully agree and disagree with each other, which I thought was really great.*

Segment 19

Nancy: *I learned how to work with a research team and to see everyone else's different opinion in science. Because in school, you don't really have that much of a chance to know what other people think about what you're learning and to hear [their ideas]*

In our design, collaboration played the dual role of representing the way that science researchers build science knowledge and of being the primary mechanism by which the learners build understandings about the ecohydrological system. First, when conducting science investigations, science researchers are involved in a wide range of activities, including conducting background research, asking questions, hypothesizing, planning, observing, collecting and analyzing data, proposing explanations, and communicating results (Edelson, 1998; Duschl, Schweingruber, & Shouse, 2007). Science is not just conducting investigations to gather data—the rather simplistic view held by many learners. Rather, it advances through interactions among members of the research community as they test new ideas, solicit and provide feedback, articulate and evaluate explanations, and reach consensus (Duschl, Schweingruber, & Shouse, 2007). It was important to us that our design provide opportunities for learners to engage in these types of authentic science practices, which together involved the learners in the actual *doing of science*.

Second, our understandings about the role that language plays in the process of learning had particularly relevant implications for the design of the Club. Social interactions are foundational in knowledge building and in developing higher-order thinking capabilities (Vygotsky, 1978). Vygotsky's work emphasizes the fundamental relationship between language and individual thought. All higher mental functions have social origins—they are first produced between individuals, but over time, they are internalized within the individual (John-Steiner & Mann, 1996). Language also serves an important self-regulatory function, as people use it to plan, guide, and monitor their activities. Thus, it was important to us that our design provided opportunities for learners to engage in collaboration, discussion, and reflection as a means of developing systems thinking.

We employed a number of social tools to support learner collaboration, including the structure of the research team, the shared science notebook, the organization of the activities, and the sentence frames posted on the wall and listed in their science notebook ("Can you be more specific?", "I disagree with your idea/reasoning because…", "I agree with you, but I also think…"). In addition to these tools, we also scaffolded productive collaboration by modeling and coaching active listening to, critiquing, and respectfully responding to ideas.

To understand our success in creating and maintaining a collaborative environment, it is necessary to understand the context in which the Club was implemented. The 4th and 5th grade participants were all recruited from the same school, and in many cases, from the same classes. All but two of the learners had been in school together since kindergarten. Thus, these learners were already comfortable with each other, making the environment risk free and safe for sharing thoughts, ideas, and misunderstandings. Moreover, both teams had at least two learners who were willing to ask questions, share their observations, and explain their reasoning. Thus, our task as facilitators was to moderate discussions, making sure that all voices were heard, and to provide access to the rhetorical frame through which learners could effectively build knowledge (e.g., making a claim, providing evidence, supporting with reasoning, making a counter claim, providing evidence, and so on). The following segments (20 through 23) illustrate the way that learners appropriated and began to use the rhetorical patterns that we modeled over time.

Segment 20 (Day 2)

Facilitator: *So what were you saying about the hot and the cold?*
Tim: *Well, the hot water is like the ocean, and the air is like the cool, so it makes it evaporate. That's what causes fog*
Noah: *No, that's not really how it causes fog*
Sean: *I disagree with you…*
Ethan: *Yeah, I disagree…*
Facilitator: *Now I think that you two just did a really great thing. So since Noah was not very polite, can we hear what you have to say, Sean?*
Sean: *No, I disagree because the ocean can sometimes be cold by itself*
Tim: *Well, yeah, yeah. I agree with that*
Ethan: *I'm pretty sure the hot thing is bringing all… is making the evaporation and in this example, the cold thing is on the top and the hot thing is on the bottom, so I don't think…*
Facilitator: *So what's the ending result here.* [to Noah] *Do you want to say something?*
Noah: *I disagree with Sean… I disagree with because usually this would be the cloud line right here* [pointing to the ice bag] *and probably the sun would be evaporating [the water]*

Segment 21 (Day 5)

Facilitator: *So they get their water from the soil*
Noah: *Also they could get it from leaves because leaves basically are a root*
Ethan: *[Roots] collect it but then it goes in the plant*
Facilitator: *Do you guys agree with that?*
Sean: *Yeah, I agree with Ethan*
Facilitator: *Who do you agree with, Sean?*
Sean: *Ethan*
Facilitator: *What do you think of Noah's statement?*
Sean: *What did you say?*
Noah: *That basically the leaves collect it but then they like…*
Sean: *Well, the plant… I disagree because the…*
Facilitator: *Good job, Sean*
Sean: *The plants need the water in the first place to have the leaves. The leaves wouldn't grow without the water.*
Noah: *Well, true, but how about a seed? You plant a seed, it gets water but how does it get water? It doesn't burst.*

Segment 22 (Day 8)

Facilitator: *let's think about it for just a second. Let's see if we can get some explanations for that. Okay, so the question that we have before us, scientists, is how does the plant transpire*

so quickly? [to Isabel] Is that what you would like to know?
Nancy: *okay, so I think when you guys drew the straw up, it's always going in the water cycle so there is always water going out [of the plant] for the new water to come in, so it's always in the water cycle because you said there's like different stages so it's always be in a stage and there's the water keeps going out so new water comes in*
Facilitator: *Okay, so what do we think about that explanation?*
Students: *no*
Facilitator: *Now, if you disagree, what I need you to say is, "I disagree with that…"*
Sean: *"I disagree strongly…*
Facilitator: *Why do you disagree?*
Sean: *I disagree with that because that doesn't really explain how it goes so fast*

Segment 23 (Day 11)

Facilitator: *So, you think that the restored plot had more water lost, but make sure you relate it back to the data first, right?*
Isabel: *It had more plants!*
Nancy: *Well, I think it had more water lost since it has more plants and that shows that there is going to be more water lost because of the plants and all they need. If it was one plant, it would need a certain amount to survive, so they need a certain amount of water and every plant needs a certain amount of water times the amount of plants that is there, and with degraded it doesn't have as much plants so with restored it has a lot of plants*

Several questions arise from our experience. First, how much did learner familiarity with each other influence the level and depth of collaboration and, thus, the extent of learning? Second, is it possible to create this level and depth of collaboration among learners who do not know each other in the amount of time that we had, and, if so, what tools and scaffolds work to support this type of collaborative thinking? Although answering the first question with evidence from our experience is not possible, the segments above do provide evidence of the influence of modeling, coaching, and questions on pushing conversations forward in a positive direction. In the segments above, the facilitator used coaching to highlight how we offer counterclaims that are based in reason and evidence. This is supported by prior research in the area of facilitating collaborative knowledge building (e.g., Hmelo-Silver & Barrows, 2008), which suggested that for collaborative learning to occur, educators needed to create opportunities for constructive discourse and then support knowledge building through open-ended questions. However, it is important to acknowledge that, even with the use of these supports, it is likely that it would take substantially more time to create a safe and collaboratively productive environment in clubs with a diverse group of learners who do not know each other well.

Lessons Learned and Implications for Redesign

The findings of this research led to five lessons learned, which will be used in the redesign of the Club. These five lessons, which are associated with the design principles, help to refine these principles as they were related to this particular design and to the systems thinking outcomes. Given a similar learning context, these lessons learned may be useful for other researchers, designers, and educators who are interested in systems thinking development.

1. Citizen Science: Although citizen science is an effective context for developing systems thinking, there needs to be stronger collaboration between researchers, designers, and educators when designing and implementing collaborative citizen science. This collaboration will help to ensure both the usability and trustworthiness of the data and the achievement of the systems thinking learning outcomes.
2. Tool Design and Use: Tools, as one of the important resources available for learning, may be able to take on different characteristics such that they can be used in multiple ways to support learning. Moreover, using physical tools (e.g., data collection equipment) in conjunction with relational tools (e.g., graphs) may help learners to forge stronger links between specific activities and systems thinking components as the use of both types of tools together work to concretize the more abstract systems concepts.
3. Connecting Activities to Systems Thinking Outcomes: Connecting activities to systems thinking ideas and outcomes serves as an important bridge between processing ideas and seeking "why" explanations. To leverage the procedural activities (e.g., data collection and graphing) as conceptual experiences, the program design should explicitly highlight and link

multiple scaffolding types that can be used synergistically to link specific activities to specific concepts. This “differentiated scaffolding” requires including both procedural and conceptual outcomes in specific session plans, and then connecting the two types of outcomes through modeling/coaching and asking questions that support deeper reasoning.

4. Time: For learners to grapple with complex systems ideas, they need time to engage in the type of high-cognitive demand tasks that force them to struggle. In addition, it takes time over a sequence of days to surface, understand, and address the naïve conceptions that learners either bring with them or that they generate through the various activities and investigations. Thus, the Club needs a) more time each day so that learners have time to discuss, elaborate on, and evaluate their thinking, and b) more time in the sequence so that we can check learners’ developing understandings about different aspects of the ecohydrological system.
5. Collaboration: Collaboration is a critical aspect of knowledge building. There are a number of tools, supports, and scaffolds that can be used to support learner conversation and intellectual collaboration, especially around the complex concepts related to systems thinking. These tools should be explicitly designed into each lesson. In addition—and related to the challenge of time, creating a safe and collaboratively productive environment, especially with a diverse group of learners who do not know each other well, takes a lot of time.

CHAPTER 6

Conclusion

The purpose of this research was to study the extent to which participation in collaborative citizen science might facilitate youths' development of systems thinking through dialogic knowledge-building processes. The conceptual model, which was the theoretical foundation for the design, reflects the integration of the six steps of citizen science (see Table 6.1) and the eight characteristics of systems thinking (See Table 6.2).

Table 6.1
Steps in the Scientific Process (Bonney, Ballard et al, 2009)

1.	Choose/define question(s) for study
2.	Gather information and resources, generate hypothesis
3.	Design/learn to use data collection protocols equipment; use equipment to gather data
4.	Analyze samples and/or data
5.	Interpret data and draw conclusions; discuss results and ask new questions
6.	Disseminate conclusions; discuss results

Table 6.2
Eight Emerging Characteristics of Systems Thinking (Ben-Zvi Assaraf & Orion, 2010)

1.	The ability to identify, describe, and explain observable components and common processes of the ecohydrological cycle
2.	The ability to identify, describe, and explain the static relationships between or among systems components
3.	The ability, to identify, describe, and explain the dynamic relationships within the system
4.	The ability to organize system components, processes, and their interactions within a framework of system relationships
5.	The ability to identify cycles of matter and energy within the system
6.	The ability to identify, describe, and explain hidden dimensions of the system
7.	The ability to generalize—to make hypotheses, propose explanations, and solve problems based on an understanding of systems' mechanisms
8.	The ability to think temporally: retrospection and prediction

Each step in the citizen science research afforded a particular type of task and participation structure, which in turn, afforded a particular way of thinking and knowing. Thus, as learners collaboratively engaged in the different steps of citizen science, they would build knowledge and understanding of the ways in which complex systems interact. This model was tested through the study.

Overall, findings related to systems thinking reported in Chapter 4 support the conceptual model. The analysis of the research measures and transcripts suggested that teams of learners did engage in the type of systems thinking interactions predicted by the conceptual model. During the initial days of the Club, teams built an understanding of components, processes, and relationships, which then provided a foundation for understanding cycles of energy and matter, which, in turn, provided a foundation for hypothesizing, explaining, and solving problems based on their understanding of complex systems. I also found a similar pattern with respect to complexity of talk as learners could first identify, then define and describe, and finally explain in context the elements of each systems thinking characteristic. Thus, I found evidence of increasingly complex systems thinking talk as teams moved from one citizen science step to the next. There were, however, several pauses in their talk, which may have been an important part of the sequencing.

Interestingly, both the analysis of systems thinking outcomes and the analysis of the designed intervention suggested that there was a relationship between the designed intervention and systems thinking outcomes. The analysis by day revealed that teams engaged in higher levels of systems thinking earlier than predicted by the conceptual model, which appeared to be related to the nature of the task in which they were engaged. The analysis of the intervention, described in Chapter 5, showed a similar relationship between task goals and systems thinking. The findings reported in Chapter 5 also support the aspect of the model related to dialogic knowledge building, suggesting that one important mechanism for developing systems thinking is through collaborative participation in demanding tasks. These findings are represented in the revised conceptual model (Figure 6.1). The task goals related to seeking “why” explanations, which were part of generating hypotheses, led to higher-level systems thinking. Learners engaged in these tasks during Step 2 of the model when they built representations of the ecohydrological system based on their background research and then used their representations to generate, discuss, and explain their hypotheses related to system dynamics. Thus, the revised model reflects this new understanding, which suggests that youth ages 9 – 10 who participated in authentic research with designed supports were capable of the type of abstract thinking that comes with understanding how complex systems operate. Thus, this study provides a positive answer to the question of whether younger learners are capable of developing systems thinking.

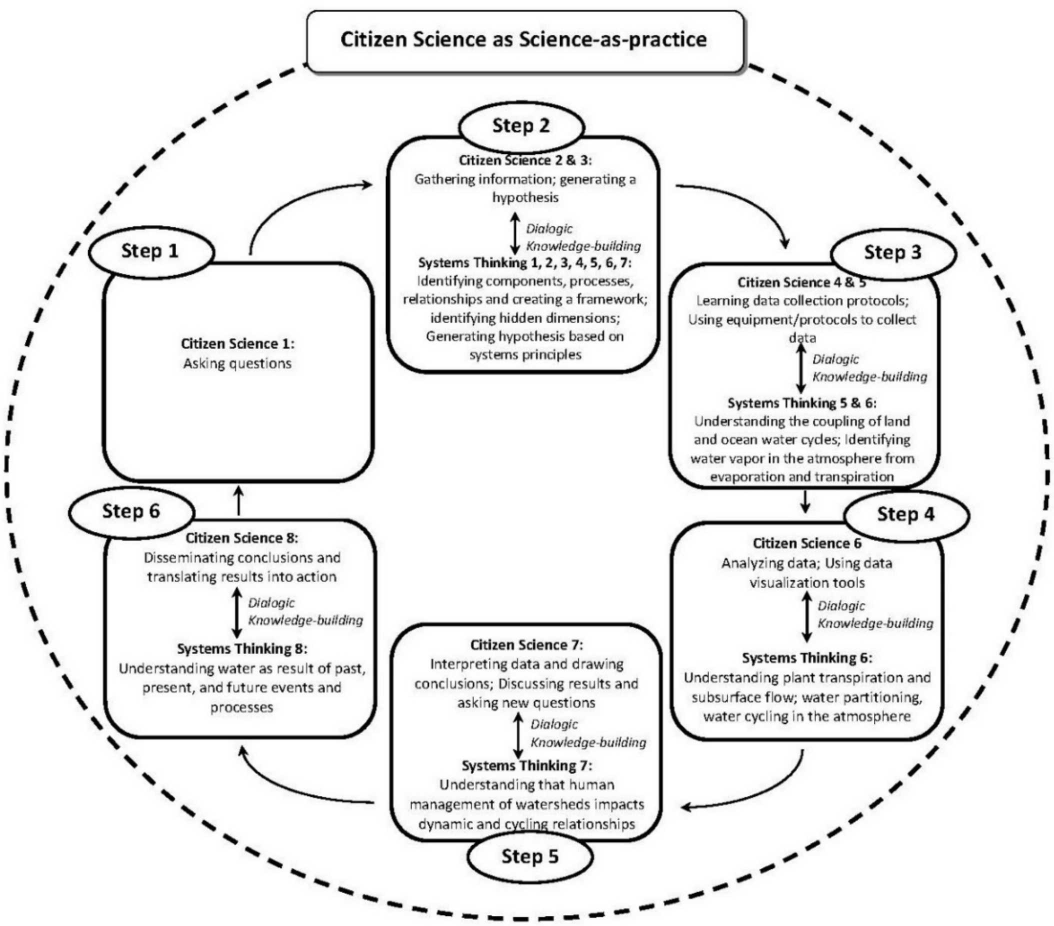


Figure 6.1 Revised Conceptual Model of Citizen Science as Science-as-Practice: Citizen Science and Systems Thinking Characteristics Integration

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Appendix A

Table A1. Daily Attendance in the Citizen Scientists' After-school Club

Name	1/14	1/16	1/21	1/23	1/28	1/30	2/4	2/6	2/11	2/13	2/18	2/20	2/25	2/27	3/4	3/6
Abby	✓		✓	✓		✓			✓	✓	✓	✓	✓	✓	✓	
Eric	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Ethan	✓	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓			✓
Fred	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Isabel	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓
Nancy	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Noah	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Sean	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Tim	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		✓	✓	✓

Appendix B
Recruitment text that appeared on the elementary school PTA's After-school Clubs website

Crystal Cove State Park and environmental researchers from UCI need your child's help with a research project in Crystal Cove State Park! We want to understand where the water goes. Your student can become a Citizen Scientist by joining the Citizen Scientists' After-school program—it's a great way for her or him to learn science by participating in a real scientific study! We will explore the park as scientists, conduct experiments on evaporation and transpiration, gather real data for our partner scientists using real science equipment, help them to analyze the data we collect, and then report our findings to the State Park land managers to help them make decisions about when and where to plant! Through the program, your child will actually be doing real science and becoming a real scientist. Program will take place at the Crystal Cove State Park's Environmental Study Loop, and it will be taught by XXX from UCI's School of Education with the help of three program aids from UCI.

We also invite your child to participate in a research study through UCI's School of Education designed to explore how children learn science by participating in authentic environmental science research. The study will take place during the After-school Club at Crystal Cove State Park. If your child is in the 4th or 5th grade at XXX Elementary School and is enrolled in the Citizen Scientists' After-school Club, he or she is eligible to be part of this study. Participation in the study is not a requirement to participate in the Citizen Scientists' After-school Club. For more information, please contact XXX, the Lead Researcher, by phone at 949-280-7080 or by e-mail at XXX@uci.edu.

Instructor: Crystal Cove State Park & UCI Staff
Minimum: 8 / maximum: 16 students

Appendix C

Initial Task Sequence

Table C1

Task Sequence aligned with Citizen Science Step and Systems Thinking Characteristic

Session	**Overview of Task**	**Citizen Science Step**	**Systems Thinking Characteristic**
Day 1: 1/4	Introduction to Club	Step 1: Asking questions	
Day 2: 1/6	Pre-tests; Exploring scientific investigation; Building a water cycle model	Step 1: Asking questions Step 2: Building background knowledge	#1 - #3
Day 3: 1/21	Exploring Soil Moisture: Soil Percolation Test	Step 2: Building background knowledge	#1 - #4
Day 4: 1/23	Exploring Transpiration: Plant Terrariums & Evaporation Tents	Step 2: Building background knowledge	#1 - #4
Day 5: 1/28	Building a model; Generating a hypothesis; Understanding data needs	Step 2: Generating hypothesis	#1 - #4
Day 6: 1/30	Learning to use equipment; Entering data	Step 3: Using equipment and data collection protocols	#1 - #4
Day 7: 2/4	Field Work: Gathering data	Step 3: Gathering data	#1 - #5
Day 8: 2/6	Field Work: Gathering data	Step 3: Gathering data	#1 - #5
Day 9: 2/11	Field Work: Gathering data	Step 3: Gathering data	#1 - #5
Day 10: 2/13	Creating tables & graphs	Step 4: Analyzing and interpreting data	#1 - #6
Day 11: 2/25	Making and justifying inferences	Step 5: Making and justifying inferences	#1 - #8
Day 12: 2/27	Designing Posters	Step 5: Drawing conclusions Step 6: Disseminating findings	#1 - #8
Day 13: 3/3	Disseminating results, Asking new questions	Step 6: Disseminating findings	#1 - #8
Day 14: 3/6	Post-test		

Appendix D
Systems Thinking Measures

Where does the water go?

Name: ________________________________ Date: ___________________________

Think about what happens to water in nature. You have 5 minutes to list 12 words or ideas that you think of when you think about where water goes.

1._____________________________________

2._____________________________________

3._____________________________________

4._____________________________________

5._____________________________________

6._____________________________________

7._____________________________________

8._____________________________________

9._____________________________________

10.____________________________________

11.____________________________________

12.____________________________________

Thank you!

Word Association

Where does the water go?

Name: ________________________________ Date: ___________________________

You have 10 minutes to use as many words on this list as you can to draw a picture of where the water goes in nature. You don't have to use all of the words. Make sure that you label everything in your picture.

Ocean	Plant	Precipitation
River	Leaf	Infiltration
Lake	Sun	Melting
Rain	Animal	Freezing
Cloud	Evaporation	Water vapor
Soil	Transpiration	Underground flow
Groundwater	Condensation	Surface flow

Thank you!

Where does the water go?

Name: ________________________________ Date: ___________________________

You have 15 minutes to make a list of the components of the ecosystem that you see in this picture of an ecosystem, and add any components to the ecosystem that you think are missing. Show the relationship between the components of the picture, and give then picture a title.

List of Components:

Thank you!

Where does the water go?

Name: ________________________________ Date: ___________________________

You have 15 minutes to complete both sides of the questionnaire. Circle your answers, and then write a short explanation of why you chose your answer.

1. Clouds are the starting point of the water cycle and the ocean is the ending point of the water cycle.

   Agree Disagree Uncertain

   Why?____

   ____

   ____

   ____

   ____

2. The amount of water in the ocean grows each day because rivers are continually flowing into the ocean.

   Agree Disagree Uncertain

   Why?____

   ____

   ____

   ____

   ____

Please turn over the page to answer the rest of the questions.

Questionnaire – Page 1

3. Plants take up water from the soil through their roots and release water to the atmosphere from their leaves.

Agree Disagree Uncertain

Why?____

____

____

____

____

4. All water that falls in a rainstorm runs off into the ocean.

Agree Disagree Uncertain

Why?____

____

____

____

____

Thank you!

Appendix E
Systems Thinking Coding Frameworks

Table E1.
Word Association and Drawing Analysis Coding Framework: Components and Processes

A. Components within the water cycle

1. Plant
2. Roots
3. Leaf
4. Animal
5. Ocean
6. Water
7. Water vapor
8. Soil
9. Groundwater/Aquifer
10. Rain
11. Snow
12. Cloud
13. Lake/Pond/Spring
14. Sun/Heat
15. Wind/Air
16. Human
17. Humidity/Mist/Fog
18. Puddle
19. River/Stream/Spring
20. Mountains/hills
21. Glaciers
22. Minerals
23. House/Farm/School/Park
24. Sewer/Pump/Pipe

B. Processes within the water cycle

1. Evaporation
2. Transpiration
3. Precipitation
4. Condensation
5. Percolation
6. Infiltration/soil absorption
7. Underground flow
8. Melting
9. Freezing
10. Cycle
11. Surface flow/runoff
12. Use by humans/animals
13. Use by plants

Table E2
Drawing Analysis Analytic Framework: Dynamic Relationships

1	Cloud formation and precipitation
2	Evaporation of sea water
3	Soil is affected by rain
4	Rivers flow to the sea/lakes
5	Evaporation of river, stream, puddles water
6	Plants transpire water
7	Plant roots take up water
8	Sun causes water to evaporate
9	Animals drink water
10	Sun causes ice to melt
11	Underground flow comes from groundwater
12	Evaporation from soil

Table E3
Drawing Analysis Analytic Framework: Framework of Relationships

1 = Simplistic: The drawing correctly represents at least 2 of the following processes and related components: evaporation, condensation, and precipitation; there are 3 or more misconceptions present in the drawing
2 = Developing: The drawing correctly represents 3-4 of the following processes and related components: evaporation, condensation, precipitation, transpiration; there less than 3 misconceptions represented in the drawing
3 = Complex: The drawing correctly represents 4 or more of the following processes and related components: evaporation, condensation, precipitation, transpiration, infiltration, surface flow, underground flows; there are 0-1 misconceptions present in the drawing

Table E4
Drawing Analysis Analytic Framework: Cycles of Matter and Energy

0 = No cycles present
1 = Evaporation and connection via rain on the ocean
2 = Evaporation and connection via rain on the land
3 = Precipitation and connection via rivers from land to the ocean
4 = Precipitation and connection via plant transpiration or underground flow

Table E5
Drawing Analysis Analytic Framework: Hidden Dimensions

1	Water vapor in the atmosphere
2	Transpiration from plant leaves
3	Plant roots taking up water
4	Underground water flow
5	Infiltration into soil
6	Water percolating into aquafer (groundwater)

Table E6
Ecology System Inventory Analytic Framework: Hidden Dimensions

0 = no added components

1 = (a) Added components or processes that already existed in the picture, or (b) added components that were related to an existing component

2 = Added new components or processes that are located on the Earth's surface, but were not included in the original picture

3 = In addition to adding components or processes included in level 2, added components that are located beneath the Earth's surface or in the atmosphere that cannot be seen

Table E7
Ecology System Inventory Analytic Framework: Hidden Dimensions Inventory

Water vapor in the atmosphere
Transpiration from plant leaves
Plant roots taking up water
Underground water
Water Infiltrating into soil
Water percolating to aquifer (groundwater)

Table E8

Systems Thinking Transcript Analytic Framework

1. The ability to identify, define, or explain system components and processes			
Dimension	*1 – Simplistic*	*2 – Developing*	*3 – Complex*
Youth Talk	Intuitively identifies observable components and common processes of the ecohydrologic cycle; Learner identifies; facilitator defines • *Components*: plant, leaf, human, animal, house/farm/school/park, sewer/pump/pipe, water, ocean/sea, rivers/stream, lakes/pond/spring, puddle, sun, rain, water vapor, clouds, snow, mist/fog, wind, mountains/hills, glaciers, soil • *System Processes*: evaporation, condensation, precipitation, surface flows/runoff, melting, freezing, cycle, human/animal use, plant use	Defines/describes observable components and common process of the ecohydrologic cycle; Learner defines and/or describes • *Evaporation is when liquid water turns into water vapor.* • *Precipitation is when water in the form of rain, snow, sleet, or hail falls to the ground.* • *Condensation is when water vapor turns into liquid water.* • *Clouds are visible masses of condensed water vapor floating in the atmosphere.*	Explains observable components and common processes of the ecohydrologic cycle • *The sun heats water from the bodies of water (ocean, lakes, streams), and the water turns into water vapor in the atmosphere.* • *Clouds form when water vapor condenses in the atmosphere.* • *Rain that does not soak into the ground can run off into a river or the ocean.*

2. The ability to identify simple (static) relationships between or among system components			
Dimension	*1 – Simplistic*	*2 – Developing*	*3 – Complex*
Youth Talk	Intuitively identifies static relationships between system components with no explanations; has naïve conceptions of relationships • *There is water in the soil.* • *There is water in plants.* • *There is water in the air.*	Defines/describes the static relationships between or among system components • *The water in the soil comes from rain.* • *The water in the plants comes from the soil.* • *There is less soil moisture in the restored plot.* • *There is more soil moisture in the degraded plot.* • *Water evaporates from the ocean*	Explains the static relationships between or among system components • *There is more water in the soil when it rains.* • *If there is more water in the soil, then plants have access to more water.* • *There is less soil moisture in the restored plot because there are more plants.* • *There is more soil moisture in the degraded plot because there are fewer plants.*

3. The ability to identify dynamic relationships within the system			
Dimension	*1 – Simplistic*	*2 – Developing*	*3 – Complex*
Youth Talk	Intuitively identifies dynamic relationships within the system • *The stream affects the ocean.* • *The rain affects the soil.* • *The rain affects the plants.* • *Plants need water.*	Defines/describes the dynamic relationships within the system • *The stream affects the ocean since the water that flows in the stream reaches the ocean.* • *The rain affects the soil since it soaks into the ground.* • *Plants need water to grow.* • *Different landscape types have different amounts of soil moisture.*	Explains the dynamic relationships within the system • *The rain affects the plants because water sinks into the soil and then the plants use it to grow.* • *The rain affects the soil differently because there are different types of soil.* • *Different landscape types have different rates of transpiration/amounts of soil moisture because they have different plant species/soil type.*

4. The ability to organize the system components, processes, and their interactions within a framework of relationships			
Dimension	*1 – Simplistic*	*2 – Developing*	*3 – Complex*
Youth Talk	Relates at least two of the following processes: evaporation, condensation, and precipitation and the related components	Relates three to four of the following processes: evaporation, condensation, precipitation, transpiration, and the related components	Relates four or more of the following processes: evaporation, condensation, precipitation, transpiration, infiltration, surface flow, underground flow, and the related components

5. The ability to identify cycles of matter and energy within the system			
Dimension	*1 – Simplistic*	*2 – Developing*	*3 – Complex*
Youth Talk	Relates evaporation and connection via rain on the ocean	Relates evaporation and connection via rain on the ocean, evaporation and connection via rain on the land, and precipitation and connection via rivers from land to the sea	Relates evaporation and connection via rain on the ocean, evaporation and connection via rain on the land, precipitation and connection via rivers from land to the sea, and precipitation and connection via underground water flow or plant transpiration

6. The ability to recognize hidden dimensions of the system—to understand natural phenomena through patterns and interrelationships not seen at the surface			
Dimension	*1 – Simplistic*	*2 – Developing*	*3 – Complex*
Youth Talk	Identifies hidden dimensions • *Water vapor in the atmosphere* • *Transpiration from plant leaves* • *Plant roots taking up water* • *Groundwater* • *Infiltration into soil* • *Water percolating into aquafer*	Defines/describes hidden dimensions • *Water vapor in the atmosphere comes from evaporation or transpiration.* • *Plant leaves transpire water that they get from the soil.* • *Liquid water can infiltrate into the soil.* • *Partitioning: Water can "go into plant, go underground, and some of it evaporates."*	Explains the hidden dimensions • *Plants take up water through their roots. Water travels to the leaves where it is released to the atmosphere to cool the plant, to take in more nutrients, to allow* CO_2 *to enter the plant, and/or to allow for more water uptake.* • *The sun affects the water in the atmosphere because if the sun is not out the plants won't transpire as much.*

7. The ability to make generalizations—to make hypotheses, propose explanations, and/or solve problems based on systems mechanisms			
Dimension	*1 – Simplistic*	*2 – Developing*	*3 – Complex*
Youth Talk	Makes simple hypotheses and/or proposes explanations/analyses or solutions to problems related to science research <u>Hypothesis</u> • *The Degraded landscape will lose the most water.* <u>Analysis of Data</u> • *I disagree with that because we thought we would lose more to transpiration in the restored then in under restoration, but they're actually the same amount.* <u>Solve problems</u> • *Plants have an effect on the water in the plot.* • *Different species of plants use different amounts of water.* • *Plants use different amounts of water as they grow.*	Makes hypotheses, proposes explanations/analyses, and/or solutions to problems related to the science research that include simple relationships between system components and processes <u>Hypothesis</u> • *The Degraded landscape will lose the most water through evaporation.* <u>Analysis of Data</u> • *Plants get water through their roots, so if there is more water in the soil in the under restoration plot, there may have been transpiration even if there were fewer plants.* <u>Solve problems</u> • *If you plant more plants, the landscape will lose less water through evaporation.* • *If you plant different species of plants, the landscape will lose more/less water,*	Makes hypotheses, proposes explanations/analyses and/or solutions related to the science research that are based on the dynamic interactions among system components <u>Hypothesis</u> • *The Degraded landscape will lose the most water through evaporation because there are fewer plants for shade and/or to lose water through transpiration.* <u>Analysis of Data</u> • *When I look at these charts, I see that there isn't more transpiration in the restored plot then in the under restoration plot. Also, the restored plot doesn't have a lot more water in the soil then the under restoration plot. I'm thinking that it's supposed to be a lot better in the restored plot, but it's not that much better because this only has a little bit more [transpiration] but this has a lot less [soil moisture], so why don't you keep it under restoration?* <u>Solve problems</u> • *If you plant different species of plants of water together, you can affect the amount of water that is lost because of the way that water is partitioned into evaporation and transpiration.*

8. The ability to think temporally: retrospection and prediction			
Dimension	*1 – Simplistic*	*2 – Developing*	*3 – Complex*
Youth Talk	Identify the past and the present condition • *In the past, Moro Canyon was a trailer park. Moro Canyon is now a State Park that is under restoration.*	Describe how the decisions made in the present are influenced by past decisions and will affect the future • *State Park land managers are restoring Moro Canyon by changing the species of plants in the area to restore it to its native form.* • *In the restoration, fewer plants might be better for where the water goes.*	Explain how the decisions made in the present are influenced by past decisions and will affect the future • *State Park land managers are changing the species of plants in Moro Canyon because they are concerned about the amount of water that native species of plants use.* • *If the State Park land managers take out invasive species of plants and put in native species of plants, then the way that water is partitioned between evaporation and transpiration will be influenced.* • *Fewer species of plants might be better for where the water in Moro Canyon goes because of the way that water is partitioned by plants.*

Appendix F

Intercoder Reliability Statistics for Systems Thinking Measures

Table F

Intercoder Reliability Statistics for Systems Thinking Measures (calculated in Kappa)

Word Association	
a. Components	.77
b. Processes	.85
Drawing Analysis	
a. Components	.90
b. Processes	1.00
c. Dynamic Relationships	.65
d. Framework of Relationships	.70
e. Cycles of Matter and Energy	1.00
f. Hidden Dimensions	.79
Cyclic Thinking Questionnaire	
a. Clouds are the starting point of the water cycle, and the ocean is the ending point of the water cycle.	.70
b. The amount of water in the ocean grows each day because rivers are continually flowing into the ocean.	.72
c. Plants take up water from the soil through their roots are release water to the atmosphere from their leaves.	.83
d. All water that falls in a rainstorm runs off into the ocean.	.68
Ecology System Inventory: Hidden Dimensions	1.00

Appendix G
Transcript Analysis: Systems Thinking Segments

Table F1

All Systems Thinking Segments Across All Days

Citizen Science Step		2				Total	3				Total	4		Total	5	Total
Day		2	3[1]	4	5	#	6	7	8	9	#	10	11	#	12	#
ST	L															
Components & processes	1	3	1	3	10	17	2		1		3		3	3	2	2
	2	6	1	2	6	15	3				3			0		
	3	4		4	2	10			1		1			0		
Simple relationships	1			1	4	5			1		1		3	3		
	2				6	6	1				1		3	3		
	3			3	2	5			1	1	2	3		3		
Dynamic relationships	1		3	6		9		1	2		3			0	7	7
	2		2	5		7								0	1	1
	3		1	6		7	1		3		4	2	1	3	2	2
Framework of relationships	1				1	1	1				1			0		
	2					0								0		
	3				1	1	2				2			0		
Cycles	1				1	1	1				1			0		
	2				1	1	1				1			0		
	3				4	4				1	1			0		
Hidden Dimensions	1			5	8	13	1		1		2		1	1	7	7
	2		1	1	5	7	3		2		5		5	5	5	5
	3				2	2								0	4	4
Generalizations	1		1			1							9	9	2	2
	2		1		2	3							7	7	2	2
	3				6	6			1		1	1	2	3	5	5
Think temporally	1					0								0	5	5
	2					0								0	4	4
	3					0								0	5	5
Total		13	11	36	61	121	16	1	13	2	32	6	34	40	51	51

ST = Systems Thinking; L = Level of Complexity | [1]No Green team data for this day

Table F2

Whole Group Systems Thinking Segments Across All Days

Citizen Science Step		2				Total	3				Total	4		Total	5	Total
Day		2	3	4	5	#	6	7	8	9	#	10	11	#	12	#
ST	L															
Components & processes	1	1	1	1	3	6	1		1		2		1	1	1	1
	2	2	1	1	3	7	1				1					
	3			2	1	3			1		1					
Simple relationships	1			1	1	2			1		1		2	2		
	2				2	2	1				1		3	3		
	3			2	1	3			1		1	1		1		
Dynamic relationships	1			1		1			2		2					
	2			1		1										
	3			1		1	1		3		4	1	1	2		
Framework of relationships	1				1	1	1				1					
	2					0										
	3					0										
Cycles	1					0	1				1					
	2					0	1				1					
	3					0										
Hidden dimensions	1				3	3	1		1		2		1	1		
	2			1	2	3	3		2		5		1	1		
	3				1	1										
Generalizations	1					0							1	1		
	2				2	2							2	2		
	3				6	6			1		1	1	1	2		
Think temporally	1					0										
	2					0										
	3					0										
Total		3	2	11	26	42	11	0	13	0	24	3	13	16	1	1

ST = Systems Thinking; L = Level of Complexity

Table F3

Green Team Systems Thinking Segments Across All Days

Citizen Science Step		2				Total	3				Total	4		Total	5	Total
Day		2	3[1]	4	5	#	6	7	8	9	#	10	11	#	12	#
ST	L															
Components & processes	1			1	1	2										
	2	3		1	1	5	2				2					
	3	4		2		6										
Simple relationships	1				2	2										
	2				1	1										
	3			1		1				1	1	1		1		
Dynamic relationships	1			3		3									5	5
	2														1	1
	3			3		3						1		1	2	2
Framework of relationships	1															
	2															
	3				1	1										
Cycles	1				1	1										
	2				1	1										
	3				3	3										
Hidden dimensions	1			4	4	8									4	4
	2				3	3							2	2	3	3
	3															
Generalizations	1												6	6	1	1
	2												1	1	2	2
	3															
Think temporally	1															
	2															
	3															
Total		7	0	15	18	40	2	0	0	1	3	2	9	11	18	18

ST = Systems Thinking; L = Level of Complexity | [1]No data for this day

Table F4

Yellow Team Systems Thinking Segments Across All Days

Citizen Science Step		2				Total	3				Total	4		Total	5	Total
Day		2	3	4	5	#	6	7	8	9	#	10	11	#	12	#
ST	L															
Components & processes	1	2		1	6	9	1				1		2	2	1	1
	2	1			2	3										
	3				1	1										
Simple relationships	1				1	1							1	1		
	2				3	3										
	3				1	1						1		1		
Dynamic relationships	1		3	2		5		1			1				2	2
	2		2	4		6										
	3		1	2		3										
Framework of relationships	1					0										
	2					0										
	3					0	2				2					
Cycles	1					0										
	2					0										
	3				1	1				1	1					
Hidden dimensions	1			1	1	2									3	3
	2		1			1							2	2	2	2
	3				1	1									4	4
Make generalizations	1		1			1							2	2	1	1
	2		1			1							4	4		
	3					0							1	1	5	5
Think temporally	1					0									5	5
	2					0									4	4
	3					0									5	5
Total		3	9	10	17	39	3	1	0	1	5	1	12	13	32	32

ST = Systems Thinking; L = Level of Complexity

Appendix H
Conjecture Map Coding Pathways

Conjecture	Embodiment			
Authentic Activities	Task Structure	Task Sequence		
		Task Goals	Processing Ideas/Connecting Activity to Ideas/Seeking "why" explanations	
		Topic & Question		
		Activity Selection	Use tools/collect data/represent data/ analyze data/ Construct arguments	
	Tools & Materials	Equipment		
		Images, Models, & Graphs	Image/Model/Graph	
		Equipment Instructions		
		Protocols		
		Data Sheets		
		Data		
	Participation Structures	Collaborative Participation	Productive/Not Productive	
		Supports & Scaffolds	Coaching or Modeling/Questioning	Questioning: Share, Expand, Clarify/Deepen Reasoning/Listen to others/Think with others
ST Explicit through Tools	Tools & Materials	Images, Models & Graphs	Image/Model/Graph	
		Equipment Instructions		
		Protocols		
		Data Sheets		
		Data		
	Participation Structures	Collaborative Participation	Productive/Not Productive	
		Supports & Scaffolds	Coaching or Modeling/Questioning	Questioning: Share, Expand, Clarify/Deepen Reasoning/Listen to others/Think with others

Conjecture	Embodiment			
Collaboration	Task Structure	Task Organization	Balanced/Not Balanced	
		Activity Selection	Use tools/collect data/represent data/ analyze data/ Construct arguments	
	Tools & Materials	Images, Models, & Graphs	Image/Model/Graph	
		Notebooks		
		Sentence Frames		
	Participation Structures	Collaborative Participation	Productive/Not Productive	
		Supports & Scaffolds	Coaching or Modeling/Questioning	Questioning: Share, Expand, Clarify/Deepen Reasoning/Listen to others/Think with others
Investigations	Task Structure	Task Organization	Balanced/Not Balanced	
		Task Goals	Processing Ideas/Connecting Activity to Ideas/Seeking "why" explanations	
		Activity Selection	Use tools/collect data/represent data/ analyze data/ Construct arguments	
	Tools & Materials	Images, Models, & Graphs	Image/Model/Graph	
		Notebook Pages		
		Sentence Frames		
	Participation Structures	Collaborative Participation	Productive/Not Productive	
		Supports & Scaffolds	Coaching or Modeling/Questioning	Questioning: Share, Expand, Clarify/Deepen Reasoning/Listen to others/Think with others
Time	Task Structure	Unit Sequence		
		Task organization	Balanced/Not Balanced	
	Tools & Materials	Notebooks		
	Participation Structures	Collaborative Participation	Productive/Not Productive	
		Supports & Scaffolds	Coaching or Modeling/Questioning	Questioning: Share, Expand, Clarify/Deepen Reasoning/Listen to others/Think with others

Appendix I
Example from Day 2: Connections between Task Design, Preparation, Implementation, and Debrief

<u>Conjecture</u>
Provide opportunities, tools, and scaffolds to run observational ecohydrological investigations

<u>Tasks Goals</u>
1) Processing ideas
2) Connecting activity to systems thinking ideas

<u>Task Design (from lesson plan)</u>

Purpose of Activity
The purpose of this activity is to draw out learners' understandings of the water cycle and to help them organize what they know and what they need to know. The outcome of the activity will be an initial model of the water cycle, including components and processes, that they will use to ask their research question and generate their hypothesis about where the water goes. Learners will refine their models as they gather data and draw conclusions.

Procedure
1. ***Setting up their investigation:*** While students are moving to their tables, hand out the equipment. Demonstrate how to set up the water cycle dish. Have the students quickly set up their investigation. When each team has their equipment set up, set timer for 2-4 minutes, depending on how much time we have left.
2. **Discussing their investigation:** Once the dishes have been set up, have the students read and talk about the questions on the next page. Remind them to predict what they think will happen in the dish.

Questions from Notebook
Examine your drawings, and discuss these questions with your teammates.
1. What is in the center ring? How did it get there? Was your prediction correct?
2. Why is this called the water cycle?
   – Describe the components and processes of the water cycle that are modeled in the water cycle dish.
   – How do you think that this similar to what happens in the real world? How is it different from the real world?
3. What could we add or change to make it more like Moro Canyon?
4. How does what you observed in the water cycle dish help us to understand where the water in Moro Canyon goes?

<u>Preparation Discussion (from field notes)</u>

Discussed in the preparation meeting
1. Start thinking about the water system in its most simple terms of evaporation, condensation, and precipitation
2. Build on that next week by adding transpiration and infiltration next week
3. If we can get them started on models – look and draw one arrow

<u>Learner Interactions (from transcripts)</u>

Segment 1 (Processing ideas)
Facilitator: *Now what happened in the middle? Did you start off with water in the middle?*
Ethan: *Oh no. It went to the top [uses fingers at outer ring] and then went to the middle [points to the inner ring)*
Sean: *It evaporated and then fell back in*
All: *Yeah*
Facilitator: *How did that happen?*
Tim: *Because it was to cool so it became [liquid] water again*
Sean: *Yeah, it's too cold so it became water again and fell back in the middle*
Tim: *Yeah*
Ethan: *The dew went to the top of this [holding top, point to top] and then went all the way down [pointing to ridges on top] and then went all the way down… and dropped*
Facilitator: *Um hum*
Tim: *Yeah because of the ice… because it's cooling it down… the steam*
Sean: *Yeah, it's cooling it*
Noah: *Yeah*
Sean: *and as the heat stopped and then it falls back down*
Facilitator: *Yeah*
Tim: *That's why the water's cool now*

Segment 2 (Connecting activity to systems thinking ideas)

Noah:	*Well, Tim maybe when you lifted it up the water could have…*
Tim:	*Look now there's no more fog because when we lifted it up…*
Noah:	*Oh*
Tim:	*because we opened it and the fog just went out into the and up there* [points up]
Noah:	*It evaporated to the* [points to the center ring]
Sean:	*Oh! And that's why this is pointed* [points to the point in the lid]
Tim:	*look, look, look so it would drop right there*
Sean:	*and then it would cool it and then it would fall in there* [points to the center]
Tim:	*yeah… so it's like if it's rain. That's the water cycle…*
Sean:	*now there's even more water…*
Tim:	*It's fog* [hand up], *rain* [hand moves down] *after it evaporates. Fog… except it goes to ice and the sun melts it…*

Debrief Discussion (From field notes)

Alice

"I taught the group that I was working with the word. I asked if they knew what the word is for that. 'Do you know what that is called when a gas turns into a liquid?' They said, 'no.' It's good for them to know the vocabulary. Students may not have learned the water cycle – they may have had change of matter."

Laura

"Even though that last investigation was really rushed, I think that they still got it. They still had enough time to gather information and draw some conclusions."

Alice

"I was trying to get them translate this into the real water cycle. What are these different components: What is the water on the bottom? What is the water on the top? Kids said, 'It's like clouds, like a lake, like rain…'"