# THE IMPACT OF EXPLICIT STRATEGIES FOR TEACHING SYSTEMS THINKING SKILLS IN ORDER TO ACCESS THE CROSSCUTTING CONCEPTS

by

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A professional paper submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Science Education

MONTANA STATE UNIVERSITY
Bozeman, Montana

July 2022

# DEDICATION

This paper is dedicated to my mother who first inspired me to pursue education and who always supports me in following my dreams.

## ACKNOWLEDGEMENTS

I would like to acknowledge the support of my advisor, Walt Woolbaugh, who has always been understanding of my questions and concerns. His support and praise have helped fuel me as I worked my way through the MSSE program. I also want to thank my best friend, Dee Norman, who was always happy to lend an ear to any of my concerns and who happily gave feedback any time I asked for it. Many thanks go to Rachelle Savoie, our instructional coach, who was there with me to help me first narrow down my project and who supported me in my implementation of it. Thanks go to Brenda Foster and Jessie Schmidt for proofreading once the paper was done. A final thank you to my reader, Paul Andersen, for being an inspiration in my growth as a teacher of the NGSS.

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# ABSTRACT

The issue this project addressed was the implementation of the Crosscutting Concepts (CCCs) of the Next Generation Science Standards (NGSS) in a sixth grade science classroom. The hope was that by addressing the CCC of systems and systems models, students would have a more three-dimensional experience in the classroom, learning to build connections between different concepts and units and enhancing their ability to utilize the Science and Engineering Practices and attain mastery of the unit core ideas. The methodology involved explicit instruction of systems thinking strategies such as defining the components of a system and modeling the interactions between those components. Students with better content knowledge and spatial thinking skills were better at systems thinking both before and after the treatment unit. Treatment was effective for the majority of students to improve a variety of systems thinking skills. Students also gained confidence in their understanding of systems and ability to perform systems thinking skills. As such, this action research project showed that this approach to teaching systems thinking was effective.

# CHAPTER ONE

# INTRODUCTION AND BACKGROUND

## Educational Context and Background

The American School of Dubai (ASD) is a private, not-for-profit, international school in the city of Dubai in the United Arab Emirates (UAE). The school includes students from nursery through grade 12, and all students are assessed using standards-based grading on a 4-point grading scale. The school is an American curriculum school meaning that student learning is based on standards used in American schools such as the Common Core and the Next Generation Science Standards.

As a school that uses the Next Generation Science Standards (NGSS), the hope is that we teach through three-dimensional instruction. This would mean that the students learn the Disciplinary Core Ideas (DCIs), learn how to do the Science and Engineering Practices (SEPs), and come to understand and think through the lens of the Crosscutting Concepts (CCCs). The majority of science teachers have easily migrated to addressing the DCIs and SEPs, as these are what science teachers have always taught – the science content and the science skills. The Crosscutting Concepts, however, have remained more nebulous, and many teachers will admit that they do not really address them. To have a three-dimensional classroom, this would need to change. As such, I chose to address the Crosscutting Concepts as a focus of my project.

# The Crosscutting Concepts

## Defining the Crosscutting Concepts

The National Research Council (NRC) describes the Crosscutting Concepts as "concepts that bridge disciplinary boundaries, having explanatory value throughout much of science and engineering...These concepts help provide students with an organizational framework for connecting knowledge from the various disciplines into a coherent and scientifically based view of the world" (NRC, 2012, p. 83). In looking through both science and engineering, the NRC determined that the following were the main unifying concepts that touched all disciplines of science as well as engineering: patterns; cause and effect; scale, proportion, and quantity; systems and system models; stability and change; matter and energy; and structure and function. The NRC notes that teachers have often assumed that students will come to see these themes and utilize them to build connections between disciplines and concepts on their own, but – in order to emphasize the necessity of this connection-making – they chose to emphasize the CCCs as an essential dimension in the NGSS.

## Using the Crosscutting Concepts

There are various ways to consider the role of the Crosscutting Concepts in the implementation of a science unit. Rivet et al. (2016) describe four ways of utilizing them in science instruction. First of all, the CCCs can be used as lenses through which to examine a phenomenon. Depending on which lens students use, they will look at the situation in a different way, emphasizing specific aspects depending on the CCC. For example, a student could study the water cycle through the lens of matter and energy, and so they would focus on the transfer of matter through the water cycle and the flow of energy that causes this. Alternatively, they could look at that same phenomenon through the lens of stability and change, and their focus would be on how the cycling of water maintains stability in a region and what factors can interfere with – or change – that stability.

Secondly, the Crosscutting Concepts can be used as a bridge to connect different phenomena and to make connections across the disciplines of science. An example of this might be when studying the rock cycle. A student could employ the concept of systems and system models to make connections with the water cycle when they study the role of water in causing weathering and erosion. One factor to consider is that students might struggle to determine which connections are relevant and helpful in explaining and understanding scientific phenomena (Rivet et al., 2016).

The third use of the Crosscutting Concepts is as cognitive tools. Students can use the CCCs "to engage with the Science and Engineering Practices in more effective and meaningful ways" and to "leverage students' prior knowledge and understandings to explain phenomena or address problems" (Rivet et al., 2016, p. 972). In these situations, the students are using the CCCs to improve their use of the other dimensions of the NGSS. It is important to remember, however, that since different students are at a range of skill levels with the SEPs and have varied amounts of prior knowledge, the effectiveness of the CCCs as a tool will vary from student to student (Rivet et al., 2016).

The fourth and final use of the Crosscutting Concepts is as rules of the game. As rules for thinking about science, the CCCs can "provide order and structure to students' understanding" of the world (Rivet et al., 2016, p. 972). They provide students with ways to approach problems, a means to determine what is relevant for explaining phenomena, and a "shared language" for discussing science (Rivet et al., 2016, p. 972). For example, if using the systems CCC for approaching a phenomenon, students will know to first define the system, then identify the components, and then map out the relationships and interactions between those components (Andersen, 2022).

These different ways of using the CCCs allow teachers to determine which use is applicable in a lesson or a unit and thus how that use can be leveraged to help students build a deeper understanding of the phenomena at hand and of science as a whole. It is important to note, however, that when considering the CCCs in unit planning, a teacher must remember that use of a CCC "needs to support students in making connections across science ideas and disciplines of science (independent of content) as well as enhance the students' understanding of a specific science idea (dependent on the content)" (Fick, 2018, p. 8).

### The Crosscutting Concepts in My Action Research Project

As noted above, systems and systems models is one of the seven CCCs, and this aligned most closely with the grade six science curriculum at my school, as we address the four Earth systems throughout the year – biosphere, hydrosphere, atmosphere, and lithosphere. My hope was that by teaching systems thinking, students would gain a deeper understanding of the content, have a means to make connections and build bridges between different units as we moved from system to system, and be able to dive deeper into the application of the SEPs by using the CCCs as a thinking tool.

These possible improvements would be applicable to the teachers in my science department, as they would be able to teach their students these systems thinking skills as well. As systems are not only found in the realm of science, students would be able to apply these thinking skills to other subjects too. Beyond the realm of subject areas, our school's mission is to build students who can "adapt and contribute in a rapidly changing world" (American School of Dubai). An ability to utilize systems thinking can help students understand the world around them, so this project could impact our school mission as well.

## Purpose, Focus Questions, and Research Design

With all of this in mind, my purpose for this project was to determine the effectiveness of a possible approach to teaching systems thinking in the context of the hydrosphere in the United Arab Emirates (UAE). I utilized a mixed methods approach to answering these questions, collecting a variety of qualitative and quantitative data related to students' learning. I focused on one main question and four supporting questions within the project.

My focus question was, How does explicit instruction of systems thinking processes impact student understanding of and skill with the Crosscutting Concept of systems and system models?

My sub-questions include the following:

1. What impact does explicit instruction of systems thinking skills have on student confidence related to systems thinking?
2. In what ways does systems thinking impact three-dimensional learning in my classroom?
3. What factors impact students' ability to utilize systems thinking?
4. How does systems thinking instruction impact me as a teacher?

# CHAPTER TWO

# CONCEPTUAL FRAMEWORK

## Systems and Systems Thinking

### The Crosscutting Concept of Systems and System Models

The National Research Council (NRC) (2012) defined a system as “an organized group of related objects or components that form a whole” (p. 92). These components are often interdependent with each other, and understanding a system involves not only identifying the components but understanding how they interact with one another. Due to these interactions, a system can have what is known as emergent properties, which are properties that the components do not have on their own. A system is also defined by its boundary, which can be something real – like the skin of the human body – or an artificial boundary decided upon by the engineer or scientist who is studying the system.

Systems also often have sections within them which can be studied on their own. These can be referred to as nested systems (Fick, 2018) or subsystems (NRC, 2012). An understanding of systems thus requires a recognition of this aspect of the related Crosscutting Concept of scale, proportion, and quantity. A second connection to scale is that systems often have “hidden dimensions” (Ben-Zvi Assaraf & Orion, 2005).  These are components that are unable to be seen, whether because they are too small, too large, or not visible to the human eye at any scale.

### Systems Thinking

There are many characteristics of systems thinking, and there are different methods of organizing these characteristics. Looking over a body of literature on the topic, Ben-Zvi Assaraf and Orion (2005) note that there are “eight emergent characteristics of systems thinking” (p. 523). These characteristics are as follows:

1. Identification of components and processes
2. Identification of relationships and interactions
3. Organization of components and processes into a “framework of relationships” or interactions
4. Making generalizations about the system
5. Identification of dynamic relationships within the system
6. Identification and “understanding of hidden dimensions” within the system
7. Understanding of cycles within the system
8. Using the dimension of time within the system to make retrodictions and predictions (Ben-Zvi Assaraf & Orion, 2005, p. 523).

It is when a student has a grasp on all of these characteristics and an ability to apply them to a variety of systems that they are a true systems thinker. The question one might ask is why it is important for a student to be a systems thinker, and this can be explained through a study of how systems thinking benefits student learning.

## The Purpose of Teaching Systems Thinking

### Making Learning Whole

Science education is often organized by topics. We teach these topics hoping that students learn to master their complexities and make connections between concepts and the domains of science. As Harvard education professor David Perkins (2009) notes, the main approaches to teaching students about complex topics are to teach the elements first and build up to making connections later or to learn about something before learning to do it. Perkins posits that allowing students to "play the whole game" of science (or any subject) makes learning far more effective. The topic can be modified to be a "junior version," but designing learning so that students are doing science rather than learning about science "lets learners in on the big picture, so that the challenges along the way become meaningful. And it gives learners a chance to develop the largely tacit knowledge involved in active engagement" (Perkins, 2009, p. 6). This learning by wholes or learning the whole game helps students build mental models that provide structure to what they are learning. This leads to true understanding on the part of students, where "they can think and act flexibly with what they know" (Perkins, 2009, p. 49).

Playing the whole game aligns closely with NGSS, as the phenomenon-based approach of instruction provides a context for playing the whole game. Students are given a problem to solve or a scenario to figure out; in this way they work their way through the Science Practices to come to a final conclusion. This is a junior version of what scientists do when they are performing research. The teacher may already know what the general solution to the problem or explanation for the phenomenon is, but this does not negate that students are asking questions, investigating, and constructing their own understanding as a scientist does.

Thinking in systems also aligns with playing the whole game. If a student is mapping out how a system works, identifying components and constructing a framework of interactions for those components, they are thinking in wholes. They are not examining components and interactions in an isolated fashion but with an eye towards the interconnected whole of the system. This is, again, what scientists do. Hmelo-Silver et al. (2007) found in a series of interviews with both novices and experts about the functioning of aquarium systems that expert scientists “focus on global, dynamic relationships” when describing those systems (p. 320). They look at the big picture or the whole game. If we want students to learn to think like scientists, then we need to build up their systems thinking skills so they can do so.

Effect of Systems Thinking on Students

If systems thinking does truly teach the whole game as defined by Perkins, then it promotes deep understanding and could likely transfer knowledge. Practicing transfer is, in fact, one of Perkins’s principles for teaching in wholes. Students need to learn, as he says, to “play out of town…applying the games [they] learn not just in their original contexts but elsewhere, in some other setting where they might be helpful” (Perkins, 2009, p. 110). When learning, students often focus on surface features of content, or the structures or components that make up a system (Hmelo-Silver et al., 2007, p. 318; Perkins, 2009, p. 112). They need to be taught to transfer this knowledge. I posit that using systems thinking as a structure for instruction can be a tool for promoting transfer. The principles of system thinking can be applied in a variety of contexts, and using these principles with different content can help students make connections between the domains of science and various concepts. To understand a system is to understand connections, after all. So, by embedding systems thinking into the science classroom, students will be more likely to make connections and be better able to transfer their knowledge to novel phenomena.

Beyond promoting deeper understanding and an ability to transfer knowledge, systems thinking also creates students who are critical thinkers. In their literature review of 107 publications related to systems thinking in STEM education, York et al. (2019) discovered five main benefits to teaching students this skill. First, there is an increased “retention of material” and problem solving skills (York et al., 2019, p. 2742). Second, students become more actively engaged in learning. Third, they "learn content more deeply and conceptually," fourth, they "ask better questions," and fifth, they "make more connections between concepts both within and between disciplines" (York et al., 2019, p. 2742). This shows that systems thinking creates overall better students. The goal of education should be to have students who learn content at a deep level and remember what they learn, who are active participants in their learning, who can solve problems, and who ask good questions to push them forward through cycles of inquiry. If systems thinking does all of this, then it is truly important to teach this skill to our students.

## Factors Affecting the Student Attainment of Systems Thinking

### Student Specific Factors Affecting Attainment

As with every thinking skill, especially those that involve critical thinking, there are factors that affect student learning of the skill. Ben-Zvi Assaraf and Orion (2005) noted a few different elements that affected student attainment of advanced systems thinking in their research with 50 Israeli eighth grade students during a unit on the water cycle. One of these elements is student cognitive ability. The authors found that students who came into the unit already strong in complex thinking skills were the ones with the most advanced performance at the end of the treatment unit. Even engagement in all learning activities was not enough for some students. There were a variety of cognitive barriers that stood in the way of gaining the relevant skills. It could be the "ability to perceive the dynamic relationship among the system's components," "the ability to organize components within a network of relationships," or "the ability to make generalizations" about the system (Ben-Zvi Assaraf & Orion, 2005, p. 555). This elucidated that a variety of supports would be required when teaching systems thinking, in order to scaffold for students in the different advanced reasoning skills.

Working memory can also be a barrier to attaining system thinking skills, as "understanding and reasoning about complex systems places a huge burden on working memory" (Hmelo-Silver & Azevedo, 2006, p. 54). Since students are required to think of multiple components and interactions and how they all fit to make a whole, that is a great deal for the working memory to hold at once. Students with attention disorders or processing issues will often struggle with this cognitive aspect. This meant that graphic organizers would be a helpful tool for such students to support them in taking some of the burden off of their working memory by recording aspects of the system in a scaffolded format.

Other factors that can affect student attainment of systems thinking skills are temporal and spatial thinking. In Eilam's (2012) research into 50 Israeli ninth graders' systems thinking related to feeding relationships, she noted that "students' understanding of webs was constrained by deficiencies in temporal and spatial thinking, which in turn affected students' ability to identify causal and implicit interactions" (p. 231). This shows the need to address multiple Crosscutting Concepts while teaching systems thinking.

Not only are other Crosscutting Concepts important to mastering the systems CCC, but the Disciplinary Core Ideas and Science and Engineering Practices are as well. Hmelo-Silver and Azevedo (2006) note that students need to understand modeling, relevant content knowledge, and specific science reasoning skills such as conducting investigations and data analysis to become systems thinkers. This highlights the importance of teaching three-dimensionally. Learning about systems needs to be grounded in a specific phenomenon and thus involve specific DCIs. As Eilam (2012) notes, "the path to acquiring system understanding and system thinking is bidirectional – from concepts to systems and from systems to concepts" (p. 233). The SEPs need to be connected as well so that students have methods through which to construct understanding of the systems and to be able to model the framework of the system.

<u>The Importance of Explicit Instruction</u>

There are clearly many factors to consider when teaching systems thinking, and thus there are various theories as to how the skills should be taught. There are two opposing theories for how students should be taught the skills of the Crosscutting Concept of Systems and System Models; it is a case of implicit instruction versus explicit instruction. Based on her research into a systems-focused watershed unit for 70 middle school students, Fick (2018) argues that students should first be taught about a system using implicit strategies.

However, Fick's research only shows that students gained deeper systems understanding of watersheds, as shown through their assessing pre- and post-unit visual models. There is no evidence that the students were able to apply systems thinking skills to other topics or units of study or that they could even articulate what a system was and how a watershed is a system. Other research seems to show that it is likely that the students would not be able to articulate or transfer the systems thinking skills they utilized in the unit.

For example, in a study of 52 sixth graders in a small US city, Hogan (2000) found that "constructing, observing, and polluting mini-ecosystems, along with several class discussions, worksheets, and readings, were not sufficient to affect students' understanding of ecological system dynamics" (Hogan, 2000, p. 28). Even after the unit, most students still thought linearly when asked about impacts of perturbations with a particular species. The author noted that the lack of explicit instruction into how systems behave likely impacted the student ability to think systemically about ecosystems.

Research by Kali et al. (2003) stands as another example of the problems with implicit instruction of systems thinking. They saw that even after 40 hours of instruction on rock cycle processes, including a trip out into the field, 81% of the 40 Israeli seventh grade students in the research study were not able to successfully answer questions that required students to apply their knowledge of the system to new phenomena that was still related to the topic of geology. However, with the implementation of an additional series of lessons that included systems mapping with whiteboards and process and product cards, “students became more aware of the dynamic and cyclic nature of the rock cycle” (Kali et al, 2003, p. 560). In fact, after the explicit systems mapping activity, “76% of students improved their systems thinking of the rock cycle” (Kali et al., 2003, p. 560).

This research is summarized by Perkins when he says “explicit wins. The problem with the implicit approach is that students do not pick up on the message” (Perkins, 2009, p. 208). As much as a teacher might wish, students do not learn through osmosis. They need the explanation of the principles and rules and ways of thinking. Essentially, this connects back to Rivet et al.’s (2016) perspectives on the Crosscutting Concepts. A student cannot use systems thinking as a lens for looking at a phenomenon or as the rules of a game for solving a problem if they do not know what the lens is or what the rules are.

## The Importance of Scaffolding when Teaching Systems Thinking

Another factor that affects the attainment of systems thinking is the provision of scaffolds to build students’ abilities as systems thinkers. Fick et al.’s (2021) study of an urban runoff unit taught to 397 fifth and sixth graders “suggest[ed] explicit scaffolding of the CCCs is important for students to understand and use systems CCCs” (p. 689). There are a variety of ways to provide this scaffolding as suggested by the literature. Both Fick et al. (2021) and Ben-Zvi Assaraf and Orion (2005) used one form of scaffolding in the drawing-type models they had students complete. This was to give a partially complete drawing to students and have them add to it to show their understanding of the concepts. This would give students a base from which to start their drawing-type models. A similar approach to this would be to utilize a graphic organizer, such as the ones modified and shared by NGSS consultant Paul Andersen on his website, The Wonder of Science (2022).

Another area that needs scaffolding is concept mapping, which is a commonly used tool for demonstrating students' understanding of a system. Ben-Zvi Assaraf and Orion (2005) did this with the eighth-grade students in their research project. Students first practiced making concept maps in pairs on a "simple, familiar topic, such as their favorite television program" (Ben-Zvi Assaraf & Orion, 2005, p. 529). To apply this to the science content, students initially completed a word association activity, brainstorming words related to the water cycle. Then they chose pairs of words to connect with arrows and linking words or phrases; during this process, they were allowed to use the same word more than once. Then, once students had this basis of connections mapped out for the water cycle, they created a concept map. Students also created concept maps at the end of the unit to show evidence of growth.

An approach that can be used alongside this is from Andersen's Wonder of Science website (2022). There are a series of mini-lessons that can be used to help teach students these systems thinking skills. These mini-lessons can be shown directly to the students to teach them how to analyze a system. They start with simple everyday phenomena and help students learn how to identify the components as well as the interactions or relationships that are often considered the processes. Students can also see how to develop simple models that show these interactions and even the inputs and outputs of the system. This scaffolded practice allows students to play the whole game of systems analysis while also playing “away games” that allow the students to practice their systems thinking skills with a variety of other phenomena. This would allow them to cement the skills into their repertoire and thus be able to apply them to the unit phenomenon and transfer them to later phenomena in the course of the year.

## Data Collection Strategies from the Literature

### Modeling: Drawings and Concept Maps

Once students have been scaffolded into performing systems thinking, it will be important to assess their achievement. Both the Fick (2018) research paper and the Ben-Zvi Assaraf and Orion (2005) research paper have analyses of student drawings as part of their assessment of the projects. They had similar approaches in that they created lists of what they were looking for in the drawings and then counted whether students addressed it or not, which allowed them to compare inclusion of those processes and components in the pre-assessments and post-assessments. This allowed them to see the changes in what students included in their drawings and whether they gained a more complete understanding of the water cycle.

Another means of assessing systems thinking is the concept map, the use of which can be found in multiple articles. As noted earlier, Ben-Avi Assaraf and Orion (2005) had students create pre- and post-assessment concept maps and analyzed the maps in a variety of ways, looking for changes in which concepts and processes were included as well as the number of links between words. These counts allow the authors and readers to see if there was growth in knowledge in the overall student population. How the links are mapped also elucidates whether students' systems thinking becomes more advanced (Kinchin, 2000; Raved & Yarden, 2014). As maps progress from more linear chains or "single, pairs, or trios of concepts" to maps organized in a net-like or web-like fashion, they show growing complexity in student thinking (Raved & Yarden, 2014, p. 6). The concept map showing multiple linkages in a net or web shows a greater ability on the student's part to make connections between concepts (Kinchin, 2000).

### Explaining the Connection to the Crosscutting Concept

Fitch (2019) includes another means of assessing students' understanding of systems thinking in her action research project relating to the Crosscutting Concepts. One strategy she used to determine her high school earth science students' ability to connect the CCCs to Disciplinary Core Ideas was asking students to explain the connection between a Crosscutting Concept and a presented phenomenon. It allows the teacher to see if students understand the Crosscutting Concepts and can use them as a lens through which to view a phenomenon.

### Self-Confidence Surveys

Another way to track student growth in systems thinking is having the students self-assess. Both before and after her treatment period, Fitch (2019) had students complete a Google Form self-assessment on their understanding of each of the Crosscutting Concepts. Her research did show improvement in student self-confidence from the beginning to the end of the treatment. If students become more confident, this likely indicates improvement in students' capabilities with Crosscutting Concepts, such as systems and systems models.

## Summarizing Systems Thinking

In conclusion, systems thinking is an important process to teach our students. It helps them become better critical thinkers and better able to make connections between concepts within one or different disciplines. However, since it requires such complex thinking, scaffolding and explicit instruction for this skill is important to help students build up their ability to think at a systems level as well as to develop ways to show that capability, which can then be used to assess students' systems thinking skills. This shows that there is great value to focusing on systems as a Crosscutting Concept in this action research project, as there could be a great benefit to helping students grow as systems thinkers. The research indicates that a treatment designed for this action research project would require specific explicit instructional strategies to teach the skills of systems thinking and to provide scaffolding to students as they work. Models such as drawings and concept maps, written explanations, and self-assessments can all be used as means for students to demonstrate their systems thinking abilities.

# CHAPTER THREE

# METHODOLOGY

The purpose of this study was to identify if the proposed treatment plan was an effective method for teaching systems thinking skills in an effort to make classroom instruction more three-dimensional and to improve students' ability to make connections between concepts and understand the big ideas of science. I wanted to see what factors might affect student success in gaining systems thinking ability and whether the instruction was more effective for some students than others. The research design aligned to these goals because it had a set treatment plan to explicitly teach systems thinking skills in a three-dimensional format. Additionally, there were also a variety of data types that would elucidate some different factors that might influence student success.

## Research Sample and Demographics

My school is a private, international day school located in Dubai in the United Arab Emirates (UAE). This country is located on the Arabian/Persian Gulf in the Middle East. In the 2021-2022 school year, the school had approximately 1980 students from nursery through grade 12. The students were 51% male and 49% female. As the school is a fee-paying school for which parents or their employers must pay tuition, students were all from middle class backgrounds or above. The UAE is a country of expatriates and immigrants with almost 90% of the population falling into one of those two categories. The ASD community mimics this diversity. The student body is approximately one-third Muslim, one-third Christian, and one-third of other or unreported religions. Since many students have multinational, multicultural, and/or multiracial backgrounds, the school does not collect specific data on race and ethnicity. School data for 2021-2022 showed that students hailed from 81 different nations, based on what parents reported as first and second passports. Many students had parents from different cultures or countries, and students may have lived in multiple countries over the course of their short lives but possibly not ever in the countries for which they have a passport. As such, the majority of students were Third-Culture Kids (TCKs), meaning that they have diverse backgrounds and do not necessarily identify with one culture or nationality and may not even feel as if they are a member of the nationality or nationalities for which they have passports.

The sixth-grade demographics mimicked that of the entire school, with students coming from both economically privileged and culturally diverse backgrounds. I taught five of the seven classes of sixth grade science. Cumulatively, this was 89 students with 46 boys and 43 girls. I chose to implement this treatment with all five sections of sixth grade science that I teach. Class sizes ranged from 13 to 21, and there were 89 total students on whom I collected data throughout the project. I decided to utilize all of my students for the capstone as it would give me a good sample size and would allow me to come to more valid, reliable conclusions. I did have to remove one male student from the study due to excessive absences throughout the unit, so my final N-value was 88.

Twelve of the 88 students were identified as learning support students. Of those twelve, ten had issues identified in reading as well as identified issues in executive functioning and/or processing. One student did not have identified executive functioning issues but did struggle with reading comprehension. The final student struggled with executive functioning but had no identified issues with reading.

## Treatment Plan

The treatment unit with which I taught systems thinking skills to students focused on the water system in the UAE. Additionally, the UAE was an interesting area to study when it comes to water because there is such a low amount of fresh water and subsequent advanced technologies are used by humans here to provide the residents with potable water. An outline of this system can be found in Table 1, which is modeled off a systems organization table found in the literature (Fick, 2018) with certain additions of further characteristics of systems from other literature (Ben-Zvi Assaraf & Orion, 2005).

Table 1. System defined with water system examples.

| System Components | Definition | Example in water systems |
|---|---|---|
| Inputs | The components that enter the system. | Heat energy from the sun; water moves into the UAE from other locations; human activity moves water from place to place, desalinates water, and adds salts for cloud seeding |
| Outputs | The components that leave the system. | Water into people's homes; water taken in by animals and plants; movement of water |
| Processes | The components have relationships or interactions that can be seen as processes. | Evaporation, condensation, transpiration, precipitation, runoff, infiltration, desalination, cloud seeding, water uptake through wells, water movement through pipes, removing water from air via condensation |
| Boundary | The limits of the system; usually marked by humans. Can change due to scale. | Artificial boundary of the UAE, as unit focuses on water processes within the country |
| Nested Systems | Systems are comprised of subsystems that interact to make up the larger system. | Desalination factories; water treatment facilities; plants; etc. |
| Hidden Dimensions | All systems have components and processes that can't be seen. This can be due to scale or due to happening where we cannot see. | Water processes happen due to solar energy and the movement of molecules, neither of which can be seen. Water cannot be observed once it percolates into soil. |

Table 1 provided an outline of how the Crosscutting Concept of systems connects to the content (Disciplinary Core Ideas). As such, it could be used as a list of the major science ideas students needed to understand in order to explain the phenomenon. Having all of this organized at the beginning of planning a unit ensured that I could design assessments that looked for student understanding of these components and then lessons that would build towards these assessments. Without this outline it would be a struggle to ensure that students were able to create a complete and accurate mental model of the system.

As indicated in the table, the Disciplinary Core Idea (DCI) addressed in the unit was that of the roles of water in Earth's surface processes. After completing pre-assessments for the various systems thinking skills, students were introduced to the concept of systems thinking through a Paul Andersen systems mini-lesson video. Students then continued to apply systems thinking skills and be introduced to a variety of ways to think about the system – and systems in general – throughout the unit. The unit ended with the post-assessments. An outline of lessons can be seen in Table 2. Within this outline, readers can see that students utilized five of the SEPs (asking questions, developing models, constructing explanations, conducting investigations, communicating information), one DCI, and three CCCs (systems, matter and energy, cause and effect).

Table 2. Unit pacing guide with relevant information for each lesson.

| Lesson | Description of Activities |
| --- | --- |
| 1<br>(70 min) | -Initial survey– systems confidence and general systems skills (pre-assessment)<br>-Introduce water in the UAE phenomenon with 3 videos<br>-Students ask and classify questions about water in the UAE (pre-assessment)<br>-Students develop initial models in diagram form (pre-assessment) |
| 2<br>(70 min) | -Review concept map creation and create group concept map with familiar topic<br>-Students create initial systems model/concept map (pre-assessment) |
| 3<br>(70 min) | -Students create systems model for a propeller-powered LED (pre-assessment)<br>-Watch Andersen (2021) minilesson on systems and use to update systems model<br>-Students create other systems models for other phenomena |
| 4<br>(70 min) | -Water cycle stations investigation exploring different natural water cycle processes<br>-Students reflect on the connections to systems after completing the investigation |
| 5<br>(70 min) | -Students create definitions for investigation terms<br>-Students draw an investigation model with components, processes, and interactions<br>-Students examine and explain a published water cycle model<br>-Students explain the roles of energy and gravity in the water cycle |
| 6<br>(105 min) | -Students investigate and research roles of humans in the UAE water system<br>- Students reflect on the role of humans in the water system and on the interactions between the hydrosphere and other Earth systems |
| 7<br>(105 min) | -Students reflect on what they've learned about the systems and how the hydrosphere serves as a subsystem within the larger system of the Earth<br>-Class creates a list of required elements for a water systems model<br>-Students create an updated systems model connecting all components and processes<br>-Students provide each other feedback |
| 8<br>(140 min) | -Systems Check In #2<br>-Minilesson: asking and classifying systems questions<br>-Students write systems questions for a selection of water cycle processes<br>-Students plan and act out skits for water cycle processes<br>-Students explain the role of energy and gravity in water cycle processes using Andersen's (2021) cause and effect graphic organizer and a causal loop diagram<br>-Update concept map/systems model |
| 9<br>(70 min) | -Deep dive into thinking about the water cycle as a system<br>-Students consider input, output, and hidden dimensions of the hydrosphere<br>-Introduce and discuss system boundary<br>-Students model subsystem of the water cycle that includes an input and output |
| 10<br>(70 min) | -Students create a final model in diagram form showing how water moves and changes around the UAE (post-assessment)<br>-Students reflect on change in their models and thinking across the unit |
| 11<br>(70 min) | -Students create a final model in concept map form showing how water moves and changes around the UAE (post-assessment)<br>-Students reflect on change in their models and thinking across the unit |
| 12<br>(30 min) | -Students complete final survey on systems skills and confidence (post-assessment) |

## Data Collection

The process of collecting data was done with a mixed methods approach and was approved by the Montana State University IRB review board (Appendix A). Both quantitative and qualitative data were collected through a variety of instruments to help answer the main and supporting questions for this study. An overview of the data instruments can be seen in Table 3.

Table 3. Data collection matrix for this systems thinking research project.

| Question | Tool 1 | Tool 2 | Tool 3 |
|---|---|---|---|
| Main Question:<br>How does explicit instruction of systems thinking processes impact student understanding of and skill with the Crosscutting Concept of systems and system models? | CCC Pre- and Post-Assessments | Student surveys | Student interviews |
| Supporting Question 1:<br>What impact does explicit instruction of systems thinking skills have on student confidence related to systems thinking? | Student confidence surveys | Student interviews | Teacher journal |
| Supporting Question 2:<br>In what ways does systems thinking impact three-dimensional learning in my classroom? | CCC pre- and post-assessments | Rubrics assessing SEPs and DCIs | Teacher journal |
| Supporting Question 3:<br>What factors impact students' ability to utilize systems thinking? | MAP test scores | Pre-assessment scores | CAT4 spatial thinking scores |
| Supporting Question 4:<br>How does systems thinking instruction impact me as a teacher? | Teacher journal | Meetings with instructional coach | Student survey on teacher performance |

The most important source of data for the research project were the pre- and post-assessments. These assessments tracked students in four different systems thinking skills – asking systems questions, drawing systems models, creating systems concept maps, and explaining how and why a phenomenon is or includes a system. These skills were assessed with rubrics (Appendix B) based on my school's four-point standards-based grading scale. Rubrics were created using expectations from the task-neutral rubrics for the Science and Engineering Practices designed by my science department. Having created those initial rubrics as a team of teachers using the NGSS appendices and evidence statements as a research source ensured that the rubrics were an effective means of measuring student success. The one exception was the rubric for creating concept maps, as this utilized the expectations described in the systems thinking articles utilizing concept maps (Ben-Zvi Assaraf & Orion 2005; Fick 2018; Kinchin et al., 2000; Raved & Yarden 2014). Basing the expectations on professional articles means that the rubric should be both valid and reliable. Rubrics were also shared with students so they would know the expectations for each skill.

Along with the rubrics, there were a variety of graphic organizers to help students practice these skills. The asking questions organizer (Appendix C) required that students' questions connect to a specific concept in the form of a DCI as well as a Crosscutting Concept. A systems question would be a question about the system of study that asks about the components, processes, and function of the system. Myself and two other teachers in my department have been utilizing this graphic organizer for the past year and a half, so we feel that it has some degree of being valid and reliable.

For assessing systems models and concept maps, students were provided with word banks for both pre- and post-assessment, showing the components and processes occurring in the water system in the UAE (Appendix D). Students completed their pre-assessment models using a Paul Andersen graphic organizer for systems models (Appendix E). This graphic organizer has been used by teachers all over the world, and this helped me be sure that it was a valid and reliable means of assessing students' ability at developing systems models. Of note, this graphic organizer was also used as a formative assessment later in the unit. It was meant to be used for the summative models as well, but students found that they could not fit their final models within the box even when on A3 paper (11.75 x 16.5 in.), so that ended up being completed on blank paper, often with multiple sheets of paper taped together.

Throughout the unit, students responded to three different surveys via Google Forms – a pre-treatment survey (Appendix F), a mid-treatment survey (Appendix G), and a post-treatment survey (Appendix H). The initial survey was designed to assess student confidence in each of the four systems thinking skills examined in this project, along with an additional question to assess the students' ability to explain why a phenomenon was an example of a system. The second survey was implemented in lesson eight of the unit, and it was designed to check in on students' ability with three of the systems thinking skills and to determine student thinking on the difficulty level of the different skills. The third survey was given after the treatment unit was over and questions were written to look for student thinking on confidence levels, beneficial activities within the unit, their ability to apply systems thinking to the next unit, and how systems thinking could be applied to other classes and everyday life. Further information about the design, purpose, reliability, and validity of the surveys can be read in Appendix I.

Similar to the surveys, there were three rounds of interviews throughout the treatment unit – at the beginning (Appendix J), after lesson eight (Appendix K), and at the end (Appendix L). I interviewed six students chosen through a stratified random-selection process. I asked the students a variety of questions to be able to delve deeper into systems thinking from students who showed a spectrum of abilities. Two were learning support students, one of whom scored in the fifth percentile on the science Measurements of Academic Progress (MAP) standardized test and one who scored in the 86th percentile. Another was a low-performing student not identified as learning support; he scored in the 43rd percentile on the MAP. One was an average student who scored in the 59th percentile on the MAP. The final two were high achieving science students, who scored in the 75th and 97th percentiles on the MAP respectively. Further details about the interview planning process can be seen in Appendix M.

Other data sources included the science MAP results and CAT4 spatial thinking data. These are both standardized tests implemented in Dubai private schools due to governmental mandates. These tests were taken by students prior to the treatment unit and assessed science ability and knowledge (the MAP) and cognitive ability (the CAT4). A final piece of data was my teacher journal that I kept up almost daily throughout the unit. I tracked what went well each day, as well as daily challenges and any other thoughts I had related to the project that day.

It is clear, then, that I collected a variety of quantitative and qualitative data throughout the treatment unit. This aligned with my mixed methods approach and gave a solid foundation for data analysis both while the treatment was ongoing and after it was complete.

# CHAPTER FOUR

# DATA AND ANALYSIS

## The Impact of the Treatment on Students' Systems Thinking Abilities

The pre- and post-assessments for this treatment unit involved looking at four systems thinking skills: asking systems questions, explaining why an entity is a system, drawing systems models, and creating systems concept maps. As noted in the methodology, each was assessed on a four-point scale using a standards-based rubric. The four scores were added together to a highest possible cumulative score of 16. The cumulative pre- and post-assessment scores can be seen below in Figure 1.

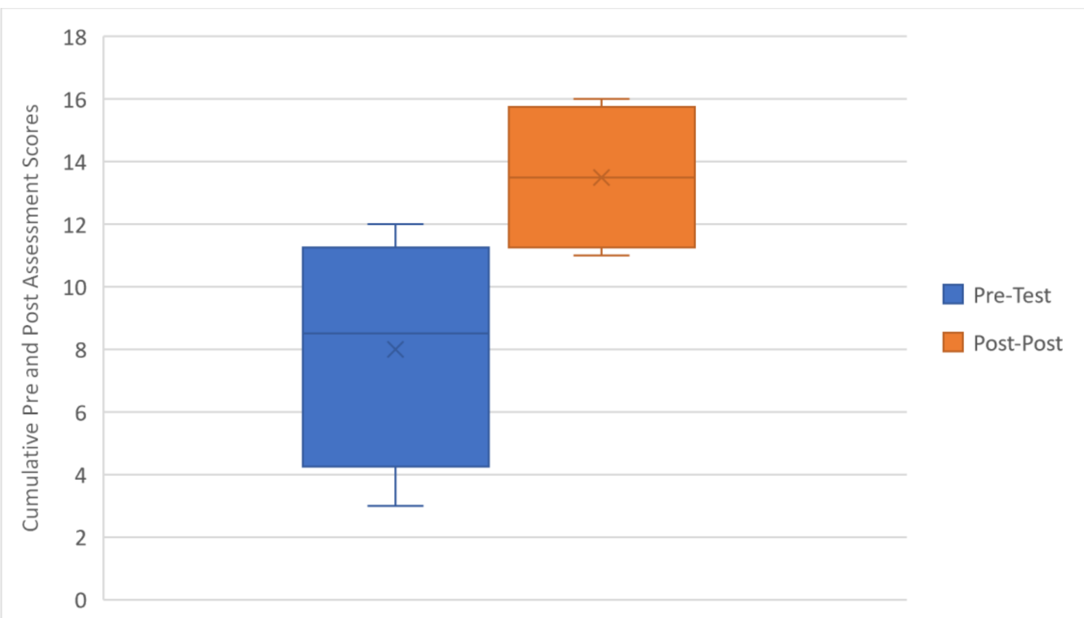



Figure 1. Cumulative pre- and post-assessment scores for the treatment unit, (*N*=88).

Comparing these two assessments shows clear evidence of growth. The mean for the cumulative pre-assessment score was eight out of 16, and this grew to 13.5 out of 16 for the post-assessment. This shows a normalized gain of 0.69, which falls right at the cusp between what is considered medium and high gains when comparing pre- and post-assessments (Hake, 1998). The range for the post-assessment was also smaller than on the pre-assessment, five points as compared to nine points, showing that the treatment led to a narrowing of variation in skills within the student population.

On the pre-assessment, only one student began the unit already proficient in all four systems thinking skills. One other student was proficient in three of the four skills. By the end of the treatment unit, the majority or 60% of the students were proficient or above in all skills, with a further 20.5% being proficient in three of the four systems thinking skills assessed. This shows distinct improvement in the students' ability to utilize systems thinking.

When examining a subgroup, eight of the twelve learning support students were among the 20% that did not have at least three systems thinking skills mastered. Five had two skills at which they scored adequate and two for which they were proficient, one student was only proficient at one skill, and one student was proficient at none of the systems thinking skills at the end of the treatment unit. However, this does not mean that these learning support students did not show growth. The learning support student with the highest level of need started the unit showing a limited ability to ask systems questions, develop systems models, and create concept maps. She was not able to even attempt to write an initial explanation, writing on the initial survey that she "did not know how to explain what a system is" and saying "I'm not sure" when asked to explain why a phenomenon she identified was a system. By the end of the unit, she had improved in all areas, with adequate (level two) ability at asking questions and developing models and proficient ability with concept mapping and explaining why and how the hydrosphere is a system. For example, in the final survey she wrote,

> [the hydrosphere] is a system because it is a process to do cloud seeding and then when the salt goes in the droplets of water, the droplets expand they get heavier and drop out of the cloud that is one process for getting water, After that they need to get the underground water and then desalinated it so it is clean for us to drink.

Though this explanation is lacking a variety of the natural processes in the water system, this student went from a point of no understanding of systems in general and the water system in particular to being able to articulate processes, components, and interactions within the hydrosphere.

For the individual systems thinking skills assessed, all four skills showed growth in the student population, as can be seen in Table 4.

Table 4. Student proficiency with systems thinking skills on pre- and post-assessments, (*N*=88).

| Systems Thinking Skill | Students proficient or above on pre-assessment | Students proficient or above on post-assessment |
|---|---|---|
| Asking systems questions | 31.8% | 72.7% |
| Drawing systems models | 10.2% | 87.5% |
| Creating systems concept maps | 38.6% | 86.4% |
| Explaining why a phenomenon is a system | 9.1% | 87.5% |

There was an increase of at least 40% in proficiency in every skill assessed, with some skills increasing in student proficiency by almost 80 percentage points after the treatment unit. These improvements can be seen if comparing student work samples from the beginning and end of the treatment unit. One student's pre-assessment concept map, created after watching three introductory phenomena videos, can be seen in the figure below. The concept map only includes human-caused processes such as desalination and cloud seeding. There are a few different bodies of water mentioned, and the connecting words are relatively basic (to, from, give). This concept map received a score of two/adequate on the standards-based grading rubric.

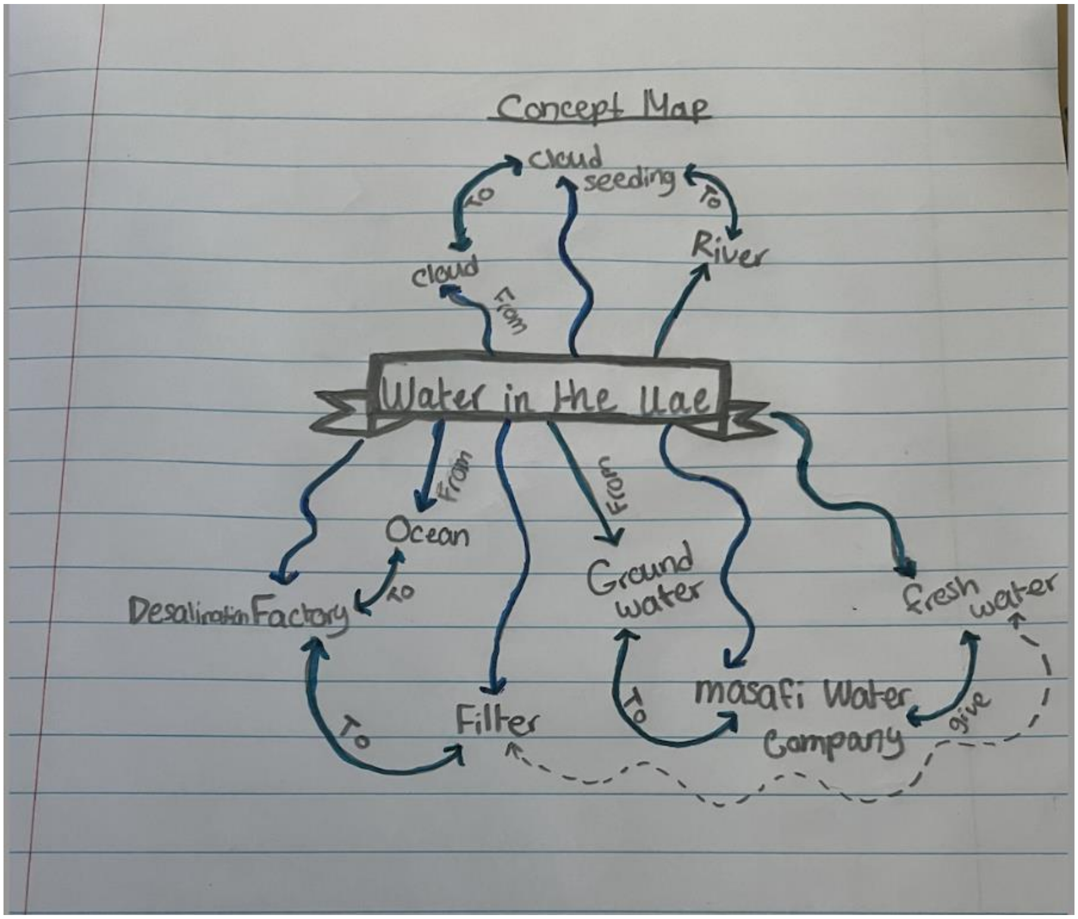



Figure 2. Student pre-assessment concept map which earned a score of adequate/2.

This student showed clear growth in this skill by the end of the unit, for their final concept map received a score of four/exemplary. Students were able to use notes from the unit while creating their final models. As can be seen in the following figure, there was a clear increase in processes and components included in the final concept map, including multiple natural water system processes not included on the initial map. The student also utilized some more advanced linking words such as “evaporates,” “heats,” and “spreads out.”

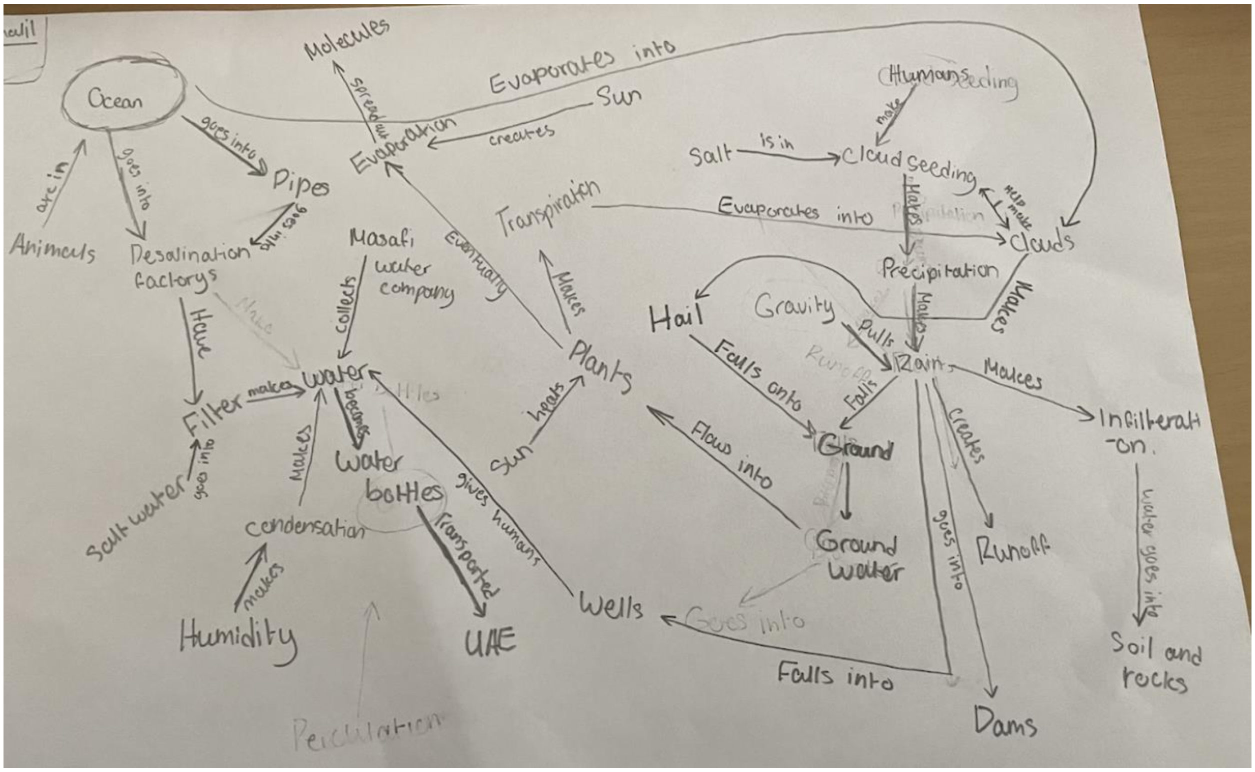



Figure 3. Student post-assessment concept map that received a score of exemplary/4.

As can be seen from the quantitative and qualitative data shared, there was a clear increase in students' systems thinking abilities across the unit, with large increases in the number of students assessed as proficient with systems thinking skills and growth shown in students who did not finish the unit at proficiency.

## Student Confidence with Systems Thinking Skills

Student confidence with systems thinking skills was assessed in both pre- and post-treatment surveys. In the final survey, 100% of students stated that they had improved in their understanding of systems across the course of the unit. One student noted that "[my understanding] has improved a lot because when we actually have a system to learn about you understand more about it….Knowing what a system is shows [how] an actual system works together or interacts with each other." Students originally ranked their confidence in their ability with each systems thinking skill on the initial survey (Appendix F), and the intent was to compare that with student confidence ratings in the post-treatment survey (Appendix H). However, as one student noted in the post-treatment survey,

> On the initial form like this one, I remember to have scored [my confidence] in either 3 or 4 [out of 5], but I think that might have been wrong. I definitely learned more about systems, because we drew models, conducted experiments, and learned more and more about systems.

I agreed with this student that the initial confidence scores seemed inflated and noted in my journal that on the pre-treatment survey "some [students] were just picking 3 [out of 5] because they weren't sure what to put." Additionally, I thought that "even if [the students] start at a confidence level of 5, [they can note if] they still think their understanding improves over the course of the unit." As such, I added Likert type questions to the final survey asking students to agree or disagree with the statement that they had improved in each skill throughout the unit and thus whether their confidence had increased. Figure 4 shows the students' responses to the Likert question relating to the skill of asking systems questions, which was the weakest area for students at the end of the treatment unit. Even with the skill with the lowest number of proficient students at the end of the unit, only one student disagreed that they had improved in this skill and 17 students felt neutral. The remaining 60 students or 79.5% agreed or strongly agreed that their skill in this area had improved. This shows that the majority of the students had increased confidence with asking systems questions. The responses for the other skills showed even further increases in confidence in the post-treatment survey.

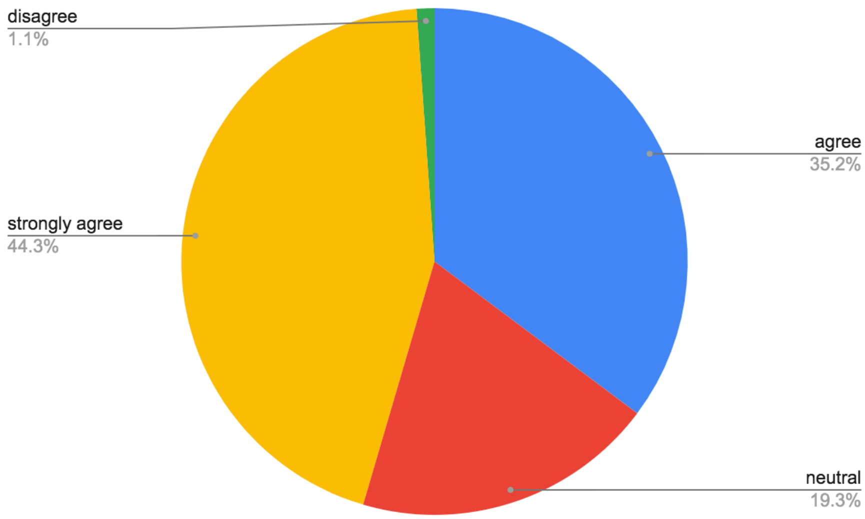



Figure 4. Pie chart showing student responses to the Likert scale statement "My ability to write systems questions has improved during this unit" on the post-treatment survey, (*N*=88).

Student written responses showed similar thinking. One student noted, "I have learned more examples of systems and how they work, increasing my understanding of them by learning the difference between some and more of them, allowing me to not just know more but understand more of how they work." This student clearly felt that the mini-lessons and activities in the unit allowed them to understand and compare a variety of systems at both the levels of knowledge and understanding. Another student noted, "I can identify components and processes first, then see how they link together," which indicates that this student realized they had achieved at least the first three of the "eight emergent characteristics of systems thinking" (Ben-Zvi Assaraf & Orion, 2005, p. 523). It is clear, then, that student confidence rose across the course of the treatment unit.

<u>The Impact of Systems Thinking on Three-Dimensional Instruction</u>

With systems as one of the Crosscutting Concepts of the NGSS, I intertwined this instruction with the Science and Engineering Practices students performed in the unit as well as the actual content knowledge pertaining to the Disciplinary Core Ideas of the unit. This was done to create three-dimensional instruction in the classroom where all three dimensions of the NGSS were addressed in every lesson.

Systems Thinking and the Science Practices

Students overwhelmingly agreed that learning about systems helped them with their skill at the science practices (Figure 5).

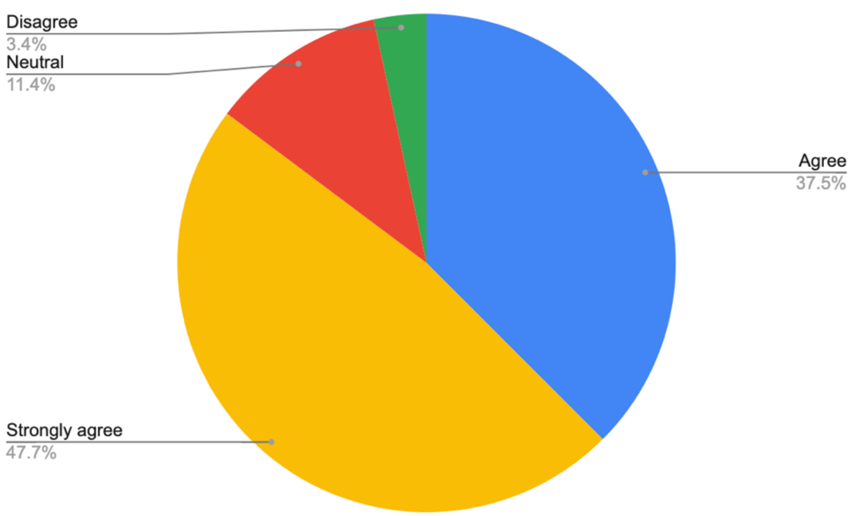


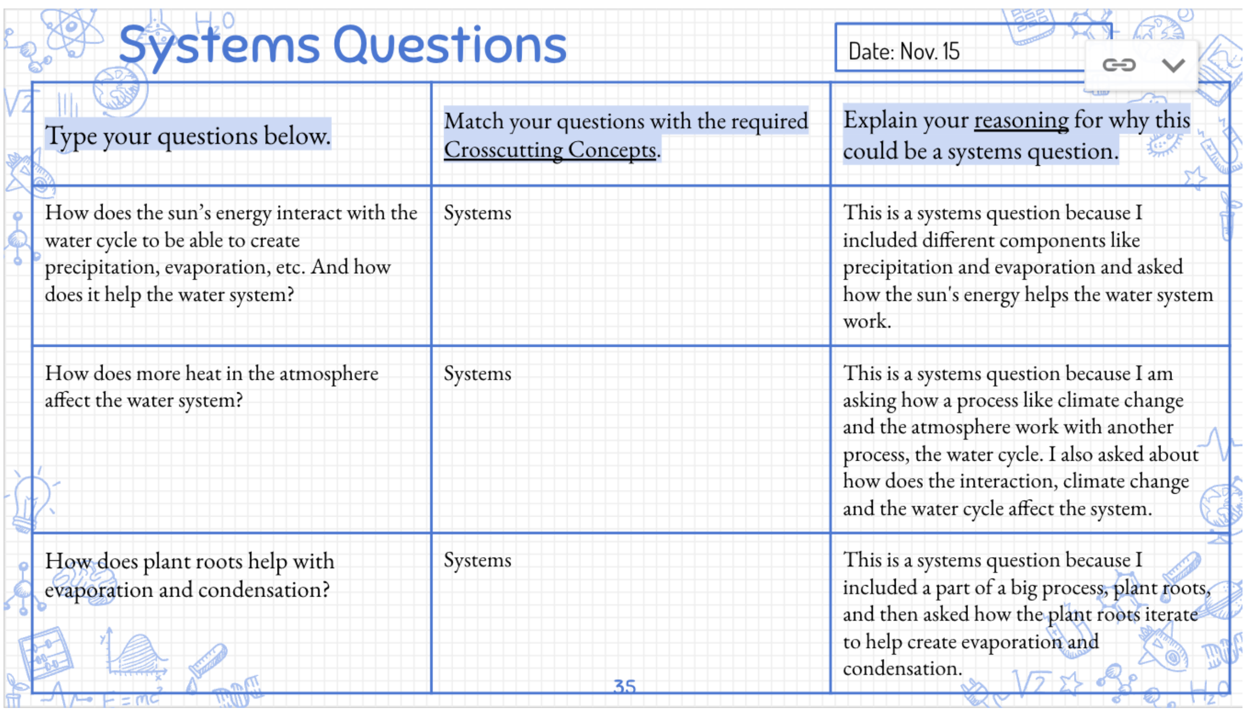

Figure 5. Pie chart showing student responses on the post-treatment survey to the question "Has learning about systems helped you with our science practices/skills (asking questions, developing models, conducting investigations," (*N*=88).

Of the students surveyed, 85.2% agreed or strongly agreed that systems thinking helped them improve their ability level with the science practices. One student wrote,

> [It] has helped ask better questions because good scientific questions should include the crosscutting concepts…I understand systems now, so I can easily ask good

> systems questions. It has helped me draw better models because I can connect almost everything to each other.

I myself noted after a mini-lesson on how to write systems questions that the students were able to provide good examples of questions and were using key words from a list we co-constructed to structure their questions in a scientific format. For example, another student started off the treatment unit with this systems question: “What is the process in the cloud that makes it larger just from the salt?” She then explained this was a systems question by saying “because there are different things working together to create or achieve one thing.” After the mini-lesson, she was able to write and connect the questions below to systems (Figure 6).



Systems Questions

Date: Nov. 15

| Type your questions below. | Match your questions with the required Crosscutting Concepts. | Explain your reasoning for why this could be a systems question. |
|---|---|---|
| How does the sun’s energy interact with the water cycle to be able to create precipitation, evaporation, etc. And how does it help the water system? | Systems | This is a systems question because I included different components like precipitation and evaporation and asked how the sun's energy helps the water system work. |
| How does more heat in the atmosphere affect the water system? | Systems | This is a systems question because I am asking how a process like climate change and the atmosphere work with another process, the water cycle. I also asked about how does the interaction, climate change and the water cycle affect the system. |
| How does plant roots help with evaporation and condensation? | Systems | This is a systems question because I included a part of a big process, plant roots, and then asked how the plant roots iterate to help create evaporation and condensation. |

35

Figure 6. Student systems questions and reasoning for why each question is a systems question.

The student included some deeper thinking in her later questions, using words such as “interact” and “energy.” She included other Crosscutting Concepts in her questions as well, touching on cause and effect relationships and matter and energy. Her reasoning also showed deeper thinking than her re-statement of the definition of system in her reasoning from the beginning of the unit.

Asking questions was not the only science practice that improved in the unit, as I noted in my journal that creating concept maps, a strategy from the systems thinking toolbox, after the natural water processes investigation pushed the students to do "a really good job showing connections between the processes." Modeling also improved across the unit. Students had so much to include in their post-assessment models that many needed to use multiple sheets of paper taped together to be able to capture their complete understanding of the system. Far more natural processes from the water cycle were used in final models, and there were increases in the number of both components and processes in the models. One example can be seen in Appendix N. The initial model included three human-related processes dealing with water and no natural processes, whereas the final model included all the natural processes of the water system as well as the processes from the pre-assessment with some additional human-related processes. The evidence from asking questions, creating concept maps, and developing models shows that the multidimensional approach to teaching the unit DCI allowed the students to improve in their skill with the different Science Practices as well as make more sense of concepts and build a deeper understanding of the hydrosphere.

## Systems Thinking and the Disciplinary Core Ideas

In the final treatment survey, 95.5% of students either agreed or strongly agreed that learning about systems helped them understand the water cycle in the UAE (Figure 7).

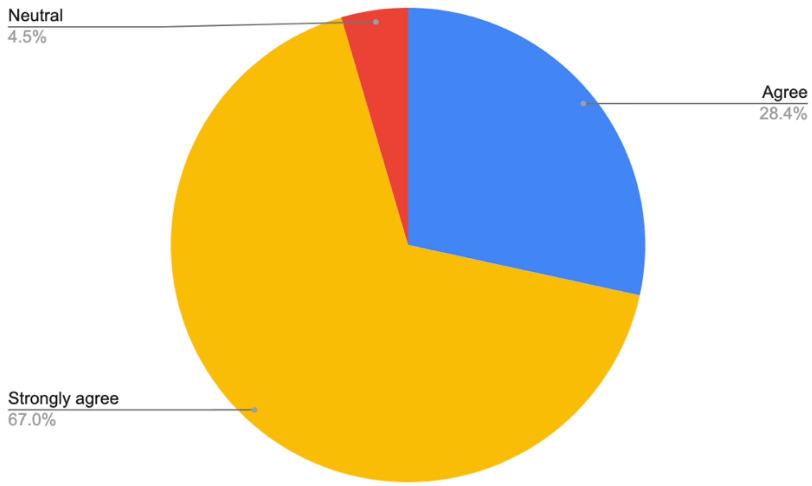



Figure 7. Pie chart showing student responses on the post-treatment survey to the question "Has learning about systems helped you understand the water cycle in the UAE," (*N*=88).

One student noted, "it has helped me better because if I didn't learn about systems before this unit I would have trouble understanding how all the processes work together to accomplish things." This student is highlighting that systems thinking helped them understand how the hydrosphere works as a whole, as opposed to just listing separate processes and drawing them in a circle or series of steps. As I noted myself on October 31, 2021, "the direct connections we're making to the different aspects of systems thinking are helpful in building the kids analysis skills, and we're already seeing deeper conversation from students than we had last year in the pilot unit." Utilizing systems thinking pushed the students to dive more deeply into the content than teaching without the systems focus.

One student noted in an interview that the connection went the other way as well. When asked if learning about systems helped her understand the water cycle better, she noted, "it's kind of the opposite for me. Doing the work helps me understand more about systems" and agreed that doing the practices helped her understand systems better as well. This connects back to the literature, as Eilam (2012) noted that acquiring systems thinking skills is "bidirectional," with learning about the system helping students to understand a phenomenon but learning about the phenomenon also helping students to understand systems (p. 233).

## Factors that Impact Student Ability with Systems Thinking

Research indicated that there are a variety of factors that impact student ability to achieve systems thinking skills, such as working memory, spatial thinking skills, and cognitive ability (Ben-Zvi Assaraf & Orion, 2005; Eilam, 2012; Hmelo-Silver & Azevedo, 2006). Utilizing standardized testing scores and student pre- and post-assessment scores indicated that this was also the case with my own students. One standardized test mandated for students by Dubai's department of education for private schools is the Cognitive Abilities Test known as the CAT4. This test measures student cognitive skills in the areas of verbal reasoning, quantitative reasoning, non-verbal reasoning, and spatial ability. Students' spatial ability is scored on a stanine from one to nine, and looking at students in larger groups did indicate that there is a correlation between student spatial thinking skills and their systems thinking skills both at the beginning and the end of the treatment unit (Table 5).

Table 5. Mean cumulative pre- and post-assessment scores compared to spatial ability scores on the CAT4 test, (*n*=77).

| Stanine Ranges | Mean Pre-Assessment Score | Mean Post-Assessment Score |
|---|---|---|
| 1-3 | 8.13 | 11.63 |
| 4-6 | 8.17 | 12.72 |
| 7-9 | 8.83 | 14.09 |

While students in the lower six stanines had relatively similar mean cumulative pre-assessment scores, the students in the highest three stanines did begin the unit at almost an entire proficiency level above in one of the four systems thinking skills assessed. The mean post-assessment scores show an even more obvious trend, with each stanine band scoring higher than the previous one by at least one proficiency level in one skill. This seems to indicate that students with more advanced spatial thinking skills may already have some systems thinking ability before these skills were even directly taught. Additionally, these spatial thinkers also finished the unit as the students with the most advanced systems thinking skills. There were outliers, of course. Twelve of the 46 students in the middle range of the spatial ability stanines scored above the mean for the top stanine range, and two of the 23 students in the top stanine range scored below the mean for the mid-range students. Despite these outliers, it still stands that students assessed with higher spatial ability were more likely to be exemplary systems thinkers at the end of the treatment unit.

This idea of the students who started strong finished strong is further supported by comparing pre-treatment concept map scores to post-treatment concept map scores, as can be seen in Table 6.

Table 6. Comparisons of pre-treatment and post-treatment concept maps, (*N*=88).

| | | Post-Treatment Concept Map | | | |
|---|---|---|---|---|---|
| Pre-Treatment Concept Map | Percent | Limited | Adequate | Proficient | Exemplary |
| | Limited | 0 | 0 | 4 or 100% | 0 |
| | Adequate | 0 | 10 or 20% | 20 or 40% | 20 or 40% |
| | Proficient | 0 | 1 or 2.94% | 7 or 20.59% | 26 or 76.47% |
| | Exemplary | 0 | 0 | 0 | 0 |

There was one outlier student who finished the unit with a less advanced concept map than she began with, but this was likely because she lost her summative concept map and then rushed the day it was due to try and recreate it in order to turn it in before the winter break. Other than her, approximately 20% of students did not advance their concept mapping skills, but the vast majority improved. In fact, 40% of the students starting with adequate concept maps, which have a more basic spoked organization, were able to finish the unit with exemplary concept maps that showed a complex, web-like understanding of the water system in the UAE. In comparison with this, though, almost 77% of the students who started the unit with already proficient concept maps were able to advance their maps to that exemplary level. This shows that while the majority of students improved their systems thinking skills, those coming into the unit with already strong skills were more likely to finish the unit as the strongest systems thinkers.

Starting the treatment unit with more scientific knowledge and better science practices skills also impacted students' ability to access systems thinking. The Northwest Evaluation Association's (NWEA) General Science Measures of Academic Progress (MAP) test was taken by all 88 students prior to the treatment unit. Breaking out the students into the NWEA's MAP test sub-groups did show some correlations between higher test scores and better performance on the pre-assessments. Figure 8 shows the concept mapping scores for students in the different ranges of the MAP test, which are based on performance percentiles – high (80-100%), high average (60-79%), average (40-69%), low average (20-39%), and low (0-19%).

The correlation between higher MAP test scores and pre-treatment success was especially evident with concept mapping. Of the 34 students who scored proficient on their concept map, 22 of those students were in the high range on the MAP test and 7 were in the high average range. For the lower students who scored proficient, one was a student who admitted to rushing on the MAP test, and another was one of the learning support students with executive functioning skills. The length of the MAP test and structures around its proctoring likely made it more difficult for him to show his actual ability levels on the MAP test. It seems clear from this graph that higher MAP scores were a predictor of better systems thinking skills at the beginning of the unit, particularly for concept mapping.

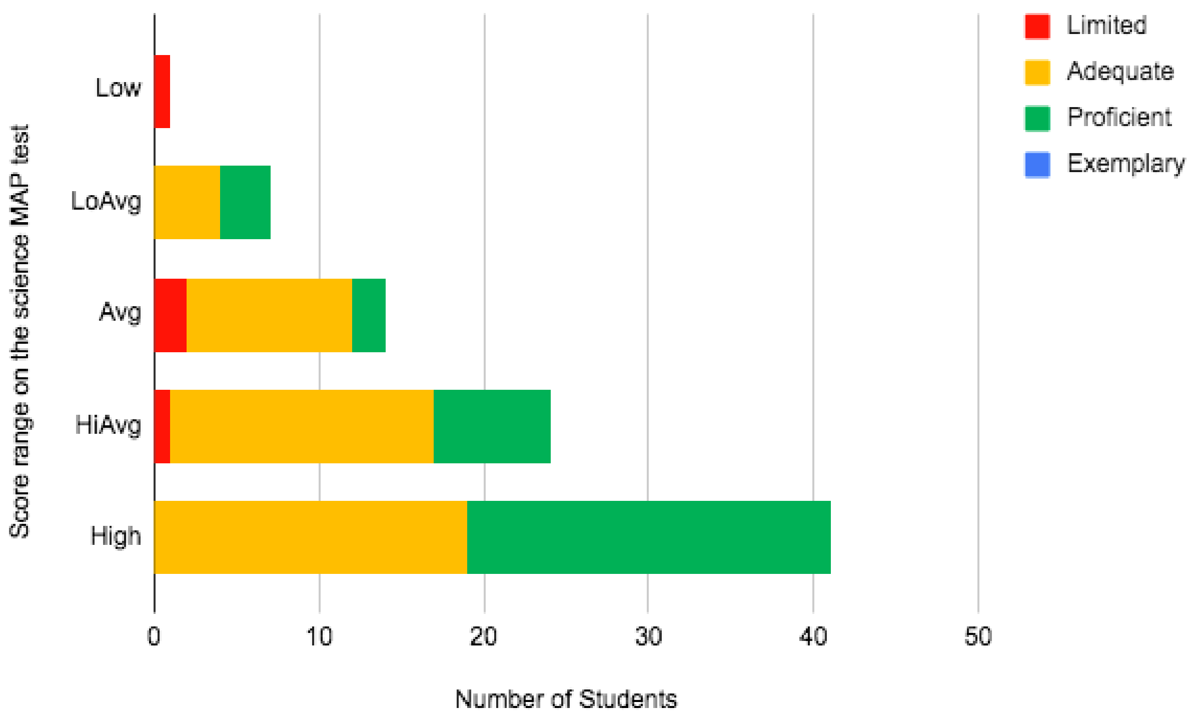



Figure 8. Creating systems concept maps pre-assessment scores broken out by MAP test range subgroups, (*N*=88). The colors indicate assessment grades for the concept maps created by the students in each MAP testing subgroup.

This trend held up somewhat when looking at the post-assessments. Figure 9 shows concept mapping post-treatment scores based on MAP score range.

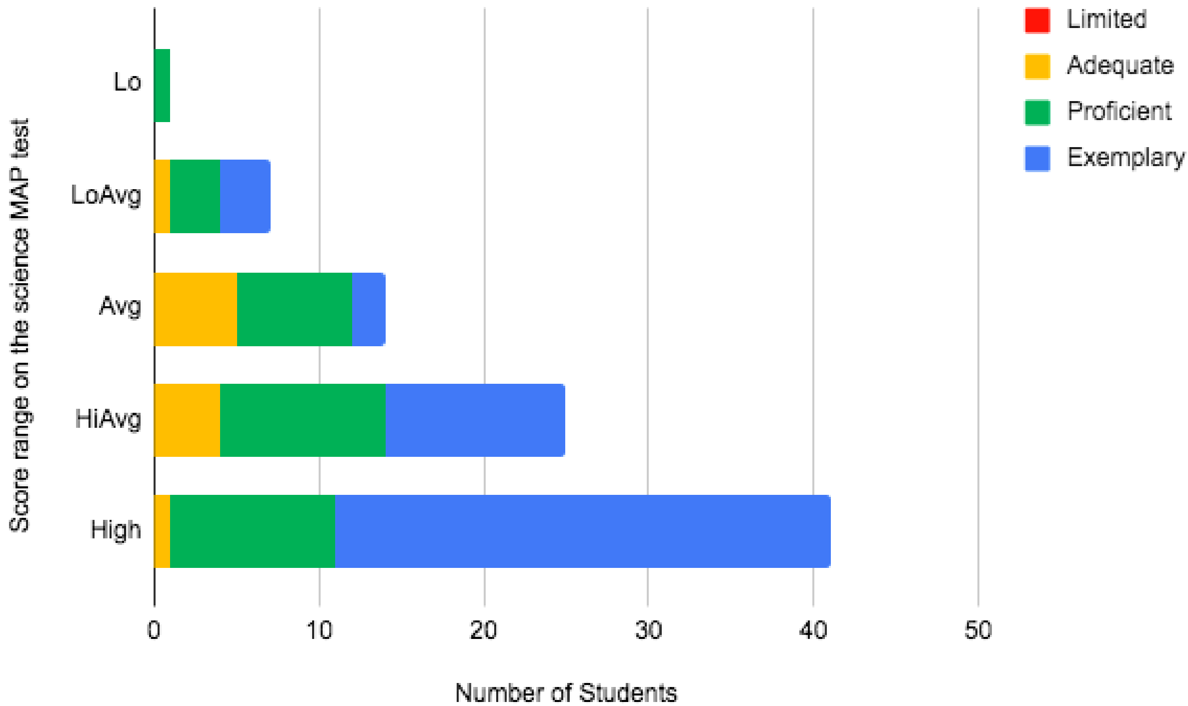



Figure 9. Creating systems concept maps post-treatment scores broken out by MAP test range subgroups, (*N*=88). The colors indicate assessment grades for the concept maps created by the students in each MAP testing subgroup.

Students in the highest range for the MAP test were less likely to score below proficient and more likely to score above proficient than students with lower MAP scores. Students with average MAP scores were much less likely to be exemplary than higher scoring students. Some interesting outliers are the students who scored in the low average range on the MAP test. While one was only adequate – typical for her work in class, which is often left uncompleted – the rest were all proficient or exemplary. The two earlier mentioned outliers from the pre-treatment concept map histogram brought their proficient concept maps up to exemplary, and thus grew in their systems thinking skills throughout the unit. Two other outliers were other learning support students who brought their concept mapping scores from adequate to proficient for one and exemplary for the other. These two children were always very engaged in the lessons, participating in all activities, actively discussing their thinking, and trying to do their best on every assignment. Their efforts show that the systems thinking mini-lessons could be effective for students with special learning needs and lower science content knowledge if the students actively engaged in said mini-lessons.

# CHAPTER FIVE

# CLAIMS, EVIDENCE, AND REASONING

## Impact of the Treatment Unit on Student Systems Thinking Abilities

The overarching question of this project asked about the impact of explicitly teaching systems thinking skills and strategies to students. The data supports the claim that explicit instruction of systems thinking skills improves student ability to utilize systems thinking strategies. The normalized gain showed very close to a high level of growth across the treatment unit, with it being only 0.01 away from what Hake considered a high level of growth. There were large increases in the number of students proficient or above in each of the four systems thinking skills assessed (Table 4). For example, explaining why an entity is a system went from 9.1% proficiency to 87.5% proficiency. Even students who had not finished the unit with proficient skills showed improvement in at least one or more systems thinking skill. All students improved their systems thinking abilities across the course of the unit due to the explicit instruction in those skills.

Considering a subgroup of students, eight of the twelve learning support students did not finish the unit proficient in at least three systems thinking skills. As noted in the evidence, they did all show growth in some areas, just not necessarily to proficiency. This indicates that the strategies were effective for learning support students to an extent. However, they likely needed more time, more practice, and further support to attain proficiency in all areas of systems thinking. This is a point in the favor of the curriculum we have for grade six science at my school, as we address all of the Earth systems, so that would give further units through which the struggling students could continue to grow in their systems thinking capabilities.

One skill in particular that most of these eight needed to improve was asking systems questions. There were also 16 other students who finished the unit less than proficient in this area. It was the skill with the lowest level of proficiency and above, with 72.7% of students reaching the desired level. What the majority of these students struggled with was not writing a question that addressed the dynamics of a system but the second component to a proficient systems question. As shown in the asking systems questions rubric (Appendix B), I required students to "attempt to explain why their questions address the functioning of the system of study and its components." Most of the students who scored as adequate/2 only parroted the definition of system in their explanation. When thinking back, in the mini-lesson on writing systems questions, we came up with a list of terms that could be used to construct systems questions and wrote practice systems questions about a phenomenon student groups chose, but we did not focus as much on explaining why their questions were systems questions. A few students did this orally in a discussion, but I did not require it of all students. It is likely that for the number of students who were proficient in writing systems questions to improve, students would need to practice writing those statements that explained the connection between their question and the Crosscutting Concept of systems.

If we refocus on the successes of the treatment approach, the majority of the post-treatment concept maps showed themselves to be in a more advanced format than the pre-treatment concept maps, showing more components and processes and including further connections. Based on the research, this advancement in their concept maps showed a greater ability on the students' part to make connections between concepts, as students with more advanced concept maps have a more interconnected understanding of the larger phenomenon (Kinchin et al., 2000). As such, the growth in scores indicated that the design of the treatment unit with explicit instruction of systems thinking skills led not only to growth in students' understanding of systems, but also in their ability to use systems thinking as a lens for understanding the movement of water throughout the United Arab Emirates and the water cycle in general, and in their ability to make connections between different processes and concepts. This validated the approach I took based on David Perkins' 2009 book, wherein he states that students need to explicitly learn and practice the "rules of the game" for whatever content area you are teaching.

## Student Confidence with Systems Thinking Skills

The first supporting question asked if the explicit instruction of systems thinking skills improved student confidence with those skills. As noted in the data analysis section, 100% of students reported that their understanding of systems improved across the course of the treatment unit. This shows that all students were feeling more confident in their ability to utilize systems thinking strategies. The majority of the students even agreed with this when it came to specific systems thinking skills. Even the least positive of the results when asking about the specific systems thinking skills had approximately 80% of students agreeing that they had improved. Student reflections indicated that students saw the specific activities designed around teaching systems helped them better understand how systems work, how to make connections between components, and compare different systems, which would lead to increased confidence about their knowledge pertaining to systems. This reinforced the literature relating to the importance of explicit instruction. Just as Kali (2003) saw that explicit systems mapping activities improved students' systems-level understanding of the rock cycle, explicit instruction in the various systems thinking skills improved my students' systems-level understanding of the water cycle. Increased skill is generally going to lead to increased confidence, which was reflected in the students' reflections on whether their knowledge had improved.

## The Effect of Teaching Systems Thinking on Three-Dimensional Instruction

My second supporting question asked how systems thinking impacted three-dimensional instruction in my classroom. As noted in the introduction, the premise of this project was to help transition from a more two-dimensional classroom focused on the Science Practices and Disciplinary Core Ideas to a three-dimensional approach that also included the Crosscutting Concepts. Implementing the systems approach to this unit automatically created a three-dimensional approach, as I was addressing all three dimensions of the NGSS. I have already explained how students' understanding of the Crosscutting Concept (systems and systems models) improved, but data also showed that the inclusion of explicit instruction for the CCC benefited students in the areas of the SEPs and the unit DCI as well. As seen in Figures 5 and 7, the majority of students agreed or strongly agreed that learning about systems helped them improve in their use of the Science Practices in the unit as well as the unit Disciplinary Core Idea. This indicates that taking the three-dimensional approach improves outcomes in all dimensions of the NGSS. Students described further that the three-dimensional approach helped them make connections between the different processes and components of the hydrosphere, improve their ability to ask questions and make models, and get a better grasp on the Crosscutting Concept of systems.

I believe that student questions improved due to explicitly discussing how to write systems questions, which was a mini-lesson designed around a three-dimensional approach. This improved their question writing in general because students started to think about terms they could use in their questions to look more deeply into phenomenon, as we had specifically discussed in our systems question writing mini-lesson. I was able to prompt in later units to ask what sort of terms they could center questions around when they were struggling with writing questions about specific phenomena. As the terms connect to specific Crosscutting Concepts, this is evidence that the multidimensional approach helps improve student skill with the asking questions Science and Engineering Practice.

As students said, models also improved through the course of the treatment unit (see Appendix N for an example). The act of creating multiple concept maps throughout the unit – part of the three-dimensional approach in including the CCCs – increased the focus on making connections between different concepts and components of systems. This led students to have a more interconnected understanding of the unit, which was seen in the many links they made between components in their final models.

The connection went the other way as well, with the Science and Engineering Practices helping students understand the content of the unit and the Crosscutting Concepts. For example, students completed several investigations into natural processes in the water cycle. This helped them to understand the processes so that they were able to make the connections described above, which is key to systems thinking. This was seen when I interviewed the learning support student with the highest level of needs and asked her what activities helped her better understand the water system. She was able to explain the concept of differential percolation between sediment types a few weeks after the investigation based upon what she had seen in class. This shows that the three-dimensional approach is tridirectional, with each element of the NGSS helping with learning the others.

These results match with claims researchers have made about the connection between systems and concepts/content (Eilam, 2012, p. 233) as well as between systems and performance of science skills (Rivet at al., 2016; York et al., 2019). Learning about systems and practicing systems thinking skills improves understanding of content knowledge as well as the students' ability to practice science as student scientists, and the opposite is true as well.

## Factors that Impact Student Ability with Systems Thinking

The third supporting question asked what factors might impact students' ability to attain systems thinking skills. The MAP scores from before the treatment unit show an initial variation in systems thinking capabilities. Students with higher MAP scores were more likely to come into the unit already proficient in at least one of the systems thinking skills (Figure 8). This was apparent for students in the high range on the MAP test (80-100 percentile) as well as the high average range (60-79 percentile). This seems to indicate that greater depth of science knowledge and scientific logical thinking, both of which are assessed on the science MAP test, are correlated with stronger systems thinking skills.

Spatial thinking skills also impacted students' ability to participate in systems thinking skills. Table 5 shows that the students with the highest spatial thinking stanine on the CAT4 assessment were already slightly better at systems thinking than the students with weaker spatial thinking ability. This means that spatial thinking capability impacts students' ability to utilize systems thinking, as noted in the literature (Eilam, 2012, p. 213).

All of this showed that some students were more prepared for thinking about concepts on a systems level than others. Lower scoring students needed more scaffolding to grow their systems thinking skills, with specific mini-lessons and scaffolded steps essential to building their abilities. Higher scoring students needed to be given opportunities to analyze the systems at greater depth, since they were more prepared to push their systems thinking abilities at that level. Figure 9 and Table 6 show that the specific mini-lessons and scaffolded steps helped the majority of the students improve their systems thinking skills by the post-assessment. It also showed that the opportunity to dive into analyzing a specific system led to the already proficient students finishing the units as the strongest systems thinkers, which the literature had indicated (Ben-Zvi Assaraf & Orion, 2005). For the students who did not reach proficiency, the majority were students who scored lower on the spatial thinking section of the CAT4 and on the science MAP test. This meant that lower performing students would need further units and more phenomena to build their systems thinking skills to proficiency.

## Values of the Study

### Impact of Research on the Author

I find that using systems thinking instruction requires me to think more holistically as I create the lessons. I have to focus on how to build students' abilities to make connections between concepts. Additionally, in order to practice students' systems thinking skills I need to make time for students to process information. In the past, I have structured my units tightly to work through the Science and Engineering Practices as students investigate a phenomenon. I did not always build in time for students to summarize what they had learned or connect different activities together. However, in planning to build students' systems thinking skills, I had to schedule time for students to draw models or concept maps to show how the processes they had learned about worked together. This gave much needed processing time for students to think about the investigations they had conducted or research they had done. As I noted in my teacher journal, this approach "gave them [the students] a better idea of the big picture of science…It gave them a broader view of the concepts and had them connect to other earth systems." In thinking of improving students' skill with the Crosscutting Concept, I am internalizing the need to use it as a bridge to build connections and seeing the benefit of that ability.

Furthermore, giving the students time to map out the aspects of the system they have learned so far gives me time to check in on their understanding and find areas that need reinforcement. I noted in my teacher journal when students were mapping out the natural processes of the water cycle after a stations investigation that there was "a struggle to differentiate between evaporation and condensation - I think the station we're using is not helping, since it includes both." This prompted me to build in time for students to plan out skits to showcase evaporation and condensation, which gave them further practice with these skills. It also led to me researching possible experiments to try next year that may work better, and I now have a list that I can use to plan how to better model those processes.

Systems thinking also provided an opportunity for me to give students more choice. I have struggled with the NGSS in the past to give choices of products to students. If I am assessing students' ability to perform a certain Science and Engineering Practice, then I have felt that there is not a choice, i.e. I am assessing modeling so they have to draw a model. With the focus on systems thinking, however, I have introduced a different type of model – the concept map. This led to me giving students the opportunity to choose between a drawing-type model and a concept map when summarizing our investigations – they could draw out how the processes and components they had learned about connected or they could create a concept map. This empowered students to make the choice about which type of model would best demonstrate their understanding – one student noted in a class discussion that “I like it better when there is a drawing...I just think in my head that it’s much easier to understand a drawing,” whereas I had another say that she felt concept maps were a better way to show how all the components of the system interacted.

This gave me an opportunity to be more flexible and consider how students can perform a Science and Engineering Practice in different ways to best highlight their understanding. I was able to put this into action at the end of our geology unit later in the year, as my partner teacher and I agreed to give the students the option of a drawing-type model, a concept map, or a combination of the two, i.e. a mind map, to show their understanding of the movement of matter and energy in the lithosphere. Students expressed their appreciation for the choice and had varying reasons for the type of model they chose – for example, it being the type at which they felt they were best, or it being the type they felt worked best for the phenomenon. This aligns with the Universal Design for Learning (UDL) approach my school uses in an effort to design learning opportunities that work for all students. As the UDL website notes (CAST, 2019), providing “such alternatives reduce[s] media-specific barriers to expression among learners with a variety of special needs, but also increases the opportunities for all learners to develop a wider range of expression in a media-rich world.” As such, systems thinking has helped me broaden learning opportunities and means of expression for one important SEP that has seemed quite rigid in the past.

Implications of the Study for Myself and Others

There are many implications for myself, my department, teachers that utilize the Next Generation Science Standards, and teachers that do not. The impact of the explicit instruction on my students' performance indicates to me as a department chair that I need to continue the focus we have in our middle school science department this year on the Crosscutting Concepts. We have broken down the CCCs of systems, cause and effect, and patterns so far, with scale as our next CCC of focus. I am going to share my results with my department to emphasize the benefits of focusing on the Crosscutting Concepts.

The same applies for any teachers that teach the Next Generation Science Standards and even those that do not. If students are better able to learn content and perform science skills due to explicitly teaching them the CCCs, then it is essential that we use the CCCs as a tool to help students learn to play the whole game of science, in the words of David Perkins (2009). Students will learn to think and work more like scientists and understand scientific information better too. I plan to modify this capstone paper as a proposed article for Science Scope and perhaps other publications as well, in order to spread the information.

The aspect of choice that is added with different types of models is also one that can apply to other teachers. Once you have taught students how to make both concept maps and drawing-type models, they can choose between the two types and even create a combination of the two, which would be more akin to a mind map. Choice is an important topic for the NGSS, as assessing a Science and Engineering Practice can seem restrictive. It is important to consider the variety of ways that the SEPs can be performed by students, as well as how they can share their abilities with those SEPs with us as their teachers.

Considerations for the Future

Future research can be done to address how to continue to deepen students' systems thinking skills across various systems. The majority of the research I found involved the hydrosphere, with one or two articles involving other Earth systems or body systems. Seeing that these skills can apply to a variety of systems would be helpful. Additionally, I did not find any research like mine into explicitly teaching systems thinking in the context of the NGSS. Fick's (2018) NGSS Crosscutting Concepts research involved implicit instruction in systems thinking, and the literature that involved explicit instruction was not in the context of the NGSS. The Crosscutting Concepts in general are an area that needs more attention in research, including showing the benefits of utilizing the CCCs in the classroom but also showcasing strategies that are effective for CCC instruction.

As for myself, I have already outlined a few next steps. I need to share my research with my team to reinforce the importance and benefit of using the Crosscutting Concepts. We need to continue breaking down other Crosscutting Concepts to ensure that all of them are addressed within our classrooms. As we already have rubrics for the Science and Engineering Practices, it would be good to create a protocol for sharing assessments and learning tools to ensure that we are properly scaffolding up students' abilities with all of the Crosscutting Concepts.

More specifically for systems, I have already taken some next steps in focusing our later units on systems as well, such as in our units on the biosphere and geosphere/lithosphere. I need to put in some more work in the next school year to ensure that the later units also give students time and prompts to properly make connections between concepts and use their systems thinking skills to understand the other Earth systems.

## In Conclusion

I have learned a great deal about myself, my students, and three-dimensional instruction throughout this project, from the applicability of our mandated standardized testing to my students' success to the benefits of teaching students to use the lens of systems thinking to approach phenomena. I have grown a great deal as an educator, constantly reflecting on the benefits of my approach and how that impacted my students. However, this is only the beginning. I will continue to research the literature, administer treatments as part of my school's Reflection for Learning professional growth program and outside of it, and collect and analyze student data in order to design the most beneficial instruction for my students.

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# APPENDICES

APPENDIX A

IRB EXEMPTION

Dear Rachel,

Thank you for your application. This email acknowledges receipt of the request for IRB Review and serves as the Approval Letter for your research. **Your new IRB Exempt Protocol # is RD042921-EX.**

As the PI, it is your responsibility to facilitate subject understanding by informing subjects of all aspects of the project, providing an opportunity to ask questions, and describing risks and benefits of participation. Submit any new changes to the research protocol to the IRB via Amendment Form prior to implementing.

The research described in your submission is exempt from the requirement of additional review by the Institutional Review Board in accordance with the Code of Federal regulations, Part 46, section 101. The specific paragraph which applies to your research is:

(b)(1) Research conducted in established or commonly accepted educational settings, involving normal educational practices such as (i) research on regular and special education instructional strategies, or (ii) research on the effectiveness of or the comparison among instructional techniques, curricula, or classroom management methods.

Thank you,
Kelly Beiswanger

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https://www.montana.edu/orc/irb

# APPENDIX B

## RUBRICS FOR ASSESSING SYSTEMS THINKING SKILLS

Asking Systems Questions

| Exemplary (4) | Proficient (3) | Adequate (2) | Limited (1) |
|---|---|---|---|
| Students ask *detailed* scientific questions that seek to gather more information about the phenomenon or problem by using data.<br><br>Students *clearly explain* how their questions address the functioning of the system of study, its components, and their relationships or interactions. | Students ask scientific questions that seek to gather more information about the phenomenon or problem by using data.<br><br>Students attempt to explain why their questions address the functioning of the system of study and its components. | Students ask questions to gather more information about the phenomenon or problem.<br><br>Student questions are related to the system of study but do not articulate how the questions address the system. | Students ask questions that are not scientific and that are irrelevant to explaining the phenomenon.<br><br>Student questions are related to the system of study but do not address the function of the system and its components |

Developing system models (drawings)

| Exemplary (4) | Proficient (3) | Adequate (2) | Limited (1) |
|---|---|---|---|
| The student meets all proficiency expectations AND one or more of the following:<br><br>-The movement of energy and matter is accurately included in the model.<br><br>-The drawing makes clear the inputs and outputs of the system. | The student identifies and labels the system components required for the model. This can be done through labels or a key.<br><br>The student represents and describes all the relationships between components through the use of arrows or other visuals that indicate connections. | The student identifies and labels some of the system components required for the model.<br><br>The student represents and describes the relationships between some of the components. | The student includes some of the system components in the model.<br><br>It is unclear what the relationships are between the components. |

Developing system models (concept maps)

| Exemplary (4) | Proficient (3) | Adequate (2) | Limited (1) |
|---|---|---|---|
| The student identifies 90% or more of the components of the system.<br><br>The student represents multiple relationships between components through the use of arrows.<br><br>The student describes all the relationships between components using linking words.<br><br>The student organizes the concept map in a complex web. | The student identifies most of the components of the system.<br><br>The student represents the relationships between components through the use of arrows.<br><br>The student describes most of the relationships between components using linking words.<br><br>The student organizes the concept map in a web-like structure. | The student identifies some components of the system.<br><br>The student represents relationships between some components with arrows or lines.<br><br>The student uses some linking words to describe relationships.<br><br>The student organizes the concept map in a structure that is linear or spoked. | The student identifies a few components of the system.<br><br>The student represents a few relationships between some components with lines.<br><br>The student does not use linking words to describe relationships.<br><br>The student organizes the concept map in a linear structure. |

Explaining why a phenomenon is an example of a system

| Exemplary (4) | Proficient (3) | Adequate (2) | Limited (1) |
|---|---|---|---|
| Student explains how a phenomenon is an example of a system using multiple specific components and interactions and addresses subsystems or hidden dimensions of the system. | Student explains how a phenomenon is an example of a system using a few specific components and 1-2 interactions. | The explanation of how a phenomenon is an example of a system focuses on restating the definition of the term system. | Explanation is unclear and off topic |

# APPENDIX C

## ASKING QUESTIONS GRAPHIC ORGANIZER

# Questions: Water in the UAE

Date:

| Copy down your three best water related questions here. | Match your questions with the required Crosscutting Concepts. | Explain your reasoning for why your question matches with that Crosscutting Concept. |
|---|---|---|
| | Systems | |
| | Matter and Energy | |
| | Choose and highlight one:<br>Patterns<br>Cause and Effect | |

# APPENDIX D

## PRE- AND POST-TREATMENT INSTRUCTIONS FOR MODELING AND CONCEPT MAP CREATION

## Directions: Initial Model

Date:

Directions: Develop an initial model showing how water moves around the UAE. Use the components and processes listed below to help you structure your model.

**Components**

| | | | | | |
|---|---|---|---|---|---|
| Ocean | Dubai | Mountains | Dam with reservoir | Clouds | Plants |
| Desalination factories | Masafi Co. pulling water from ground | Pipes transporting water | Trucks transporting water | Heat energy | Water molecules |

**Processes**

| | | | | |
|---|---|---|---|---|
| Evaporation | Condensation | Cloud seeding | Desalination | Infiltration/ Percolation |
| Transpiration | Precipitation (rainfall) | Gravity pulling on water | Runoff | |

16

## Water in the UAE Systems Map Directions

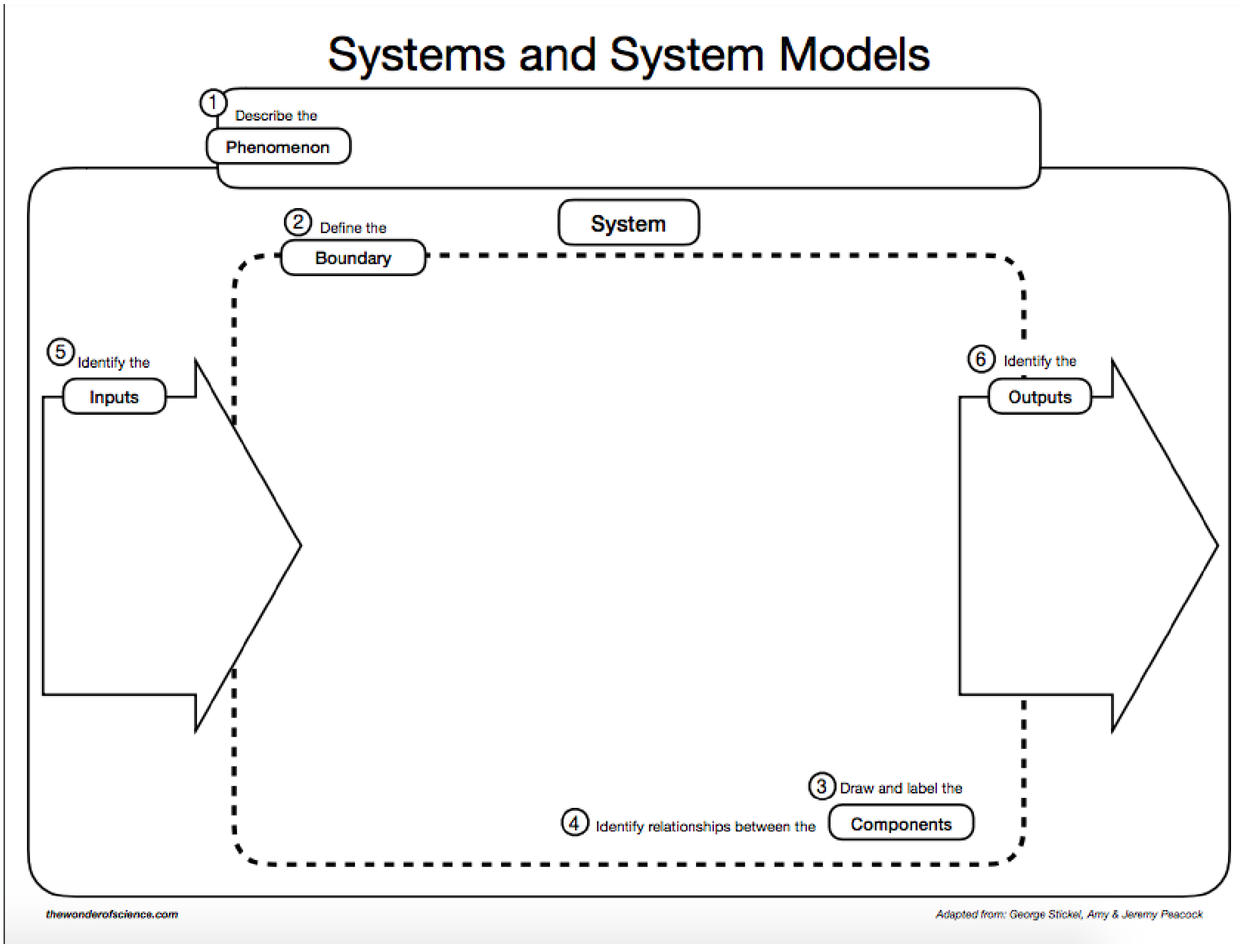
Date:

Directions: Create a systems concept map that shows how water moves around the UAE. Use as many of the following terms as you can to create your map. Feel free to add your own terms as well. Link the terms with arrows, and be sure to include linking words for each arrow.
Insert a photo or screenshot of your map on the next slide.

| | | | | | |
|---|---|---|---|---|---|
| Water | Dam | Rain | Evaporation | Clouds | Condensation |
| Cloud seeding | Desalination factories | Ocean | Salt | Hail | Sun |
| Molecules | Groundwater | Masafi water company | Pipes | Filter | Humans/ people |
| Animals | Plants | Transpiration | Infiltration | Runoff | Soil and rocks |
| UAE | Gravity | Heat | Water bottles | Buildings | Salt water |

# APPENDIX E

DEVELOPING SYSTEMS MODELS GRAPHIC ORGANIZER


Systems and System Models
1 Describe the
Phenomenon
2 Define the
Boundary
System
5 Identify the
Inputs
6 Identify the
Outputs
3 Draw and label the
4 Identify relationships between the
Components
thewonderofscience.com
Adapted from: George Stickel, Amy & Jeremy Peacock

# APPENDIX F

## INITIAL STUDENT SURVEY

# Systems Check In Form

Your responses will be used to assess your understanding and also as data for my master's research project. Participation in this research is voluntary and participation or non-participation will not affect your grade or class standing in any way.

The respondent's email (**null**) was recorded on submission of this form.

* Required

1. Email *

2. What is your last name? *

3. What is your first name? *

4. System is a key term in science. How would you define this key term? *

5. What is an example of a system in everyday life? *

6. Explain why your above example is a system. *

7. What is an example of a system you would learn about in science class? *

8. Explain why your above example is a system. *

9. Rate your understanding of systems. *

*Mark only one oval.*

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| No understanding | ◯ | ◯ | ◯ | ◯ | ◯ | I have a full and complete understanding and could teach this to someone else. |

10. Why did you score yourself at the above level? *

11. Rate your ability to write systems questions. *

*Mark only one oval.*

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| I have no idea how to do this. | ◯ | ◯ | ◯ | ◯ | ◯ | I can do this with every phenomenon and can teach someone else how to do it. |

12. Why did you score yourself at the above level? *

13. Rate your ability to explain why something is a system. *

*Mark only one oval.*

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| I have no idea how to do this. | ◯ | ◯ | ◯ | ◯ | ◯ | I can do this with every phenomenon and can teach someone else how to do it. |

14. Why did you score yourself at the above level? *

15. Rate your ability to draw a model of a system. *

*Mark only one oval.*

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| I have no idea how to do this. | ⬭ | ⬭ | ⬭ | ⬭ | ⬭ | I can do this with every phenomenon and can teach someone else how to do it. |

16. Why did you score yourself at the above level? *

17. Rate your ability to create a concept map showing how a system works. *

*Mark only one oval.*

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| I have no idea how to do this. | ⬭ | ⬭ | ⬭ | ⬭ | ⬭ | I can do this with every phenomenon and can teach someone else how to do it. |

18. Why did you score yourself at the above level? *

# APPENDIX G

## MID-TREATMENT SURVEY

# Systems Check-In 2

Your responses will be used to assess your understanding and also as data for my master's research project. Participation in this research is voluntary and participation or non-participation will not affect your grade or class standing in any way.

* Required

1. Email *

2. What is your last name? *

3. What is your first name? *

4. Thinking about systems can be difficult. What makes it difficult for you? *

5. A garden is a system we have on our school campus. Explain why it is a system. Give specific examples. *

6. An example system question about the garden is "What would happen to our garden if the bees in our hives died?" Why/how could we think about this question from a systems point of view? *

7. Write your own systems question about the school garden. *

8. Explain why/how could we think about your question from a systems point of view. *

9. How difficult are the different systems thinking tasks? Be sure to pick a most difficult and a least difficult or not difficult option. *

*Mark only one oval per row.*

| | Most difficult | Medium difficult | Least difficult | Not difficult |
|---|---|---|---|---|
| Asking systems questions | ⬭ | ⬭ | ⬭ | ⬭ |
| Developing systems models (diagrams) | ⬭ | ⬭ | ⬭ | ⬭ |
| Developing systems concept maps | ⬭ | ⬭ | ⬭ | ⬭ |
| Explaining why something is an example of a system | ⬭ | ⬭ | ⬭ | ⬭ |

10. What makes the task you chose as most difficult hard for you? *

_______________________________________________
_______________________________________________
_______________________________________________
_______________________________________________
_______________________________________________

11. What makes the task you marked as least or not difficult easy for you? *

_______________________________________________
_______________________________________________
_______________________________________________
_______________________________________________
_______________________________________________

# APPENDIX H

## POST-TREATMENT SURVEY

# Systems Check In Form

**Your responses will be used to assess your understanding and also as data for my master's research project. Participation in this research is voluntary and participation or non-participation will not affect your grade or class standing in any way.**

The respondent's email (**null**) was recorded on submission of this form.

* Required

1. Email *

2. What is your last name? *

3. What is your first name? *

4. Block *

   *Mark only one oval.*

   - Block 1
   - Block 3
   - Block 5
   - Block 2
   - Block 4

Summative Assessment

**This page is questions that will be part of your summative assessment for constructing explanations.**

5. System is a key term in science. How would you define this key term? *

6. What is an example of a system in everyday life? *

7. Explain why your above example is a system. *

8. What is an example of a system you would learn about in science class? *

9. Explain why your above example is a system. *

10. The water in the UAE is a system we've learned about in science class. Explain IN DETAIL why it is a system. Below is the rubric for how your response will be graded. *

Explaining why a phenomenon is an example of a system

| Exemplary (4) | Proficient (3) | Adequate (2) | Limited (1) |
|---|---|---|---|
| ❑ Student explains how a phenomenon is an example of a system using multiple specific components and interactions and addresses subsystems or hidden dimensions of the system. | ❑ Student explains how a phenomenon is an example of a system using a few specific components and 1-2 interactions. | ❑ The explanation of how a phenomenon is an example of a system focuses on restating the definition of the term system. | ❑ Explanation is unclear and off topic |

11. Has learning about systems helped you understand the water cycle in the UAE? *

*Mark only one oval.*

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| Strongly disagree | ◯ | ◯ | ◯ | ◯ | ◯ | Strongly agree |

12. How has learning about systems helped you better understand the water cycle in the UAE? *

_______________

_______________

_______________

_______________

_______________

13. Has learning about systems helped you with our science practices/skills (asking questions, developing models, conducting investigations/experiments)? *

*Mark only one oval.*

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| Strongly disagree | ◯ | ◯ | ◯ | ◯ | ◯ | Strongly agree |

14. How has learning about systems helped you write better questions, make better models, and/or better understand investigations? *

_______________

_______________

_______________

_______________

_______________

## Systems Confidence Ranking

This page is how you rank your knowledge of and improvement in skills related to systems thinking.

15. Rate your understanding of systems. *

*Mark only one oval.*

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| No understanding | ◯ | ◯ | ◯ | ◯ | ◯ | I have a full and complete understanding and could teach this to someone else. |

16. Why did you score yourself at the above level? *

17. Has your understanding of systems improved over the course of the unit? Why or why not? *

18. Rate your ability to write systems questions. *

*Mark only one oval.*

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| I have no idea how to do this. | ◯ | ◯ | ◯ | ◯ | ◯ | I can do this with every phenomenon and can teach someone else how to do it. |

19. Why did you score yourself at the above level? *

20. Has your ability to write systems questions improved over the course of the unit? Why or why not? *

21. Rate your ability to explain why something is a system. *

*Mark only one oval.*

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| I have no idea how to do this. | ⬭ | ⬭ | ⬭ | ⬭ | ⬭ | I can do this with every phenomenon and can teach someone else how to do it. |

22. Why did you score yourself at the above level? *

23. Has your ability to explain why something is a system improved over the course of the unit? Why or why not? *

24. Rate your ability to draw a model of a system. *

*Mark only one oval.*

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| I have no idea how to do this. | ⬭ | ⬭ | ⬭ | ⬭ | ⬭ | I can do this with every phenomenon and can teach someone else how to do it. |

25. Why did you score yourself at the above level? *

26. Has your ability to draw a model of a system improved over the course of the unit? Why or why not? *

27. Rate your ability to create a concept map showing how a system works. *

*Mark only one oval.*

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| I have no idea how to do this. | ⬭ | ⬭ | ⬭ | ⬭ | ⬭ | I can do this with every phenomenon and can teach someone else how to do it. |

28. Why did you score yourself at the above level? *

29. Has your ability to create a concept map of a system improved over the course of the unit? Why or why not? *

Teacher Feedback

This page is where you give feedback to Ms. Davis on the unit.

30. What did Ms. Davis do that helped you improve your understanding of systems in this unit? (This could be something she said or explained or an activity that she designed for you to do.) *

31. What were the most helpful experiences in the unit for helping you understand why the water system worked? Choose ONE or MORE. *

*Check all that apply.*

- ☐ Class discussions
- ☐ Watching videos
- ☐ Ms. Davis explaining something
- ☐ Doing investigations/experiments
- ☐ Talking to group members
- ☐ Drawing models
- ☐ Drawing concept maps
- ☐ Reading articles and taking notes

Other: ☐ ____________________

32. Explain why the activities you chose in the question above helped you learn. *

33. What did Ms. Davis do well in this unit? *

34. What could Ms. Davis have done better in this unit? *

35. Is there anything else you would like to let Ms. Davis know? *

# APPENDIX I

## FURTHER DETAILS ABOUT THE SURVEYS AND THEIR CREATION

For the initial pre-assessments as described in lessons one and two of Table 2, students first completed an initial survey asking about their understanding of the topic of systems and their confidence in completing specific systems thinking skills (asking systems questions, explaining why something is a system, developing systems drawing-type models, and creating systems concept maps). These were created by me to elicit student thinking around the topic of systems and their ability to understand systems in the context of concepts as well as to determine how confident they were with specific skills. This survey was piloted in the previous school year to determine whether it collected valid and reliable data. Validity and reliability were also addressed by looking at vetted published instruments and peer and professor review. Revisions were made to elicit specific explanations from students about why they ranked themselves at specific confidence levels for each skill. In this survey students also wrote an initial explanation for why a phenomenon was an example of a system. This was assessed with a constructing systems explanation rubric (Appendix B).

The mid-treatment survey had two goals. The first was to check in on students' ability to ask systems questions, explain how questions connected to systems, and to explain why an entity is a system. These were assessed to gauge students' systems thinking skills at this point in the unit. The second goal of the survey was to elicit feedback from students on the difficulty level of different systems thinking skills and what made these skills easier or more difficult. This information could be used to pinpoint which aspects of the systems thinking instruction needed more focus. The feedback received from classmates, my advisor, and my school's instructional coach ensured that the survey results would be both reliable and valid.

Students finished the unit with a final survey. This included all of the prompts from the initial survey into student confidence with different systems thinking skills and general understanding of what a system is, which would allow me to reliably compare responses on the pre-treatment survey. In case students had artificially ranked themselves high in any skills at the beginning of the unit, which could make it difficult to see any growth from pre-treatment to post-treatment survey, I added prompts for students to explain whether they thought their performance with specific systems thinking skills had improved over the unit and why. If I needed, I could compare responses to these questions with the differences in their pre- and post-treatment confidence rankings to determine whether students felt they understood more about systems after the treatment unit. In this survey, I also included some other prompts to probe for student feedback on what aspects of the instruction in the unit most helped them understand systems and any feedback on my performance in the classroom. These are similar questions that I ask on end-of-unit feedback forms, so I have learned over time how to word them to get reliable and valid results.

# APPENDIX J

ROUND 1 INTERVIEW QUESTIONS

- If I asked you to define what a system is, what would you say?
  - If a system is made up of many parts, what are some different parts that systems have?
- What is an example of a system in everyday life?
  - Why is that a system?
  - What made you think of that system?
- What is an example of a system you might learn about in science class?
  - Why is that a system?
  - What made you think of that system?
- How do you feel about writing systems questions?
  - Why do you feel that way?
  - Could you write a systems question about a phenomenon if I asked you to?
- How do you feel about explaining why something is an example of a system?
  - Why do you feel that way?
  - Can you explain why water in the UAE could be an example of a system?
- If I asked you to choose a system and explain why it's a system, would you be able to do that? Why or why not?
  - What system would you pick?
- How do you feel about drawing a model of a system?
  - Did you feel successful when drawing a model of water in the UAE?
- If I asked you to pick a system and model it, would you be able to do it? Why or why not?

    - What system would you pick?

- How do you feel about drawing a concept map of a system?
    - Why do you feel that way?
- What do you think the hardest task related to systems is?
    - Why do you think that is?

# APPENDIX K

## ROUND 2 INTERVIEW QUESTIONS

- What is the definition of a system? How are you able to remember that?
    - What are some key terms related to systems, and what do they mean?
        - If they can't think of any: What is a component? What is an interaction? Etc.
        - How do you know these terms?
- Can you identify and describe how the water in the UAE is a system?
    - Please describe some of the specific components and interactions.
    - What are some of the natural processes? What are some of the human-caused processes?
- What is a systems question we could ask about the water in the UAE?
    - Why is that a systems question?
- If you've had any trouble in this unit, what has made learning and/or the classwork difficult for you?
    - How could I have helped you with this?
- Has your understanding of systems changed or improved since the beginning of the unit? Why/why not?
    - What activities have helped you begin to understand systems better? Why were they helpful?
    - What else do you need to improve your understanding of systems?
- Has your understanding of water in the UAE changed or improved in this unit? Why or why not?

    - What activities have helped you begin to understand this system better? Why were they helpful?
    - What else do you need to improve your understanding of the water system in the UAE?
- Has talking about systems helped you understand the water cycle better? Can you give me an example?
    - If we didn't talk about systems and how they work, would this affect your understanding of how water moves around the UAE?
    - Does talking about systems help you understand the investigations/experiments? Why/why not?
    - Does learning about systems help you make better models? Why or why not?
        - Can you give me an example of this?
- How do you think teaching about systems has helped me as a teacher? Has it affected the way I teach?
    - Can you give me an example of this?

# APPENDIX L

## FINAL INTERVIEW QUESTIONS

- Now that the unit is over, how would you rate your success on a scale of 1-5?
    - Why would you give yourself that score?
- Did your understanding of systems improve over the course of the unit?
    - What sorts of activities helped you improve?
    - Why were those activities helpful?
    - Can probe about specific skills...
- We looked at four skills relating to systems: asking questions, explaining why something is a system, drawing systems models, and creating systems concept maps. Which of those do you think you are the best at? Why?
    - What makes you successful at that skill?
    - Which skill are you the least successful at? Why?
        - How could I help you improve in this skill?
- Our next unit is about another system - the biosphere or ecosystem. Do you think having learned about systems and the water system will help you understand the biosphere better? Why?
    - How can you apply what you learned about water systems to the biosphere or ecosystems?
    - How do you think these two systems might be connected?
        - How does understanding systems help you see how these two systems might interact?
    - Based on what you know about water systems and ecosystems, is the whole Earth a system? Why or why not?

        - Why do you think it is important to learn about the Earth as a system?

- Why is it important to understand systems in general?
    - How can you use systems thinking in other units or classes?
    - How does systems thinking help you in everyday life?

# APPENDIX M

## FURTHER DETAILS ABOUT THE INTERVIEW QUESTIONS AND PROCESS

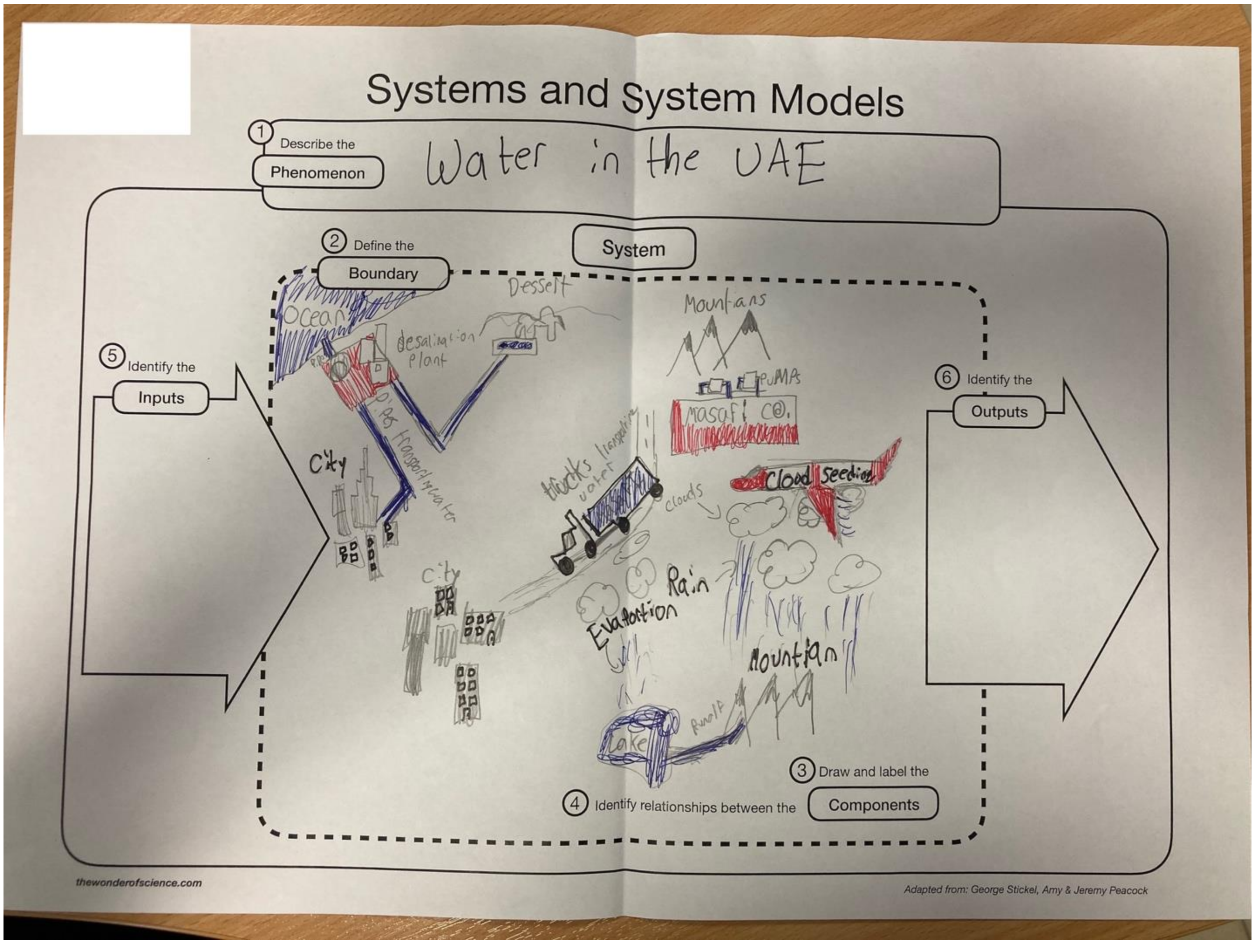
For the initial interview, questions were created to delve deeper into student thinking about systems. Interview questions were checked with masters' classmates, my school instructional coach, and my project advisor to ensure they would give me an overview of student thinking and get the information for which I was looking.

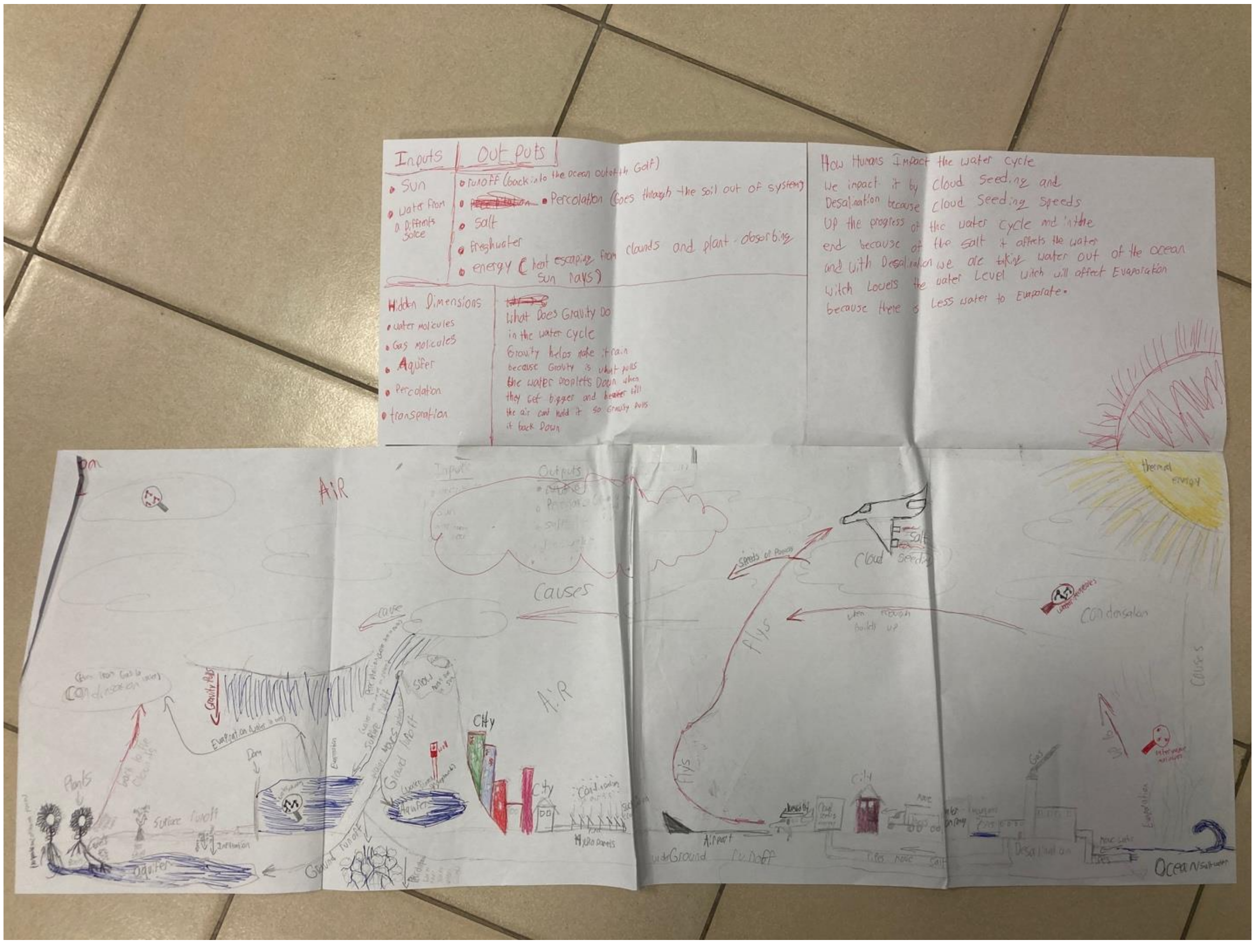
For the second round of interviews, the questions were written to probe for student understanding of systems and their ability with certain systems skills. I also wanted to see their thinking on how their understanding had changed over the course of the unit and their thoughts on what had led to those changes in understanding. Feedback was requested from my advisor, Walter Woolbaugh, to ensure that questions would get me helpful information.

The day of the final survey was also the final round of interviews with the six selected students. Questions were written to look for student thinking on confidence levels, beneficial activities within the unit, their ability to apply systems thinking to the next unit, and how systems thinking could be applied to other classes and everyday life. These questions were meant to allow me to gather more information on the impact of the treatment unit on student confidence as related to systems thinking and also to see if students had gained a realization of the role of this Crosscutting Concept in making connections between concepts, units, and topics outside the boundaries of the course. I had a member of my support team read the questions to see if they thought they would get me the responses I wanted to help ensure that the questions would get me valid results.

# APPENDIX N

## SAMPLE PRE- AND POST ASSESSMENT MODELS


Systems and System Models
1 Describe the Phenomenon
Water in the UAE
2 Define the Boundary
System
5 Identify the Inputs
6 Identify the Outputs
Ocean
desalination plant
Dessert
Mountains
Masafi Co.
Cloud seeding
City
clouds
Rain
Evaporation
Mountain
Lake
Runoff
3 Draw and label the
4 Identify relationships between the Components
thewonderofscience.com
Adapted from: George Stickel, Amy & Jeremy Peacock


Inputs
• Sun
• water from a Differnts Sorce
Out puts
• runoff (back into the ocean out of the Golf)
• Percolation (Goes through the soil out of system)
• salt
• freshwater
• energy (heat escaping from clouds and plant absorbing Sun rays)
Hidden Dimensions
• water molicules
• Gas molicules
• Aquifer
• Percolation
• transpration
What Does Gravity Do in the water cycle
Gravity helps make it rain because Gravity is what pulls the water droplets Down when they get bigger and heaver till the air cant hold it so Gravity pulls it back Down
How Humans Impact the water cycle
We impact it by cloud seeding and Desalination because cloud seeding speeds up the progress of the water cycle and in the end because of the salt it affects the water and with Desalination we are taking water out of the ocean witch lowers the water level witch will affect Evaporation because there is less water to Evaporate.
AIR
Causes
City
Condensation
Flys
Cloud Seeding
thermal energy
Desalination
Airport
Ocean