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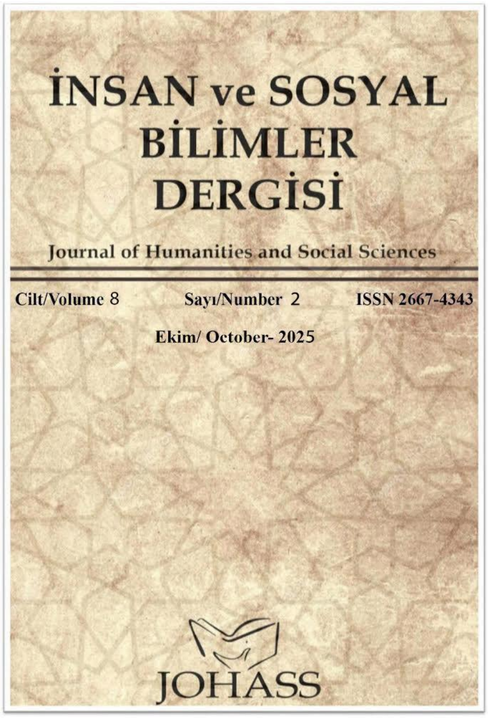

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The Development of School Students' Systems Thinking about Water Systems via an Educational Intervention*

**This article is derived from the doctoral dissertation titled "Developing Middle School Students' Systems Thinking and Conceptual Understanding Levels about Water Systems via Socio-hydrologic Issue-based Module".*

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The Development of School Students' Systems Thinking about Water Systems via an Educational Intervention

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Abstract **Research Article**

This study aimed to enhance middle school students' systems thinking about water systems through a design-based educational intervention grounded in socio-scientific issues. Thirty-two seventh-grade students participated in activities incorporating the iceberg model, relational thinking, and systems thinking maps. Data were collected via students' systems thinking maps and open-ended questions and analyzed using a rubric developed for this study. Findings indicated notable progress across all eight dimensions of systems thinking, moving from simple associations to complex, dynamic, and cyclical understandings of water systems. The study demonstrates that a socio-hydrologic issue-based unit can foster students' holistic and interconnected understanding of water, offering implications for curriculum design and sustainability education.

Keywords: Design-based research, educational intervention, socio-hydrologic issue-based unit, systems thinking, water systems

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Introduction

Water education is important with respect to protect water resources and ensure their sustainable use (Maniam et al., 2021). In the contemporary world, in which issues pertaining to water scarcity and access to clean water are becoming increasingly severe, only water-literate societies can ensure the sustainability of water resources (Larson & Redman, 2014; Tortajada & Biswas, 2018). Schools play a major role in efforts to build a targeted society (Bock, 1984). The functionality of course curricula can accelerate the achievement of relevant water education goals (Meganck, 2010).

In the national curriculum, objectives that can be included in water literacy in the substructure of various subjects such as science, geography, chemistry, biology and sometimes in noncompulsory elective subjects (Ministry of National Education [MoNE], 2018). Water-related issues are generally integrated into the final sections of textbooks or at the end of specific units (Ulger, 2011). The research analyzing the national curriculum in terms of water literacy indicates that the objectives associated with water are not directly related to water literacy, but rather, they are indirectly associated (Sozcu & Aydınozu, 2023). Although school students believe that water literacy is beneficial and important, studies have shown that students' water literacy levels are low and they have misconceptions (Ursavas, 2022).

Water education should offer students a comprehensive overview of water in the context of both natural and human systems (Covitt et al., 2009) since water-related concepts are directly related to many different disciplines (Sabel et al., 2017). Water education requires an understanding of the relationships between water and Earth systems, knowledge of hydrological systems, water consumption and sustainability, and an awareness of human activities that can modify the water cycle (Ben-Zvi Assaraf & Orion, 2005a; Benninghaus et al., 2018; Covitt et al., 2009). Water literacy refers to the possession of sufficient scientific knowledge to comprehend the relationships between water availability and usage as well as the ability to address water-linked societal problems constructively (Martínez-Borreguero et al., 2020).

Although curricula have been reformed in line with the evolving objectives of educational policy, in light of the need to develop the water-literate human capacity that is necessary to manage countries’ limited water resources, students' understanding of water continues to be inadequate due to the difficulties associated with the task of translating these changes into practice (Gouëdard et al., 2020; Maniam et al., 2021).

Previous studies have reported that students find it difficult to conceptualize and explain water-related phenomena, particularly the water cycle, which includes various processes such as evaporation, condensation, precipitation, surface runoff, and groundwater, as well as to understand water as a system (Baumfalk et al., 2019; Bar & Travis, 1991; Ben-Zvi Assaraf & Orion, 2005b; Forbes et al., 2015; Schwarz & White, 2005; Zangori et al., 2015). In addition, teachers face various challenges in the process of teaching about the water cycle (Gunckel et al., 2012; Lee et al., 2019). Many pre-service and in-service teachers struggle to apply systems thinking, for example in identifying links and interactions between subsystems, or in understanding the impact of humans on the water cycle (Lee et al., 2019). In other study, teachers mainly identified the components of a system but most did not make connections among these components and only some of the teachers clearly identified hidden dimensions that affected multiple connections (Ateskan & Lane, 2017). This limitation causes the difficulty in teaching components and processes within the water system (Lee et al., 2019).

In addition, educational curricula often present only limited explanations of water and complex water systems, and water-related teaching approaches are disjointed and unevenly distributed across different grades and disciplines (Sweeney & Sterman, 2007; Gunckel et al., 2012; Sadler et al., 2017; Shepardson et al., 2009). Accordingly, it is necessary to develop an educational intervention that adopts a systems perspective in an effort to promote water literacy by considering water from a comprehensive and interdisciplinary perspective, in contrast to the current learning environment, in which the teaching of water-related topics lacks continuity and is characterized by a fragmented understanding of water (Covitt et al., 2009; Gunckel et al., 2012; Havu-Nuutinen et al., 2011; McCarroll & Hamann, 2020; Pan & Liu, 2018; Sadler et al., 2017; Shepardson et al., 2007; White et al., 2022). Recent research suggests that educators are shifting the focus of education from a disintegrated systems to a holistic manner (Demirci, 2021). Especially when the subject concerns a complex system such as water, a systems perspective should be provided to the subject (Ben-Zvi Assaraf & Orion, 2005b, 2010; Demirci, 2021; Lee et al., 2019).

One of the critical objectives of science education is to learn how to think about the interactions between systems, the far-reaching effects of a system and the dynamic nature of systems (Goldstone & Wilensky, 2008). At this point, the importance of systems thinking skill, which the ability to see the world as a complex system defined by Sterman (1994), becomes evident. Integrating systems thinking into the educational curriculum is essential for addressing the multifaceted challenges of complex systems effectively (Stirgus et al., 2020). Research should focus on systems thinking achievement standards and the development of educational models using systems thinking (Kyungsuk et al., 2022).

In the documents of international organizations on water (Food and Agriculture Organization [FAO], 2014; Organisation for Economic Co-Operation and Development [OECD], 2015; World Health Organization [WHO], 2016), water is not regarded as an isolated resource, but rather as part of complex systems that interact with each other. These documents emphasize systems thinking approach by emphasizing that a holistic and interconnected perspective is crucial for the sustainable management of water resources and the solution of water-related problems. The Next Generation Science Standards (2013), calls for the use of systems thinking in science teaching and a holistic approach to the system in science classrooms.

Background Concerning The Desing of Water-related Courses

The approach taken to water education has evolved from a focus on understanding basic concepts pertaining to natural water to an emphasis on establishing a relationship between water and the environment as well as from a focus on understanding the relationships among water, the environment, and humans to an emphasis on contributing to the sustainability of water within this network of relationships. Changes in this vision affect the context, goals, and achievements of water education (Brody, 1995; Covitt et al., 2009; Forbes et al., 2018; He, 2018; Sammel & McMartin, 2014; Wheeler, 2012).

Systems thinking focuses on the whole and is an important tool that can be used in efforts to adopt a holistic perspective (United Nations Economic Commission for Europe [UNECE], 2012). Such a holistic understanding is necessary to comprehend the concepts, processes, and relationships associated with water (Ben-Zvi Assaraf & Orion, 2005b; Lee et al., 2019). The tasks of understanding and interpreting complex systems require systems thinking (Evagorou et al., 2009). Students can be encouraged to develop a coherent understanding of complex systems by implementing a learning approach that incorporates systems thinking (Gilissen et al., 2020; Schuler et al., 2018).

Activities that allow students to comprehend the workings of systems can enable them to obtain a profound understanding of complex systems (Hmelo et al., 2000). Abstract concepts of the water system can be concretized through experiential learning, thus facilitating the development of an understanding of the water system in the context of teaching (Kolb, 1984).

A variety of innovative and participatory pedagogical approaches can be used to equip students with adequate knowledge of critical water-related issues (Missingham, 2013; Kunwar et al., 2023). These approaches could include problem-oriented approaches to earth–water issues that are specifically designed to involve students in the task of investigating specific water-related problems (Gutierrez-Perez & Pirrami, 2011; Halvorson & Wescoat, 2002).

In addition, one requirement of water education is to emphasize sustainability (United Nations Educational, Scientific, Cultural Organization [UNESCO], 2012). The significant role that school science curricula can play in students' learning about sustainability reflects a socioscientific issues (SSI) approach (Tytler, 2012). Additionally, such an SSI-based approach promotes a holistic understanding by presenting the topic at hand in light of its social, political and ethical dimensions as well as its scientific dimension (Marks & Eilks, 2009; Simonneaux & Simonneaux, 2009).

Various inferences and insights obtained from a literature review indicated that lessons regarding water should adopt a holistic perspective and foster active participation in real-world problems. On the basis of this guidance, systems thinking was chosen as a key element in the task of understanding the water system. Additionally, the SSI-based instructional approach, which has been identified as an effective teaching method that can foster active participation in real-world problems, was chosen because it is suitable for efforts to incorporate systems thinking into teaching.

Expanding The Waterscape From A Holistic Perspective

Water is part of the Earth system as well as the human-engineered system. Therefore, understanding the water system requires a comprehensive understanding of water in the context of both natural and human water systems (Covitt et al., 2009). Furthermore, humans are powerful actors who control the dynamics of the water cycle, and their actions are viewed as an integral component of the dynamics of natural water systems (Sivapalan et al., 2011). Accordingly, water-related lessons should integrate a holistic understanding of water in both natural and human water systems, and the relationship between nature and human systems should be the focus of efforts to design a socio-hydrological issue (SHI)-based unit (see Appendix A). In this context, socio-hydrology focuses on the tasks of observing, comprehending and predicting the prospective evolution of coupled human-water systems.

The dynamic interactions between human system actions and natural water systems as well as the corresponding mutual feedback illustrate the complexity of human-water relationships. This complexity of human–water relationships should be discussed not only in terms of spatial and temporal scales but also in terms of different dimensions of the social system (political, economic, etc.) during the course of the SHI-based unit. Social, economic, political, environmental, and community contexts should be taken into account when developing solutions to the problems (Grosh et al., 2018). It is important to include social dimensions to ensure that solutions to water-related problems can be proposed and that ethical and responsible citizenship attitudes toward water can be promoted (Leitão et al., 2020). Furthermore, students are expected to examine the social and political dimensions of water sustainability and to integrate water-related information into their decision-making processes and actions (Sammel, 2014). This expectation can be fulfilled by adopting an SSI-based approach to teaching, including by incorporating relevant social dimensions into the scientific dimension of this issue. In this way, students have the opportunity to evaluate the environmental, economic, social and political impacts on water resources as a whole.

Research Purpose and Questions

Students need to possess a fundamental scientific comprehension of water as well as an understanding of the dynamic nature of the water system if they are to comprehend and explain water-related phenomena. Misconceptions and incomplete knowledge about water systems are barriers to scientific literacy. Therefore, it is recommended that curriculum should be structured to cover key water-related concepts and systems relationships (Sadler et al., 2017).

Water should be understood not only as a resource but also as a system with social, economic, and environmental dimensions (Sivapalan et al., 2011). Educational interventions and water-related units that can promote an integrated understanding of human and water systems (Covitt et al., 2009). Education that focuses on providing scientific knowledge and holistic understanding of water will strengthen students' scientific literacy and water sustainability (Maniam et al., 2021).

The middle school period, when abstract thinking skills develop, is critical for the establishment of conceptual structures and systems thinking. The cognitive competencies necessary to support systems thinking may not yet be fully developed at the elementary school level (Ben-Zvi-Assaraf & Orion, 2005b). The systems understanding developed during middle school period can be further cultivated at the high school and university levels, providing a foundation applicable to more complex environmental and social problems. The middle school curriculum is more conducive to the implementation of conceptual modelling, systems mapping, and systems understanding teaching strategies. For these reasons, it is important that the present study be conducted with middle school students, who are at a critical time for developing a developmental, pedagogical, and conceptual systems understanding of water systems.

Therefore, the aim of this study is to develop an educational intervention that can promote students' understanding of water as a systems. The research questions are as follows:

RQ1: What kind of educational intervention can enable 7th-grade students to understand water as a system?

RQ2: What initial levels of systems thinking ability with respect to water systems are exhibited by 7th-grade students, and how do their levels of systems thinking ability change over the course of a SHI-based unit?

Method

Model

The study employed a design-based research (DBR) methodology. This methodology is particularly compelling when study context demands an approach that is highly responsive to real-world challenges while simultaneously generating new theoretical insights. Our research addresses a complex educational problem. When study context is dynamic, multifaceted, and deeply embedded in real-world challenges, DBR provides a robust methodology that engenders enhanced comprehension through practical application and theoretical development (Scott et al., 2020).

The DBR process is used to develop solutions to problems encountered in various contexts, such as designing an instructional intervention and testing, how well it works (Brown, 1992). In this study, the sequential steps involved in the DBR process were as follows: 1) analysis of practical problems; 2) development of solutions with a theoretical framework; 3) evaluation and testing of these solutions in practice; and 4) documentation and reflection with the goal of generating design principles (Alghamdi & Li, 2013; Reeves, 2000).

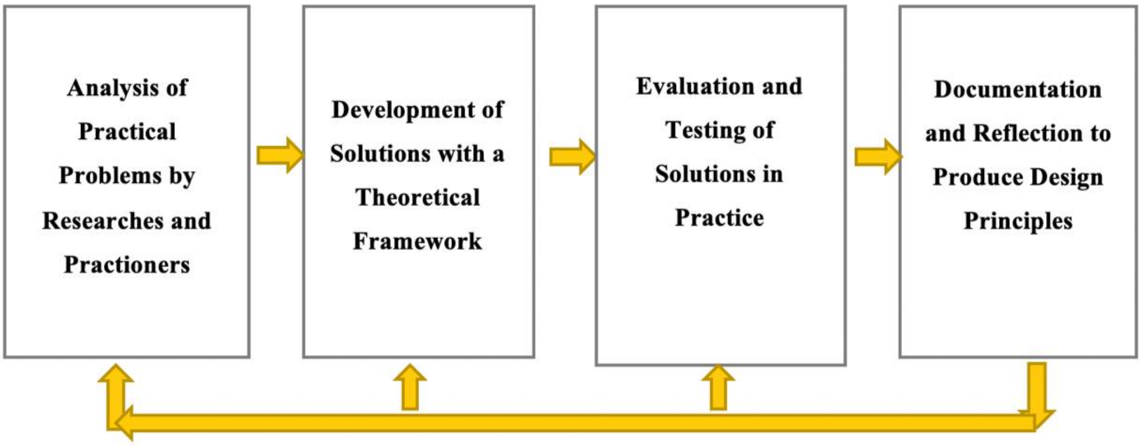


Figure 1. *Phases for carrying out design-based research (Adapted from Reeves, 2000)*

Analysis of Practical Problems

Studies have revealed that students have only a limited understanding of water, which is characterized by significant misconceptions (Bar & Travis, 1991; Bošnjak Stepanović, 2019; Brody, 1993; Cardak 2009; Koomson & Owusu-Fordjour, 2018; Sadler et al., 2017). These misconceptions can be divided into misapprehensions pertaining to water properties, phase changes, cloud formation and the water cycle (Henriques, 2002). In addition, none of the students have known which watershed they lived in or if they lived in any watershed (Wheeler, 2012). Groundwater is also often a missing component in students' conceptualization of the water cycle, and students often have an incomplete and disconnected understanding of the groundwater system (Pan & Liu, 2018; Shepardson et al., 2009; White et al., 2022). The inability of the majority of students to establish connections between the atmospheric water subcycle and the geospheric groundwater subcycle entail that they fail to comprehend the system dynamics of the water cycle (Ben-zvi Assaraf & Orion, 2005b). Students often find it difficult to think about water in terms of dynamic, cyclical systems as well as to conceptualize and explain water-related phenomena (Ben-Zvi Assaraf & Orion, 2005a, 2005b, 2010; Covitt et al., 2009; Gunckel et al., 2012).

Water is complex, as it involves water-related phenomena, particularly the set of processes underlying the dynamics of the water system (Covitt et al., 2009; Henriques, 2002). The implicit references to water contained in curriculum units and the disjointed and brief manner in which the roles played by water in both biotic and abiotic systems are addressed make it challenging for students to grasp water as a system. The lack of continuity in efforts to present water-related phenomena entails that students can obtain only a fragmented understanding and prevents them from obtaining a comprehensive and holistic understanding of water. The problem identified in this study was that students have not yet reached the desired level in terms of the outcomes of water education, particularly when they are expected to associate scientific concepts with facts in their daily lives.

As a science teacher and one of the authors of this study, I observed that middle school students can often confidently explain the importance of water with respect to life but struggle to explain topics such as the water cycle, where freshwater comes from, and the connections between engineered and natural water systems; furthermore, they express certain misconceptions and a general lack of knowledge through their explanations. Cardak (2009), confirmed students' misconceptions of the water cycle according to their drawings. Turkoz et al. (2012) observed that students do not know well the physical, chemical and biological properties of water. Students’ weak understanding of water systems is an issue which has been highlighted in the literature (Bar, 1989; Ben-Zvi Assaraf & Orion, 2005b; Covitt et al., 2009; Shepardson et al., 2009; Wheeler, 2012). We emphasize the need for an approach to instructional design that focuses on enabling students to understand water as a system, thus allowing them to engage with the critical relationships between water and civilization.

Development of Solutions through a Theoretical Framework

The design process involves making crucial decisions regarding the framework that is appropriate with respect to the purpose of the study at hand. Studies that have sought to examine complex systems have employed various frameworks, such as structure-behavior-function framework (Hmelo et al., 2000; Hmelo-Silver and Pfeffer, 2004), system dynamics perspective (Shepardson et al., 2014), and complex systems theory (Fichter et al., 2010), to understand complex systems and identify skills pertaining to systems thinking. The understanding of water systems (UWS) framework (Sadler et al., 2017) is used in our study to understand water as a system. This framework guided our efforts to promote a system understanding and revealed how the SHI-based unit could accomplish this task effectively.

The UWS framework is constituted by a matrix comprising the physical dimensions of water systems and aspects of an understanding of water systems. The physical dimensions of water systems focus on defining where water and various substances in water are located. Relevant aspects include surface water, groundwater, atmospheric water, water in biotic systems, and water in engineered systems. The aspects of an understanding of water systems emphasize processes and mechanisms, energy, scale, representations, and dependency and human action in students' thinking with regard to water systems (Sadler et al., 2017).

The UWS framework is in line with the characteristic structure of systems thinking. The characteristics of systems thinking include complexity, relationships, components, interactions, interrelationships, and dynamics (Perkins & Grotzer, 2005; Sommer & Lücken, 2010).

UWS is reflected in systems thinking on the basis of two critical aspects of water courses: first, the determination of the scope of the unit, and second, the design of activities that can encourage systems thinking and thus offer students a holistic understanding of water-related concepts, processes, and relationships. When the scope of a unit is determined in the context of UWS, it is necessary to include the relationships of water with both Earth systems and human systems. The unit designed as part of this research thus exhibited a sociohydrologic scope and covered the connections among water, earth, and human systems. This approach aimed to provide students with a holistic overview of water, thus helping them understand the dynamic relationships among these systems and to adopt a comprehensive perspective on water. In addition, we made decisions that were in line with systems thinking by incorporating water-related concepts and processes into the unit. For example, the concepts of watersheds and aquifers were incorporated into the unit, and its focus on groundwater was reinforced.

Additionally, the conventional water cycle, which emphasizes evaporation and condensation processes, was augmented with discussions of runoff, infiltration, transpiration, water treatment and the reuse of water processes.

The systems thinking approach aims to enhance students' ability to analyze the connections among parts and to understand the whole system, including the interrelationships between and within its parts as well as the effects of the system itself (Evagorou et al., 2009; Grotzer & Basca, 2003). With the goal of promoting systems thinking, three activities that aimed to encourage students to engage in systems thinking were designed. The activities were ordered in increasing level of difficulty.

The first activity, Iceberg (Meadows, 2020) involved an introduction to the activities pertaining to systems thinking with the goal of helping students become aware of systems thinking. In this activity, students were asked to think about the causes underlying water crises and to obtain insights into the interconnected nature of the corresponding system. This activity enabled students to realize that the system is a unified entity that consists of various parts that function jointly and affect each other. The second activity was the Relational Thinking activity. In this activity, students were asked to recognize system components, establish relationships among these system components and explain the corresponding causal relationships. The third activity asked students to draw a Systems Thinking Map (STM) with regard to the water system. In this activity, we asked students to analyze the components of the water system, to highlight the dynamic relationships among these components, to evaluate multiple cause-and-effect relationships and ultimately to understand the complexity of the system.

Evaluation and Testing of Solutions in Practice

The objective of this study is to enable students to develop a more comprehensive, detailed and integrated understanding of water, thereby progressing beyond their current understanding of water, which is limited, superficial and disconnected, through a series of designed instructions. In this step, the corresponding design must be tested in a real-world setting (i.e., the classroom). The impact of such an instructional intervention is evaluated on the basis of evidence pertaining to student products (Anderson & Shattuck, 2012; Barab & Squire, 2004). The SHI-based unit developed as part of our study (which can be found in Appendix A) was implemented in a context involving 7th-grade students. The impact of our educational intervention is evaluated on the basis of STMs produced by these students.

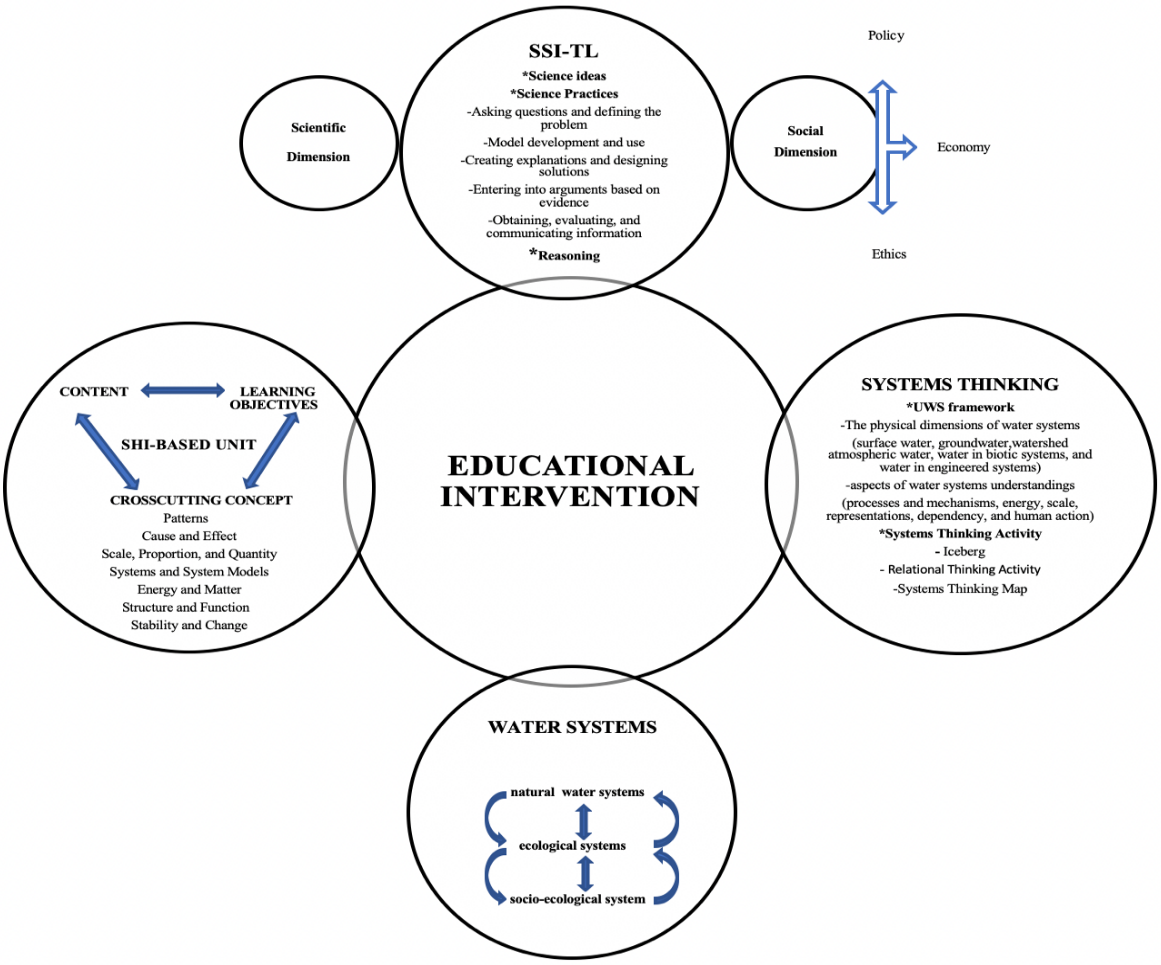


Figure 2. *Design of Educational Intervention*

Documentation and Reflection with The Goal of Producing Design Principles

The strengths of DBR include its ability to develop practical design principles and to highlight the influence of design on learning (Barab & Squire, 2004). DBR leads to practical outcomes while simultaneously contributing to students' theoretical and basic understanding (Anderson & Shattuck, 2012; Reeves, 2000). The tasks of reflecting on the design principles used in our study and reporting on the results of our intervention are crucial, as these tasks can facilitate future efforts to implement and adopt these design principles in the context of water education.

Sample and Population

Convenience sampling was preferred in the study. Prior to the beginning of the study, information was obtained regarding students' attendance and absence from school in previous years, as well as their prior involvement in seminars, events, or projects related to water. This information was deemed to be of significance with regard to the extent to which the sample reflected the general population subject to standard education. The students were regular school attendees and had no additional experience with water beyond their standard education.

The study targeted 7th grade students due to a gap in curriculum objectives, which focus on waste and recycling but do not include a specific chapter on waste water. The sample of the study consists of 32 seventh grade students (aged 12–13, female = 18; male = 14) at a middle school in Bursa, Turkey.

Implementation Process

The study was carried out within the scope of the chapter titled Household Waste and Recycling in the 7th grade "Pure Substances and Mixtures" unit (MoNE, 2018). The SHI-based unit allocates 3 weeks (12 lesson-hours). Five specific lesson plans, including scientific preparation and various activities, have been prepared to serve the objectives of the unit. The timeline for the intervention can be seen in the table 1. Further details of the lesson plans can be found in the appendix A.

Table 1

Timetable for Teaching and Activities

Time	Teaching	Activity	Material	Data Collection
1 h	Pre-education			Pre-int. STM
2 h	Introduction to SHI-based unit • Introduction to the lesson by showing the video related to SHI-based unit • Presentation of the journal article on the SHI	-Iceberg	-Work sheet: Global Water Crisis	
2 h	• Associating with the concept of watershed to deepen the socio-hydrologic issue • Thinking about the water cycle	-Conducting experiment: Water cycle -Relational thinking activity	-Work sheet: Water cycle	
2 h	• Discuss on water pollution and water scarcity • Identifying the responsibilities of individuals, institutions and organizations to ensure water sustainability	-Class discussion about attitudes and behaviors that cause water pollution and responsibilities of individuals, institutions and organizations to ensure water sustainability	-Different research sources	

2 h	• Determining the characteristics of drinking water • Thinking about the physical, chemical, biological processes of water treatment	-Class discussion: drinking water criteria -Conducting experiment: Wastewater treatment	-Work Sheet: Water treatment -Water Handbook	
2 h	• Researching countries' water resources and wastewater management policies using various sources (media, articles, website addresses)	-Presenting the gathered information -Activity: Let's determine our water policy	Work sheet: Water management	
1 h	Post-education			Post-int. STM

Data Collection Tool

Data were collected via students’ systems thinking maps (STMs) pertaining to the water system and open-ended questions prepared for the “making generalizations” and “thinking temporally” dimensions of systems thinking.

The STM was designed as a causal concept map. The development of such a concept map is important in the process of understanding the structure and dynamics of a system (Brandstädter et al., 2012; Plate, 2010). The STM can serve as an appropriate tool for efforts to identify students' systems thinking abilities with regard to the water system (especially up to the 7th dimension in this hierarchical process). To clarify the dimensions associated with the skills of “making generalizations” and “thinking temporally”, the students were also asked to answer questions that were prepared for these dimensions.

Development of the Systems Thinking Map Rubric

The data obtained in this study were analyzed through Systems Thinking Map Rubric (STMR). The STMR was used to assess both water systems STMs and students' responses regarding “make generalizations” and “thinking temporally” dimensions. The rubric was developed based on the eight hierarchical systems thinking dimensions that Ben-Zvi Assaraf and Orion (2005b, 2010) noted.

The STMR includes eight sections. Each section of the rubric was associated with the context of the water system according to the meaning of each dimension of systems thinking. Analogous rubrics (Baumfalk et al., 2018; Lee et al., 2019) were examined and a common sense was employed to rate each section of the STMR from 0 to 3, from least to most.

The rubric was tested by performing a pilot study. The pilot study involved 8th-grade students and aimed to provide more saturated data concerning the STMs. The data concerning ten students included in the pilot study guided our understanding of the appropriateness of the items included the STMR with respect to the task of evaluating students' systems thinking skills. For example, the pilot test revealed that some students expressed unrelated concepts that were not associated with to the water system, failed to express the relationships among the relevant elements, or included incorrect associations in all the concepts they highlighted. These findings helped the researchers reorganize the levels (0-3) assigned to the STM items. Expert opinions were obtained from an assessment-evaluation expert and two science education experts with respect to the STMR designed in this context.

Expert opinions were unanimous for the inclusion of objective numerical expressions in the leveling of the initial two dimensions of the systems thinking dimension features, similar to the other dimensions' (3., 4., 5., and 6.) features. The STM drawings of the students taking part in the pilot study provided the numerical data needed to concretize the scoring in the development of the 0–3 level in the STM. Moreover, as the STMR was developed for the water system, the rubric's eight systems thinking dimensions were updated for the water system issue.

In line with these expert opinions, changes were made to improve the scoring's objectivity and to make the levels linked with the systems thinking dimensions more understandable. The rubric is included in Appendix B.

Scoring Students' STMs through a STMR

The pre- and post-intervention student STMs were scored by two raters. Cohen's quadratic-weighted kappa are valuable measures of inter-rater reliability as it provides a more comprehensive assessment of agreement (Li, et al., 2023). It was calculated to measures of inter-rater reliability. Results indicated a strong agreement between the raters with a weighted-$\kappa = .89$. After discussion between the raters, 100% agreement was reached for scoring.

Ethics Committee Approval

In this research, ethical approval was obtained from the Ethics Committee of Yıldız Technical University on 28.02.2022 and numbered 20220200191.

Findings

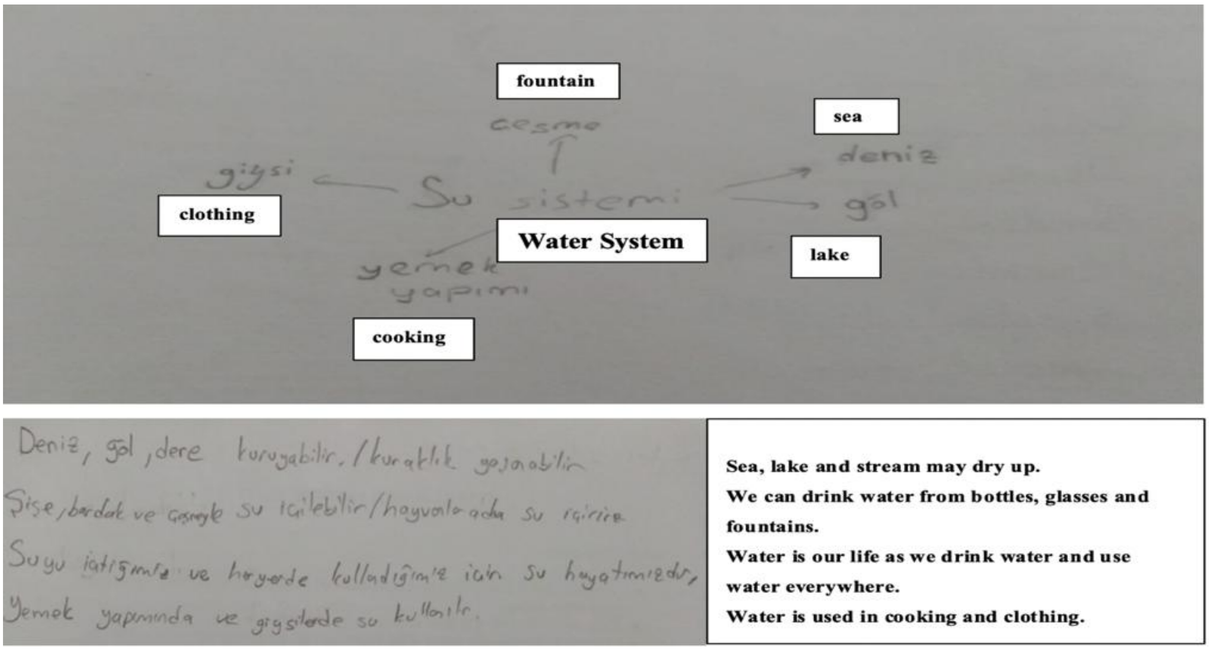
This section presents findings obtained by comparing system thinking maps drawn by students before and after the implementation of the socio-hydrologic issue-based unit, in terms of their representation of the water system.

To illustrate the scoring procedure, Table 2 and Table 3 show the scores given to the pre- intervention STM (fig. 3) and post-intervention STM (fig. 4a, 4b) produced by student S14, respectively.

Table 2

Score of Pre-intervention STM Produced by Student who was Coded as S14

Sections of STMR	Analysis of Pre-intervention STM Produced by Student Who Was Coded as S14	Score
d1. “Identifies the components of the system and the processes within the system"	He/she included system components such as sea, lake, fountain and water usage areas, but did not include system processes.	1
d2. “Identify simple relationships among the system’s components”	In his/her STM, the student made a link between the use of water and the continuity of life.	1
d3. “Identify dynamic relationships within the system”	The student could not determine the dynamic relationships within the system.	0
d4. “Organize the systems’ components and processes within a framework of relationships”	The student did not include system processes and could not present the system as a network of relationships.	0
d5. “Understands the cyclic nature of the system”	The STM produced by this student did not include the water cycle or the water treatment and reuse cycle, which could have been used to highlight the cyclical nature of the system	0
d6. “Understanding the hidden dimensions of the system”	He/she ignored hidden dimensions of the system.	0
d7. “Make generalizations”	He/she could not make generalizations.	0
d8. “Thinking temporally"	He/she could not think temporally.	0
	Total Score	2



Deniz, göl, dere kuruyabilir. / kuraklık yaşanabilir
Şişe/bardak ve çeşmeyle su içilebilir/hayvanlara da su içirilir.
Suyu içtiğimiz ve heryerde kullandığımız için su hayatımızdır,
Yemek yapımında ve giysilerde su kullanılır.

Sea, lake and stream may dry up.
We can drink water from bottles, glasses and fountains.
Water is our life as we drink water and use water everywhere.
Water is used in cooking and clothing.

Figure 3. *Pre-intervention STM of Produced by Student who was Coded as S14*

Questions regarding the dimensions of make generalization and thinking temporally (seen in Fig. 4b) were directed towards the students both pre-intervention and post-intervention. However, prior to the intervention, students had difficulty responding to these questions. Although the meaning of the questions was explained to them and students were encouraged to answer, the students could not answer the questions. They either said “I do not know” or handed in a blank sheet of paper. Students demonstrated greater proficiency in both drawing STM and responding to questions concerning these steps during the post-intervention STM drawings. For instance, a student coded as S14, whose STM score was 2 before the intervention, raised their STM score to 17 after the intervention.

Table 3

Score of Post-intervention STM Produced by Student who was Coded as S14

Sections of STMR	Analysis of Post-intervention STM Produced by Student who was Coded as S14	Score
d1. “Identifies the components of the system and the processes within the system”	He/she included more than three system components (sea, ocean, glaciers, rivers, etc.) and system processes (evaporation, condensation, transpiration, water treatment processes, etc.)	2
d2. “Identify simple relationships among the system’s components”	The student was able to identify more than 10 simple relationships pertaining to the water system.	3

d3. “Identify dynamic relationships within the system”	The student was able to identify one dynamic relationship within the system. In his or her STM, the student indicated that the water was polluted due to its use and associated the wastewater back to the water resources by passing it through the treatment processes.	1
d4. “Organize the systems’ components and processes within a framework of relationships”	He/she was able to indicate more than two causal relationships in his/her post-intervention STM.	3
d5. “Understands the cyclic nature of the system”	He/she included the water cycle in his/her STM	2
d6. “Understanding the hidden dimensions of the system”	He/she included groundwater and gravity among the hidden dimensions of the system.	2
d7. “Make generalizations”	He/she was able to identify the factors that can threaten the water system and explain how these factors affect the water system, including through examples. However, he or she could not provide an effective explanation that could address in full the question of how threats to the water system can be prevented.	2
d8. “Thinking temporally"	He/she discussed the quality of drinking water in terms of the past, present, and future. However, he/she could not explain past, present, and future interactions related to the water system by reference to a different example.	2
	Total Score	17

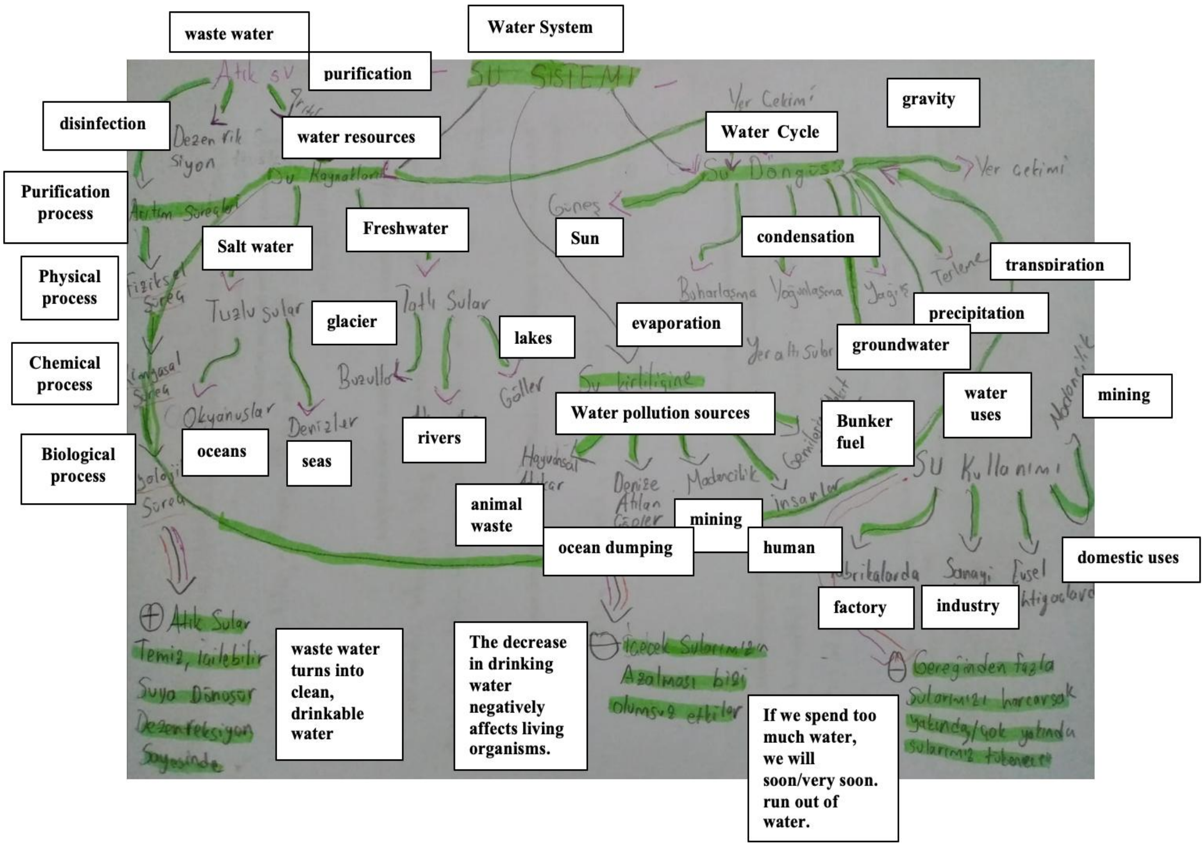
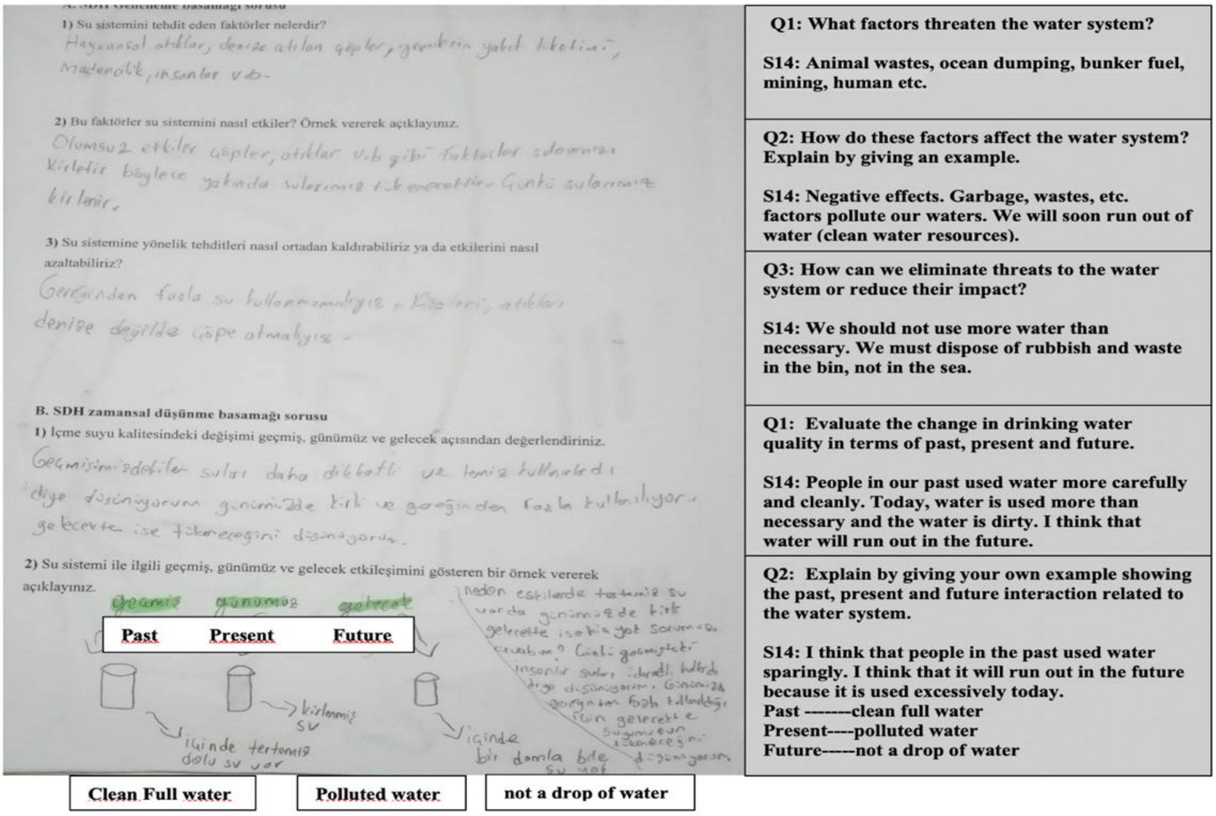


Figure 4a. *Post-intervention STM of Produced by Student who was Coded as S14*



A. SDH Genelleme basamağı sorusu

1) Su sistemini tehdit eden faktörler nelerdir?

Hayvansal atıklar, denize atılan çöpler, gemilerin yakıt [illegible], Madencilik, insanlar vb.

2) Bu faktörler su sistemini nasıl etkiler? Örnek vererek açıklayınız.

Olumsuz etkiler. Çöpler, atıklar v.b gibi faktörler sularımızı kirletir böylece yakında sularımız tükenecektir. Çünkü sularımız kirlenir.

3) Su sistemine yönelik tehditleri nasıl ortadan kaldırabiliriz ya da etkilerini nasıl azaltabiliriz?

Gereğinden fazla su kullanmamalıyız. Çöpleri, atıkları denize değilde çöpe atmalıyız.

B. SDH zamansal düşünme basamağı sorusu

1) İçme suyu kalitesindeki değişimi geçmiş, günümüz ve gelecek açısından değerlendiriniz.

Geçmişimizdekiler suları daha dikkatli ve temiz kullanırlardı diye düşünüyorum. Günümüzde kirli ve gereğinden fazla kullanılıyor. Gelecekte ise tükeneceğini düşünüyorum.

2) Su sistemi ile ilgili geçmiş, günümüz ve gelecek etkileşimini gösteren bir örnek vererek açıklayınız.

Neden eskilerde tertemiz su varda günümüzde kirli gelecekte ise hiç yok sorumuza cevabım? Çünkü geçmişteki insanlar suları idareli kullanırlardı diye düşünüyorum. Günümüzde gereğinden fazla kullanıldığı için gelecekte suyumuzun tükeneceğini düşünüyorum.

Q1: What factors threaten the water system?

S14: Animal wastes, ocean dumping, bunker fuel, mining, human etc.

Q2: How do these factors affect the water system? Explain by giving an example.

S14: Negative effects. Garbage, wastes, etc. factors pollute our waters. We will soon run out of water (clean water resources).

Q3: How can we eliminate threats to the water system or reduce their impact?

S14: We should not use more water than necessary. We must dispose of rubbish and waste in the bin, not in the sea.

Q1: Evaluate the change in drinking water quality in terms of past, present and future.

S14: People in our past used water more carefully and cleanly. Today, water is used more than necessary and the water is dirty. I think that water will run out in the future.

Q2: Explain by giving your own example showing the past, present and future interaction related to the water system.

S14: I think that people in the past used water sparingly. I think that it will run out in the future because it is used excessively today.
Past -------clean full water
Present----polluted water
Future-----not a drop of water

Figure 4b. *The Answers Given by Student who was Coded as S14 to Make Generalizations and Thinking Temporally Dimensions Questions in the Post-intervention*

Results and Discussion

This section presents results obtained by comparing system thinking maps drawn by students before and after the implementation of the SHI-based unit, in terms of their representation of the water system.

The Pre-intervention Systems Thinking Abilities of 7th Grade Students

In students' pre-intervention STM drawings, it became evident students used only limited concepts (see, e.g., Fig. 3 or Fig. 6). The most commonly identified system components were tap, rain, sea, pipe, dam and lake. Students found it difficult to identify system processes. Only 37.5% (12) of the students used system processes together with system components in their maps. The system processes identified by the students included water treatment (11) and evaporation (1). Nevertheless, students who identified specific processes were unable to demonstrate an understanding of the relationship between those processes and the system as a whole. A total of 62.5% (20) of the students were able to identify simple relationships among the system components. Only a limited number (2) of students (6.25%) were able to identify dynamic relationships within the system in their pre-intervention STM drawings. Only 4 students (12.5%) considered groundwater, which was one of the hidden dimensions of the system. Since students had only limited competence with regard to the identification of system components and encountered problems in their efforts to identify processes within the system, they failed to organize system components and processes within a framework of relationships. All the students (100%) failed to understand the cyclical nature of systems. These students lacked an understanding of the water cycle as a natural component of the water system. None of the students (32) were able to make generalizations or thinking temporally.

The Post-intervention Systems Thinking Abilities of 7th Grade Students

Notably, all of the students included system components and system processes jointly in their post-intervention STMs (e.g., see Fig. 4a or Fig. 7a). In all cases, the number of system components and system processes included in the students' STMs increased. Students' post-intervention STMs included system components (watershed, aquifer, groundwater, water vapor, precipitation, etc.) and system processes (evaporation, condensation, infiltration, transpiration, melting, freezing and runoff, etc.) that were not included in their pre-intervention maps.

According to Table 4, all the students (100%) were able to identify simple relationships among system components. More than half (17) of the students (53.12%) were able to identify dynamic relationships within the system. Eighteen students (56.25%) were able to organize the relationships among system components and processes. Twenty-four students (75%) included the hidden dimensions of the system, thus representing the majority in this context.

A total of 87.5% of the students (28) were able to indicate their understanding of the cyclical nature of the system in their post-intervention STMs. Seven students (21.8%) were successful with respect to the dimension of making generalizations and obtained full scores in this regard. Among the 16 students (50%) who attempted to think temporally, 13 (40.62%) incompletely expressed the fact that some interactions took place in the past and that future events may result from current interactions, whereas 3 students (9.37%) were able to think temporally (i.e., both retrospectively and predictively). Advanced dimensions of systems thinking, such as “make generalizations” or “thinking temporally”, were difficult for students (e.g., please see the example concerning S8 in Fig. 7b).

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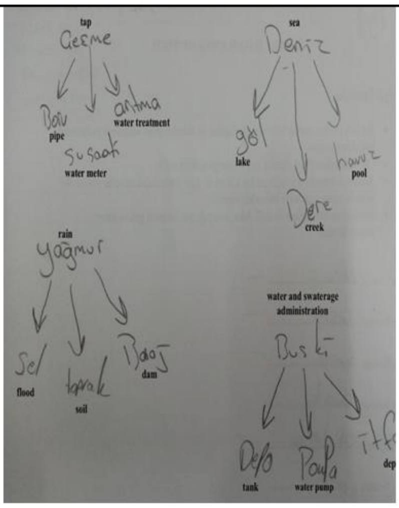
<td>


Dimension 7:
make generalizations
Answer 1: No answer
Answer 2: No answer
Answer 3: No answer
Dimension 8:
thinking temporally
Answer 1: No answer
Answer 2: No answer
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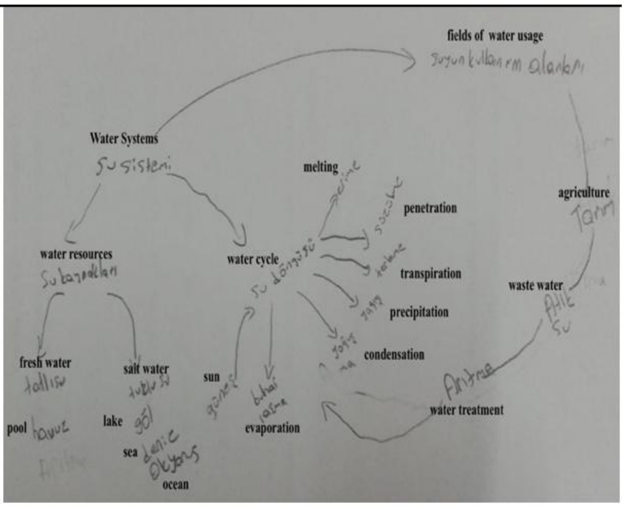

Dimension 7:
make generalizations
Answer 1: *waste water, factories*
Answer 2: *Factories dump their garbage and wastewater into the sea without treatment. This pollutes water resources.*
Answer 3: *Factories can reduce their waste by treating it.*
Dimension 8:
thinking temporally
Answer 1: No answer
Answer 2: *Soon we will be drinking dirty water.*
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<td>medium</td>
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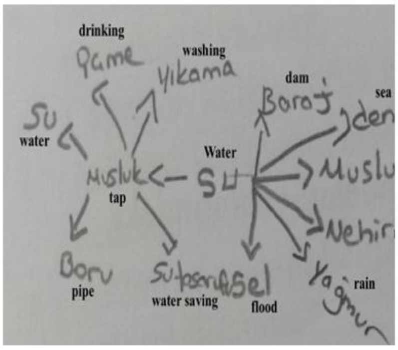

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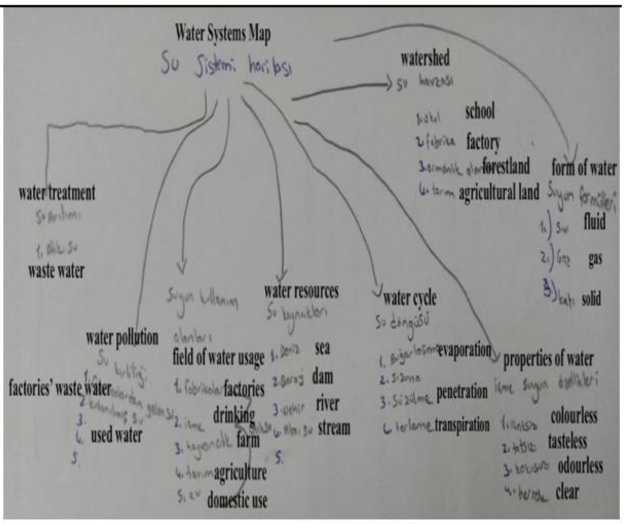

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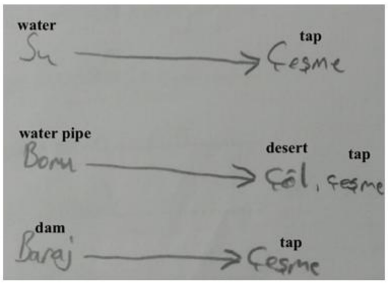
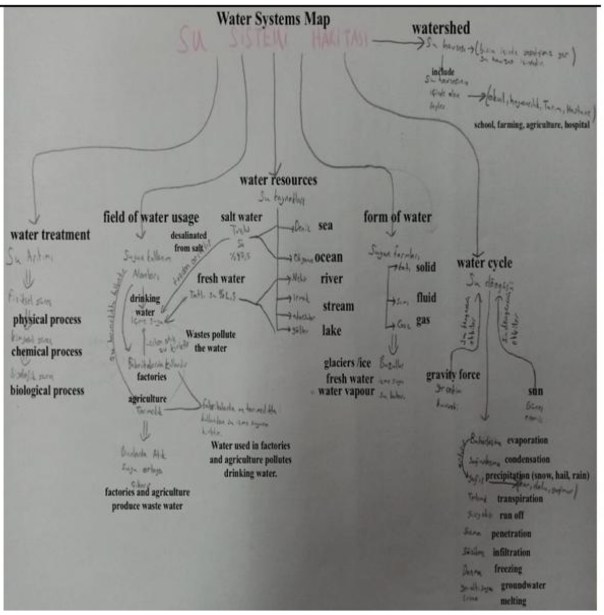




Dimension 7:
make generalizations
Answer 1: No answer
Answer 2: No answer
Answer 3: No answer
Dimension 8:
thinking temporally
Answer 1: No answer
Answer 2: No answer

Dimension 7:
make generalizations

Answer 1: *Water pollution, wastewater and global climate change are among the factors threatening the water system.*

Answer 2: *The wastewater from factories flows into streams or rivers. Our clean water becomes less and less. As global climate change progresses, glaciers melt. Life in that region is affected.*

Answer 3: *For example, we can treat wastewater from factories. We can treat salt water. So, we will have more drinking water. We can also eliminate threats to the water system.*

Dimension 8:
thinking temporally

Answer 1: *Water quality is worse today than in the past. The population was smaller in the past. There was less wastewater produced. Today, the population has increased, as has the amount of wastewater, and global climate change has occurred. It is rumoured that in the future we may not even have drinking water.*

Answer 2: *Water pollution was not so high in the past. Today, water pollution has increased considerably. In the future, water pollution may increase or decrease even more.*

Figure 5. *Differences between students' STMs Pre- and Post-intervention*

Figure 5 presents a comparison of the systems thinking maps drawn by students before and after the implementation of the socio-hydrologic issue-based unit. Upon examination of the systems thinking maps drawn by the students in terms of their representation of the water system, a small alteration was observed in the drawing of the student with code S30, a medium alteration in the drawing of the student with code S7, and a big alteration in the drawing of the student with code S2.

It was determined that the systems thinking maps drawn by the students at the post-intervention stage included a greater number of components, processes and relationships of the water system than the systems thinking maps drawn prior to the intervention. As illustrated by the findings in figure 5, some students (e.g., S2) continued to experience challenges in responding to questions designed to assess their proficiency in make generalization and thinking temporally dimensions of systems thinking, which are regarded as the more advanced facets of this discipline. Conversely, some students (e.g., S30) demonstrated notable advancements in these dimensions.

Table 4

Comparison between the Pre-intervention and Post-intervention STMs

		Pre-intervention STM		**Post-intervention STM**	
	Sections of STMR	**Frequency (*f*)**	**Percentage (%)**	**Frequency (*f*)**	**Percentage (%)**
Systems Thinking Dimensions	d1. Identifies the components of the system and the processes within the system	12	37.5	32	100
	d2. Identify simple relationships among the system's components	20	62.5	32	100
	d3. Identify dynamic relationships within the system	2	6.25	17	53.12
	d4. Organize the systems' components and processes within a framework of relationships	0	0	18	56.25
	d5. Understand the cyclic nature of systems	0	0	28	87.5
	d6. Understand the hidden dimensions of a system	4	12.5	24	75
	d7. Make generalizations	0	0	7	21.87
	d8. Think temporally	0	0	3	9.37

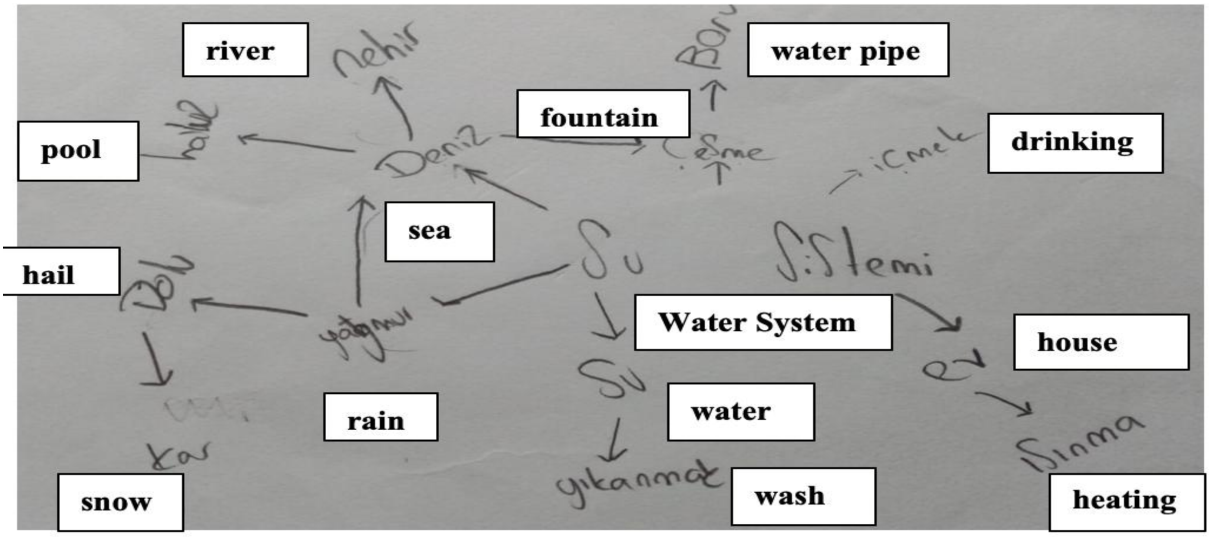


Figure 6. *Pre-intervention STM of Produced by Student who was Coded as S8*

The student who was coded as S8 did not respond to questions regarding the dimensions of make generalizations and thinking temporally in pre-intervention.

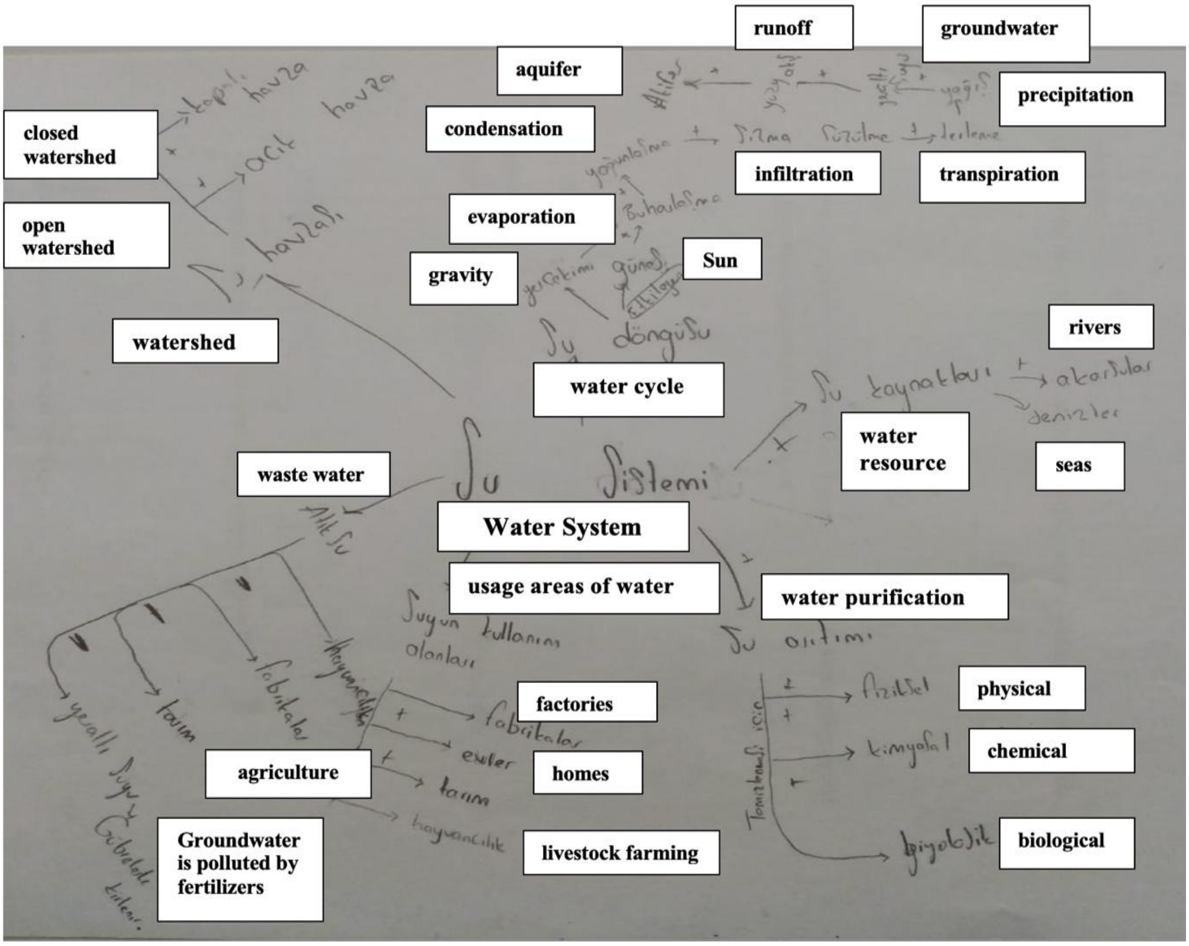
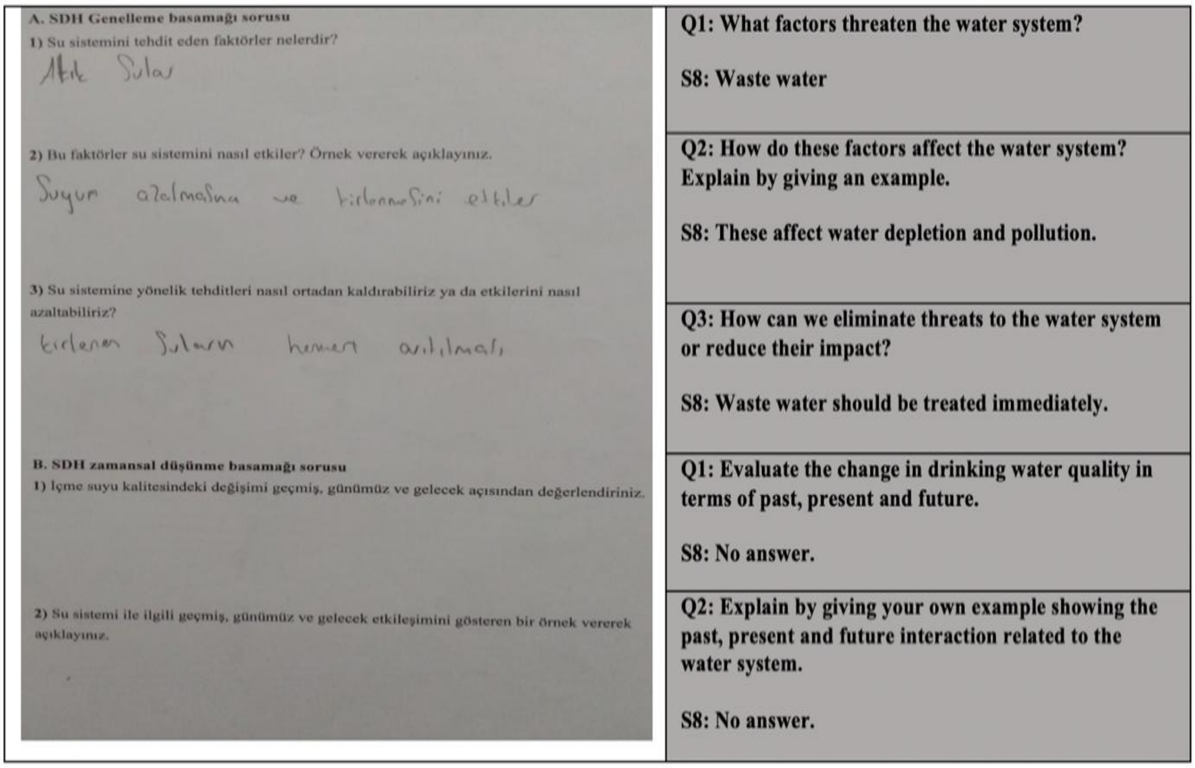


Figure 7a. *Post-intervention STM of Produced by Student who was Coded as S8*



A. SDH Genelleme basamağı sorusu

1) Su sistemini tehdit eden faktörler nelerdir?

Atık Sular

2) Bu faktörler su sistemini nasıl etkiler? Örnek vererek açıklayınız.

Suyun azalmasına ve kirlenmesini etkiler

3) Su sistemine yönelik tehditleri nasıl ortadan kaldırabiliriz ya da etkilerini nasıl azaltabiliriz?

kirlenen Suların hemen arıtılmalı

B. SDH zamansal düşünme basamağı sorusu

1) İçme suyu kalitesindeki değişimi geçmiş, günümüz ve gelecek açısından değerlendiriniz.

2) Su sistemi ile ilgili geçmiş, günümüz ve gelecek etkileşimini gösteren bir örnek vererek açıklayınız.

Q1: What factors threaten the water system?

S8: Waste water

Q2: How do these factors affect the water system? Explain by giving an example.

S8: These affect water depletion and pollution.

Q3: How can we eliminate threats to the water system or reduce their impact?

S8: Waste water should be treated immediately.

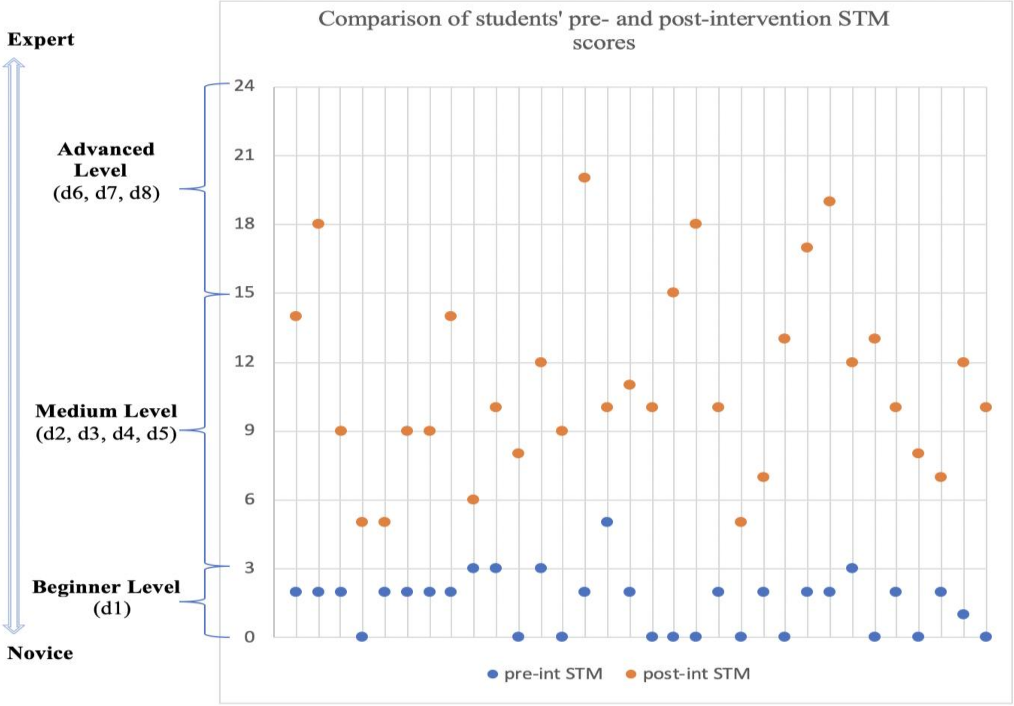
Q1: Evaluate the change in drinking water quality in terms of past, present and future.

S8: No answer.

Q2: Explain by giving your own example showing the past, present and future interaction related to the water system.

S8: No answer.

Figure 7b. The *Answers Given by the Student who was Coded as S8 to Dimensions of Make Generalizations and Thinking Temporally Questions in the Post-intervention*



* Systems thinking dimensions are represented by systems thinking levels that are specific to the present study.

** In one section of the rubric, students have the potential to obtain a score ranging from 0 to 3. Across all eight sections of the rubric, they can potentially receive a score between 0 and 24.

Figure 8. *Comparison of Students' Pre-intervention and Post-intervention STM Scores*

Students' pre- and post-intervention STMs were scored through the STM rubric on the basis of 8 systems thinking characteristics. The mean scores associated with the pre- and post-intervention STMs produced by 32 students were calculated separately for each of the eight dimensions of systems thinking included in the rubric. Students' systems thinking levels have improved (fig. 8). The students' post-intervention STMs scores were higher than their pre-intervention STMs scores. Post-intervention STMs' results was demonstrated improvement in all dimensions of systems thinking in comparison with the results of pre-intervention STMs.

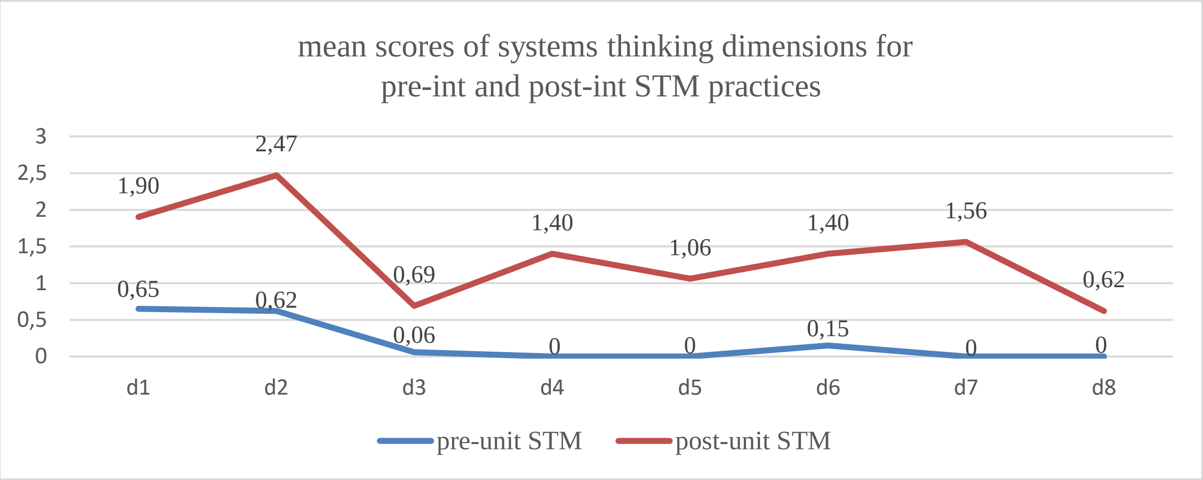


Figure 9. *Change in Mean Scores of Pre-intervention and Post-intervention STM Practices*

The discussion section is comprised of three distinct headings: The design of an educational intervention from a systems perspective, the measurement of systems thinking, and the development of students' systems thinking.

Design of an Educational Intervention with a System Perspective

Understanding systems has become an increasingly important task in the context of science education (NGSS, 2013). Water education must be integrated with a system approach, as in the case of education in geography (e.g., Cox et al., 2019, 2020), the Earth system (e.g., Ben-Zvi Assaraf & Orion, 2005b, 2010), biology (e.g., Boersma et al. 2011, Glissen et al., 2020, Hmelo-Silver et al., 2007; Moore-Anderson, 2023), and chemistry (e.g., York et al., 2019).

Although previous studies have focused on teaching concepts related to water, this interest did not encompass the whole but rather merely various parts, such as the water cycle (e.g., Bar, 1989; Cardak, 2009; Koomson & Owusu-Fordjour, 2018, Shepardson et al., 2009; Vo et al., 2015), phase changes (e.g., Bar & Travis, 1991), hydrological concepts (e.g., Dove et al., 1999; Forbes et al., 2015), and the physical properties of water (e.g., Bošnjak Stepanović et al., 2019) or groundwater (Zangori et al., 2017). Although the number of studies that have adopted a systems approach to water-related topics (e.g., Baumfalk et al., 2019; Covitt et al., 2009; Gunckel et al., 2012; Lally & Forbes, 2020; Lee et al., 2019) has increased over time, further support for such a holistic approach to water remains necessary.

This study aims to design an educational intervention (e.g., Baumfalk et al., 2019; Ben-Zvi Assaraf & Orion, 2005b; Gilissen et al., 2020) that can enable middle school students to understand water as a system by supporting their learning processes. During intervention, it is important to consider curriculum design, pedagogical strategies, and the way teachers convey complex systems concepts to students. It should be noted that there is a positive relationship between the teacher's content knowledge and students' learning progress (Hashweh, 2005). Teachers' content knowledge and pedagogical content knowledge are crucial for promoting students' systems thinking (Rosenkränzer et al., 2016). Furthermore, in order to develop systems thinking, the curriculum design focused on mechanisms and networked knowledge instead of functions and fragmented knowledge, as emphasized by Moore-Anderson (2021).

The complexity of the water system requires an approach that emphasizes the role of water within socioecological systems (Gunckel et al., 2012; Sadler et al., 2017). This requirement is one of the design principles that guided our efforts to design intervention. Students generally associate the water system with its ecological dimensions and overlook the social dimensions of the system. To overcome this challenge, we designed a SHI-based unit that focused on socioecological water and included various pedagogies (Kagawa, 2007; Martínez-Borreguero et al., 2020; Wang et al., 2022) that emphasized the interconnections among different system dimensions. This study utilized SHI to enhance middle school students' understanding of the water system at the sociohydrological system level, which is similar to previous approaches to undergraduate studies that have focused on water-related topics through the use of SHI units as a specific context (Lally & Forbes, 2020; Petitt & Forbes, 2019; Owens et al., 2020; Sabel et al., 2017).

Recent studies emphasize the importance of designing a systems-based curriculum and formal education that is focused on developing systems literacy (Bernier, 2015; Demirci, 2021). During the educational intervention, systems thinking, which is a strategy that can be used to recognize the connections among components, to identify complex causal relationships, and to understand the behavior of dynamic systems, was used to help students understand complex systems (Arnold & Wade, 2015; Ben-Zvi Assaraf & Orion, 2005b, 2010; Goodman, 1997; Hossain et al., 2020). The instructional intervention employed a systems approach, as opposed to a reductionist approach, to enable students to comprehend the water system.

Measurement of Systems Thinking

Concept maps illustrate the components and processes that comprise a system, as well as the relationships between its various parts. In this respect, concept maps can be used as an effective tool for evaluating students' systems thinking (Sommer & Lucken, 2010). But there is no general agreement about the appropriate concept map practice to assess systems thinking (Brandstädter et al., 2012). According to Tripto et al. (2013), thinking temporally requires understanding timeline interactions and processes, which concept maps may not represent. Narrative qualitative research tools are required for accurate assessment. In our study, open-ended questions were used alongside the systems thinking map to evaluate make generalizations and thinking temporally dimensions of systems thinking.

The Progression of Students' Systems Thinking

Understanding the complexity of systems is related to the ability to engage in systems thinking. As systems thinking is also a fundamental skill with respect to decision making and problem solving (Evagorou et al., 2009; Senge, 1990), it is important to develop systems thinking among students. Our study confirmed the results that have been reported by previous studies (Sweeney & Sterman, 2007; Jacobson, 2001; Jacobson & Wilensky, 2006; Wilensky & Resnick, 1999; Hmelo-Silver & Azevedo, 2006), thus indicating that students tend to overlook the complexities of the various processes and connections that are embedded within systems and to solve complex, systematic problems via simple explanations.

Students' pre-intervention STMs indicated that they struggled even to identify system components and processes, which represents the first step of systems thinking. The students associated few system components with the water system, and two-thirds of the students could not identify the system process. The results of this research revealed that students could not identify the relationships among processes such as evaporation, condensation, melting, and freezing, with which they were familiar due to their exposure to the water system in lower grades. This finding suggests that problems emerge with respect to the ecological dimensions of the system even in the context of processes that occur at the atmospheric level (Bar & Travis, 1992; Osborne & Cosgrove, 1983; Koomson & Owusu-Fordjour, 2018). Additionally, as highlighted by Ben-zvi Assaraf and Orion (2005b, 2010), most students fail to perceive the water system at the geosphere level, thereby ignoring geological components and processes as well as the hidden dimensions of the system. With respect to students' pre-intervention STMs, only 4 students included groundwater as a system component. However, these students could not highlight the connections between this component and other system component. It might be suggested that students ignore groundwater in systems components due to the lack of emphasis on groundwater in the curriculum. While students' pre-intervention STMs exhibited some simple relationships, they failed to address the dynamic relationships among different system components. Students found it difficult to understand the cyclical nature of the system. Students' understanding of systems was insufficiently develop to display that they were making generalizations or thinking temporally. Even though the students' inability to respond to the questions about systems thinking dimensions, such as make generalizations and thinking temporally, before the intervention does not necessarily indicate that they were not able to make generalizations or thinking temporally, it is imply that they were not yet ready to interact with the context.

The pre-intervention findings revealed that our students were novice systems thinkers, which is consistent with the findings of various other studies (Ben-Zvi, Assaraf & Orion, 2005b; Cox et al., 2019; Jaiswal & Karabiyik, 2022). It was also revealed that the students' levels of systems thinking needed to be improved so that they could acquire an understanding of such systems.

Students' post-intervention STMs revealed that their perceptions of the water system had developed toward an understanding of the socioecological system. Students identified more components and processes that reflected various levels (e.g., the atmosphere, geosphere, biosphere, and the relationships between the environment and human activities). These post-intervention STMs revealed that students incorporated a wide variety of components (water resources, watersheds, precipitation, forms of water, aquifers, groundwater, drinking water, wastewater, etc.) and processes (evaporation, condensation, infiltration, runoff, perspiration, water purification, etc.) pertaining to the water system. All of the students were able to identify simple relationships among various components of the system, whereas more than half of these students were able to identify dynamic relationships within the system and to organize the components and processes of the system within the framework of relationships. After the completion of the learning process, the students were able to highlight the hidden dimensions of the system, such as groundwater, water vapor, and gravity, and they understood the cyclical nature of the system in relation to the water cycle and wastewater recycling processes.

Studies that have compared experts with novices in terms of their comprehension of system components, processes, and mechanisms/behaviors have revealed that novices focus on structural components of the system, especially visible components that require a lower level of systems thinking, whereas experts focus primarily on the behaviors/mechanisms of the system itself as well as its functionality/purpose and the consequences of its behaviors (Hmelo-Silver & Pfeffer, 2004; Hmelo-Silver et al., 2007).

Previous researchers have also reported that novices overlook the connections within the system as well as the complexity of the processes involved (Jacobson, 2001). On the basis of such studies, it is reasonable to claim that our students have progressed from novices to experts (fig. 8). In students' post-int STMs, they were able to identify system processes and system components, including hidden components of the system, to identify dynamic relationships within the system, and to understand the cyclical nature of the system; these findings are evidence of such progress. During the course of the SHI unit, these students began to focus more on the mechanisms underlying the system as well as the purposes and consequences of the system's behaviors, thereby operating as experts.

This study indicated that it became easier for students to understand the dynamic behavior of the system, to highlight its cyclic structure and to explain the meaning of the characteristic dynamics when they were able to identify the processes operative within the system and to notice the hidden dimensions of the system. The students' understanding of the system also improved in terms of the higher-level dimensions pertaining to making generalizations and thinking temporally, albeit to a lesser degree than the other dimensions.

Students' progress in the task of identifying system components and processes as well as the interrelationships among them provides evidence indicating that the deliberate implementation of the SHI-based unit is conducive to the purpose of the study. SSI (specifically defined as SHI in this study), including its scientific and social dimensions, is known to represent a powerful context for science learning that can deepen students' understanding of disciplinary knowledge and practices (Sadler, 2011). Exposure to SSI can improve students' understanding of the complexity of systems (Ke et al., 2020; Leung et al., 2025). Moreover, the task of exploring SHI can enhance students' proficiency in reasoning about complex systems, which is pivotal with respect to their ability to comprehend and address the underlying issues (Petitt & Forbes, 2019; Sabel et al., 2017).

Our study revealed a connection between students' exposure to SHI and their consideration of system complexity. Similarly, a connection between the degree to which students engaged in the activities pertaining to the SHI-based unit with systems thinking and the degree to which they understood the complexity of the system was observed. Students who participated actively in the discussions throughout the unit and were more willing to invest effort into the corresponding activities made more progress in thinking about the water system in a dynamic and circular manner. At the end of the intervention, all the students recognized that solutions to water-related problems should be considered from multiple perspectives.

Conclusion and Implications

The aim of this study was to design an educational intervention to alleviate students' lack of understanding of water systems caused by educational approaches that neglect complex systems. (Liu & Hmelo-Silver, 2009). Results of the study indicate that this DBR facilitates effective teaching and learning of the water and enhances to students' understanding of the water system. In this study, students' systems thinking was developed by designing a SHI-based unit, which was constructed on the basis of the UWS framework for systems thinking.

This study has developed a teaching design that integrates socio-hydrological issues with systems thinking in a middle school context. This approach, which is usually adopted at university level, has been incorporated into the learning environment of younger students. The developed design offers an innovative approach aimed at enabling students to understand the water system holistically in terms of its natural and social dimensions.

Learning progress is defined as an ongoing process that begins with students' most naive ideas and continues toward the emergence of scientific understanding or practice (Jin & Anderson, 2012). The progress of students' systems thinking regarding water systems was monitored via STMs. Activities related to systems thinking (e.g., Iceberg, Relational Thinking, and STM) contributed to students' understanding of the underlying mechanisms, interrelationships, cyclicality, and spatial and temporal dynamics that characterize the water system. The results of our study confirm the previous research indicating that implementing systems-based, systematically designed educational interventions can improve students' understanding of complex systems (e.g., Ben-Zvi Assaraf & Orion, 2005b, 2010; Grohs et al., 2018; Lally & Forbes, 2020; Lee et al., 2019).

The educational intervention, which consisted of a series of interrelated lessons with no implicit learning outcomes, allowed students to develop a holistic and connected understanding of the water system while also improving their systems thinking based on the course content and various activities aligned with the UWS framework. The SSI-based approach facilitated the development of the students' systems thinking, enabling them to understand the complexity and to reason about complex systems. Students' limited understanding of water was transformed towards an understanding of the socio-hydrologic system, and their novice level of systems thinking progressed to a more sophisticated level.

Recommendations

This study recommends that future research aimed at encouraging students to understand complex systems should develop curriculum/units based on a theoretical framework that focuses on a holistic understanding and feature explicit learning outcomes. In order to develop students' understanding of systems, the intervention should include activities that promote systems thinking.

Our intervention emphasized both scientific and social dimensions in accordance with the socio-ecological systems perspective. During the intervention, social dimensions were incorporated into the content and activities (e.g. class discussions, policy-making activity). However, the students' inadequate knowledge and understanding of the water system necessitated prioritizing scientific development in the design of the SHI-based unit. It is recommended that students' readiness be taken into account when making design decisions for educational interventions.

This study suggests that systems thinking should be integrated into teaching and learning about water in order to enhance students' understanding of water as a system. Additionally, this study provides guidance for curriculum designers and teachers regarding ways of teaching and learning about water systems, in which context it also offers novel pedagogical resources, including various teaching tools and strategies. This research is expected to serve as a model for future studies on the design of water-related lessons and to facilitate the practical implementation of systems thinking in the context of middle school water education.

Ethics Committee Approval

In this research, ethical approval was obtained from the Ethics Committee of Yıldız Technical University on 28.02.2022 and numbered 20220200191.

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