

## Development of System Thinking Skills in the Context of Earth System Education

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**Abstract:** The current study deals with the development of system thinking skills at the junior high school level. The sample population included about 50 eighth-grade students from two different classes of an urban Israeli junior high school who studied an earth systems-based curriculum that focused on the hydro cycle. The study addressed the following research questions: (a) Could the students deal with complex systems?; (b) What has influenced the students' ability to deal with system perception?; and (c) What are the relationship among the cognitive components of system thinking? The research combined qualitative and quantitative methods and involved various research tools, which were implemented in order to collect the data concerning the students' knowledge and understanding before, during, and following the learning process. The findings indicated that the development of system thinking in the context of the earth systems consists of several sequential stages arranged in a hierarchical structure. The cognitive skills that are developed in each stage serve as the basis for the development of the next higher-order thinking skills. The research showed that in spite of the minimal initial system thinking abilities of the students most of them made some meaningful progress in their system thinking skills, and a third of them reached the highest level of system thinking in the context of the hydro cycle. Two main factors were found to be the source of the differential progress of the students: (a) the students' individual cognitive abilities, and (b) their level of involvement in the knowledge integration activities during their inquiry-based learning both indoors and outdoors. © 2005 Wiley Periodicals, Inc. *J Res Sci Teach* 00: 1–43, 2005

The last two decades can be described as the “Science for All” era of science education around the world. During this period, the main goal of the science education paradigm has shifted from preparing future scientists toward educating our future citizens. As a result, the current paradigm emphasizes the environment and environmental issues in the science curriculum. However, any attempt to develop environmentally literate students without some general acquaintance with scientific understanding of the physical environment would not reach beyond popular activities like recycling or cleaning up the schoolyard.

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### Environmental Literacy and the Earth Systems Approach

In order to develop environmental literacy, the scientific principles that are interrelated with the study of the environment must be firmly established. Students who understand their local environment and the processes taking place therein might have better tools to evaluate the changes taking place in it and might know how to live in peace with it (Mayer & Armstrong, 1990; Brody, 1993). Nevertheless, better acquaintance with environmental problems is not sufficient in itself for students to develop a sound decision-making ability concerning such environmental issues. Therefore, the main goals of the schools' science education should be to provide students with the skills needed to translate environmental problems, such as water pollution, into a more coherent understanding of the environment.

Mayer (1995) suggested that such a goal might be achieved through the earth systems approach. This approach views the world as one system, which consists of four central subsystems, namely the geosphere, hydrosphere, atmosphere, and biosphere (including humans). Orion (2002) introduced a practical model for using the earth systems approach as a framework for the science curricula. This model emphasizes the study of geochemical and biogeochemical cycles including the rock cycle, the water cycle, the food chain, the carbon cycle, and energy cycles, and the interrelations among the different subsystems in terms of transitions of matter and energy from one subsystem to another. It was also suggested that the study of the natural cycles should be discussed in the context of their influence on people's daily life. For example, pollution of rivers, the quality of drinking water, and contamination of groundwater supplies.

Orion (2003) claimed that understanding each of the earth's subsystems and the environment as a whole is indispensable for people to coexist peacefully with the environment. This understanding is actually what science is all about. For instance, most of Earth's surface is covered with water, and most of this water is found in the oceans. By learning about the earth's water systems, students can develop an understanding of the important role of water systems in the global ecosystems. In addition, students can understand that large bodies of water such as the Great Lakes in the USA greatly influence the climate and weather of the region in which they are located, and that both large lakes and oceans interact with the atmosphere through the water cycle. As students develop these understandings, they become aware of the importance of fresh and salt water to the sustainability of life on earth.

### Earth Systems and the Meaning of a System

Kali, Orion, and Elon (2003) suggested that the ability of students to deal with such geochemical and biogeochemical complicated systems is based on their ability to develop a dynamic, cyclic and systemic perception of our planet. Therefore, teaching the earth systems approach requires that teachers and students understand the concept of a system.

The term "system" is a very broad concept that relates to various areas such as social systems, technological systems, and natural systems. Therefore, this subject has been studied from different angles and points of interest (Kim, 1999; Mandinach, 1989; O'Connor & McDermott, 1997; Penner, 2000). It seems that the following characteristics of a "system" represent most of these studies: A system is an entity that maintains its existence and functions as a whole through the interaction of its parts. However, this group of interacting, interrelated or interdependent parts that form a complex and unified whole must have a specific purpose, and in order for the system to optimally carry out its purpose all parts must be present. Thus, the system attempts to maintain its stability through feedback. The interrelationships among the variables are connected by a cause and effect feedback loop, and consequently the status of one or more variables, affects the status of

the other variables. Yet, the properties attributable to the system as a whole are not those of the individual components that make up the system.

### What the Literature Tells About Students' Perception of a System

The difficulty of students to deal with the complexity of a system is not surprising and it appears in all ages. Hmelo, Holton, and Kolodner (2000) reported that sixth-grade students had difficulty in learning about the human respiratory system. They implied that the students' difficulties were derived partly by their inability to understand that there are properties of human systems that operate at both macroscopic and microscopic levels. Moreover, they indicated that it is impossible to understand these systems at different levels without understanding the functioning of the entire system.

The complexity in the process of understanding systems appeared in earth science education as well. For example, while junior high school students were asked to describe physical systems such as the water cycle, Ben-Zvi-Assaraf & Orion (2004a) revealed that students perceive the "water cycle" as a set of unrelated pieces of knowledge. They understand various hydro-biogeological processes, but lack the dynamic, cyclic, and systemic perceptions of the system. Their findings suggest that the ability of students to perceive the hydrosphere as a coherent system depends on both scientific knowledge and cognitive abilities. More specifically, cyclic thinking and systems thinking, which is the ability to perceive the water cycle in the context of its interrelationship with other earth systems. Kali et al. (2003) also reported on students' difficulties in developing systems thinking of the rock cycle, which involved a cognitive framework with a dynamic and cyclic view of the system. Nevertheless, this cognitive inability is not limited to junior and high school students. Booth Sweeny (2000) studied the system thinking skill abilities of students of the business school at MIT who had a very solid background in mathematics and science, but no prior exposure to system dynamics concepts. She used a system-thinking inventory to assess particular concepts of systems thinking such as feedback, delay, stocks, and flows. The results strongly suggest that those highly educated subjects showed a poor level of understanding some of the most basic concepts of system dynamics' specifically, stock and flows relationships, and time delay. For instance, the subjects tended to be unaware of fundamental relationships between stocks and flows, including the conservation of matter.

### What the Literature Tells About System Thinking

System thinking has become popular recently in the fields of organizational management. For example, system thinking is denoted by Senge (1990) as the fifth discipline, "the catalyst and cornerstone of the learning organization that enables success." He suggested that system thinking is a school of thought that focuses on recognizing the interconnections between the parts of a system and then synthesizes them into a unified view of the whole. Furthermore, it deals with recognizing patterns and interrelationships, and learning how to structure those interrelationships into more effective, efficient ways of thinking.

Ullmer (1986) argued that a system approach is an attitude of the mind in facing complexity; it reflects a search for the interrelationships of things in any problematic situation. Senge (1990) pointed out the connection between mental models and systemic thinking. He referred to systemic thinking as a conceptual framework of knowledge, principles, and tools that enable observing within the interrelationship and the mutual connections necessary in order to determine changeable patterns and repeated phenomena. Senge (1990) and others (Kim, 1999; O'Connor

& Mcdermott, 1997; Waring, 1996) claim that systemic thinkers are able to change their own mental models, control their way of thinking, and deal with the problem-solving process. They suggested that within the system, “cause and effect” might not be closely related in time and space. Therefore, one of the mechanisms for using system thinking in a problem-solving situation is based on the ability to enlarge the systems’ borders and expose hidden dimensions of the system. In organization systems this dimension is expressed by social factors such as values, beliefs, and interests that lie under the surface. Also, in order to analyze the system’s behavior in time dimension, one should present backward (retrospection) and forward (prediction) thinking skills.

Other researchers (Booth Sweeny, 2000; Draper, 1993, Frank, 2000; Ossimitz, 2000) suggested that specific system thinking skills include cognitive abilities such as (a) thinking in terms of dynamic processes (delays, feedback loops, oscillations); (b) understanding how the behavior of the system arises from the interaction of its agents over time (dynamic complexity); (c) discovering and representing feedback processes that underlie observed patterns of the system’s behavior; (d) identifying stock and flow relationships; (e) recognizing delays and understanding their impact; (f) identifying nonlinearities; and (g) scientific thinking, which involves the ability to quantify relations and to hypothesize and test assumptions and models.

The type of thinking needed for understanding systems has been studied extensively in the field of engineering and business. Frank (1999) identified the cognitive and personality characteristics of engineers with high “engineering systems thinking” skills. As a result of his study, Frank (2000) “adapted” and enlarged Senge’s laws regarding the engineering systems thinking and suggested thirty “engineering systems thinking” laws, according to which, one could design a curriculum for constructing “engineering systems thinking.” Frank (2000) pointed out the close relationship of the above characteristics of system thinking to other higher-order thinking skills. Similarly, Booth Sweeny (2000) argued that effective system thinking also requires good scientific reasoning skills such as the ability to use a wide range of qualitative and quantitative data. These abilities are attributed to higher-order thinking abilities. Resnick (1987) pointed out that scientific and mathematical thinking, solving problems, critical thinking, and refining ideas in creative ways, involve complex higher-order thinking characteristics.

Although Senge (1990) deals mainly with economic and social systems and with the analysis of complex organizations, note that system thinking is regarded as a higher-order skill required in the domains of science, technology and everyday life. But, little is known about system thinking in the context of science education.

In the field of computer modeling of system thinking, system dynamics developed by Forrester (1968), attempts to understand the behavior of complex phenomena over time. Based on the concept of change, system dynamics uses simulations and computer-based models to represent complex relationships among variables. Later, Mandinach (1989) and Steed (1992) reported that the software product STELLA (Structural Thinking Experimental Learning Laboratory with Animation) helps clarify the connection between the system process and its structures. The process involving the underlying structures takes place as STELLA models are built and modified. Thus, system dynamics provides a way to understand the connections among elements in a system and how they contribute to the whole. Mandinach (1989) presented the Systems Thinking and Curriculum Innovation (STACI) project, which examined the cognitive and curricular impact of learning from a system thinking approach while using Stella simulation-modeling software in secondary school curricula to teach content-specific knowledge as well as to enhance general problem-solving skills.

Another study that was conducted in a computer-supported environment is the Penner (2000), which focused on a small group of middle school students as they developed an understanding of

emergent systems. Such systems are notable in the fact that macro-level properties emerge as the result of micro-level interaction between the system components. In addition, Penner described students' initial understanding of emergent systems, as well as the ways in which their thinking came to reflect the following heuristics: (a) recognizing that there may not be a singular causal force underlying the system; (b) distinguishing between the micro and macro levels of analysis; and (c) comprehending that even small changes at the micro level can have significant effects at the macro level. Penner's study revealed that middle school students might have little experience thinking with and about even a simple nonemergent system. Therefore, he suggests that science educators need to consider the types of activities that will best facilitate students' thinking about emergent systems in a real world context. Moreover, he pointed out the need to study the ways in which domain-specific knowledge and explanatory heuristics guide learning about specific systems.

One of the prominent disciplines that confronts those two educational challenges is that of the earth science education. Gudovitch (1997), who studied systems thinking of high school students, developed a system-oriented curriculum in the context of the carbon cycle. Gudovitch explored students' prior knowledge and perceptions concerning global environmental problems in general and the role of man among natural systems in particular. Importantly, the educational unit provides a means of stimulating students to explore the Carbon cycle system, in which students' progress in a system-thinking model consists of four stages: The first stage includes an acquaintance with the different Earth systems, and an awareness of the material transformation between these systems. The second stage includes an understanding of specific processes causing this material transformation. The third stage includes an understanding of the reciprocal relationships between the systems. The fourth stage includes a perception of the system as a whole. The same principles guided Kali et al. (2003), who characterized students' conceptions of the rock cycle system following a program in which the effect of a concluding knowledge integration activity on students' systems thinking was studied. They reported that while answering an open-ended questionnaire, students presented a systems-thinking continuum, ranging from a completely static view of the system, to an understanding of the system's cyclic nature. Yet, Kali et al. (2003) implied that an understanding of the more complex systems, such as the water cycle or the carbon cycle, requires a high degree of systems thinking concerning each of the earth's systems. Moreover, they emphasized the importance of cyclic and dynamic thinking skills as a tool for analyzing earth systems.

The research regarding the type of thinking needed for understanding earth systems expenses the characteristics of system thinking, which has been traditionally defined in the fields of engineering, organization, and business.

Nevertheless, it is suggested that other system thinking skills, which were mentioned in the context of these disciplines, are also crucial while using system thinking in an environmental problem-solving situation. Orion (2002) claimed that because the natural environment is a system of interacting natural subsystems, students should understand that any manipulation in one part of this complex system might cause a chain reaction. The understanding of physical systems such as the earth is also based on the ability to enlarge the systems' borders and expose hidden dimensions of the system. This dimension is expressed by elements that may not be seen as part of the system, such as groundwater or the atmosphere. Analyzing environmental problems such as groundwater pollution involves questions such as: What was the cause of the groundwater pollution? What will be the outcome of the pollutants in the groundwater system? How could humans be affected? How long can those chemicals stay in the rocks? The ability to deal with such questions requires also backward (retrospection) and forward (prediction) thinking skills.

The above literature review reveals eight emergent characteristics of system thinking. The following are these characteristics and the expression of each of them in the context of the hydro-cycle system:

1. *The ability to identify the components of a system and processes within the system:* The meaning of this characteristic in relation to the hydro-cycle system is the ability to identify components such as oceans, rivers, lakes, glaciers, ice caps, rain, and clouds; and processes such as evaporation, condensation, precipitation, penetration, underground and surface flows, melting, freezing, and dissolution.
2. *The ability to identify relationships among the system's components:* The expression of this characteristic within the hydro cycle system is, for example, the acknowledgement of the connection between the composition of the water solution and the rocks that they pass through; or the understanding that polluted rivers could directly affect the water quality.
3. *The ability to organize the systems' components and processes within a framework of relationships:* Figure 6 presents a good example of such framework in the context of the hydro-cycle system.
4. *The ability to make generalizations:* Such generalization might be expressed within the hydro-cycle system by the understanding that this system is dynamic and cyclic. This understanding could later be implemented for preventing environmental threats in the context of the hydrosphere system.
5. *The ability to identify dynamic relationships within the system:* Understanding the transformation of matter within the earth systems involves the identification of dynamic relationships within the hydro-cycle system such as human influences over the groundwater through pollution by fertilizers and pesticides; Water leaches through sand rock; water dissolves the mineral within the rocks.
6. *Understanding the hidden dimensions of the system:* Recognizing patterns and interrelationships which are not seen on the surface. The hydrosphere system is a good example of this characteristic, since a meaningful part of this system is located under the surface.
7. *The ability to understand the cyclic nature of systems:* Understanding of the hydro-cycle system as a system includes the idea that we live in a cycling world. The hydro-cycle system itself consists of several subcycles, such as (Figure 6): evaporation and connection via precipitations on oceans and land; precipitation and connection via rivers from land to sea; and penetration and connection via drawing underground water or transpiration from plants.
8. *Thinking temporally: retrospection and prediction:* Understanding that some of the presented interaction within the system took place in the past, while future events may be a result of present interactions. This notion is expressed within the hydrosphere system, for instance, through the ability to understand that the present quality of drinking water in a specific area is a result of the events and processes that this water went through along the geological and the human history. The ability to predict might be expressed, for example, by trying to predict the influence of an industrial site or construction of a freeway in specific areas on the quality of water in those regions.

### Research Questions

The main objective of this research was to evaluate the development of system-thinking skills in the context of earth systems among junior high school students. It deals with the following research questions specifically:

1. Might junior high school students deal with complex systems?
2. What does influence students' ability to develop system thinking?
3. What kind of relationships exist among the cognitive components of system thinking?

## Methods

### *Sample*

The sample of the current study included 70 junior high school students (eighth grade) from three classes in two different schools. Both schools are located in the very populated urban region of the central coast of Israel. About 90% of the Israeli population live in this region of the country and both schools are regular schools that represent the vast majority of junior high schools of Israel in relation to both students and teachers. Each class included about 23 students from various socioeconomic backgrounds. According to the teachers' characterizations of their classes, about 25% of the students in each class express cognitive or behavioral difficulties. As a result, the teachers had difficulties in encouraging students to collaborate in the learning process. The teachers defined these classes as typical classes that they use to teach for at least the last 10 years. It is important to note that the socioeconomic backgrounds and cognitive characteristic of this sample represent about 80% of the junior high school classes in Israeli cities.

According to the Israeli Ministry of Education science curriculum, all science topics in the elementary and junior high school levels are supposed to be taught as an integrated subject: "Science and Technology." Yet, most of the teachers who teach science in junior high school are trained only as biology teachers. Therefore, the two science teachers who taught the classes of this study participated in an in-service training program of 2 hours a week which followed six months of teaching activities of the "Blue Planet" program.

### *Research Structure*

The research structure included the following three phases.

*Phase 1: Development of the Learning Setting.* In order to study how junior high students might deal with a complex earth system, they should be exposed, of course, to such learning experience. However, a preliminary survey of all the learning materials for the junior high level revealed that no such program was available. Therefore, the first stage of the study was the development of a multidisciplinary environmentally based study program for junior high school students. The program named, "The Blue Planet," emphasized the transportation of water within the earth systems and is based on the water cycle taxonomy, used by hydrogeology scientific community (Schlesinger, 1991). It includes 45 hours of laboratory and outdoor learning inquiry-based activities. These activities were developed to assist students in gaining systems thinking in the context of the water cycle. All the students had learned the water cycle in elementary school. Therefore, the curriculum units at this level mainly deals with the upper ground component of the water cycle, emphasizing its physical context (e.g., evaporation, condensation, and precipitation). The students were also exposed to various aspects of the geosphere (e.g., penetration, rocks, and groundwater), in a social studies-based unit (geography). However, that unit ignored the scientific aspects of the water cycle and its environmental application.

Since the studying of the "Blue Plant" program served as a central component of the treatment, it is important to specify its main characteristics below:

IDENTIFYING A REALISTIC ENVIRONMENTAL "COVER STORY". The "cover story" of the program was the question "How should we act in order to preserve our water resources." In order to answer the question, students had to explore the interrelationships among the earth systems and between each of them and humans.

THE REAL WORLD PHENOMENA AS A CONTEXT FOR MEANINGFUL LEARNING. The outdoor learning environment was included as a central and integral part of the program. Throughout the program, students explored the following phenomena: a spring, a stalagmite cave, a polluted river near their hometown, and a water treatment plant.

UNDERSTANDING THE HOLISTIC NATURE OF THE WATER SYSTEM ON EARTH. Exploring the components of the water cycle should provide the students with an understanding of the interrelationships between the earth systems and man. Later on, they compared the water quality in the different locations and raised questions about daily life phenomena, which were discussed back in class, such as, What are the differences between the tap water that I drink and the mineral water that I buy?; What are the properties of the water solution on earth?; and Who influences the groundwater that I drink?

KNOWLEDGE-INTEGRATION ACTIVITIES. In order to promote students' construction of the water cycle as a dynamic, cyclic system, the students participated in several types of knowledge-integration activities such as concept maps, drawings, and summarizing the outdoor experiences. In these activities, they were asked to present scientific knowledge in a way that emphasizes the water cycle components and their interrelationships. While completing these tasks the students had to identify the system components; they created relationships among the components and organized and placed them within a framework of connections. These connections served as a mechanism by which students could create an entire cycle. In fulfilling these assignments, the students identified the chemical and physical processes that take place within the water resources, such as evaporation, condensation, precipitation, and transpiration, which serve as water transportation mechanisms within the water cycle. For a more detailed description of the program, see Ben-Zvi-Assaraf & Orion (2004b).

*Phase 2: Implementation and Analysis of the Learning Environment.* The implementation of the earth systems-based program in the schools enabled us to move up to the second stage of the study. This stage mainly focused on the identification of the various factors that may influence the students' ability to deal with system perception. In terms of the system thinking approach, we might call this stage as the analysis of the learning environment. This environment for itself appears as a complicated system that includes various elements, such as: the physical environment (outdoor, classroom, and the lab); the learning materials; the students' cognitive ability, and the students' involvement within the learning process.

*Phase 3: Synthesis.* The third stage of the study involved the synthesis of the data concerning the variables that were analyzed during the previous stage. This stage allowed us to answer the second research question concerning the interrelationships among the various factors that influenced students' ability to deal with the hydro cycle as a system. The synthesis stage enabled us to go one step forward and draw some generalization concerning the hierarchical relationships that are exist among cognitive components of system thinking.

### *Research Approach*

Addressing the research questions requires control of a large number of variables. As a result, we had to use various research tools. This multi research tools approach enabled the collection of



data in relation to same factor by different research tools. The triangulation of the data that came from different sources enabled us to increase the reliability and the validity of the research tools. To obtain a general picture of the students' prior knowledge and perceptions of the water cycle first, quantitative research tools were used with a large sample. Then, with a smaller sample that was selected randomly out of the larger sample qualitative research tools were used. This has given an insight into the students' development of system thinking in the learning process, as well as validating the quantitative tools.

In summary, to ensure objectivity, reliability and validity of the current study, the following characteristics were included:

1. Integration of qualitative and quantitative techniques
2. Cross-reference of sources (e.g., interviews, observations, and comparing among the questionnaires' findings and the findings of the interviews and observations)
3. Triangulation: omitting the categories which did not appear in at least three interviews or in three different data collection methods
4. "Cross examination": repeating questions
5. Presentation of findings to the subjects in order to examine the extent of their agreement with the interpretations given to them (respondent validity)
6. Tape recording of most of the interviews
7. Prolonged stay of the researcher on the research sites in order to examine the subjects thoroughly and to avoid the influence of prejudicial concepts as much as possible

### *Research Tools*

The data collection was based on a series of about 10 quantitative and qualitative research tools. Because of the highly complex nature of system thinking characteristics, one of the main challenges of this study was to evaluate the strengths and weaknesses of each research tool in order to define the specific systemic thinking skill that it might identify. Moreover, since most of the research tools were designed specifically for this research, a major effort was invested in establishing their validity and reliability. To achieve it, a year before the main study a small sample pilot study was conducted with 20 eighth-grade students from one of the two schools from which the large sample came later. The main objective of the pilot study was to develop reliable research tools and establish their validity. The students of the pilot study participated in the Blue-Planet program and then answered 20 in-depth open, nonstructured interviews, which were held in regard to the research tools as described below. As a result, each of the research tools was refined and later was evaluated through an expert judgment procedure in order to define the specific systemic thinking skill that it may identify.

Following is a brief description of the research tools that were used and the specific systemic thinking skills that they identify.

*Likert-type Questionnaires.* The items of the questionnaires were developed based on the categories found in the interviews of the pilot research, and in the literature reviewed. To represent the three questionnaires mentioned below, 30 original items were constructed. For the purpose of content validation, three Earth science education senior researchers were provided with the list of the 30 items. They were asked to assess the quality of each of the items, assign their classification according to the scale, and suggest which items may need revision. As a result of the interviews that were conducted in the pilot study, we have improved the questionnaires by deleting a few items and modifying few other items. According to the sample size no statistical measures for reliability and validity were conducted.

Although Likert-type questionnaires provide direct and reliable assessment of attitudes when the scales are well constructed, their application is questionable. One shortcoming of this questionnaire is that students who have reading difficulties might receive lower scores, since they do not understand the meaning of the statements. To decrease the effect of this constraint, two types of measures were taken. First, one of the authors was present in each classroom reading to those who were not sure about the meaning of any statement and encouraged the students to call her for help, if they were not sure. Second, students were asked to write an explanation for each of the statements. This Explanatory Questionnaire was included as a second part of each of the three Likert-type questionnaires as described in this study. It allowed us to test whether the students' wrong answers derived from misinterpretation of the meaning of the statement or from their alternative frameworks. The following Likert-type Questionnaires were developed for this study.

**GROUNDWATER DYNAMIC NATURE QUESTIONNAIRE (GDN).** This questionnaire was developed for identifying students' ability to identify relationships among the components. To be more specific, it measured students' previous knowledge and understanding of the dynamic nature of the groundwater system, and its environmental relationship with humans (Table 1). The statements of this questionnaire appear in Table 6.

**CYCLIC THINKING QUESTIONNAIRE (CTQ).** This questionnaire was developed to identify students' understanding of the cyclic nature of the hydrosphere and the conservation of matter within the earth systems (Table 1). The statements of this questionnaire appear in Table 8.

**GLOBAL MAGNITUDE QUESTIONNAIRE (GMQ).** This questionnaire was developed to identify students' understanding about the quantity of each component of the water cycle (Table 1). The statements of this questionnaire appear in Table 5.

*Drawing Analyses (DA).* There is evidence that students' drawings may serve as a useful tool for probing their level of understanding of natural phenomena (Dove, Euerett, & Preece, 1999)<sup>Q1</sup> and as a tool for identifying the gap between students' alternative conceptions and the scientific view (Novick & Nussbaum, 1978). However, using drawings to elicit understanding may have its limitations, since what the students produce is partly limited by their drawing ability. Therefore the drawings cannot reveal the depth or breadth of the understanding of an individual subject. Hence, incorporating writing or an interview allows more ideas to be presented (Dove et al., 1999; Hulland & Munby, 1994).

In the current study, in addition to answering a questionnaire the students were asked to draw the water cycle. In order to reduce the influence of the limitations mentioned above, they were instructed to incorporate within their drawings as many items as possible. The items were taken from a list of the main stages and processes of the water cycle. The students were assured that they were not expected to perform an artistic drawing. It appear that the students showed no resistance in performing the drawing assignment.

The analyses of the students' drawings enable us to come up with the following components: the ability to identify the system's components and processes; the existence of the earth systems; the ability to identify dynamic relationships within the system; the existence of the human aspect; the appearance of cyclic perception of the water cycle according to the connections among the water cycle components; the ability to organize components and place them within a framework of relationships (Table 1).

Table 1

*Adjustment of each research tool to characterize the various system thinking skills*

System thinking skills	Research tools								
	GDN	CTQ	GMQ	D	WA	CM	HD	FI	RG
Identifying the system's components and processes			☑	☑	☑	☑			
Identifying relationships among components	☑					☑	☑		
Identifying dynamic relationships within the system	☑			☑	☑	☑			
Understanding the cyclic nature of systems		☑		☑		☑			
Organizing components within a framework of relationships				☑		☑			
Making generalizations								☑	☑
Understanding the hidden dimensions of a system								☑	☑
Thinking temporally: retrospection and prediction								☑	☑

GDN, Groundwater system dynamic nature Questionnaire; CTQ, Cyclic Thinking Questionnaire; GMQ, Global Magnitude Questionnaire; D, Drawing; WA, Word association; CM, Concept maps; HD, The hidden dimension inventory; FI, The factory inventory; RG, Repertory Grid.

**Word Association.** The current study involves Word Association as a research tool for evaluating the students' ability to identify the system's components and processes (Table 1). The students were asked to write down all the concepts they were familiar with regarding the water cycle. Word Association directly probes the association that a person perceives for a set of concepts. It is a procedure designed to elicit the relationships that people have formed between concepts. If one could determine those relations, one would have an insight into the quality of the person's understanding of the elements (White & Gunstone, 1992). In order to limit possible weakness of this technique namely that responses might be sensitive to variations in the procedure, the first was always present in the classroom while the students conducted this assignment. Again, students were encouraged to ask for help. Anytime students claimed: "I don't know anything about the water cycle," this was the response: "Imagine the rain, where does it come from?" And "What happens to it after it falls on your schoolyard?"

**Concept Map.** Concept map is a powerful research tool that allows examination of the way learners restructure their knowledge. It does so by identifying misconceptions, and recognizing different learning styles (Martin, Mintzes, & Clavijo, 2000; Mason, 1992; Novak & Gowin, 1984; Roth, 1994). Moreover, concept maps focus on the structure and the links that the student perceives; Mapping is a means of eliciting the relationships that each student perceives among the concepts (White & Gunstone, 1992). Similarly, Novak and Gowin (1984) argued that the concept label leads to increased meaning and precision of the meaning of the concept. Therefore, a concept map is a schematic device for representing a set of the concept meanings embedded in a framework of propositions.

Students need to understand how to do the task before their concept maps can be helpful as an assessment of their learning (White & Gunstone, 1992). Therefore, in the current study the students began with a simple, familiar topic, such as their favorite television program. So that it was easier for them to concentrate on task. They were also instructed to make their first concept map in couples.

In this study, 30 students created concept maps at the beginning and the end of the learning process. The making of the concept maps involved the following three stages:

- Stage 1: Students were asked to choose 15 concepts from a given list and make a word association that was related to the water cycle.
- Stage 2: Students were asked to connect within any single sentence two concepts. They could use the same concept more than once (see example in Figure 1).
- Stage 3: Students were asked to make a concept map concerning the water cycle.

Note that the students in this study were specifically instructed not to make hierarchical maps. Nonhierarchical maps are often more revealing due to the greater diversity of patterns that they admit. Also, constructing a map in the context of understanding the system requires a complexity of links between the concepts, which might be ignored with hierarchical maps.

Novak and Gowin (1984) argued that meaningful learning most easily proceeds when new concepts or concept meanings are subsumed under broader, more inclusive concepts. Therefore, concept maps should be hierarchical; that is, the more general, more inclusive concept should be at the top of the map, with progressively more specific, the less inclusive concepts are arranged below them.

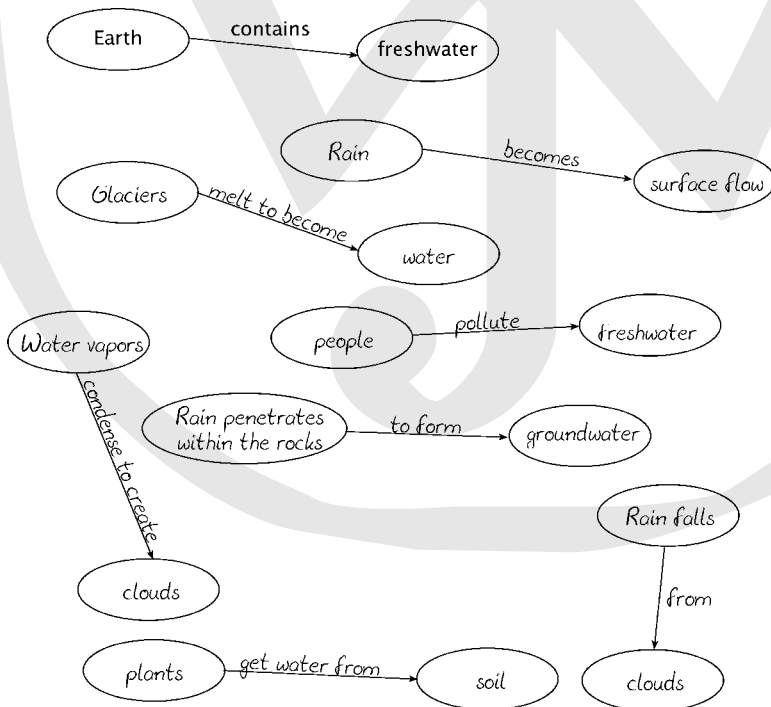


Figure 1. Tami's preparation stage of the concept map, in which she was asked to connect two concepts by a sentence.

However, in that type, the concept maps will not provide all the ideas and links held by students (White & Gunstone, 1992). Ruiz-Primo and Shavelson (1996) argued that task content structures refer to the intersection of the task demands and constraints with the structure of the subject domain to be mapped. Therefore, there is no need to impose a hierarchical structure methodologically or conceptually. White and Gunstone (1992) argued that, in contrast to traditional forms of summative assessment, it is rare for students to perceive a competitive threat in concept mapping, although the intellectual demand of the task cannot be denied. Possibly, this derives from the fact that the task has a purpose and involves physical acts, or because there is no single correct answer. No one map is ever demonstrably better than the rest. Yet students often find writing down the relations explicitly, the most annoying part of the procedure, and wish to skip it if possible. Similarly, in this study one third of the students stopped the concept map-making process in stage three, and refused to make a full concept map. Some students made the concept map without the writing part.

Roth (1994) emphasized the benefits that the collaborative construction of concept maps provides. He argued that students who constructed concept maps collaboratively showed more meaningful learning than those who engaged in this activity on their own, much according to the social constructivist view. However, in this study, in order to identify personal conceptual changes, the students worked individually. But, two other opportunities to construct collaboratively the concept maps were incorporated in the learning process. Following Ruiz-Primo and Shavelson (1996) who suggested that reaching a judgment about an individual's knowledge and skills requires the integration of several pieces of information, the validation of the concept maps in the current study had to involve expert judgment and interviews (to be described later).

The analyses of the students' concepts maps enable us to look for the following system thinking components: the ability to identify the system's components and processes (number of concepts); the appearance of the earth systems; The ability to identify dynamic relationships within the system (number of linkages); the appearance of the human aspect; the appearance of cyclic perception of the water cycle according to the cycles that were constructed within the concept map; the ability the ability to organize components and place them within a framework of relationships, which reflect a more holistic perception of the system using a concepts map (Table 1).

*Interviews.* This study used a "semi-structured" interview format used as a qualitative research method in order to achieve some in-depth information about the students' system thinking abilities in the learning process. Semi-structured interviews offer topics and questions to the interviewee, but are carefully designed to elicit the interviewee's ideas and opinions on the topic of interest, as opposed to leading the interviewee toward preconceived choices. They rely on the interviewer following up with probes to get in-depth information on topics off interest (White & Gunstone, 1992).

In order to explore a wide range of students' abilities, the criterion for the selection of the interviewee for the current study was students' achievement in the science class. Together with the science teacher of this class it was found that the students can be grouped into four clear levels of achievers: high, good, average and low. The teacher categorized the students according to these four categories and then two students were selected randomly from each category for the interviews. However, during the interview process, it was found that about one half of the eight students had difficulties or lacked the motivation to express themselves and therefore were replaced by more articulate students. The interviews were conducted in the beginning, the middle, and the end of the learning process. Since the two low-achievement students (according to their

teacher opinion) did not participate in more than 30% of the class they were interviewed only in the beginning of the process.

The interviews had two main objectives: (a) a tool for validating the students' answers of the questionnaires, concepts maps and drawings, and (b) for receiving an in-depth information concerning students' system thinking abilities.

In relation to the questionnaires, students were asked to read their answers, and to say whether they still agreed with their initial response to the questionnaire's statements, and then to elaborate on their answers. They were asked also to elaborate on their drawings. The interviews also helped identify whether the absence of system's components in their drawing derived from the students' drawing ability or from their poor acquaintance with those components.

Students were also asked to choose three concepts and to think about new links among those concepts, and mark them in a different color. This process was performed twice using different colors, in order to probe more deeply into the relations that students see between two or three important terms. In the interview the terms were limited to those key ones and the students were asked to make multiple links between them.

Two additional qualitative research tools that involve interviews were developed specifically for this research. During the interviews, each student had to perform an assignment and then elaborate on their answers. The following is a brief description of these new research tools.

**THE FACTORY INVENTORY.** For students to be able to make an operative conclusion regarding an environmental subject such as water quality and water as a resource in shortage, they need to present their thinking temporally and retrospectively, [as](#)<sup>Q2</sup> well as with prediction abilities (Table 1).

To identify the above abilities, we used the question about a "factory" assignment interviews. In the interview students were told about a factory for chemicals that was suppose to be constructed in their town. The students were provided with a list of experts in the fields of geology, economy, environment, hydrology, and chemistry. They had to ask each "expert" three questions in order to decide whether they would recommend to build the factory. During the interview, the students elaborated on their questions and explained for each question why it was important and relevant to the assignment. Note that at first, all students performed this assignment in a form of a questionnaire, but the validation process of this assignment indicated that the students' questions did not reveal the students' abilities adequately, whereas in the interview they expressed themselves better verbally while elaborating on their question. Therefore, in the result section we will present the data analysis of the interviews.

**HIDDEN DIMENSION INVENTORY.** This research tool was developed to explore students' perception of the hidden dimension of the hydrosphere system (e.g., processes, which takes place under the surface) (Table 1). During this assignment, 25 students were presented with a picture, which describes the ecology system (Figure 2). The students were asked four questions: (a) What are the components that you can see in this picture?; (b) If you were the painter of this picture and you would like to finish it? What components would you wish to add?; (c) What are the relationships between the components of the picture?; and (d) Please give a title to this picture.

**Repertory Grid.** The Repertory Grid tool was adopted in order to receive an additional angle concerning the ability to identify dynamic relationships within the system; the ability to make generalizations; understanding the hidden dimensions of a system; thinking temporally (Table 1). This technique was conducted after Fetherstonhaugh and Bezzi (1992). It combines two processes

of creating personal constructs. First, the constructs are elicited from the students by comparing groups of three elements. For example, comparisons between the elements: Ocean, Rivers, and Aquifer, may create the construct “High salinity,” which characterizes the element Ocean compared with the two other elements: Rivers and Aquifer. Second, students were requested to use the constructs in order to rate every element in the grid on a scale of 1–5.

*Observations.* In this study, observation was used as a tool for identification of students, learning materials, and teacher interactions. We also used focused observations in order to evaluate students’ involvement in the activities and the teachers’ teaching strategies. During the learning process one of the authors was present in each classroom as a participant observer. During the observations the researcher took brief notes of the event and immediately after the participated observation she completed it through more detailed descriptions. In some cases during the interviews, the students were asked to react to events that were observed earlier by the researchers.



Figure 2. The picture of an ecology system that was used in the ecology system assignment.

Table 1 presents each of the research tools and the specific systemic thinking skill that it might identify.

### *Data Analysis*

*Likert-type Questionnaires.* To distinguish between the above sources of the wrong answers, the Explanatory Questionnaires were analyzed and graded on a 4-level scale (0–3). In this scale, “0” means not scientifically correct, not relevant to the statement or “I don’t know the answer”; “1” means intuitively correct; “2” means partially scientifically correct; and “3” means a scientifically correct explanation.

Since various statements in the questionnaires have different numbers, they were standardized to a mark of 100% for easier comparison and are being reported as such in this paper. Mean scores, standard deviation, and sample sizes were determined. In the Likert-type questionnaire, mean scores were determined for each statement.

*Drawing Analyses (DA).* Students’ responses to the drawing activity were analyzed using a coding framework prepared by Rennie and Jarvis (1995). To increase the reliability and consistency of the drawing analysis, both authors of the current study analyzed and individually coded the same drawings of all the students. After comparing and discussing the two separate analyses, they developed a standardized coding system. The drawings were analyzed according to the following criteria: (a) the appearance of the earth systems; (b) the appearance of processes; (c) the appearance of human consumption or pollution; and (d) cyclic perception of the water cycle according to the connection point among the water cycle components (where “0” referred to atmospheric cycle; “1” to the connection via rain on the land; “2” to the connection via rivers from land to the sea; and “3” to the connection via underground water flow or plant transpiration).

*Word Association.* The concepts that were written by the students classified according to their relation to a unifying concept such as processes in the water cycle, location, the geosphere, hydrosphere, biosphere and atmosphere, human use of water, and environmental and chemical aspects.

*Concept Maps.* Since concept maps provide a graphic representation of individual knowledge structures, quantification of the maps remains a controversial issue. Novak and Gowin (1984) suggested scoring using a number of criteria: the number and significance of the link between concepts, the extent to which the map shows an appropriate hierarchy among the concepts, the existence of links between different parts of the concept hierarchy and the provision of appropriate examples. Although White and Gunstone (1992) suggested not to score concept maps, they defined good maps as those that displayed considerable amount of details, a variety of types of relations, and rich patterns of cross-relations.

In this study, we did not give a general mark to the concept maps. In order to give them a quantitative value, we evaluated the maps according to the number of concepts, their linkages, and their organization within the map (Table 4).

To assess students’ ability to present their understanding of dynamic processes within the system, we identified the concept map-dynamic value. This dynamic value was determined in three stages: (a) counting the “dynamic concept” (number of concepts connected by a node that described a process); (b) counting the “classifying concept” (number of concepts connected in a



classifying manner); and (c) dividing the number of “dynamic concepts,” on the average, the total number of concepts (both the “dynamic” and “classifying concept”) of the sample, and so the value varies from 0 to 1.

The cyclic thinking value was determined by counting the cycles that were constructed within the concept map and by dividing the resulting number by five, which makes five levels of cycles presented in the concept maps. Thus the value varies from 0 to 1. The five levels are (a) no cycle appears in the concept map; (b) the atmospheric cycle of evaporation and connection via rain on the ocean; (c) connection via rain on the land; (d) connection via rivers from land to the sea; and (e) penetration and connection via underground water, drawing or transpiration from plants.

*Interviews.* Each of the interviews was transcribed and analyzed qualitatively. The adopted methods of analysis were based on different approaches of qualitative research (Fontana & Frey, 1998; Creswell 1998; Miles & Huberman, 1994) and included the following stages and procedures:

1. *Initial analysis of each interview:* At this stage, the entire interview was read and thereafter, was divided into sections for expressions that constitute a response to a specific question asked (or not asked) by the interviewer. These “responses” to different concepts are content categories.
2. *Mapping the categories:* At this stage, organization of the content categories that were determined at previous stages and linking different categories to new concepts. The validity of the categories was based on an expert’s judgment procedure of the first five interviews. An examination of the reliability of the categories revealed that it was satisfactory.
3. *Looking for the focus:* This stage of analysis relates to the reorganization of the interview categories, so that the researchers can concentrate on the most interesting. A general framework was arranged to focus on the interviews, based on the research questions. Any response or explanation offered by the students was coded and linked to a category. Thus, the unit of analysis is the explanation itself, rather than the individual student.
4. *Content analysis:* At this stage, the aim was both to search for patterns between different concepts expressed by the interviewees, and to make the similarities and differences more distinct.

*Repertory Grid.* To assess students’ system thinking abilities, the data analysis of the Repertory Grids involved two processes. First we qualitatively analyzed the elements elicited by the students. These elements classified according to their relation to a unifying concept such as processes in the water cycle, location, the geosphere, hydrosphere, biosphere and atmosphere, human use of water, and environmental and chemical aspects. We then led a qualitative analysis of the constructs that were used by the students, in order to rate every element in the grid on a scale of 1–5. To assess students’ ability to present their understanding of dynamic processes within the system, we identified the constructs according to their dynamic characteristics (transformation of matter between the earth systems).

*Observations.* Each of the observations was transcribed and analyzed qualitatively. Similarly to the interviews we adopted the methods of analysis they were based on (Fontana & Frey, 1998; Creswell 1998; Miles & Huberman, 1994). To evaluate students’ involvement in the activities and the teachers’ teaching strategies, the observation categories includes the following:

*Student–teacher interaction:* This aspect was evaluated according to the type and amount of students' questions during the learning and the type of teachers' answers to these questions.

*Student–learning environment (outdoor, lab) interaction:* This component was evaluated quantitatively by the number of students who were engaged in on-task activities during the lab lessons and the field trips and the quality of their involvement.

An additional way to evaluate the quality of the involvement of the students in the learning process was through the analysis of their booklets. Once a month the first author collected all the booklets of the students and analyzed the amount of activities that each student has conducted and the level of understanding that was shown through his/her answers to the assignments.

## Results and Discussion

For the sake of clarity, we organized the large amount of data that was collected by this study according to the following three research questions.

### *Question 1: Could Junior High Students Deal With Complex Systems?*

In<sup>Q3</sup> order to answer this first research question, the data that emerged from the various research tools is presented under the following [three](#)<sup>Q4</sup> categories:

*Ability to Identify the Components and Processes of the System.* The analyses of the students' drawings at the beginning of the learning process indicated that most of them possessed an incomplete picture of the water cycle and had many misconceptions. Most of the students, who initially presented only the atmospheric component of the hydro cycle (i.e., evaporation, condensation, and rainfall) and ignored the groundwater component of the water cycle, had increased their acquaintance with the components of the water cycle significantly. For example, 90% of the students incorporated the penetration of rain within the soil and rocks in their posttest drawings (Table 2A, item 4) and an increase in the percentage of students who incorporated rocks in their posttest drawing to 44% from 15% in the pre-test (Table 2B, item 9). However, less than one third of the students incorporated in their drawing those processes and components that were learned only in the lab and were not included in the outdoor learning concrete activities such as transpiration, capillarity in plants, and pollution in the posttest (items 10–12 of Table 2A). Similarly, most students did not include components of the biosphere such as plants, humans and animals in their drawing (items 1–3 of Table 2B).

Analysis of the word association of this sample revealed similar results. The summary of all the concepts that were mentioned in the word association during the learning process can be collapsed to nine main categories: atmosphere, hydrosphere, geosphere, biosphere, earth, association with the environment, human activities, change of state, and processes. Table 3 presents the number of concepts that were mentioned and the percentage of students who mentioned them in regard to each of the categories. In the pre-test, most of the students wrote concepts that take place in the atmosphere, namely, rain, clouds, and evaporation (item 1 of Table 3), whereas in the posttest more students mentioned concepts that reflected the interaction between man and water such as environmental aspects or human activities.

The data in Table 3 also revealed that students expanded their view to include additional earth systems such as the geosphere, biosphere, and the earth (items 3–5).

The improvement in students' acquaintance with the water cycle components and processes was manifested and was clearly revealed in the concept maps. The data in Table 4 revealed that the

posttest maps are richer and include more concepts that reflect the variety of locations within the earth system (items 1–6). Moreover, an analysis of the posttest and concept maps revealed that students had increased the number and variety of processes (items 8 and 9). Similar results were obtained in the word association (item 9 of Table 3). Furthermore, students clarified their characterization of the various components through sentences that they used with their concept maps, for example, sentences that described the manner in which water exists in the geosphere, such as “Stream is an example of runoff; sand rock has a granular structure; lime rock has cracks; a spring is form between a lime rock and a chalky rock” appeared only in the posttest concept maps.

Understanding the water cycle characteristics included knowledge of the distribution of water on earth. An analysis of the Global Magnitude Questionnaire (GMQ) presented in Table 5 revealed a significant increase in the percentage of students who thought that the amount of water that exists in rocks in the earth is higher than the amount of water that exists in lakes and rivers. Moreover, about 20% of students provided a scientific explanation for their choice as compared to 8% at the beginning of the learning process (item 1). However, students’ conceptions revealed not only their views about each of the water reservoirs on earth but also their view concerning the role of man on earth. Most of the students in the pre-test (GMQ) exaggerated the human part in the water cycle. Consequently, as shown in Table 5, only about 25% of them agreed that the amount of water that

Table 2

*Students’ perceptions of the water cycle as shown in their pre- and post-drawing (McNemar’s test)*

	Pre (%)	Post (%)	<i>M</i> -value	<i>p</i> -value
A: Process within the water cycle				
1. Evaporation	96.1	98.1	0.3	NS
2. Condensation	71.1	78.8	1.1	NS
3. Precipitation	100.0	98.1	1.1	NS
4. Penetration	65.3	90.3	8.8	0.003
5. Underground flow	11.5	61.6	24.1	0.001
6. Surface flow	38.4	63.4	8.0	0.005
7. Melting	0	23.1	—	0.01
8. Freezing	0	7.7	—	NS
9. Dissolution	0	19.2	—	0.01
10. Transpiration	0	26.9	—	0.001
11. Capillarity	0	23.1	—	0.001
12. Pollution	0	13.3	—	0.005
B: Components within the water cycle				
1. Plant	5.7	40.4	16.2	0.001
2. Human	3.8	13.4	5.0	0.02
3. Animal	5.7	5.7	0	NS
4. Ocean	94.2	82.6	4.5	0.03
5. River	36.5	50.0	1.9	NS
6. Glacier	0	9.6	5.0	0.025
7. Spring	7.7	19.2	3.0	0.0008
8. Soil	69.2	82.6	2.8	NS
9. Rock	15.4	44.2	10.7	0.001
10. Groundwater	40.4	65.3	6.7	NS
11. Clouds	98.1	98.1	0.5	NS
12. Rain	98.1	96.1	0.3	NS
13. Sun	30.8	25.0	0.6	NS
14. Water pollution	3.8	13.4	5.0	0.02
15. Water consumption	11.5	21.1	2.2	NS
16. Well	5.8	23.1	6.2	0.01
17. Sewage	7.7	9.6	0.1	NS

Table 3  
*Students' perceptions, as shown in the word association task (McNemar's test)*

Groups of concepts	The number of concepts that were mentioned in regard to each category				Percentage of students who mentioned a representative item of each category			
	Pre	Post	<i>M</i>	<i>p</i>	Pre	Post	<i>M</i>	<i>p</i>
1. Atmosphere	3.5	2.3	3.7-	0.0005	98.1	94.2	1.0	NS
2. Hydrosphere	3.2	2.9	0.2-	NS	92.3	92.3	0	NS
3. Geosphere	0.5	2.1	6.8	0.0001	50.0	86.5	13.4	0.001
4. Biosphere	0.3	0.5	1.4	NS	19.2	34.6	3.2	NS
5. Earth	0.3	1.1	3.1	0.002	19.2	50.0	11.6	0.001
6. Environment quality	0.2	0.7	3.7	0.0005	11.5	42.3	12.8	0.001
7. Human activities	0.8	0.7	0.4-	NS	32.1	48.1	3.2	NS
8. Change of state	0.4	0.7	1.3	NS	21.1	36.5	3.2	NS
9. Processes	1.1	2.1	0.2	0.0001	69.2	92.3	10.3	0.002

Representative concepts of each category:

1. Atmosphere: Rain, moisture, precipitation, cloud, snow, hail, water evaporation, and sky.
2. Hydrosphere: Fall, waves, puddles, underground water, oceans, rivers, streams, and icebergs.
3. Geosphere: Limestone, mountains, soil, rocks, cracks, and mineral water.
4. Biosphere: Food, life, thirst, human beings, organisms, plants, tears, and nature.
5. Earth: Recurrence, earth, winter, summer, wind, climate, and weather.
6. Environment quality: Contamination, purification, sewage water, acid rain, and economizing.
7. Human activities: Boiling, drinking water, cooking, agriculture, shower, kettle, and tap.
8. Change of state: Gas, liquids, solids, temperature, cold, and heat.
9. Processes: Evaporation, condensation, precipitation, water flow, defrost, and flood.

Table 4  
*Students' perceptions of the water cycle as shown in their concept maps*

Dimension within the concept maps	Pre		Post		Significant	
	Mean	Std	Mean	Std	<i>t</i>	<i>p</i>
1. Number of concepts	11.9	3.9	15.1	5.3	3.6	0.003
2. Number of linkages	14.4	4.9	17.8	7.8	2.3	0.03
3. Related to the hydrosphere	8.4	2.8	6.8	2.9	2.6-	0.01
4. Related to the atmosphere	1.6	1.3	1.3	1.2	0.9-	NS
5. Related to the geosphere	0.8	0.7	3.0	2.4	4.8	0.0001
6. Related to the biosphere	0.6	0.8	0.9	1.4	1.1	NS
7. Human activities	0.3	0.6	2.1	1.6	6.4	0.0002
8. Number of processes	3.5	2.7	6.1	2.8	3.1	0.005
9. Variety of processes	2.3	1.8	4.6	1.8	3.4	0.003
10. Concept related to more than two concepts	2.7	1.4	4.2	2.1	3.5	0.002
11. Number of key sentences	6.3	2.2	9.0	2.6	3.4	0.002
12. Dynamic value	0.3	0.3	0.5	0.2	2.6	0.001
13. Cyclic value	0.1	0.1	0.3	0.2	2.3	0.03

Table 5

*Students' perceptions as shown in a Global Magnitude Questionnaire (GMQ)*

Items	Pre			Post			<i>t</i>	<i>p</i>
	AG	UC	DIS	AG	UC	DIS		
1.	8.3	30.0	61.7	14.3	35.7	50.0	2.7	0.0001
2.	24.1	48.3	27.6	50.0	28.6	21.4	2.9	0.006
3.	25.0	53.3	21.7	50.0	41.5	8.9	2.8	0.008

Items	Pre				Post				<i>t</i>	<i>p</i>
	NS	IC	PC	SC	NS	IC	PC	SC		
1.	86.0	2.0	4.0	8.0	62.8	9.3	7.0	20.9	1.9	0.05
2.	79.6	8.2	10.2	2.0	79.6	45.9	13.5	5.4	3.4	0.02
3.	75.0	15.0	7.5	2.5	41.7	25.0	2.8	30.6	3.5	0.001

Item 1: The amount of water that exists in rocks in the earth is much greater than the amount of water that exists in all lakes and rivers.

Item 2: The amount of water that exists in sewage produced by man is much less than the amount of water that exists in the groundwater.

Item 3: The amount of water that exists in sewage produced by man is much less than the amount of water that exists in all rivers and lakes.

exists in sewage produced by humans is much lower than the amount of water that exists in all rivers and lakes, or in the groundwater (items 2–3). The posttest revealed that 50% of the students hold a more scientific view, which was revealed also in their explanation (item 3). In the explanatory questionnaire, about 80% argued that “it is not true. Humans produce a lot of sewage” or “people produce a lot of garbage,” whereas about 40% of the students still held this view in the posttest.

*Ability to Identify Relationships Among Components.* In the water cycle, phenomena such as the quality of ground water and the formation of mineral water stemmed from the interrelationship between rocks and water. Yet, as shown in Table 6, the GDN pre-test revealed that only 30% of the students acknowledged the connection between the composition of the water solution and the rocks that they pass through, saying “Rocks don’t affect the composition of water that penetrates them” (item 3). After studying the program, about 70% of the students acknowledged the connection between rocks and water, and about 44% perceived the scientific view of the dissolution process as a mechanism by which rocks and water interact (item 3).

Ben-Zvi-Assaraf & Orion (2004a) found that students perceived the interaction between the rocks and the groundwater as a mechanical process and they tended to diminish the influence of the geosphere on the other water cycle components. They reported that as a result of students’ conceptions of the static nature of the underground water system, most of them failed to associate human activity with water quality. Similarly, in this study only 53% of the students acknowledged the influence of humans on the quality of water pumped from wells (item 7 of Table 6). Moreover, in the Explanatory questionnaire only 2% of the students could give a concrete example such as “the water was polluted by chemicals leaching into the groundwater” and “penetration of salts into the wells contaminated the drinking water.”

At the end of the learning process, about half of the students characterized the above and other examples of groundwater contamination. However, most of them still had difficulties in describing certain relationships between the various components of the systems, which take place

Table 6

*Students' perceptions as shown in the Groundwater Dynamic Nature (GDN) questionnaire*

Level of agreement %										
Items	Pre			Post			<i>t</i>	<i>p</i>		
	AG	UC	DIS	AG	UC	DIS				
1	18.6	42.4	39.0	58.9	17.9	23.2	4.9	0.001		
2	66.1	23.2	10.2	52.7	18.2	29.1	2.3	0.02		
3	23.7	45.8	30.5	14.5	14.5	70.9	4.3	0.001		
4	36.7	23.3	40.0	21.4	7.1	71.4	2.8	0.007		
5	27.6	48.3	24.1	14.3	30.4	55.4	3.4	0.001		
6	80.0	13.3	6.7	89.1	1.8	9.1	1.6	NS		
7	53.3	43.3	3.3	87.5	0.0	12.5	5.0	0.001		
8	15.0	31.7	53.3	3.6	10.7	85.7	3.3	0.002		
Level of explanations %										
Items	Pre				Post				<i>t</i>	<i>p</i>
	NS	IC	PC	SC	NS	IC	PC	SC		
1	67.4	15.2	10.9	6.5	17.6	29.4	14.7	38.2	4.1	0.004
2	80.4	8.7	10.9	0.0	51.2	12.2	7.3	29.3	2.8	0.009
3	31.6	23.7	36.8	7.9	16.0	10.0	30.0	44.0	3.9	0.0004
4	46.3	16.7	35.2	1.9	12.0	8.0	24.0	56.0	6.5	0.0001
5	73.9	23.9	2.2	0.0	32.6	13.0	19.6	34.8	5.4	0.0001
6	13.6	54.5	27.3	4.5	5.3	26.3	42.1	26.3	4.4	0.0002
7	39.6	39.6	18.7	2.1	4.5	13.6	34.1	47.7	6.2	0.001
8	23.0	7.8	27.5	41.2	0.0	0.0	13.0	87.0	4.6	0.001

AG, agreement; UC, uncertainty; DIS, disagreement; NS, not scientifically correct/I don't know/not relevant; IC, intuitively correct; PC, partially scientifically correct; SC, scientifically correct explanation.

Item 1: Most of the underground water persists in the small pores of the rock, similarly to a well-watered sponge.

Item 2: Underground water is similar to underground lakes that are located in spaces inside the soil.

Item 3: Rocks don't influence the composition of the water that penetrates them.

Item 4: Only when rocks are cracked can water penetrate them.

Item 5: Ground water can be found only in rainy areas.

Item 6: Many factories have their sewage flow into streams thus polluting the water we drink.

Item 7: Part of the wells in the State of Israel contain polluted water.

Item 8: Rain that falls on the surface and penetrates within the soil can reach a depth of several meters.

underground. For example, whereas most of the students agreed that polluted rivers by sewage could directly affect the water quality, less than one third of them chose to explain it through processes such as penetration and underground flow (item 6 of Table 6).

Students' improvement of this ability to identify relationships among components can be seen in their concept maps. A pre and post analysis of the concept maps showed a significant improvement in the number of interrelations that students understood about earth systems in general and the water cycle in particular ( $t = 3.13$ ,  $p = .005$ ).

The data analysis of the sentences within the concepts maps revealed that many of the sentences that appeared only in the posttest concept maps emphasize the relationships among components within the system, for example, "Sewage and pesticides pollute the water in the wells; humans drink polluted water and get hurt; humans and factories pollute the water in the underground water."

It is suggested that the wide appearance of relationships that take place in the geosphere, such as "Water leaches through lime rock; water does not leach in chalky rock; water is affected by the

rock salinity,” may have originated from the newly acquired ability of the students to identify processes and components of the geosphere.

During the learning process, the students were engaged in indoor and outdoor learning activities. In the authentic outdoor environment they explored a spring, a stalagmite cave, and a water treatment plant. While exploring these components of the water cycle, the students created mental models of the interrelationships between the natural earth systems and man. Later on, they compared the water quality within the various locations and raised questions about daily life phenomena that were later discussed with the teacher in the classroom. For example, “What are the differences between the tap water that I drink and the mineral water that I buy?” or “What influences the groundwater that I eventually drink?”

The contribution of the outdoor learning experiences to the learning process was mentioned by many of the students. The following is a representative quotation:

“The field trips to the stalagmite cave, waste water treatment plant, and the spring that went out of the layers of the rocks contributed me a lot. . . . I think that it simply helped me to learn. It is possible to learn it in class, it is possible to explain everything, but it is not as it looks like with your eyes, seeing the phenomena as they occur in nature.”

The analysis of the concept maps indicated a significant correlation between the number of the system components and their characteristics and the number of new connections among the water cycle components (Pearson correlation coefficients value .782,  $p = .0002$ ). The growing number of connections was found only among those students who also grew the number of components. No such improvement was found among those students who did not extend their acquaintance with the system’s components.

In summary, our findings indicate a relationship exists between the students’ ability to identify the system components as a result of a learning process, and their ability to identify relationships among these components. Note that although most of the students improved their ability to create new connections within the system, almost every student created unique concept maps. Although the components of the maps were very similar, each student chose to present them from a different line of story and as result, with different connections and relationships. For example, Figures 3 and 4 present Tami’s pre and post concept maps, which demonstrate the development of her ability to identify relationship. Tami’s maps were chosen because her maps represent the group of students who improved their system thinking abilities and of her explicit explanations in the interviews that enabled us to evaluate the conceptual change that took place during the learning process. Tami’s maps demonstrate that she has improved mainly her ability to identify the relationship between humans and the water cycle (Figures 3 and 4). At the end of the learning process, she suggested that (a) man influences groundwater through pollution by fertilizers and pesticides; (b) man can be influenced by groundwater as a consumer; and (c) man can change the water’s quality through purification (Table 7, item 15). Nevertheless, some other students demonstrated in their maps the relationship between the water and rocks in the geosphere such as (a) water leaches through sand rock; (b) water does not leach through chalky rock; (c) rock is affected by water salinity; and (d) the water dissolves the mineral within the rocks. These new connections among components, which most of the students presented according to their stories, indicated that they improved their ability to create new connections within the system, rather than by memorizing examples, which were taught in the class.

*Ability to Identify Dynamic Relationships Within the System.* Analyzing the various research tools indicated that the students improved their ability to identify dynamic relationships within

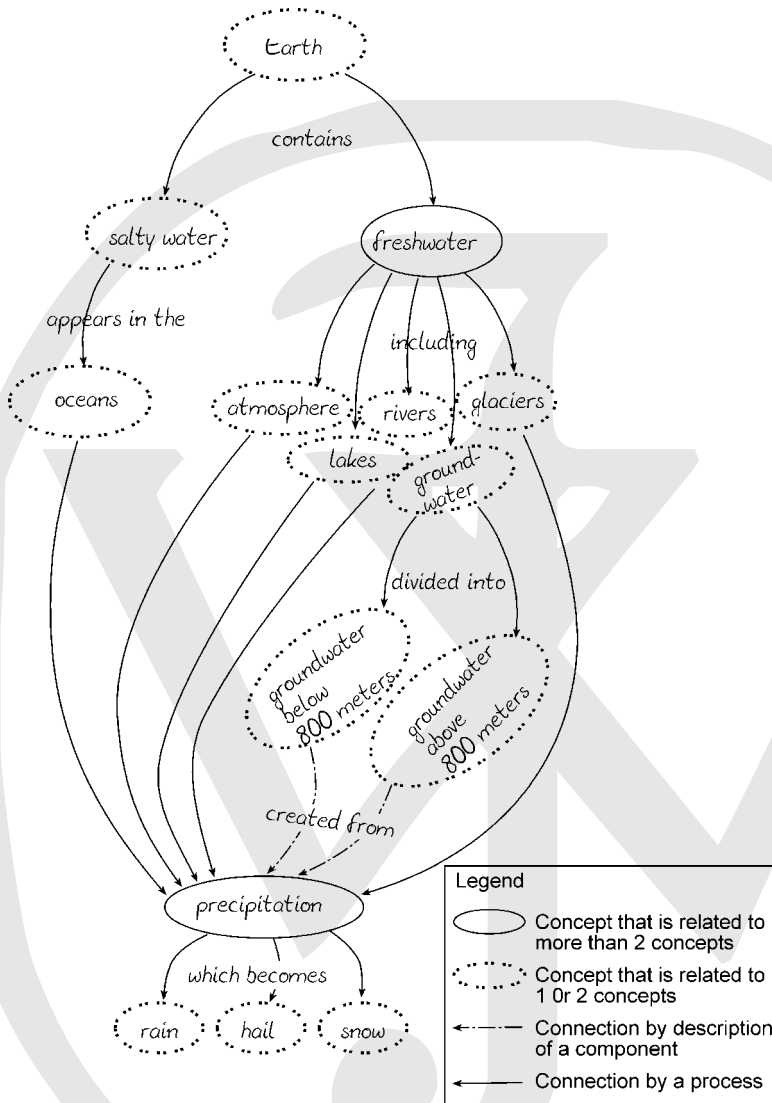


Figure 3. Tami's pre-test concept map.

the system. Table 6 indicates that at the beginning of the learning process 66% of the students described the groundwater as a static, subsurface lake (item 2). However, in the posttest 60% of them presented a scientific model of underground water movement through porous rocks (item 1). Thus, during the learning process most of the students improved their understanding of the groundwater's role in the transportation of matter within the water cycle. Nevertheless, 50% of them still held a nonscientific static model in a parallel manner with the scientific view (item 2). Consequently, in their explanation students argued that the movement of underground water through porous rocks takes place in the upper part of the soil, but after it reaches a certain depth, it arrives to a subsurface lake. This conception was presented in some of the students' drawings.



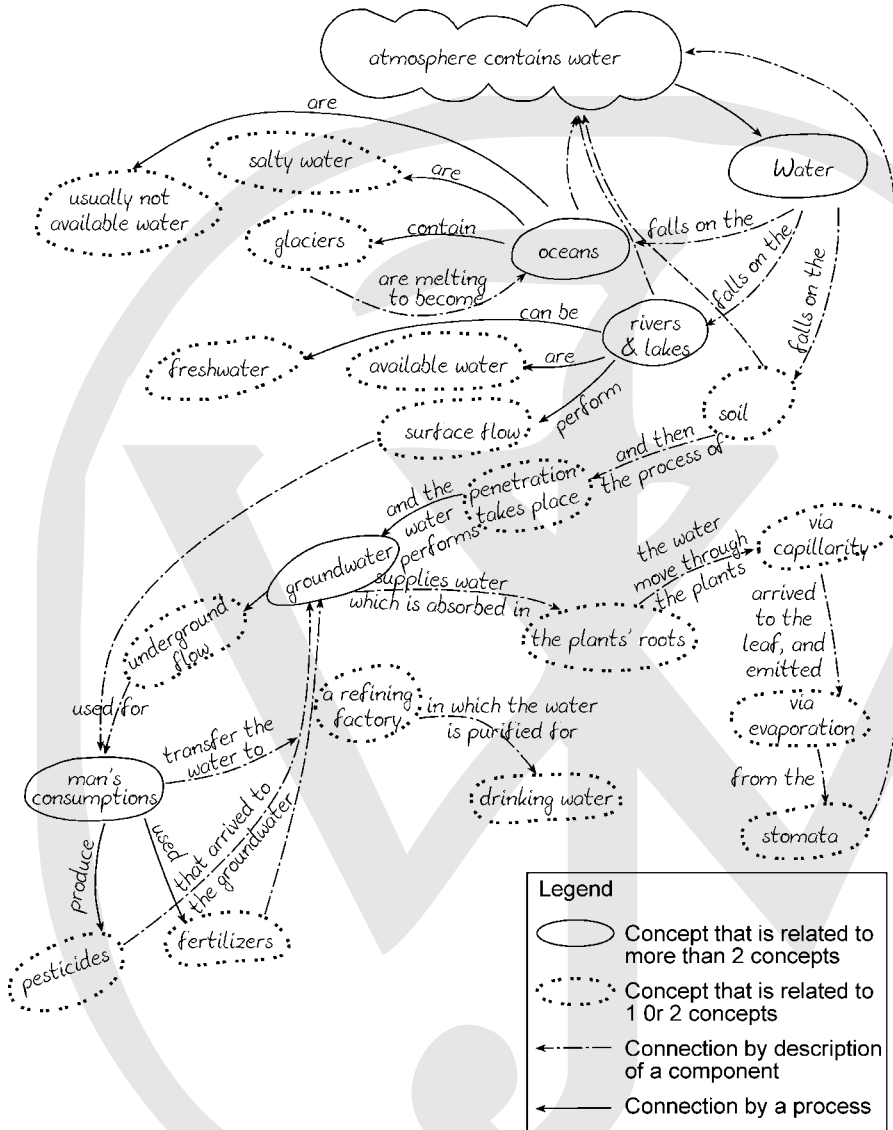


Figure 4. Tami's post-test concept map.

Students' difficulties in understanding the dynamic nature of groundwater were revealed when they needed to elaborate on the statement "Ground water could be found only in rainy areas." At the beginning of the learning process, in order to explain the presence of groundwater in arid areas, 73% of the students used an upper ground "Rivers flow" model (item 5 of Table 6). In this model, water flows from rainy areas by river to arid areas, where it penetrates the soil and acts as groundwater. The analysis of the GDN posttest, as shown in Table 6, revealed that half of the student population perceived correctly the horizontal dynamic model of underground water movement through porous rocks (items 1 and 5). A comparison of this finding to the very low number of students who answered these items correctly at the beginning of the learning process

Table 7

*Temi's pre-post analysis of the concept maps*

At the beginning of the learning process		
Dimensions within the concept maps	No. of items	Examples
1. Related to the hydrosphere	12	Earth, freshwater, saltwater, glaciers, rivers, lakes, rain, snow, hail, oceans, precipitation
2. Related to the atmosphere	1	Atmosphere
3. Related to the geosphere	2	Groundwater below 800 meters, Groundwater above 800 meters
4. Concept related to more than two concepts	3	Groundwater, freshwater, precipitation
5. Sentences that present a transformation of matter	1	Groundwater is created by rain
At the end of the learning process		
Dimension within the concept maps	No. of items	Examples
6. Related to the hydrosphere	8	Water, freshwater, saltwater, glaciers, rivers, lakes, rain, oceans
7. Related to the atmosphere	1	Atmosphere
8. Related to the geosphere	4	Groundwater, soil, underground flow, penetration
9. Related to the biosphere	5	Plants' roots, stomata, humans, transpiration, capillarity
10. Human activities	4	Refining factory; drinking water, fertilizers, pesticides, available water, water not available
11. Variety of processes	9	Evaporation, penetration, underground flow, surface flow, transpiration, capillarity, pollution, melting, purification
12. Concept related to more than two concepts.	8	Water, atmosphere, ocean, rivers, and lakes, groundwater, humans
13. Number of cycles	4	Atmospheric cycle: connection via rain on the ocean; connection via rain on the land; penetration and connection via water drawn by man; penetration and connection via underground flow to the ocean or transpiration from plants
14. Sentences that present the transformation of matter	7	a) Water can fall in the oceans, rivers, soil, and lakes; (b) the glaciers in the oceans are melting, the water in the soil penetrates and then groundwater flows as underground flow; (c) humans consume water from surface flow such as rivers and lakes; (d) roots of plants absorb groundwater; (e) water moves through the plant via capillarity; (f) the water is transferred in pipes by man to the refining factory; (g) fertilizers and pesticides are flooded into the groundwater system
15. Relationships among the systems' components	3	(a) Man influences groundwater through pollution of fertilizers and pesticides; (b) man can be influenced as a consumer by groundwater; (c) man can change the water quality through purification

indicates a meaningful improvement of the students' understanding of the dynamic nature of groundwater. The analysis of the concept maps also supports the improvement of the students' perception of the dynamic processes within the system (item 12 of Table 4). Figure 5, which is also based on the analysis of the concept maps, represents the progress of students during the learning process in terms of their dynamic perception. This improvement was notably shown in relation to those students who extended their acquaintance with the dynamic processes.

Students' understanding of the transformation of matter within the earth systems indicated their understanding of the dynamic nature of the earth systems. A  $t$  test analysis of the pre and post "transformation of matter" sentences in the concept maps revealed that students improved their increased dynamic perception of the water system on earth ( $t = 2.14, p = .04$ ) significantly as well. A zoom-in picture of this improvement can be seen in Figures 4 and 5, which are Tami's pre and post concept maps. An analysis of Tami's "transformation of matter" sentences is presented in Table 7 (items 13, 9).

*Students' Understanding of the Cyclic Nature of the System.* The analysis of the pre-test (CTQ), which is presented in Table 8, [Table 9<sup>Q5</sup>](#), indicated that about 62% of the students explained that the water cycle has a beginning and an ending (item 1). These findings indicate the students' difficulties in understanding the cyclic nature of the water system. The common responses to the statement: "Clouds are the starting point of the water cycle and the tap at home is its end point" were "it's not true because oceans and rivers are the starting and ending points, respectively," or "there are additional starting points." About 12% of the students suggested a more progressive view such as "in the cycle, there is no starting point and no ending point" or "a cyclic process never ends" (item 1). The posttest indicated that half of the students still encountered difficulties in understanding the cyclic nature of the water system, and therefore agreed that the water cycle has beginning and ending points. Nevertheless, 30% of the students gave a scientific explanation, as compared to 12% at the beginning of the learning process.

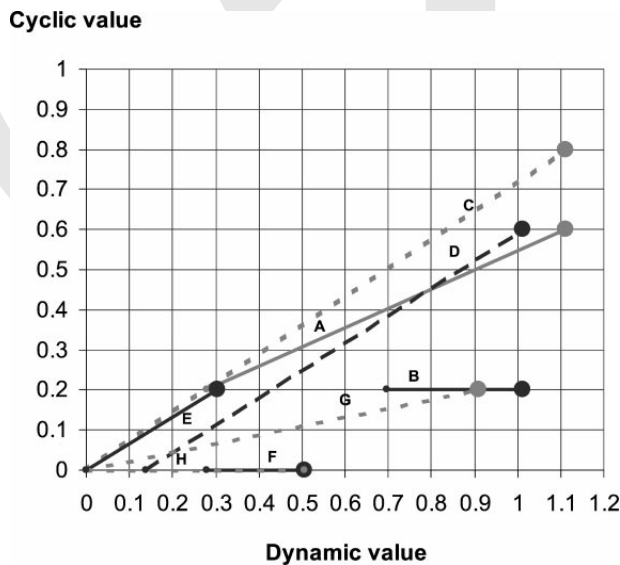


Figure 5. A graph that illustrates the relationships between cyclic perception and dynamic perception.

Understanding the water cycle as a system included the idea that we live in a cycling world of cycles of matter and energy that is built upon a series of subsystems (geosphere, hydrosphere, biosphere, and atmosphere), which interact through an exchange of energy and materials. This idea has been implemented in the learning process via a series of small cycles that present matter (water) transformation between the earth sub systems. These cycles included (a) the atmospheric cycle of evaporation and connection via rain on the ocean; (b) evaporation and connection via rain on the land; (c) precipitation and connection via rivers from land to the sea; and (d) penetration and connection via drawing underground water or transpiration from plants (Figure 6).

The drawings analysis indicated that most of the students had significantly shifted from a fragmented perception of the water cycle, which presented a transformation of matter only within the atmosphere, to a more holistic view of the water cycle ( $std = 1.08$ ,  $t = 5.99$ ,  $p = .001$ ). However, most of the students still had presented difficulties in understanding the hidden processes that demonstrate the cyclic nature of the system. Consequently, about 37% of the students presented in their posttest drawings a connection through the rivers, through underground water flow or transpiration, compared to 3.7% in the pre-test (Figure 7).

Table 8  
*Students' perceptions as shown in a Cyclic Thinking Questionnaire (CTQ)*

Level of agreement %										
Items	Pre				Post				<i>t</i>	<i>p</i>
	AG	UC	DIS		AG	UC	DIS			
1	25.4	40.7	33.9		13.3	55.0	31.7		1.6	NS
2	13.3	55.0	31.7		16.1	7.1	76.8		4.3	0.001
3	48.1	23.3	28.3		30.4	8.9	60.7		3.1	0.03
4	58.3	20.0	21.7		52.7	18.2	29.1		1.5	NS
5	28.8	61.0	10.2		24.1	27.8	48.1		3.6	0.009
6	53.3	26.7	20.0		74.1	9.3	16.7		3.6	0.009
Level of explanations %										
Items	Pre				Post				<i>t</i>	<i>p</i>
	NS	IC	PC	SC	NS	IC	PC	SC		
1	62.5	14.6	10.4	12.5	39.5	14.0	16.3	30.2	3.1	0.004
2	48.2	12.5	12.5	26.8	12.2	2.0	8.2	77.6	5.3	0.001
3	55.6	2.2	20.0	22.2	20.0	5.0	27.5	47.5	2.4	0.02
4	65.3	16.3	10.2	8.2	44.2	11.6	7.0	37.2	3.2	0.003
5	80.5	4.9	4.9	9.8	35.0	5.0	5.0	55.0	5.2	0.0001
6	44.4	24.4	15.6	15.6	15.0	37.5	15.0	32.5	2.6	0.01

AG, agreement; UC, uncertainty; DIS, disagreement; NS, not scientifically correct/I don't know/not relevant; IC, intuitively correct; PC, partially scientifically correct; SC, scientifically correct explanation.

Item 1: Clouds are the starting point of the water cycle and the tap at home is its end point.

Item 2: The amount of water in the ocean is growing from day to day because rivers are continually flowing into the ocean.

Item 3: The increase of evaporation as an effect of the earth global warming may lead to a decrease in the amount of water on earth.

Item 4: If the population on earth will continue to grow, water consumption will increase, thus decreasing the amount of water on earth.

Item 5: The amount of water that evaporates into the atmosphere from the entire surface of the earth is not equal to the amount of rain that falls on the earth's surface.

Item 6: the amount of water which flows into the ocean does not influence of their total amount of water, since an enormous amount of water evaporate each year from the ocean.

Table 9

*Students' retrospection and prediction abilities as shown in the Question about system-assignment*

Area of expertise	The Questions
Environment Quality	<ol style="list-style-type: none"> <li>1. Will the establishment of the factory affect the environment?</li> <li>2. Will the residual pollutants of the factory be discarded into the sewage only?</li> <li>3. Will the factory smoke pollute the air?</li> </ol>
Geology	<ol style="list-style-type: none"> <li>1. Are any rocks near the stream?</li> <li>2. What kind of rocks?</li> <li>3. Have those rocks any cracks?</li> </ol>
Ecology	<ol style="list-style-type: none"> <li>1. Will the factory affect the animals that are living around this area?</li> <li>2. Will the animals live as usual also after the factory build-up is completed?</li> </ol>
Hydrology	<ol style="list-style-type: none"> <li>1. Will the factory residual wastes be discarded into the sewage only?</li> <li>2. Should some of the wastes will find its way into the stream, will it much affect the residents?</li> <li>3. Are you intending to purify the sewage?</li> </ol>
Economy	<ol style="list-style-type: none"> <li>1. What budget you plan to allocate for the factory purification?</li> <li>2. Will you cut the budget in this regard or you will allocate a suitable budget?</li> </ol>
Chemistry	<ol style="list-style-type: none"> <li>1. Are those toxic materials that should not be near human?</li> <li>2. Will those materials severely pollute the stream in case they will find their way into it?</li> </ol>
Engineering	<ol style="list-style-type: none"> <li>1. How do you plan to build-up the spill that will pour the wastes into the sewage and how did you plan to build up the factory?</li> </ol>

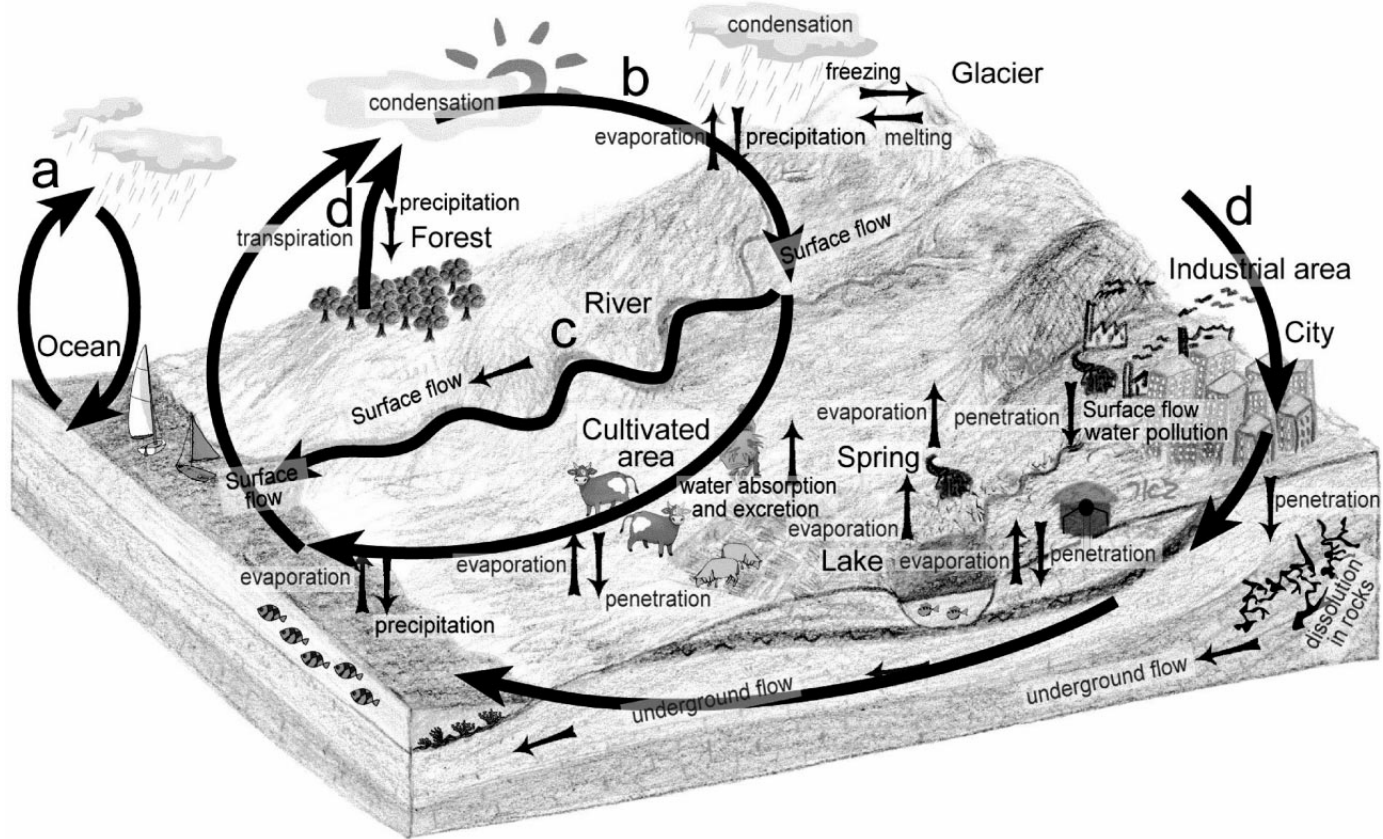
Analysis of the concept maps revealed a similar result. It appears that most of the students improved their cyclic perception value significantly (item 13 of Table 4).

The analysis presented in Figure 5 enabled us to evaluate the relationships between the development of cyclic perception and the dynamic perception of a system. In order to create a cycle, students should combine a variety of dynamic processes into a coherent cyclic structure. Analyzing the graph presented in Figure 5 revealed two patterns of the cyclic–dynamic development during the learning process. The first pattern presents students who improved their cyclic perception, as well as their dynamic perception (students A, C, D, and E). Moreover, the curves of students A and D indicate that students who entered the learning process with a minimal initial level of dynamic perception can improve remarkably both their dynamic and cyclic perceptions. The second pattern presents students who improved their dynamic perception, but whose cyclic perception was not improved (students B, F, G, and H).

Note that the improvement of students' cyclic perception is always followed by an improvement of dynamic perception. The analysis of the concept maps indicated a significant correlation between the students' dynamic and cyclic values (Pearson correlation coefficients value .63,  $p = .0002$ ). Thus, it is possible that the ability to identify dynamic processes is a mandatory condition for the development of cyclic perception, but it is not the only condition and there are other factors that influence this ability.

Figures 3 and 4 present Tami's (Students C) pre and post concept maps, respectively, and demonstrate the development of her cyclic thinking. It is clear that, at the beginning, Tami ignored the cyclic nature of the system (water cycle). Following the learning process, Tami was able to acknowledge four cycles (connection via rain on the ocean; connection via rain on the land, and penetration and connection via underground water movement, drawing or transpiration from plants (Table 7, item 13).

Most of the students in the posttest (CTQ) realized that in a cyclic process the overall amount of matter is being conserved. For example, about 76% of the students did not agree with the statement "the amount of water in the ocean is growing from day to day," because "rivers are



*Figure 6.* The main cycles those take place within the water cycle. (a) The atmospheric cycle – evaporation and connection via rain on the ocean; (b) Evaporation and connection via rain on the land; (c) Precipitation and connection via rivers from land to sea; (d) Penetration and connection via underground water or transpiration from plants.

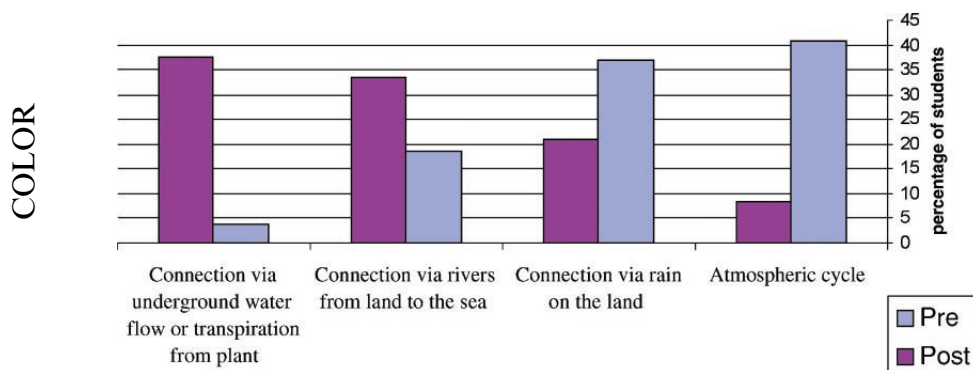


Figure 7. A pre-post comparison of the number of closed cycles that were presented by the student's drawings.

continuously flowing into the ocean,” compared to 31% of them in the pre-test (item 2, Table 8). Furthermore, the pre-test revealed that despite students' acquaintance with the evaporation process, they diminished its influence as a natural phenomenon. For example, only about 26% of the students mentioned, in their explanation, evaporation as a mechanism of transferring water from the ocean to the atmosphere (item 2, Table 8). A common explanation that emerged during the interviews was “true, water evaporates from the ocean, but the total amount of the water that evaporates is too small.” The posttest indicated that about 77% of the students acknowledged that evaporation was a mechanism for transforming matter within the system (item 2, Table 8). An additional example of students' difficulties in understanding the transformation of matter within the water cycle is reflected in their view that the total amount of water that evaporates from the entire surface of the earth into the atmosphere does not equal the amount of rain that falls on the earth's surface. The posttest indicated that more than 55% of the students used cyclic thinking in their explanation as compared to 10% in the pre-test (item 5, Table 8).

The findings might indicate that students' difficulties in understanding the proportion of the various reservoirs in the water cycle could be affected by their habit of overemphasizing the human part of the water cycle. For example, in the posttest explanatory questionnaire, 44% of the students claimed that “the more people that exist, the more water is consumed”; “people will use more water than water is being consumed, thus water will disappear more” (item 4, Table 8). In contrast, only 37% of the students gave a progressive explanation such as “human beings have only a slight effect on the global amount of water” or “the water quantity on earth is constant and only water quality is being changed” (item 4, Table 8). It appears that the students encountered their difficulties in the learning process, since only about 8% of them presented a full scientific explanation at the beginning of the learning process.

*Ability to Organize Components and Place Them Within a Framework of Relationships.* Analysis of the concept maps revealed that at the end of the learning process two thirds of the students succeeded in presenting a meaningful concept map. The other students stayed at the level of connecting pairs of concepts, but still could not connect these pairs to a framework. Analysis of the concepts maps revealed that the number of connections between the concepts and the number of concepts that could be related to more than two concepts had significantly increased (items 2 and 10, Table 4).



Figures 3 and 4 demonstrate the growth of Tami's ability to organize components and place them within a framework of relationships. The concepts that are related to more than two other concepts create a map of focal point that can tell us a lot about the "story" of the map. At the beginning of the learning process, most of the focal points of Tami's map related to hydrospheric components, such as freshwater, salty water, glaciers, rivers, lakes, rain, snow, hail, oceans, and precipitation. This map presented the story of the distribution of fresh and salty water on earth (items 4 of Table 7). Although Tami's title to her map was "The Water Cycle," the map lacked a process that actually takes place in the water cycle. Moreover, it included mainly the hydrosphere and generally ignored the other earth systems, namely the geosphere, atmosphere, and biosphere including human activity (items 1–3 of Table 7). However, looking at Figure 1, which presents the sentences that Tami created in the preparation stage of the map, reveals her acquaintance with processes such as penetration and surface flow, and human activities such as desalination. This gap between students' knowledge of the system components and their ability to incorporate it within a mental model of a system appears in many of the concept maps that were analyzed in this study. Apparently, the awareness of processes and locations is insufficient to create a network of relationships describing the system. As the learning process proceeded, more and more components were incorporated into the concept map. Nevertheless, some students still presented a fragmented perception of the system, which does not incorporate the relationships that were presented using other research tools.

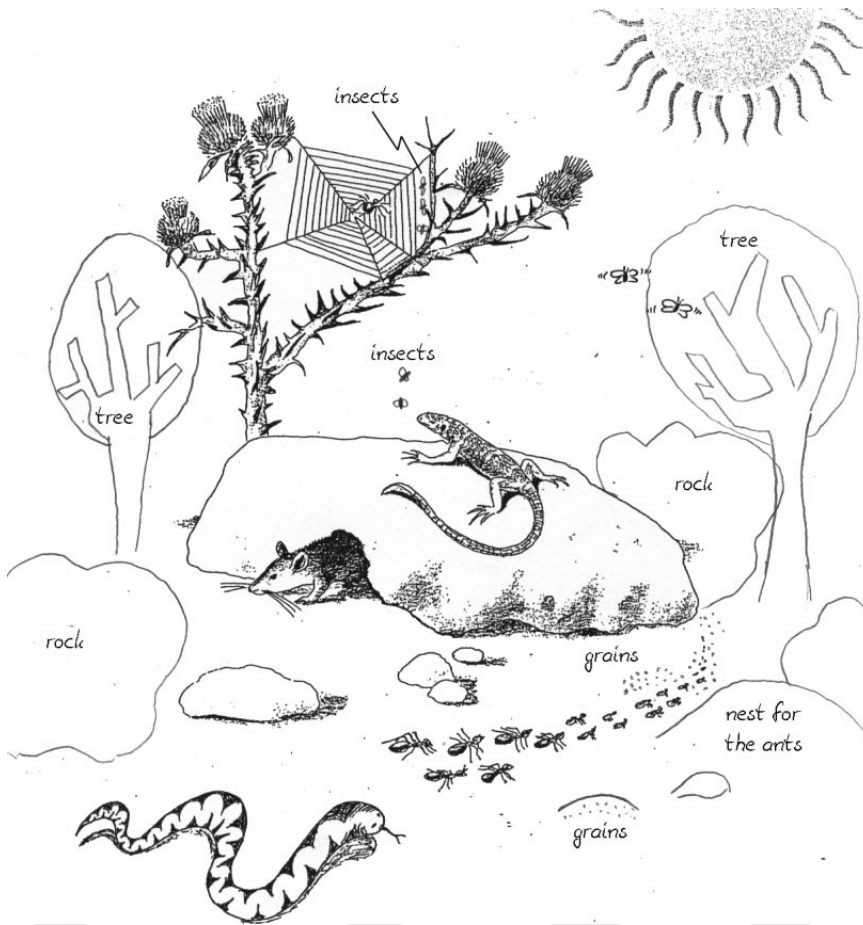
This phenomenon is also expressed by the students' drawings. More than 80% of the students revealed an awareness of the environmental pollution and 50% of them even provided reasonable scientific explanations of the phenomenon (Table 6, item 7). Less than 25% of the students combined in their drawings environmental aspects of human beings, such as water pollution, sewage, and water consumption (Table 1, items 14–17).

*Ability to Make Generalizations.* At the beginning of the learning process most of the students had a poor understanding of the systemic nature of the water cycle. The level of generalizations that had been expressed in their concept maps was limited to the characters of the system component. For example, the most common generalizations that appeared in the pre-test were "in the earth there is salt water and fresh water" or "animals and people need water to survive." The posttest revealed that students extended their variety of generalizations concerning the system. For example, the following expressions appeared only in the posttest concept maps: "The water on earth exists in systems such as the biosphere and atmosphere"; "Earth is mainly covered by water"; "Israel faces a shortage of water"; "There are relationships between the geosphere and hydrosphere"; "The availability of water to humans is affected by the natural system and man's activity."

*Understanding of the Hidden Dimension of the System.* Another aspect of a system thinking was related to the perception of hidden dimensions of the system e.g., a hydrospheric system process, which takes place under the surface (ground water) are exemplified a hidden dimension of the system. The analysis of 25 interviews concerning the "ecology system picture" assignment (Figure 1) revealed the following three levels of abilities to identify the hidden parts of the system:

Level A includes students who (a) added components that already existed in the picture such as a spider, bush, insect, rodent, and ants; or (b) added components that were related to an existing component. For example, Figure 8 presents David's outcomes of the "ecology system picture" assignment. David drew a snake that eats the rodent, or a nest for the birds.





*Figure 8.* An example of a student who added already existing components (for example, an additional rock, an additional tree, additional insects, etc.) and components, which are related to an existing component (for example, food and a nest that were added for the ants).

Level B includes students who added new components that are located on the earth's surface but were not included in the original picture, for example, soil, layers of rocks, water, plants, a house, and human activity.

Level C includes students who, in addition to adding the components of level B, also added components that are located beneath the earth's surface such as ground water, wells, and a spring.

At the beginning of the learning process, nine students reached level A (components that already existed in the picture) and 16 students reached level B (components that are located above the earth surface), but none of the students added the most hidden parts of the system that existed beneath the surface.

At the end of the learning process, five students moved from level A to level B and five students moved from level B to level C. Figure 9 presents Dana's outcomes of the "ecology system picture" assignment. Dana drew clouds, rain, pesticides, factory, man, a well and stalagmite cave. All of these components were emphasized in the learning process regarding the water cycle. It is suggested that Dana is an example of an eighth-grade student who enlarged the systems' borders and exposed hidden dimensions of the system.

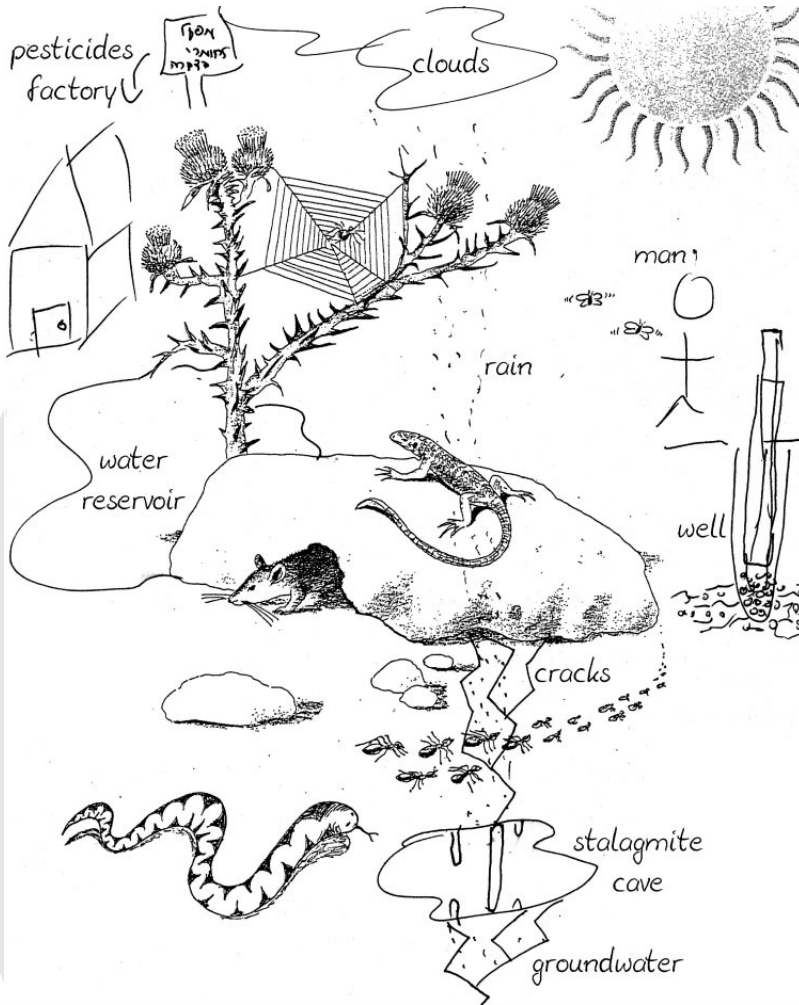


Figure 9. An example of a student who added new components above and beneath the surface that were not in existence or hinted by the original picture, for example, a cloud, rain, upper and underground water, and human activity.

*Thinking in a Time Dimension.* It is important to note that the same students who improved their ability to understand the hidden dimension of the system also presented thinking in a time dimension.

Dana's questions during the interview regarding the factory inventory and her elaboration revealed her ability to retrospect and predict. For example, Figure 10 presents Dana's questions, in which questions concerning the fate of chemicals in the environment demonstrated the abilities to predict.

Where students used their system thinking ability in a problem-solving situation, they translated their understanding that a system is an entity that maintains its existence and functions as a whole through the interaction of its parts. Thus, the system forms a complex and unified whole that has a specific purpose. However, regarding the earth systems, each earth system functions also as a component in a more large-scale system, the earth. By the end of the learning process in this

### Is industrial pollution necessary? An exercise in asking questions.

The following is a story describing an initiative for establishing a factory. Read the story well.

A certain city in Israel initiated the establishment of a factory for manufacturing paint products. It is known that during the process of paint production the factory was using water-soluble substances, and that its wastes were rinsed into the sewage. Adjacent to the factory there is a valley cleft, on whose edge a park was, established in which the city residents tour on weekends and holidays. The establishment of the factory must be rapid to overcome the serious unemployment situation of this city, involving hundreds of positions for the city residents.

Recently, you have been nominated as the head of the city's representative committee. The committee's mission is to prepare a document determining the effect of establishing the factory on the environment, and on the water property, especially. The committee that you are managing will eventually decide if the factory will be established.

To your service there is an expert team that is specialized in preparing surveys on the effects on the environment (i.e. a survey which determines the effect of certain projects on the environment).

**Please, write at least two questions for each expert:**

Area of expertise	The questions
Environmental quality	1. Will the establishment of the factory affect the environment? 2. Will the residual pollutants of the factory be discarded into the sewage only?
Geology (rocks science)	1. Are there any rocks near the stream? 2. What kind of rocks? 3. Do those rocks have any cracks?
Ecology (research of living creatures)	1. Will the factory affect the animals that are living around this area? 2. Will the animals live as usual also after the factory's build-up is completed?
Hydrology (water sciences)	1. Will the factory's residual wastes be discarded into the sewage only? 2. Should some of the wastes find their way into the stream, will they much affect the residents? 3. Do you intend to purify the sewage?
Economics (financial management)	1. What budget do you plan to allocate for the factory's purification project? 2. Will you cut the budget in this regard or will you allocate a suitable budget?
Chemistry	1. Are those toxic materials that should not be kept near humans? 2. Will those materials severely pollute the stream in case they will find their way into it?
Architect (house and landscape planning)	1. How do you plan to build-up the spill that will pour the wastes into the sewage and how do you plan to establish the factory?

*Figure 10.* The outcomes of Dana's response of the "factory" assignment, which represents her retrospection and prediction abilities.

study, most of the students still encountered difficulties in the implementation of this idea. Nevertheless, the qualitative data analyses of the Repertory Grid revealed that some students intuitively built a more holistic perception of the system. An example of this process can be shown by comparing the constructs (that are elicited by comparing groups of three elements), used by a

student named Sara, at the beginning and at the end of the learning process. The data revealed that Sara's constructs, at the beginning of the learning process, focused mainly on the characters of locations of the water on earth, salinity, the state of matter, the amount of water, and water consumption by man. For example:

Question: Sara, what can you tell about these three elements: rivers, oceans, and iceberg?

Sara: "The oceans are exceptional; They contain salty water, whereas rivers and iceberg contain fresh water. So level 1 refers to fresh water and level 5 refers to salty water. Water in the atmosphere gets 3 because it contains salty water as well as fresh water."

Question: How does the salty water go to the atmosphere?

Sara: "Well, this is how it evaporates from the ocean."

Question: "Now, what can you tell about these three elements: lakes, humans and rivers?"

Sara: "The concepts that are similar are lakes and rivers. Humans are exceptional because they consume the water from water reservoirs like lakes, rivers, and groundwater."

Question: "The next three elements are: rivers, seas, and rain. Is there any similarity among them?"

Sara: "The concepts, rivers and seas seemed similar, but rain is different. Oceans get 5 because they contain a huge amount of water. Seas get 4, and rivers, lakes, and humans."

Question: "The last three elements are: groundwater, iceberg, and wells."

Sara: "The similar concepts are groundwater and wells, whereas the different one is iceberg. The water in the icebergs appears solid, so 5 will be solid, 3 will be liquid, and 1 will be gas."

The following is an example of Sara's conception of the dynamic nature of the system via rain. "The concepts puddle and seas are similar. Wells are an exception because the water in the wells arrived from groundwater, but puddles and seas get their water from rain. So oceans, seas, and lakes get 5 because they get the water from the rain. Humans and wells get 1."

The analysis of the repertory grid and Sara's oral elaboration during the interview revealed that, following the learning process she improved her ability to build a more holistic perception of the system. In the end, Sara created constructs which were more process-based. In addition, when Sara compared the concepts: atmosphere, rivers, and spring, she addressed the dynamic nature of the system, and suggested that "Water reservoirs such as oceans, seas, and lakes bring water to the atmosphere and clouds, but also accept water, which is collected in them."

Question: "Among the concepts atmosphere, rivers, and spring, which is the different?"

Sara: "Well the atmosphere and rivers are places where water arrived to, and springs crash through. It comes from groundwater." "So level 5 represents things like the atmosphere and rivers where water arrived to, and 1 represents things that water seldom can arrive to." "I put clouds in level 5 because water can move into it from the atmosphere."

Question: "What are the sources of this water?"

Sara: "Water reservoirs included oceans, seas and lakes. Those places bring water to the atmosphere and clouds, but also accept water, which is collected in them."

Moreover, when she compared the concepts of atmosphere, rivers and lakes, she suggested that the atmosphere is a system and rivers and lakes are parts of a system. Her definition of a system included the system's complexity as well as its dynamic characteristic.

- Sara: "Among the concepts of lakes, the atmosphere and rivers, the atmosphere is an exception because it is a system, and rivers and lakes are part of a system."  
 "So 1 is the system and 5, is part of a system." "Groundwater gets 3 because it is a system but not as the hydrosphere or atmosphere."  
 Question: "What make the groundwater a system?"  
 Sara: "their location and the water movement within it, and also how many parts it includes. For example, the hydrosphere includes oceans, icebergs, lakes, seas, but there are others."

However, Sara tends to hold on to some basic constructs, which she found hard to replace. For example, when describing the concepts rivers, streams, and groundwater she used the construct "appears above the surface" and "appears under the surface." Only after she was asked specifically about the source of the groundwater she suggested the process of penetration as a valid construct.

- Sara: "Groundwater is under the surface, and rivers and streams appear above the surface."  
 Question: "Is there any other common factor to rivers and stream, which is different from groundwater?"  
 Sara: "I don't think so."  
 Question: "What is the source of groundwater?"  
 Sara: "I understand that rivers and streams can penetrate into the soil to form groundwater, and groundwater cannot penetrate when it arrives to an impermeable rock layer."

In summary, the findings presented in this section suggest that the use of the large battery of research tools and the integration of qualitative and quantitative research approaches enable us to address our initial research questions. At the same time, the overlapping that was obtained among the findings of the various tools increased the validity of the findings.

The pre-test findings indicate that most of the sampled students expressed meaningful difficulties in all the aspects of system thinking even in regard to the very basic aspects of identification of the system components. They entered the eighth grade with an incomplete and naive perception of the water cycle. At this stage they were only acquainted with the atmospheric component of the cycle (i.e., evaporation, condensation, and rainfall) and ignored the groundwater, biospheric, and environmental components. Moreover, they lacked the dynamic and cyclic perceptions of the system and the ability to create a meaningful relationship among the system components. The phenomenon of disconnected "islands of knowledge," which was reported by Kali et al. (2003), regarding students' abilities to connect a set of geological phenomena to a coherent rock cycle, was found here as well. Most of the students were unable to link the various components of the water cycle together into a coherent network. Some of them presented the ability to create relationships among several components, but at that stage, even those students were not able to draw a complete network of relationships.

In light of the initial knowledge and cognitive abilities of the students, the posttest findings are quite encouraging. These findings indicate that most of the students shifted from a fragmented perception of the water cycle toward a more holistic view of it. About 70% of the students, who initially presented only the atmospheric component of the hydro cycle, significantly increased their acquaintance with the components and processes of the water cycle. For about half of the students, this wide acquaintance with the systems' components yielded an improvement in their ability to identify relationships among components within the system. The analyses of concept

maps revealed that the number of concepts, and connections between them and the number of concepts that were related to more than two concepts significantly increased. Moreover, most of the students improved their dynamic perception of the system. About one third of them reached the higher level of cyclic perception and a meaningful improvement was also noticed in relation to the students' ability to identify hidden parts of a system.

Thus, to our first research question ("Could junior high students deal with complex systems?") the answer is positive. Taking into account the very low starting point of the sample of students regarding their system thinking abilities in general and their initial knowledge about the hydro system in particular, one might suggest that their final outcomes are very encouraging. It is also suggested that if they would engage in their previous studies with the basic elements of system thinking as well as to study the water cycle with all its earth sciences components, their achievements in the eighth grade may improve.

### *Question 2: What Influenced the Students' Ability to Deal With System Perception?*

The synthesis of all the data collected by this study points on two main factors that might be the source of the differential progress of the students: (a) the students' individual cognitive abilities, and (b) their level of involvement in the knowledge integration activities of their inquiry-based learning both indoors and outdoors.

The analysis of the classroom observations and the knowledge integration assignments that were submitted by 25 students revealed a heterogeneous pattern of students' learning involvement. More specifically, the following three levels of students' learning involvement emerged:

*Minimal involvement in the learning process:* there are 8 students who belong in this category. The characteristics of this group include partially presented in the classroom and lab lessons and the outdoor learning activity; while participating in the lessons they did not usually follow the experiments' instructions and ignored the leading questions in the worksheet; None of them submitted any knowledge integration assignment.

*Partial involvement in the learning process:* Ten students participated actively in the indoor and outdoor learning activities. However, they answered the questions in the worksheets partially and submitted only part of the knowledge integration activities.

*Full involvement in the learning process:* This group included seven students who participated actively in the indoor and outdoor learning activities. They followed the leading questions to the letter and submitted all the knowledge integration assignments, where they exhibited a high performance level.

None of the eight students who showed minimal involvement in the learning process presented a meaningful concept map and stayed at the level of connecting pairs of concepts. In addition, they did not improve their acquaintance with the water cycle components and processes. Consequently, they did not improve their dynamic and cyclic perception of the system.

The common factor for all the students who improved their "hidden" perception of the system as well as their time dimension is that they all conducted the knowledge integration activities, scientific inquiry, and were involved in a learning field trip. However, some of the students who were fully involved in the learning process did not succeed in using a high level of dynamic and cyclic perception of the system. Therefore, it appeared that they had a cognitive barrier that prevented them from using the full potential of their involvement in the knowledge integration activities, or the field trip. Alternatively, students who presented a high level of system thinking at the end of the learning process initiated this process with a relatively broad variety of

relationships among the system's components and had a relatively good cyclic perception of the system. For example, Dana's drawing at the beginning of the learning process has already included relationships between the water cycle components such as "Humans pollute the water in the wells" or "Drinking water has been created by water that was leached," which was rarely found in the drawing of other students.

The data presented above indicate that one factor that clearly influences system thinking ability is cognitive difference. Frank (2000) and others already claimed that system thinking involves high-order thinking skills. Such skills involve a cluster of elaborative mental activities requiring nuance judgment and analysis of complex situations according to multiple criteria (Resnick, 1987). These complex thinking skills create a cognitive barrier for many students especially at the junior high school level. Since almost any population is cognitively heterogeneous one might expect a differential cognitive development as was found by the current study. As it was mentioned before, not all the students who were actively involved in the learning process reached the highest level of system thinking. For some, it was the cognitive barrier was the ability to perceive the dynamic relationship among the system's components; For others, it was the ability to organize components within a network of relationships and there were those for whom the barrier was the ability to make generalizations.

The thinking skills with which the junior high school students were engaged in the current study can be clearly classified as high-order thinking skills and therefore the current findings are aligned with Resnick (1987), who claimed that the term "higher order" skills is fundamentally misleading, because it suggests that another set of skills, presumably called "lower order," needs to come first. She suggested that the kinds of activities traditionally associated with thinking are not limited to an advanced level of development and might be an integral part of even elementary levels of many branches of learning.

As already mentioned, the triangulation of all the research tools indicates that only those students who actively participated in both indoor and outdoor activities and submitted all the knowledge integration assignments throughout the learning process reached the higher ability levels of identifying a network of coherent relationships and hidden components of the system. It is important to emphasize that not all the students who were actively involved within the learning process reached those higher levels, but there was no student who did not submit all the knowledge integration assignments and presented such high system thinking abilities.

In light of the long lasting discussion on whether thinking skills or problem-solving strategies should be taught in the context of subject areas or in separate courses, it seems that our findings support the approach of Csapó (1999) that a content-based method has a considerable effect on the development of general thinking skills.

The finding that the common factor for all those students who crossed all the cognitive barriers was their high involvement within the learning process might indicate that system thinking is not only influenced by the initial cognitive potential of a the students, but also by appropriate learning strategies. In other words, system thinking is a cognitive ability that can be developed through instructional learning. Our findings, together with the findings of Kali et al. (2003), might also suggest that such learning should be based on inquiry-based learning both indoors and outdoors and in knowledge integration activities.

### *Question 3: What Kind of Relationships Exists Among the Cognitive Components of System Thinking?*

The differential distribution of students' achievements concerning the various components of system thinking is the key to our ability to address the third research question. According to this



distribution, which was based on the triangulation of the various research tools, it is possible to classify four groups of skills.

The first group was represented by 70% of the students and includes “the ability to identify the system’s components’ and “the ability to identify the system’s processes.” Both abilities can be classified together as “the system’s analysis skill.”

The second group includes two skills, both of which were presented by about 50% of the sample: “The ability to identify relationships between separate components,” and “The ability to identify dynamic relationships between the system’s components.”

The third step includes three skills, which were presented by about 30–40% of the sample population: “The ability to understand the cyclic nature of systems’; “The ability to organize components and place them within a network of relationships,” and “The ability to make generalizations.”

The fourth group was presented by a small number of the interviewed sample population (10–30%) and includes the perception of the “hidden components of the system’ and the perception of the system within the dimension of time, namely the ability to make a prediction (thinking forward) and the ability to look backward at the history of the system (retrospection).

Following the assumption that the number of students who hold a specific system thinking skill is correlated with its difficulty level, the above classification might present a graded pyramid structure of the development of system thinking skills. Furthermore, an analysis of the data indicated that students do not pass over any of the following groups, namely the second group, which includes only students of the first group and the third group, which includes only those students who acquired the skills of the second group, etc. This finding might lead us to a very important assumption that these four groups are hierarchical and that each group of skills serves as a basis for the development of the next higher group of skills.

This hierarchical notion is well demonstrated by the relationships between the dynamic perception and the cyclic perception of the system. As already mentioned in the results section, there were students who improved their dynamic perception without improving their cyclic perception, but no students improved their cyclic perception without also improving their dynamic perception. This outcome suggests that dynamic perception is mandatory for the development of cyclic perception.

The findings also might suggest two pathways that students have to go through in order to cross the third step. One pathway is the development of the cyclic dynamic perception of the system, whereas the other pathway is the development of the ability to represent the system as a network of interrelationships. These two pathways are not disconnected from each of other. In as much as the students have improved their understanding of transformations of matter within the system, they have improved their ability to close them into cycles at the same time. The improvement of this cyclic perception serves as a mechanism for identifying interrelationships among components, and organizing them into a network. Furthermore, only those students who exhibited a good cognitive ability in both of the above pathways were able to reach the fourth and highest level of the system thinking.

Support for the suggested hierarchical model of system thinking development comes from two earlier studies concerning the development of system thinking in the context of an earth systems curriculum. The study by Kali et al. (2003), which was conducted in the context of the rock cycle supports the interrelationships between dynamic perception and cyclic perception, whereas Gudovitch (1997) suggested a hierarchical structure of students’ perception of the carbon cycle. Thus, it suggested that the findings of the current study, which was conducted in the context of the hydro cycle, can be generalized to the study of the earth systems.



However, since research in education in the area of the earth systems is in a preliminary stage, more research is needed in order to test the current findings in relation to additional learning events, different age levels, different earth system subjects, and different cultures. Moreover, it is also suggested that the current findings and their interpretation should be tested in the context of other systems, namely technological, physical, biological, and sociological.

### Application

In light of the findings and conclusions of the current study, it is suggested that the following aspects might contribute to improve students' abilities to develop system thinking:

1. Introduction of the first steps of system thinking at the elementary school level learning, namely skills such as the ability to identify the components of a system and identifying relationships between two components (if the students enter junior high school with adequate abilities of the lower levels of the system thinking pyramid, more of them might be able to reach the higher levels of system thinking already during the junior high school)
2. Focus on inquiry-based learning
3. Use of the outdoor learning environment for the construction of a concrete model of a natural system
4. Use of knowledge integration activities throughout the stages of the learning process

### Future Research

As already mentioned in the introduction to this work, only a few studies about system thinking were conducted in the context of the earth systems in general and specifically in relation to junior high school level students. Therefore, a lot of additional research is needed to test and to extend the findings of the current study.

Some suggested topics for further research include the following:

1. To what extent students' earlier studies, focus on dynamic thinking in the context of an earth system such as the rock cycle, influence the development of their cyclic thinking while studying more complex earth systems such as the hydro system?
2. How does studying the water system in the context of the development of system thinking influence the study of more complex earth system such as the carbon cycle?
3. To what extent the model for developing systemic thinking skills in the context of the earth systems (as suggested here) is applicable for studying technological or social systems?
4. What factors influence students to take an active or passive role in the knowledge integration activities?

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