Fostering Learners' Collaborative Problem Solving with RiverWeb

Roger Azevedo[1], **Mary Ellen Verona**[2], **Jennifer G. Cromley**[1]
[1] *University of Maryland, Department of Human Development, College Park, MD 20742, USA*
{ra109@umail.umd.edu, jcromley@aol.com}
[2] *Maryland Virtual High School, 51 East University Boulevard, Silver Spring, MD 20901, USA*
{mverona@mabelode.mbhs.edu}

High-school students' understanding of science as a result of using the RiverWeb^{SM} Water Quality Simulator (WQS), a Web-based water management simulation, is described. Eight student pairs participated in a series of science activities, which revolved around using the WQS to explore the impact of land use on water quality. Students received scaffolded pedagogical support from several teachers while they completed three on-line science inquiry units integrating curriculum issues related to chemistry, ecology, and environmental science during a week-long period. The students' emerging understanding was assessed through an analysis of their discourse during collaborative problem solving episodes conducted throughout the week-long data collection period. The results indicate that RiverWeb fostered student engagement in sustained inquiry-based activities and scientific reasoning. However, students experienced a number of difficulties (e.g., comparing and analyzing multiple representations, reformulating hypotheses, defining tasks). Findings will be used iteratively to build new features such as content assistants, argumentation palette, and visualization tools to support students' inquiry-based science activities.

1. Introduction

The RiverWeb Water Quality Simulator (WQS) teaches students about environmental science by illustrating the causes of non-point source pollution within an "archetypal watershed." Water quality indicators provide information about how the land use for each of seven subregions affects the water quality at the mouth of the river. High school students can use RiverWeb to investigate how precipitation and land use affect selected water quality indicator values and can reduce pollutants by improving the management of the subregions. In prototyping the WQS, we aim to design a sound pedagogical and technical framework for structured individual or group explorations of water quality issues, within the context of the secondary science curriculum.

The WQS represents an initial step in developing a number of "online science labs" we term "WebSims" [1]. The vision behind "WebSims" is to develop Web-mediated learning environments that enable students to collect and visualize data and critically evaluate graphical representations of dynamic changes in relevant variables. A digital notebook linked to a database of questions tied to simulation variables allows the student to make visible his/her thinking by recording observations, articulating hypotheses to explain and/or predict the behavior of selected variables, and citing appropriate evidence [2]. The notebook and allied question database also enable teachers to structure student investigations, assess the learning process as it unfolds, and provide scaffolding to connect students' existing ideas and notions with new data they encounter during their explorations.

In partnership with high school teachers, we are examining the design elements that relate to the Web interface, the underlying computational model, scaffolding, and pedagogy that can maximize the potential of Web-mediated, computer-based simulation environments. There are five specific goals which guide our research and prototyping activities. (1) To foster cooperative learning at the 9-12th grade levels that is focused on an authentic problem—in this case, how land use alters water quality. (2) To foster appreciation among "tomorrow's citizens" of how scientific knowledge about rivers and watersheds can guide difficult societal choices about managing the environment. (3) To apply modeling and simulation to integrate science content and process skills (e.g., asking questions, forming hypotheses, gathering evidence, analyzing data) in tandem with authentic problem solving. (4) To incorporate modeling and simulation into K-12 professional development and the pre-service and secondary science curriculum. (5) To develop flexible, customizable tools to facilitate authentic, performance-based assessments linked closely with the learning process itself. The purpose of this paper is to describe the RiverWeb WQS environment, present the theoretical framework and curriculum design principles, present the results of students' discourse during collaborative problem solving science inquiry activities, and discuss how we plan to extend RiverWeb's framework to support students' scientific reasoning and argumentation.

2. RiverWeb: A Web-based Water Quality Simulation Environment

RiverWeb is a Web-based watershed management simulation environment designed by science educators, environmental scientists, and computational scientists (http://mvhs1.mbhs.edu/riverweb/index1.html). In RiverWeb, high school students work collaboratively in a simulated watershed environment and use monitoring stations to study how different land uses, including pristine forest, agriculture, lumbering forest, residential area, commercial/industrial area, wetlands, and urban area, affect water quality. Each water monitoring station allows students to test for physical and chemical characteristics of the tributary, such as total flow and nitrogen concentration. Once students have developed an explanation for how land use influences water quality, they discuss the recommendations that should be made to local policymakers to solve problems. Students learn to examine scientific data, such as time series reports and scatterplots, and then record their observations in a digital notebook.

Targeted at the grades 8-12 science and math curriculum, the simulator enables students to explore the dynamic behavior of a variety of indicators of non-point source pollution within a hypothetical river system comprising of a number of sub-watersheds, each corresponding to a distinct land use. Through a dynamic graphical Web-based interface to a computer model that runs on a remote server, students learn how water quality indicators vary over time in relation to land use and precipitation. They then apply their understandings to evaluate relative benefits and costs of different strategies aimed at mitigating non-point pollution within the watershed.

The WQS depicts the effects of various land uses on water quality in an archetypal watershed. By limiting each sub-watershed to one land use, the effect of that land use on can be seen on the quality of the water that students "test" within its boundaries. The cumulative effect of the combined land use determines the water quality shown by the indicator values found at a common river outflow (see area 7 on Figure 1). After the user logs in, a map of the archetypal watershed appears (see Figure 1). Water quality monitoring stations located throughout the watershed are depicted on the map. The user may click on the map to investigate any sub-watershed using the RiverWeb graph window. By default, the graph window displays the variation of nitrogen over time in the top window, and precipitation over time in the bottom window (see Figure 2). Other indicators may be selected; for example, the student might compare nitrogen concentration between two stations (e.g., residential area vs. wetlands) and/or compare different indicators at the same station (e.g., phosphorous vs. dissolved oxygen in the urban area). In addition, reducing the range of days for each graph provides the ability to zoom in on a particular time period.

Other RiverWeb features include a scatterplot graph that enables students to further explore the relationship of a pair of indicators or stations. A tour, which may be selected at login, uses frames to combine the WQS with instructions leading the user through most of the simulator capabilities. Clicking on a hyperlink in the graphical display invokes the Web-based notebook. Linked to a flexible database on the server, a digital notebook keyed to currently selected indicators provides a space for students to record their observations, pose hypotheses, and answer questions designed to promote problem-solving as they explore connections between watershed variables. Teachers can use the notebook to structure their students' explorations by customizing the questions to fit the needs of their students and curriculum and to assess student learning.

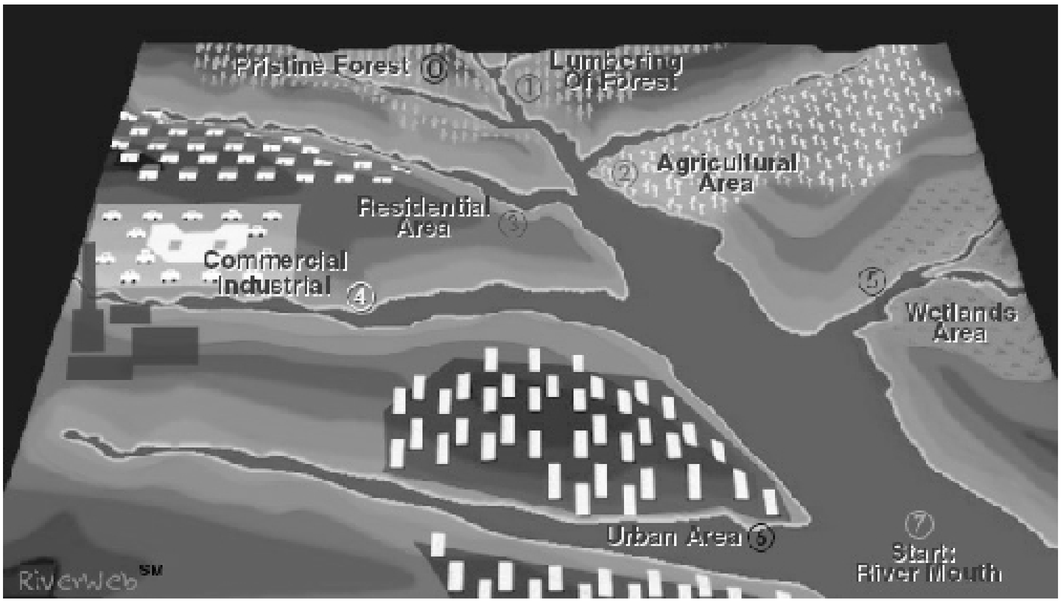
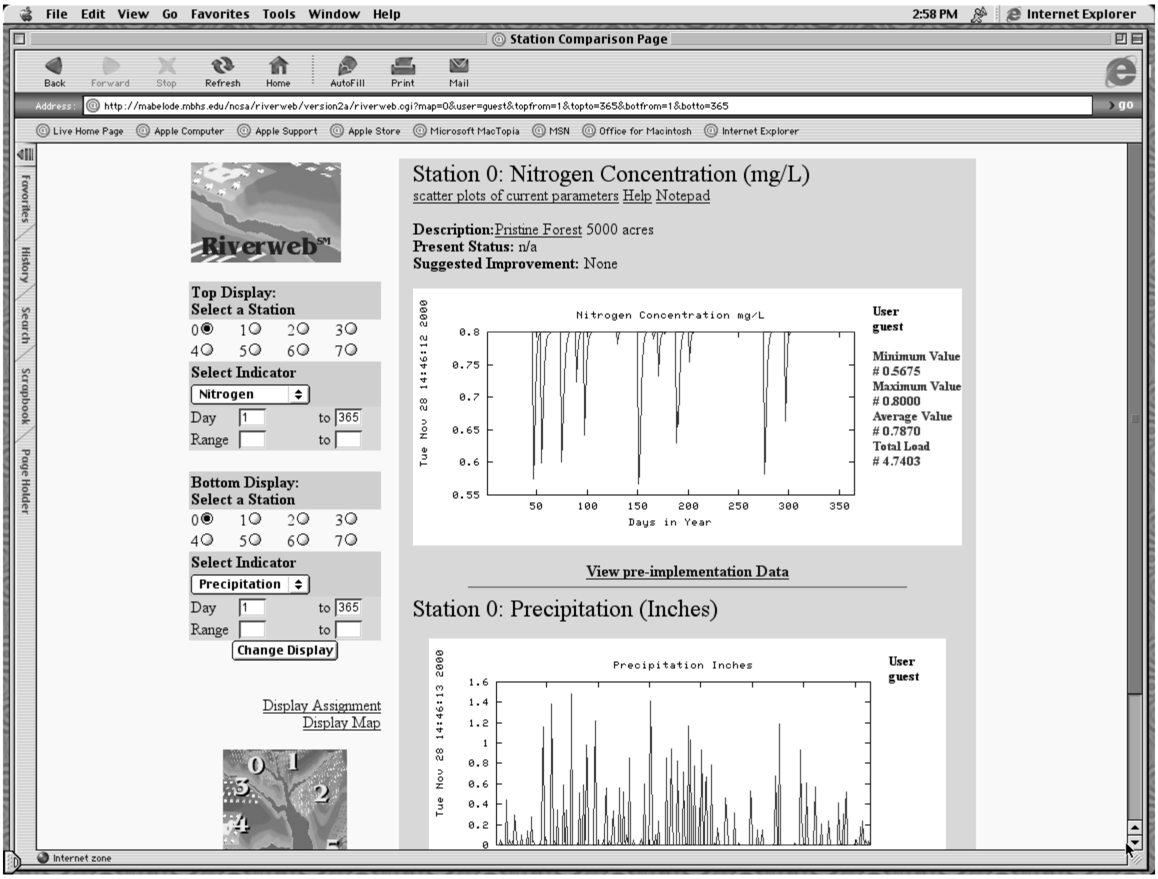


Figure 1. RiverWeb interface displaying the seven watershed subregions



http://mabelode.mbhs.edu/ncsa/riverweb/version2a/riverweb.cgi?map=0&user=guest&topfrom=1&topto=365&botfrom=1&botto=365

Top Display:
Select a Station
0● 1○ 2○ 3○
4○ 5○ 6○ 7○
Select Indicator
Nitrogen
Day 1 to 365
Range to

Bottom Display:
Select a Station
0● 1○ 2○ 3○
4○ 5○ 6○ 7○
Select Indicator
Precipitation
Day 1 to 365
Range to
Change Display

Display Assignment
Display Map

Station 0: Nitrogen Concentration (mg/L)
scatter plots of current parameters Help Notepad

Description: Pristine Forest 5000 acres
Present Status: n/a
Suggested Improvement: None

User
guest

Minimum Value
 # 0.5675
Maximum Value
 # 0.8000
Average Value
 # 0.7870
Total Load
 # 4.7403

View pre-implementation Data

Station 0: Precipitation (Inches)

User
guest

Figure 2. RiverWeb interface illustrating a student comparing the variation in nitrogen (top window) and precipitation (bottom window) over time in the pristine forest (Station 0).

3. Theoretical Perspective and Curriculum Design Principles

The underlying theoretical framework for our research on fostering high school students' understanding of science with a Web-based Water Quality Simulation (WQS) is based on a social constructivist perspective [3-5]. Social constructivism is an approach to learning in which students construct knowledge through their interactions with and interpretations of their world, including interactions with others [6]. There are four fundamental features associated with this theoretical framework—active construction, situated cognition, community, and discourse. Research has shown that students are more likely to develop a deep understanding when they are provided with opportunities to actively construct their understanding of a discipline [7-11]. Actively engaging in understanding requires that learners become immersed in the content of a discipline, which provides learning situations where learners have the opportunity to learn through increasingly autonomous activity, together with social and intellectual support. Learners' socialization into the culture of scientific inquiry is a critical component of this project, which involves developing close collaboration with the teachers and students of the Maryland Virtual High School (MVHS). A goal of this project is to create a Modeling Inquiry Community (MIC) to support high school students' structured scientific explorations using Web-based simulation environments. Participation within any community requires the use of language to exchange and negotiate meaning of ideas among its members. Language becomes a critical component as learners are introduced into the community by more competent others (i.e., teachers) and use language to learn how to participate in the community, construct learning, and engage in the discourse of the community.

We have used the social constructivist perspective to develop curriculum materials, collaborating with teachers, university researchers, educational researchers, and curriculum developers. We have derived curriculum design principles similar to those adopted by other educational researchers [2,3,5,9,10] to develop extended science inquiry activities using RiverWeb. In this section we provide a brief description of each curriculum design principle. The seven principles include context, standards-based, inquiry, collaboration, learning tools, artifacts, and scaffolds. In RiverWeb learners are provided with a context in which they solve meaningful and challenging science problems using the various components of the WQS. The activities are standards-based, in that students engage in activities based on benchmarks and standards from the larger scientific community (e.g., AAAS) [12] related to practices and methods for asking questions and solving problems, emphasizing the effect of the human presence on the earth, and common themes such as systems and dynamic change. Students engage in sustained inquiry activities, which is the accepted norm in the scientific community for solving problems. By engaging in sustained scientific investigations, students learn to collect, analyze, interpret, share information, and negotiate the meaning of information. To successfully participate in a community of learners the students must collaborate by interacting with peers, teachers, and community members to share information and negotiate meaning. The integration of Web-based learning environments such as RiverWeb are used to support students' scientific reasoning by allowing students to pose science questions, propose hypotheses, view scientific data, modify arguments, share data and negotiate about its meaning. Students create artifacts (e.g., concept maps, scientific models, lab reports, notebook entries, group presentations) as they conduct scientific investigations. These artifacts are external representations of ideas that can be shared, critiqued, and revised to enhance learning. The use of scaffolds to support student learning is strongly associated with the four fundamental features of social constructivism – active construction, situated cognition, community, and discourse. Here, the assistance of more competent members of the community can be used to assist more novice learners to accomplish more difficult tasks. The MVHS community provides scaffolding at several levels—(1) projects are designed to guide learning as students are introduced to challenging science problems; (2) learning materials (e.g., RiverWeb's notebook) are designed to reduce complexity, foster the use of inquiry strategies, foster collaboration; and, (3) because the Web-based environment is used in the classroom teachers have the opportunity to model, coach, articulate and externalize their reasoning, and give feedback whenever possible.

4. Research Questions

In this section we present several research questions which informed our initial research agenda. Some have resulted in preliminary findings, while other questions have emerged from the early classroom observations. The following is an initial set of cognitively-oriented research questions. (1) How do students use the multiple graphical representations of model inputs and outputs (line graphs, scatter plots, bar charts) in constructing chains of causal reasoning? (2) Can students correctly use mathematical concepts related to correlation, scale, time series, lag, frequency of variation, etc. in reasoning about watershed problems? (3) What naïve conceptions about dynamic systems, as well as the strengths and limitations of scientific models to represent processes in the "real world," does the WQS elicit? (4) Does student articulation of observations, explanations and supporting evidence through the notebook lead to self-questioning and retracing of causal connections? (5) To what extent and how does the WQS environment elicit hypotheses generation and testing? (6) How and when do students utilize scaffolding provided by the teacher, peers or digital resources (questions, links to information)? (7) How do student explorations of the WQS change as they progress from novices to experienced inquirers?

As we began to analyze our transcripts we started to see emerging patterns in the data that went beyond these cognitively-oriented questions. For example, discourse patterns between students, levels of teacher scaffolding, and a wider variety of self-regulatory processes and student misconceptions began to emerge beyond what we initially hypothesized. This has led us to expand the scope of our research questions, theoretical framework, and analytical procedures, in keeping with our design experiment approach [13].

5. Method

5.1 Participants

Sixteen grade 9 high school students (8 girls and 8 boys) from two Honors Biology classes volunteered to participate in this study. None of the students had taken high school chemistry. The sample included students with mixed ethnic backgrounds. Data was collected in October 2000, one month into the school year. In the classroom, students had received an introduction to the interdependence of diverse living organisms within the components of the biosphere, based on the Maryland State Core Learning Goals. This included approximately 3 hours of class time learning about water quality.

5.2 Procedure

The student groups were videotaped and audiotaped on two separate occasions over a 1-week period. In total, we collected 10 hours of audio and video data over four days (two student pairs during each daily 75-minute classroom period). One researcher acted as a complete participant during the data collection period. She is an experienced environmental science teacher who introduced the science activities to all of the students and provided scaffolding during activities. The regular classroom teacher and a visiting teacher also provided scaffolding during all science activities. The other two researchers acted as complete observers rather than participants in the classrooms, remaining on the sidelines to take notes and manage taping equipment, interacting minimally with the students and teachers during class periods. Taping was done for whole class periods during which the teachers moved in and out of interaction with individual groups as they tackled the science inquiry questions. Therefore, data was gathered as the groups of target students worked both with and without teacher assistance.

5.3 Data Sources and Analyses

Several data sources, data collection methods, and analysis techniques were used to obtain an in-depth understanding of students' emerging understanding of science phenomena. The main data sources were the videotapes and transcripts of students' interactions. A total of 10 hours of video and audio data were collected, and subsequently transcribed for fine-grained analysis. The students' emerging understanding was assessed through an analysis of student interactions during science inquiry activities. Video and audio data were collected for each student pair during all on-line science inquiry sessions with RiverWeb. This allowed for in-depth analysis into student content discussions while engaged in science inquiry activities and what types of resources (e.g., graphing tools) they used. In addition to the video and audio data, we also collected notebook entries, prediction statements, video and audio data of student pairs, and pre- and post-tests, which we are presently analyzing.

6. Results

The results of the discourse between student pairs engaging in various science activities related to RiverWeb is presented in four section—overall findings, student difficulties, engaged student behavior, and teachers' scaffolding. Overall, the simulator fostered student engagement in sustained inquiry-based activities and scientific reasoning. Students were actively involved in searching for information on the WQS by using multiple representations to answer questions. They engaged in scientific reasoning, argumentation, and collaborative problem solving in order to understand the underlying causes and relationships between indicators and land use. Results indicate that prolonged use with RiverWeb leads students to engage in high-order cognitive skills (e.g., reasoning and argumentation) by automating low-level skills (e.g., finding different RiverWeb features by scanning the interface). Students engaged in long reasoning chains as they jointly solved problems presented in the worksheets and notebook by accessing multiple representations and other WQS features. Students often summarized their problem solving performance and hypothesized about factors which affect runoff. This also led some students to provide extensive explanations about the data they have collected and how it is related to their present task.

However, our results also indicate that students experienced several difficulties while using RiverWeb to complete their science activities. For example, they were unable to establish whether the differences observed between indicators was due to cause-and-effect or was based on a relationship of both variables to a common causal factor. They lacked an understanding of the definitions, concepts, and vocabulary that are required to communicate ideas clearly with each other and solve problems (e.g., run-off, pH, heavy metals, dissolved oxygen, total flow, watershed). They had difficulty reading graphs since pairs of graphs are not always on the same scale, and had difficulty reading and comparing (both quantitatively and qualitatively) two graphs and inferring their underlying meaning. They exhibited a great deal of variability in their qualitative categorizations of graphical data (e.g., "it goes up," "it's higher," "it decreases," "that's more"). They also exhibited a great deal of variability in their (qualitative) comparison of indicators (e.g., "it goes up and down, like, at the same time," "it has a direct relationship," "pH got much more acidic when rain got higher," "when precipitation increased, acidic levels got a little higher"). They also showed difficulties associated with reading graphs, including the relationship between minimum and maximum levels, average levels, and calendar days. Students seldom raised new hypotheses regarding the effect of or relationship between indicators.

Sometimes students were unclear about how to define the task/problem. In some cases, this was still an issue even after a teacher had provided clear objectives and presented the features of RiverWeb. In other cases, students spent several conversational turns trying to figure out what to do next. Students created incorrect analogies and/or used incorrect visual representations of complex concepts. This situation often led to long reasoning chains, as students jointly attempted to understand a complex concept (e.g., water flow from a land use area). For example, students' literal interpretation of "water flow—a stream of water flowing out of land" led them to erroneously infer that the pristine forest was a stream ("therefore wetlands would be more likely to keep or retain…sediments or whatever comes into them, than a flowing bottom-body of water such as the river and pristine forest"). Students lacked basic understanding of science concepts (e.g., "nitrogen and sediments are examples of heavy metals"), and also had informal misconceptions which may be difficult to remediate (e.g., "I know that toxins are an example of nitrogen, phosphorous, and sediments. Is heavy metals part of toxins?"). This was also related to students' literal interpretation of concepts (e.g., "….because wetlands they have nowhere to run off to", "a wetland is a marsh"). Students failed to access the RiverWeb glossary which could have clarified some of these concerns.

Students were not sure how to complete the concept maps, which were supposed to depict how the factors influence water quality. This is a problem because their general lack of understanding between cause-and-effect and relationships interfered with their ability to properly represent which factors influenced water quality. Students had no problems with placing the indicators on the concept maps ("the factors have the little circles"), however, they sometimes failed to mention the type or direction of the links between the concepts ("with the little things coming off the factors").

Engaged students generated very complex argument structures as they attempted to understand unexpected findings (e.g., "…toxins didn't increase or decrease at all, toxins didn't change. No relation at all. So there's no relation at all. I don't know why"). However, they had difficulty in understanding unexpected findings, especially if the teacher was not available to provide scaffolding. Engaged students discussed the assumptions underlying certain aspects of the simulation. For example, they assumed that wetlands didn't have any heavy metals unless they were put there by humans. One student pair stated, "I guess we're supposed to assume that man hasn't been there." Engaged students were metacognitively aware of their performance and addressed deficiencies by reviewing what they knew, reviewing their arguments, reviewing their problem solving steps, revisiting graphs generated by RiverWeb, reflecting on the quality of their answers, and seeking scaffolding from each other and/or teachers.

Teachers play a crucial role during collaborative problem-solving by providing different levels of scaffolding such as modeling (e.g., showing the student how to set up the interface to facilitate the viewing of various RiverWeb features need to answer particular questions), articulating (e.g., teachers making their thinking visible to students), coaching (e.g., teachers providing hints and feedback based on students' progress), and fading (e.g., teacher silently watching students' progress). Please refer to [14] for a detailed description and explanation of teachers' scaffolding used to support student learning when using the WQS.

7. Future Directions

Based on the patterns in student data noted above, two features will be added to the RiverWeb environment: content assistants and a hypothesis-testing area. In the transcripts, we noticed that students struggled to understand how different land uses affect different indicators. When one of the teachers happened to be present, she could scaffold the students' understanding, often by pointing out features of the displays or by asking questions that focused students' attention on critical issues. For example, when two students were considering what effect lumbering might have on water temperature, the teacher 1) reframed the question, 2) reworded the students' answer to point out a causal relationship, 3) pointed out that students should test their prediction, 4) quantified the students' answer, and 5) suggested a second comparison students could make to confirm their answer.

However, the teacher cannot scaffold learning for every student simultaneously; therefore, RiverWeb could benefit from incorporating on-line content assistants which would provide graduated levels of scaffolding. At the highest level, students would be provided with direct explanations (e.g., explanations of the relationships between land uses and water quality indicators). These on-line assistants could be provided in multiple formats—from animations of different relationships to explanations spoken by a teacher on a video clip. These on-line assistants could free up the classroom teacher to help students in the few cases where they are so confused or lack so much prior knowledge that they cannot benefit from the on-line assistants. Animations placed side-by-side with graphs might also help students to coordinate multiple representations of these environmental relationships [15].

A second addition to the RiverWeb environment will be a hypothesis-testing area, where students would practice linking pieces of evidence to craft an argument. We noted in the transcripts that students sometimes struggled with the relationship between their predictions and the patterns they noted in the RiverWeb environment (e.g., nitrogen level is elevated in an agricultural area compared to pristine forest). Students sometimes attributed changes in the indicators to land use, which were really due to seasonal changes (e.g., regardless of land use, air temperature increases in the spring and summer and decreases in the fall and winter). Students also sometimes reversed cause and effect, e.g., arguing that dissolved oxygen would cause pollution rather than pollution causing changes in levels of dissolved oxygen.

The hypothesis-testing area would have an evidence palette, where students could collect evidence, and an argumentation area, where they could link together evidence to make an argument. This area would be similar to BioWorld [16] and Belvedere [17], which give students feedback on arguments constructed from data collected during scientific explorations. Belvedere asks students open-ended questions about the relationships among pieces of evidence, the direction of causal links, and the relationships between particular pieces of evidence and arguments. A hypothesis-testing area in RiverWeb might encourage students to more carefully examine the relationship between the argument they are making and the evidence they are marshalling to support that argument.

In sum, it is critical to note that this research program is based on a design experiment approach [13], which features a cyclical interaction between two complementary aspects of design and research. Working from an existing theory and research base [e.g., 3,4], and our results reported here we plan to design new RiverWeb components and assess their effectiveness in fostering students' scientific reasoning and argumentation in collaboration with MVHS teachers and system developers. We are presently conducting experiments to investigate issues related to students' ability to regulate their own learning when using RiverWeb (e.g., learner-generated goals vs. teacher-set goals). Lastly, we are also planning on using AI techniques in future versions of RiverWeb, based on our empirical evidence.

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References

[1] Verona, M.E. (2000). WebSims: Creating an Online Science Lab. In L. Vandervert & L. Shavinina (Eds). Provocative and do-able futures for cybereducation: Leadership for the cutting edge. New York: Liebert, Inc.
[2] Linn, M., & Hsi, S. (2000). Computers, teachers, peers: Science learning partners. Mawah, NJ: Erlbaum.
[3] Blumenfled, P., Marx, R., Patrick, H., & Krajcik, J. (1997). Teaching for understanding. In B. Biddle, T. Good, & I. Goodson (Eds.), International handbook of teachers and teaching (pp. 819-878). Netherlands: Kluwer.
[4] Cobb, P. (1994). Where is the mind? Constructivistic and sociocultural perspectives on mathematical development. Educational Researcher, 23(7), 13-20.
[5] Singer, J., Marx, R., Krajick, J., & Chambers, J. (2000). Constructing extended inquiry projects: Curriculum materials for science education reform. Educational Psychologist, 35(3), 165-178.
[6] Rogoff, B. (1999). Cognition as a collaborative process. In W. Damon, D. Kuhn, & R. Siegler (Eds.) Handbook of child psychology (vol. 2) (pp. 679-744). NY: Wiley.
[7] Azevedo, R., Guthrie, J.T., Wang, H., & Mulhern, J. (2001). Do different instructional interventions facilitate students' ability to shift to more sophisticated mental models of complex systems? Paper to be presented at the Annual Conference of the American Educational Research Association, Seattle, WA.
[8] Lajoie, S.P., & Azevedo, R. (2000). Cognitive tools for medical informatics. In S.P. Lajoie (Ed.), Computers as cognitive tools II: No more walls: Theory change, paradigm shifts and their influence on the use of computers for instructional purposes (pp. 247-271). Mahwah, NJ: Erlbaum.
[9] Songer, N. B. (1996). Exploring learning opportunities in coordinated network-enhanced classrooms: A case of Kids as Global Scientists. The Journal of the Learning Sciences, 5(4), 297-327.
[10] Wallace, R., Kupperman, J., Krajcik, J., & Soloway, E. (2000). Science on the web: Students online in a sixth-grade classroom. Journal of the Learning Sciences, 9(1), 75-104.
[11] Perkins, D., Crismond, D., Simmons, R., & Unger, C. (1995). Inside understanding. In D. Perkins, J. Schwartz, West, M., & Wiske, M. (Eds.), Software goes to school: Teaching for understanding with new technologies (pp. 70-87). NY: Oxford University Press.
[12] American Association for the Advancement of Science. (1993). Benchmarks for science literacy. NY: Oxford.
[13] Brown, A. L. (1992). Design experiments: Theoretical and methodological challenges in creating complex interventions in classroom settings. The Journal of the Learning Sciences, 2(2), 141-178.
[14] Verona, M.E., Curtis, D., & Shaffer, D. (2001, May). Supporting teacher development in enacting the RiverWeb Water Quality Simulator. Paper to be presented at AI-ED conference, San Antonio, TX.
[15] Kozma, R., Chin, E., Russell, J., & Marx, N. (2000). The roles of representations and tools in the chemistry laboratory and their implications for chemistry learning. Journal of the Learning Sciences, 9(2), 105-144.
[16] Lajoie, S.P., Lavigne, N., Guerrera, C., Munsie, S. (in press). Constructing knowledge in the context of BioWorld. Instructional Science.
[17] Suthers, D. (1999). Representational bias as guidance for learning interactions: A research agenda. In S.P. Lajoie, & M. Vivet (Eds.), Frontiers in artificial intelligence and applications. Open learning environments: New computational technologies to support learning, exploration and collaboration (pp. 121-128). Amsterdam: IOS Press.