



## Development of an environmental virtual field laboratory <sup>☆</sup>

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### Abstract

Laboratory exercises, field observations and field trips are a fundamental part of many earth science and environmental science courses. Field observations and field trips can be constrained because of distance, time, expense, scale, safety, or complexity of real-world environments. Our objectives were to develop an environmental virtual field laboratory to study environmental properties and processes that stimulate the higher-order cognitive skills of students. We considered the following criteria for our virtual field laboratory: (i) global access, i.e., web-based implementation; (ii) simulation of a variety of learning mechanisms; (iii) interactivity to engage students; (iv) compartmentalization and hierarchical organizational structure; (v) abstraction of 2D and 3D geographic objects (e.g. soils, terrain) and dynamic ecosystem processes (e.g. water flow) using geostatistics and scientific visualization techniques. Cognitive science was considered during the design of our computer-aided instructional tools to enhance the effectiveness for learning. Our virtual field laboratory mimicked the students' learning processes that operate during real field trips and/or field observations; and provided students with a simulation environment to study environmental processes in space and time that cannot be provided on a real field trip. We implemented the following learning mechanisms: (i) exploration-based learning; (ii) analogy-based learning; (iii) science inquiry learning; (iv) abstraction-based learning. To engage students in our environmental virtual field laboratory, we implemented multiple interactivity functions including the exploration of 3D models and adaptive selective simulations. We used Virtual Reality Modeling Language, Java, Java Script, and External Authoring Interface to develop the environmental virtual field laboratory for a 42-ha flatwood site in Florida for which

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extensive datasets existed. Our digital learning environment offers potential to enhance existing on-campus courses and/or distance education courses.

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## 1. Introduction

Environmental science courses and curricula aim to train students in holistic thinking, which includes taking into account the interrelationships between environmental factors and processes. Such training is rooted in a fundamental understanding of ecosystems. Laboratory exercises, field observations and field trips are a fundamental part of many earth science and environmental science courses. Experiencing the world first-hand provides students with the opportunity to develop practical and observational skills not readily available from classroom teaching. The real world offers authenticity, complexity, and true sensory immersion (Soloway et al., 1999). But reality has two important characteristics that limit field observations and field trips. First, for reasons of distance, time, expense, scale, or safety, real-world environments might simply be inaccessible. Limited budgets at academic institutions, costs for landscape-scale experiments and monitoring programs, or the distance to travel to a specific location are prohibitive for many field trips. There are limitations to how many soil pits students can dig on a field trip and how many water wells they can measure to characterize a larger study area. Other constraints include the observation of specific events (e.g. rainfall-runoff event) or microscopic observations such as water flow in a soil pore. If inquiry grows from the observation of phenomena, the lack of an environment within which one might draw from that experience limits the range of accessible content domains.

A second, complementary, problem derives from the very richness of the real world. Even a small slice of the world offers nearly unlimited opportunity for observations. The spatial and temporal variability of many earth properties is diverse and commonly anisotropic. The characterization of landscapes requires a high frequency and spatially dense set of observations that cannot be gained from only a few field trips. Moreover, data derived from the real world can be untidy, sometimes to the extent that it obscures the very relationships the activity is intended to reveal. These problems – accessibility and complexity – are often addressed through the use of simulation models (Grunwald & Norton, 1999). Computer simulation models provide access to otherwise inaccessible phenomena; they integrate spatial and temporal datasets, and make ecosystem processes transparent. In addition, simulation models offer a platform for hypothesis testing. Students can use simulation models to test multiple scenarios to get an idea of possible outcomes, while considering diverse assumptions and model inputs. Simulation tools are ideal media to support inquiry and discovery learning (de Jong et al., 1999; Friedler, Nachmia, & Linn, 1990). Simulation models and virtual e-learning environments offer the potential to improve learning. Learners literally create the phenomena of interest. With the advent of emerging geographic information technologies, limited academic budgets, and an exponentially growing e-learning market, the development of a virtual field laboratory offers new opportunities to enhance the quality of existing on-campus and distance education courses.

Numerous digital applications have been developed to demonstrate laboratory experiments, real-world landscape processes or microscopic objects. Hays, Phirman, Blumenthal, Kastens, and Menke (2000) presented a tool that integrated processes and displayed earth science data. Barak and Nater (2002) developed a virtual learning environment for minerals and molecules used in the study of soil mineralogy. A synchronous experimental machine vision virtual laboratory was developed by Thai and Upchurch (2002). Troy and Czapar (2002) employed Virtual Reality Modeling Language (VRML) to evaluate conservation practices. They generated a three-dimensional (3D) environment for the Lake Springfield watershed in order to visualize environmental factors and to direct the planning, installation, and maintenance of conservation practices. Authors found VRML useful in the promotion of properly placed best management practices (BMPs). Miller, Dunham, and Chen (2002) used VRML to model rural environments and document land use changes. They emphasized that the virtual reality (VR) environment has the potential to aid in communication, decision making and scenario testing. Lovett et al. (2002) used a VRML-based approach for sustainable agricultural management exemplified by a virtual landscape. Grunwald, Barak, McSweeney, and Lowery (2000) developed similar soil-landscape models implemented in VRML at four different spatial scales for sites in southern Wisconsin. Soil-landscape models facilitated students' intuitive comprehension of soil-landscapes, while they gained insight into complex environmental systems. Most existing learning tools focus on more or less stable soil, terrain, geologic, or other properties. The integration of ecosystem processes (e.g. water flow) into virtual worlds is more challenging and few four-dimensional (4D) learning tools exist.

Virtual worlds and laboratories make use of scientific visualization (SciVis). According to Gordon and Pea (1995), SciVis improves learning because it supports the thought process and methodologies practiced by scientists. These include learning from observation, developing hypotheses to explain observations and testing of hypotheses with datasets, thereby iteratively developing more detailed and sophisticated analyses. This process mimics the manner in which science is conducted and enables students to improve their learning process. Barraclough and Guymer (1998) argued that advanced visualization techniques communicated spatial information between students of different backgrounds. Just as maps visually enhance the spatial and temporal understanding of phenomena, 3D representations of geographic objects enhance our understanding of complex environmental systems and the underlying transport processes driving soil and water quality. Both authors pinpointed that interactivity enhanced the perception and interpretation of ecosystems. Koussoulakou and Kraak (1992) tested the usefulness of different SciVis methods, static maps, series of static maps, and animated maps, and found significantly better response times for animated maps. According to Fisher and Unwin (2002), visual interfaces maximize our natural perception abilities, improve the comprehension of huge amounts of data, allow the perception of emergent properties that were not anticipated, and facilitate understanding of both large-scale and small-scale geographic ecosystem features.

Renshaw and Taylor (2000) suggested that computer-aided instruction (CAI) that considers cognitive science during the design of the learning environment positively impacts the higher-order cognitive skills of students. Kulik and Kulik (1989) found that CAI promoted the rote memorization of factual knowledge. Students learned faster and liked their classes more than students in traditional on-campus classes. Cognitive scientists believe that to learn, the material

must have meaning to the learner. Cognitive science may be defined as a multi-disciplinary approach to studying how mental representations enable an organism to produce adaptive behavior and cognition (Keil, 1998). According to Keil (1998) contemporary cognitive science is steering away from its early, simple information-processing models. Contemporary models offered by cognitive science are complex and diverse, but buttressed by evidence suggesting that simpler models fail to capture the richness of natural cognitive systems. The primary implication of cognitive thinking on teaching and learning is the importance of structuring experiences that involve the learner as an active participant in the process. The more instructional design can incorporate activities that require deep-level processing, thinking. In a virtual learning environment, students given tasks that involve exploring, testing of hypotheses, finding and organizing material and synthesizing content results in better learning.

Our objectives were to develop an environmental virtual field laboratory to study environmental properties and processes that stimulate the higher-order cognitive skills of students.

We considered the following criteria for our virtual field laboratory:

- Global access, i.e., web-based implementation.
- Stimulation of a variety of learning mechanisms.
- Interactivity to engage students.
- Compartmentalization and hierarchical organizational structure.
- Abstraction of 2D and 3D geographic objects (e.g. soils, terrain) and dynamic ecosystem processes (e.g. water flow) using geostatistics and scientific visualization techniques.

## 2. Methodology

### 2.1. Experimental dataset

Flatwood landscapes are common in Florida. In numerous field courses at the University of Florida the spatial distribution of soils and hydrologic patterns are studied. To create our environmental virtual field laboratory we selected a 42-ha flatwood site, about 33 km northeast of Gainesville, Florida. An extensive environmental dataset was collected for this site in a research study conducted from April 1992 to March 1998. A detailed description of the study can be found in Bliss and Comerford (2002) and Crownover, Comerford, Neary, and Montgomery (1995). The geographic data included 123 wells 1–1.4 m deep installed in approximately a 100 × 100 m grid. Water table levels were monitored biweekly. Adjacent to each well location soil characteristics including horizon depth were mapped to a depth of 50–60 cm. Hydric and non-hydric soils were distinguished. A digital elevation model (DEM) was developed for the study area using a laser level. Precipitation data were recorded daily at a weather station located at the study site. Cypress swamps (*Taxodium distichum*) covered approximately 31% and a *Pinus elliottii* (slash pine) plantation covered 69% of the study area. In 1994, two silvicultural treatments were administered to the research area:

- (1) The southeast (SE) block was clear-cut, including both the pine plantation and the pine–cypress swamps (clear-cut);
- (2) The northwest (NW) block only the pine–cypress swamps were harvested (cypress-cut);
- (3) The southwest (SW) block was left as a control.

These treatments provided information about the impact of different forest management regimes on water table dynamics.

## 2.2. Implemented learning mechanisms

We considered cognitive science during the design of our computer-aided instructional tools to enhance the effectiveness for learning. Our virtual field laboratory mimicked the students' learning processes that operate during real field trips and/or field observations. We implemented the following learning mechanisms:

- (i) *Exploration-based learning* – students explore an environmental system by walking and experiencing soils, terrain, land use and a variety of environmental factors. Intuitively, students gain a better understanding of the spatial distribution of environmental factors.
- (ii) *Analogy-based learning* – students explore one specific soil-landscape and learn about the environmental processes within a defined geographic domain. Students transfer their knowledge to other unvisited environmental systems.
- (iii) *Science inquiry learning* – students mimic the thought process and methodologies practiced by scientists. These include learning from observations, developing hypothesis and testing these hypothesis thereby iteratively developing more detailed and sophisticated analyses. This process leads to an understanding of how scientific research is conducted.
- (iv) *Abstraction-based learning through a hierarchy of abstraction spaces* – students explore relationships between environmental factors at different spatial and temporal scales.

We selected abstraction spaces that represent the complexity of real-world objects and behavior (Fig. 1). Simple ASCII text in Hypertext Markup Language (HTML) provided a description of the flatwood site. Flat maps showed spatial patterns of vegetation. Interactive 3D soil-landscape models represented soil and terrain properties. To represent water table dynamics, we developed interactive space–time simulations. The higher levels represented more abstract descriptions of the geographic domain, whereas lower levels focused on the quantitative character space (data). We implemented a linkage between quantitative data and abstract model representations. For example, users can click on a soil profile to get access to the collected soil characteristics.

## 2.3. Implemented interactivity functions

To engage students in our environmental virtual field laboratory, we implemented multiple interactivity functions summarized in Fig. 2:

- (i) Animations.
- (ii) Focus questions.
- (iii) Navigation through hyperlinks.
- (iv) Exploration of 3D models.
- (v) Adaptive selective simulations.

Students can trigger animations that start a specific sequence of events. During the animation there are no interactive functions available, therefore, this technique is limited to passive viewing. However, combined with focus questions that encourage students to observe closely the ecosystem processes animations, it can be a highly effective technique to improve learning. This mimics the instructional activity of a teacher on a real field trip. The navigation through hyperlinks based on

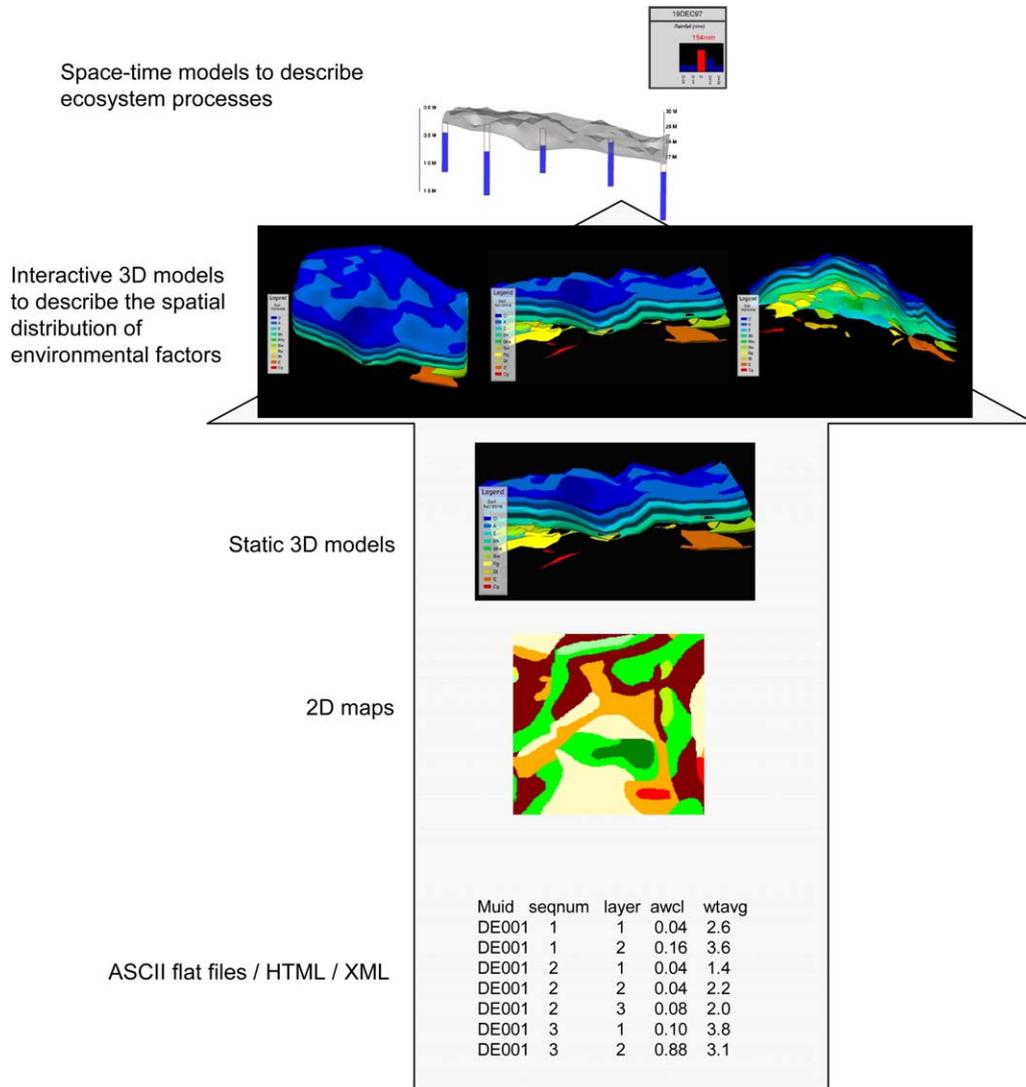


Fig. 1. Hierarchy of abstraction spaces implemented in the virtual field laboratory.

a hierarchal structure is commonly used in CAI. Three-dimensional models of soils and four-dimensional water dynamic models can be explored using zoom, pan, rotate and other basic geographic navigation functions provided by the VRML-based browser. The adaptive selective simulation technique is innovative. Students are provided with a variety of options before they trigger an event, animation or simulation. Depending on the selection (e.g. selection of a well at a specific geographic location), only a subset scenario (e.g. water level dynamics at the selected well location) is displayed. Students can repeat the selection process to study other scenarios and space–time processes. Adaptive selective simulation stimulates experimental learning through the observation of ecosystem processes using a sequence of events: trigger an event – observe ecosystem process – interpretation – assimilation.

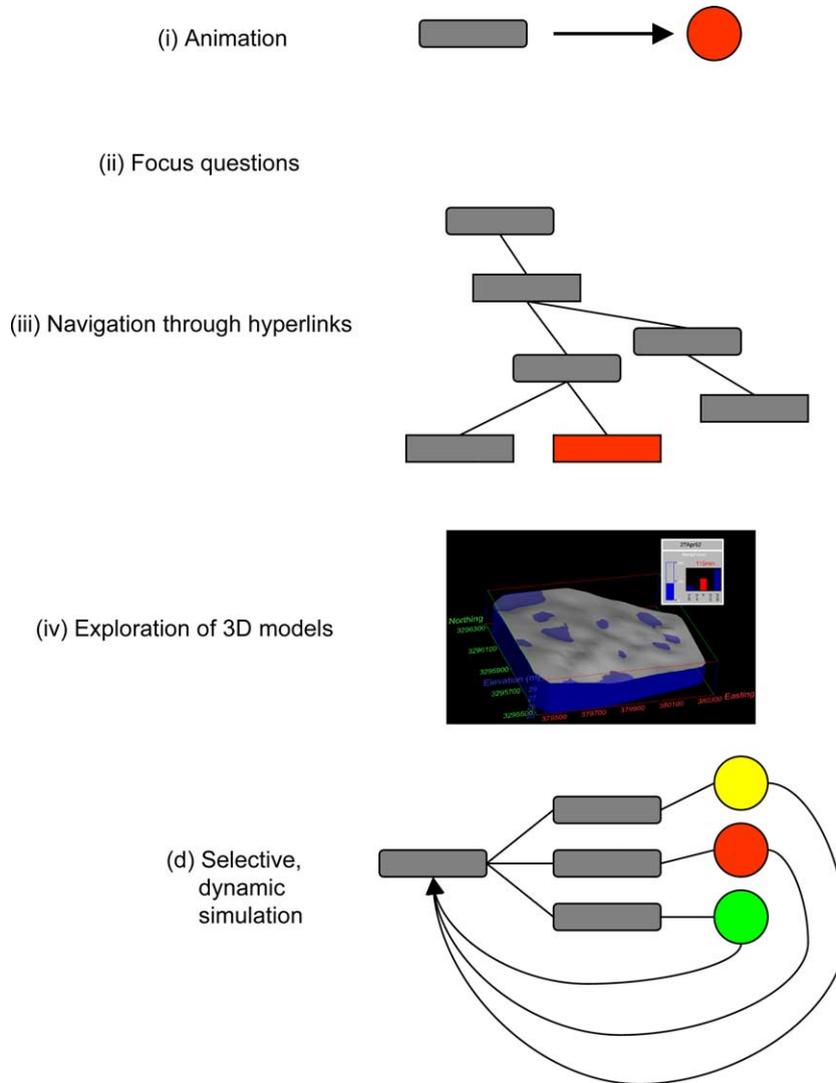


Fig. 2. Implemented interactivity techniques.

#### 2.4. Reconstruction and scientific visualization of geographic objects and behavior

To build our environmental virtual laboratory, we used Virtual Reality Model Language (Lemay, Couch, & Murdock, 1999; <http://www.Web3D.org>). VRML was designed to render 2D and 3D worlds into the World Wide Web (Web). It consists of instructions stored in an ASCII file with a ‘wrl’ extension. VRML is an object-oriented language where nodes represent classes and fields denote attributes of nodes (Lemay et al., 1999). Field values define attributes like color, size, or position, and every field value is of a specific field type, which describes the kind of values allowed in the field. To view the 3D content of the VRML file a VRML browser like ‘Blaxxun’ is

required (<http://www.blaxxun.com>). The browser decodes the file and a visual picture of the file is displayed to the user. In short, VRML facilitates the creation of 3D representations of environmental systems; including all its components such as soils, terrain, land use, monitoring wells, and other geographic objects.

#### 2.4.1. Three-dimensional soil-landscape models

Three-dimensional soil-landscape models were developed to describe the spatial distribution and characteristics of soil properties across the flatwood site. The geo-referenced soil data were merged with terrain characteristics to show changes in elevation (e.g. micro depressions). Workflow models summarize the steps we used to create the 3D soil profile model and 3D soil layer model (Fig. 3). For the 3D soil profile model, 13 soil profiles were selected to show contrasting soils at different geographic locations across the flatwood site. Geographic objects in VRML were created using the Environmental Visualization System software (EVS-PRO; CTech Development Corporation, Huntington Beach, CA). Cylinder objects were created in VRML to represent pedons (soil profiles) and photographs of soil profiles were draped onto corresponding cylinders using the *ImageTexture* feature in VRML. Cylinders were linked to quantitative datasets using Java Script embedded into VRML. Each soil profile has a sensor node, which senses the computer mouse. Once the user selects a soil profile, an event is sent to the Java Script through the Java External Authoring Interface (EAI) and attribute data are displayed in a textbox adjacent to the 3D soil model.

The 3D soil layer model was created to show the spatial distribution of soil layers (horizons) across the flatwood site. Each layer was represented by a polyhedron created in EVS using ordinary kriging (OK). The DEM was created as a surface using 2D OK and integrated with the soil

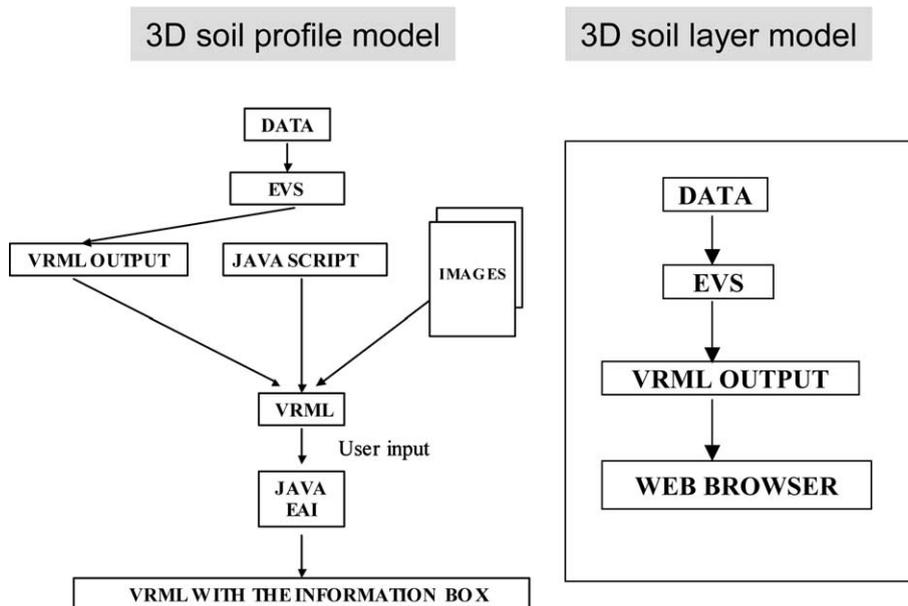


Fig. 3. Reconstruction of 3D soil-landscape models.

layer model using  $x$  and  $y$  coordinates. Each layer was represented by a unique color. Users can select to view all soil layers at once or deactivate soil layers to view subsets.

The EAI provides an interface to communicate between a VRML world and an external environment. It defines the set of functionality of the VRML browser that the external environment can access. The VRML Java EAI allows a Java script to control a VRML object in the following way:

- Access the functionality of the browser interface (e.g. to create new geometry).
- Send events to *eventIns* of nodes inside the scene (e.g. to change positions or colors of objects).
- Read the last value sent from *eventOuts* of nodes inside the scene (e.g. to find the last position of an object).
- Notify when events are sent from *eventOuts* of nodes inside the scene (e.g. when an object is being clicked).

#### 2.4.2. Space–time water table animation

Different interactive space–time simulations were created to show the changes in water table dynamics on the flatwood site. We described in detail the construction mechanism that created the adaptive selective simulation of water table levels at well locations (Fig. 4). Each well was represented by a polyhedron created using the Building module of EVS. A Java program reads the measured water table level in each well at a specific time period. The *CoordinateInterpolator* VRML node was used to interpolate water levels across the flatwood site. Since 123 water levels were measured over a period of 6 years the output for students would be overwhelming. Hence, we added a graphical user interface for an adaptive selective simulation. Users are able to select a number of wells (Fig. 7) and then trigger the simulation showing water table dynamics constrained to the well subset (Fig. 8). To implement the adaptive selective simulation, we constructed

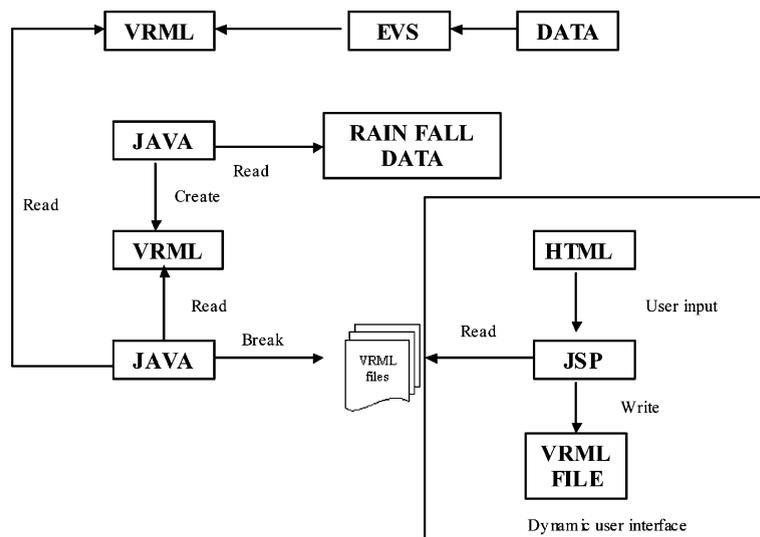


Fig. 4. Construction of the adaptive selective space–time water table animation.

VRML files water table dynamics at each of the 123 sites. The user can select the wells to be displayed. In the upper right corner of the display, the precipitation data and time are displayed. During the space–time animation, each date corresponding to measured precipitation is posted. The precipitation data for the previous two days and the next two days are also displayed. These data help the user to understand the relationship between the precipitation and the water table dynamics using a scientific visualization technique. Java Server Pages (JSP) is Sun Microsystems solution for developing dynamic web sites. Java Server Pages provides excellent server side scripting support for creating dynamic web applications and enables developers to directly insert Java code into JSP files. This provides a simple environment to develop and update code. A web server parses the JSP page and sends the response to the client. We used the Tomcat server developed by Apache Software Foundation.

### **3. Results and discussion**

Snapshots of our environmental virtual field laboratory are shown in Figs. 5–8. Our virtual laboratory can be found at <http://3dmodel.ifas.ufl.edu>. The 3D soil-landscape models help students learn about the spatial distribution of soils and soil properties; as well as how these properties relate to topography. For example, soils in depressions differ from soils at higher elevations. Slight changes in topography have a major impact on soil formation and hydrologic patterns. Soil horizons that have evidence of impeded water drainage (e.g. Bg horizons) are readily identified. Fig. 7 shows the graphical user interface used to select wells. We implemented an adaptive selective simulation of water table dynamics. Users select specific well locations before a space–time simulation is triggered. The display is limited to the previously selected well locations (Fig. 7). Users have the option to repeat the simulation with different well selections in order to investigate hydrologic patterns at different geographic locations. Results are interpreted in the context of the 3D soil-landscape models that influence hydrologic patterns. Other simulation models show ponding across the flatwood site. Here, adaptive selective simulation was used to enable users to constrain the time period they would like to view. Different scenarios (e.g. silvicultural treatments) and their impact on hydrologic pattern can be studied in detail.

We used a graduate level course “GIS in Land Resource Management” (GIS: Geographic Information Systems) as a test environment in order to evaluate the usefulness of our virtual field laboratory. Our intention was to involve students in future refinements and enhancements of the environmental virtual field laboratory and to receive preliminary response. Students in this course principally work with 2D GIS files and liked the extension to the 3rd and 4th dimensions. In particular, soils that are 3D natural bodies are commonly reduced to flat polygon maps with attached attribute tables. The 3D soil-landscape models represented the spatial distribution much more realistically.

The adaptive selective simulation facilitated the creation of many worldviews “on-the-fly”, providing multiple perspectives. This interactive tool stimulated interest to test different scenarios and students discussed possible cause-effect relationships for differences in water levels at well locations. Scenarios can be readily tested, which stimulates the student’s abstract geographic

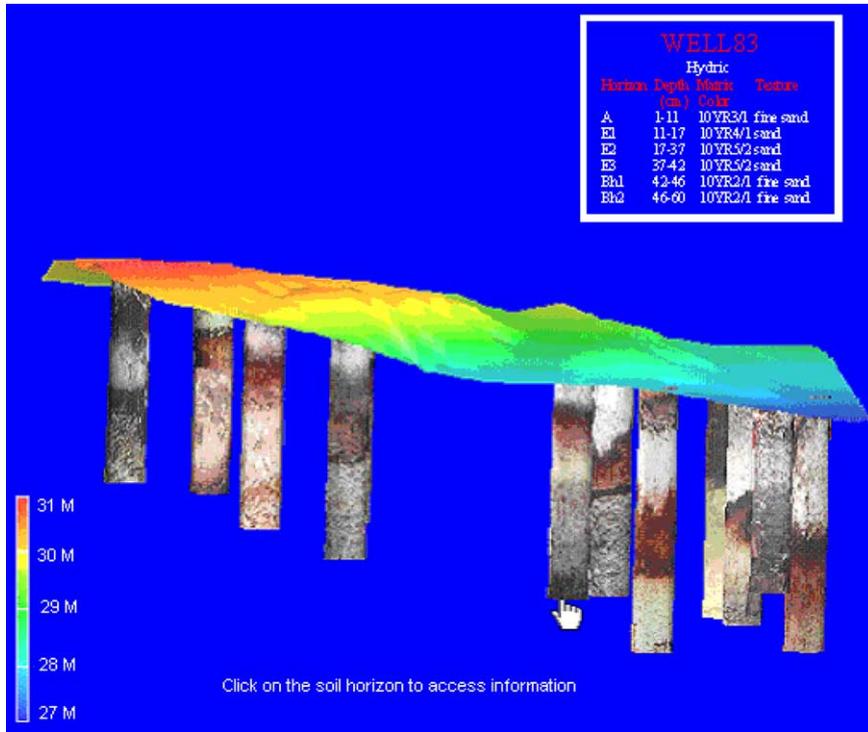


Fig. 5. Three-dimensional interactive soil profile model.

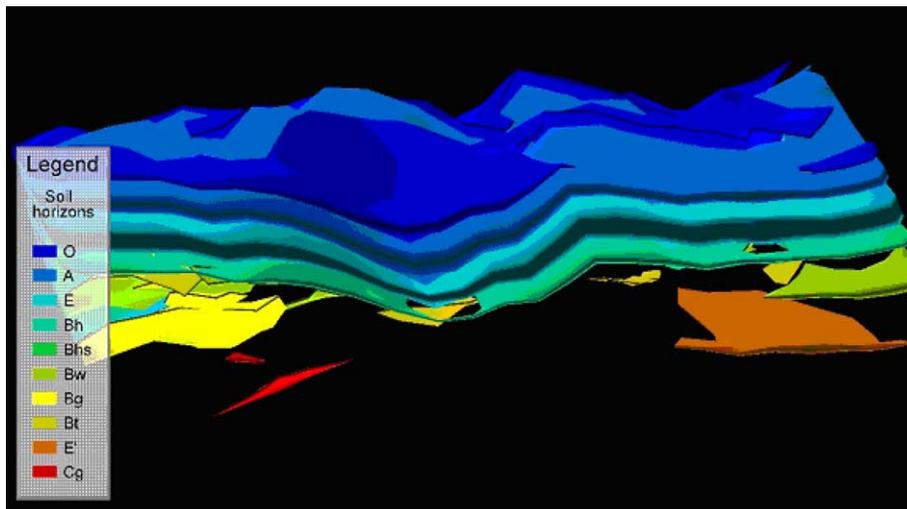


Fig. 6. Three-dimensional interactive soil layer model.

thinking skills. This method is well suited to learning about ecosystem processes. Students on a traditional field trip do not have the same experience as do students using the environmental virtual field laboratory. These students, who were trained in GIS, did not have problems

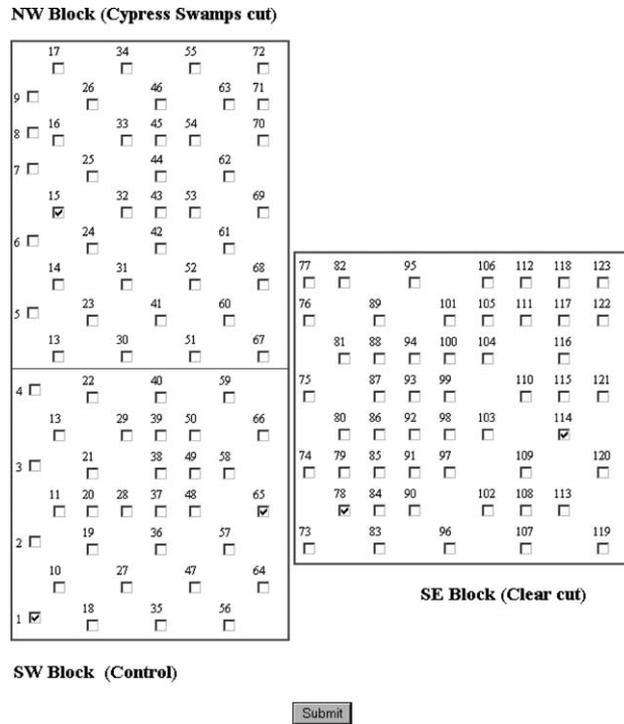


Fig. 7. User interface to select well locations (part of the adaptive selective simulation).

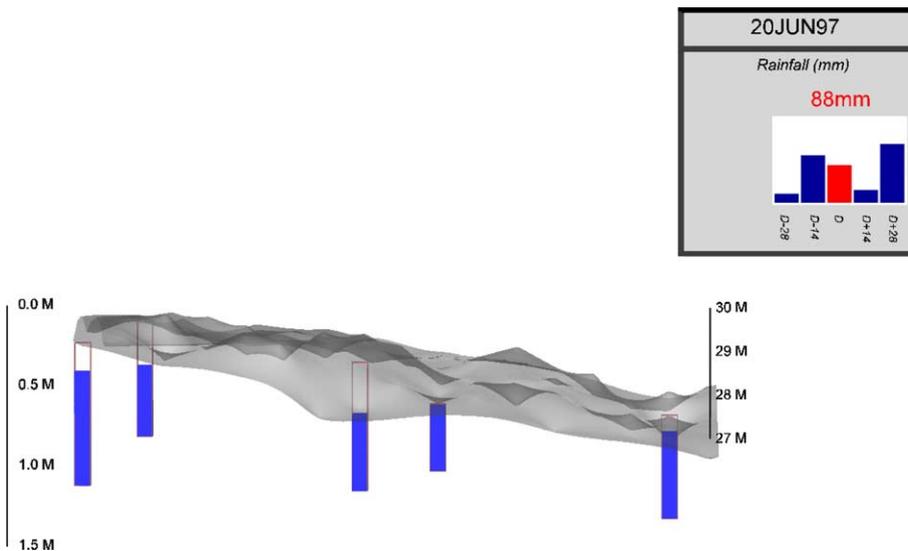


Fig. 8. Snapshot of the space-time animation of water table dynamics at selected well.

understanding the environmental virtual field laboratory. Yet, students not trained in using GIS might have had more difficulties. A more comprehensive survey is planned to evaluate our environmental virtual field laboratory.

The designers of the virtual field laboratory learned through a continual process of constructing, interpreting, and refining virtual models. Developing the environmental virtual field laboratory required intensive effort. It took about 1 year to create the tool. However, the tool can be reused many times and in a variety of courses. We developed a customized and domain specific e-learning environment that offers unique opportunities for student-centered investigations, shifting the traditional instructor roles to mentor and co-learner. Such a virtual field laboratory offers opportunities for distance education courses. Experimental learning through an asynchronous e-learning tool has the potential to enhance learning. We plan to integrate the environmental virtual field laboratory within a GIS course that is offered through the Soil and Water Science Department, Graduate Distance Education Environmental Science Track at the University of Florida. Digital learning environments offer potential benefits as a teaching environment and may be used to extend the learning experience.

Our interactive learning tools go beyond what an instructor can provide to students on a real field trip. Lockard, Abrams, and Many (1994) identified two general groups of computer aided learning and teaching (CAL and CAT) application systems: Type 1 involved using computer resources to do activities carried out without the aid of computers, while Type 2 involved using computers to enable teaching and learning in ways that had not been previously possible with conventional teaching approaches. Type 1 applications do not generally change the teaching strategy but do assist in making leaning independent, as well as helping reduce the need for direct teacher involvement. Our environmental virtual field laboratory implemented both types of CAL/ CAT applications. It mimicked learning about environmental properties and processes through field observations combined with a simulation environment that cannot be provided to students on a real field trip. Limitations of virtual field laboratories include the lack of landscapes experiences such as mosquitoes, humidity, and getting dirty. Our virtual field laboratory complements and/or enhances existing courses but is not meant as a complete substitute for field experiences. Who would like to miss a real field trip with getting wet feet in a swampy flatwood landscape?

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