Interactive Groundwater (IGW): An Innovative Digital Laboratory for Groundwater Education and Research

SHU-GUANG LI, QUN LIU

Department of Civil and Environmental Engineering, Michigan State University, East Lansing, Michigan 48824

Received 5 May 2003; accepted 29 July 2003

ABSTRACT: In this study, we present an award-wining software environment for groundwater education and research. The software functions as a "digital laboratory" in which students can freely explore: visually creating an aquifer of desired configurations and then immediately investigating and visualizing the groundwater system. Students learn by active exploration and interaction. The software allows introducing routinely research and complex problem-solving into the classroom. © 2004 Wiley Periodicals, Inc. Comput Appl Eng Educ 11: 179–202, 2003; Published online in Wiley InterScience (www.interscience.wiley.com.); DOI 10.1002/cae.10052

Keywords: virtual laboratory; groundwater modeling; real-time visualization; active learning; contaminant transport

INTRODUCTION

Need for Continued Groundwater Education

Since the 1980s, hydrologists, civil and environmental engineers, chemists, microbial ecologists, and many other scientists have been involved in characterizing, evaluating, and cleaning up hazardous-waste sites and contaminated groundwater. There has been an explosion in the number of site characterizations and remedial investigations related to active and abandoned hazardous-waste disposal sites, leaking tanks, and spills across the United States and around the globe. According to a recent report [25], almost half a million sites with potential contaminants have been reported to state or federal authorities over the past 15 years in the US. Of these, about 217,000 sites still require remediation. The US Environmental Protection Agency (EPA) estimates that the cleanup of these remaining sites will take up to 75 years and cost approximately $187 billion in 1996. The EPA further predicts that federal, state, and local governments and

---

IGW was named the Premier Courseware of 2002 at the 2002 Frontiers in Education Conference in Boston, Massachusetts.

Correspondence to S.-G. Li (lishug@egr.msu.edu).

Contract grant sponsor: National Science Foundation; contract grant numbers: EEC-0088137, EAR-9805357, BES-9811895.

Contract grant sponsors: Portland State University; Michigan State University.

private industries will commit billions of dollars annually over the next several decades to clean up sites contaminated with hazardous waste and petroleum products. This planned investment will fuel a strong demand for a broad range of groundwater-related characterization and remediation services and technologies, as well as, for trained professional engineers and scientists to carry out the work [25].

Need for Active Learning

The typical environmental science and engineering curriculum today teaches many of the basic scientific principles needed to understand how chemicals behave in the environment. It also teaches basic principles and techniques of groundwater monitoring and remediation, and it may provide opportunities to study remedial technologies in the laboratory. However, current curricula often fail to take advantage of more effective instructional methods and therefore do not accomplish all that they could.

Out of tradition and because of a lack of both awareness and appropriate materials, most instructors employ a lecture format in their courses. In this format, the instructor is the source of authority that along with the textbook, transmits knowledge down to students. As a consequence, students have little opportunity to employ true scientific inquiry. Conventional exercises provide opportunities for developing problem-solving and design skills, but they are inherently limited to simplistic ''paper and pencil'' solutions and often fail to take advantage of the rich visual environment that is available with todays computational tools. Students lack opportunities to visualize and to form their own ideas, and they rarely get a chance to work in any substantial way at applying the ideas of others to the real world. In this environment, students often develop a very limited view of what constitutes meaningful learning as they are only engaged in developing low level thinking skills (memorizing facts, procedures, terms, and definitions) in order to answer questions on exams.

This traditional, static lecture format results in a curriculum of disconnected items, subtasks, and subskills, one that fails to convey an understanding of the context in which these separate elements are combined to understand problems and achieve solutions. And because the opportunities to learn from experience are highly constrained, the student's development of cognitive management skills, including goal-setting, strategic planning, monitoring, evaluating, and revising, capabilities critical for effective learning and functioning, is highly limited. As a consequence, many students in conventional classrooms develop little confidence in their own ability to learn or in their own sense-making abilities. This instructional approach fails to take advantage of the fact that human beings are quintessentially sense-making, problem-solving creatures. Instruction that is fractionated and out of context fails to mobilize this powerful human characteristic [19,20].

LEARNING THEORIES AND THEIR IMPLICATIONS FOR INSTRUCTIONAL DESIGN

Action-Oriented Instructional Models

Good Teaching Actively Engages Students in the Solution of Concrete Problems. Educational researchers have suggested that if the goal of learning is to prepare students so that they can employ the concepts and theories addressed in the classroom for practical problem-solving in everyday situations, then students must engage in real-world uses of the knowledge [3,5,6,10,12]. These researchers stress that students learn little by just being ''talked at'' in the passive environment of a traditional lecture. Students need to participate actively—to explore, to question, to experiment, and to formulate their own solutions. Good teaching is not ''telling,'' which requires only that students memorize what they have heard. Students learn better, remember longer, and are better able to identify the appropriate concepts to solve new problems, when they learn by addressing concrete problems and actively participate in exploration and the pursuit of knowledge. We tend to forget what we are told, but we remember and understand deeply what we ourselves have discovered. Furthermore, students who pose questions and explore hypotheses are learning more than just information: they are learning how to learn. It is not desirable for students to just be listeners. They benefit from both producing as well as consuming knowledge [4,8].

Implementation Issues and Interactive Computer Environments

Recreating the Real World for the Classroom. Successful application of such action-oriented instructional models hinges on the availability of a learning environment in which students can engage in authentic and routine hands-on activities. However, accessing such an environment is not always easy. When teaching environmental investigation and restoration, technical and institutional limitations prevent us from using the natural subsurface environment as a testing ground for speculative remedial schemes. It is difficult to gain access to industrial sites undergoing cleanup and it is undesirable (and illegal) to contaminate test sites in order to give students a chance to actually clean them up. Moreover, the time required to test a groundwater cleanup strategy could easily exceed the time typically devoted to an undergraduate or graduate Student's education.

Interactive Environments for Learning. There is increasing agreement that high fidelity, computer-based representations, or ''microworlds,'' can provide a desirable vehicle for locating the critical characteristics of real-world investigations and design in the classroom [2,3,11,13,17]. Recent dramatic developments in computer software and hardware technologies make it possible to develop surprisingly realistic simulations and representations of complex realities. Modeling provides the ability to simulate the behavior of large-scale systems in a manageable environment (i.e., on a PC) and allows predictions of future outcomes based on previously studied events. Modeling is particularly useful in system exploration and making complex systems understandable. Finally, modeling provides a valuable means for quantifying integrated aquifer system interactions and the interactions among the geological, hydrological, and biochemical processes [1].

Many educational researchers support the potential of educational technology to bring hands-on real-world investigations within the reach of students in the classroom, particularly through interactive simulation [11]. These researchers believe a major benefit of a well-designed interactive environment is its ability to include ''opportunities for simulated apprenticeships, as well as, a wealth of learning support activities'' [24]. They note that computers give us enormous power to create situated learning environments where students gain hands-on experiences that reflect the kinds of real-world activities they are preparing for. Many other researchers see a powerful role for computer-based technologies for fosering problem-solving skills and apprenticeship-style learning [6,12,26].

INTERACTIVE GROUNDWATER (IGW) MODELING

Characteristics of Some Modeling Environments

Over the years, a number of comprehensive software environments have been developed for modeling subsurface flow and contaminant transport. These include the following: The U.S. Department of Defense (DOD) Groundwater Modeling System (GMS), Waterloo Hydrogeologic Inc. (WHI) Visual MODFLOW, Environmental Simulation, Inc. (ESI) Groundwater Vistas, and Integrated Environmental Simulation (IES) Processing MODFLOW.

Some of these environments are highly sophisticated with impressive capabilities. And although they have been widely employed to solve real-world groundwater problems, these software environments are generally not well suited to the educational setting because of the fragmented modeling paradigm they typically employ.

Traditional Modeling Paradigm's Bottleneck

The traditional modeling paradigm involves a scheme based on intermittent sequential data processing between periods of off-line visualization and analysis. A bottleneck occurs under this paradigm because of the inefficient processes employed to move information between various models and to the visualization programs. Modelers repeatedly rely on these transfer process as they refine the conceptual model and system parameters, through an iterative, trial and error process that is central to the ''art'' of modeling. This transfer of information is also an essential, critical element of an effective educational groundwater modeling environment because various models (regional flow, local flow, particle tracking, transport, etc.) and visualization programs must be coupled to one another for the student to obtain the real educational benefits of the modeling environment.

The traditional modeling paradigm employs the following steps:

(1) Create or modify a conceptual model;
(2) Assign or modify model stresses, properties, and starting/initial conditions;
(3) Solve the governing equations over the entire specified time span and store the results on a disk;
(4) Postprocess the results using a visualization package;
(5) Compare with field data;
(6) Analyze the results and make appropriate changes to the model; and
(7) Repeat.

Limitations for Educational Use

Most groundwater modeling studies involve the solution of a sequence of coupled numerical models. In this situation, each subsequent model depends on a complete solution to the previous one. For example, a typical model-based investigation on contaminant fate and transport at a waste disposal site may include four computer based stages: (1) regional-scale flow modeling, (2) local-scale flow modeling, (3) local-scale transport modeling, and (4) overall post-processing with a visualiztion package.

Although these stages are coupled and interact with each other, the traditional modeling paradigm often requires off-line processing to prepare the output from each stage prior to using it in the next; and results may not be presented in a format suitable for analysis until visual displays are developed during the final, post-processing stage. Hundreds of megabytes of information must be written to a slow storage device during the run, then processed and analyzed offline after the entire simulation has been completed, and read back into another model for the next stage of the overall study.

With a large sequence of coupled models, the preparation, execution, and analysis become an extremely laborious processes, increasing the vulnerability to human error.

Under the traditional paradigm, modelers also typically go off-line to change the conceptual model or the computational scheme, and each change in the model or input parameters requires that most other steps in the process be repeated. Further complications arise because data analysis tools are often unable to extract physically interesting quantities or the particular visualization package may provide only a limited capability because it is poorly matched to the underlying physical models used in the simulation code.

In general, while more powerful computers have enabled additional details and more realistic processes to be incorporated into routine practical model applications, these capabilities are not being transferred into the classroom. With traditional modeling environments, students quickly become more involved with figuring out how to move data around—between models, between pre- and post-processors, and to the programs used for intermediate analysis—than with real subsurface-science and engineering. This robs students of time that could be spent developing their higher order cognitive skills. These skills are better developed by focusing a student's efforts on interpreting data, evaluating assumptions, scrutinizing model accuracies, understanding subsurface processes and dynamics, characterizing contamination, or designing monitoring and remediation networks.

IGW—A COMPREHENSIVE DIGITAL LABORATORY FOR GROUNDWTAER EDUCATION AND RESEARCH

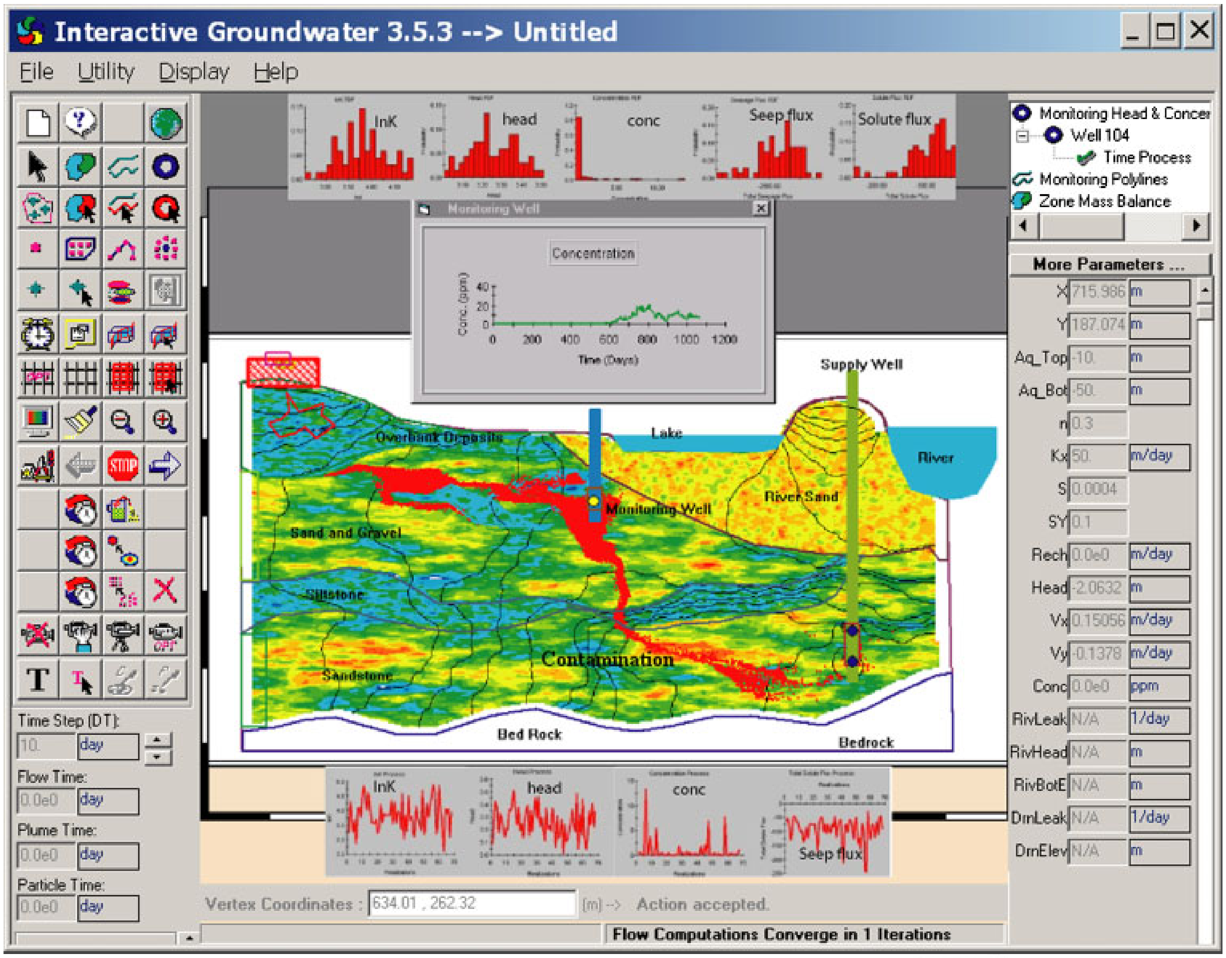
Since 1998, with the support of the NSF, the Oregon Joint Graduate School of Engineering (OJGSE), Portland State University (PSU), and Michigan State University (MSU), we have developed a comprehensive, combined research and educational software environment, that is, IGW. This software environment, currently designed for a real and cross-sectional 2D-groundwater flow and contaminant transport modeling in a one-layer aquifer, allows real-time interactive modeling, real-time visualization, real-time analysis, and real-time presentation of results.

Because of its educational potential, IGW recently won the 2002 Premier Award. The software was also recognized and demonstrated at the 2002 ASEE NSF Showcase. To further enhance its national impact, the Premier Award selection committee distributed copies of IGW to engineering schools nationwide and at major engineering education conferences (e.g., ASEE conferences and the Frontiers in Education conferences, etc.).

IGW Basic Characteristics

A single application program forms the core of this new environment. It allows execution and rapid on-line integration of multiple groundwater modeling tasks, as well as rapid presentation of complex data in a sophisticated graphical format. This interactive program permits the user to pause program execution, and rapidly explore and edit, on-line, any aspect of the model or modeling process. It allows the user to insert a hierarchy of submodel regions into a parent model, in order to provide greater detail where it is required, while numerically coupling the models. It permits the user to produce sophisticated 2D graphical displays of spatial, time-varying information at virtually any point during the modeling process. And it permits the modeler to steer the modeling process [16,21–23]. Figure 1 presents a snapshot of the IGW computational environment and a typical visual simulation.

The fact that IGW provides real-time response in an easy to understand form makes it an ideal tool for educational use and exploratory research. The software changes the role of the student in complex problem-solving projects. It shifts their primary focus away from determining how to move data among various models, pre-processors, and post-processors and onto cognitive problem-solving and decision-making tasks. The seamless model integration, visualization, and real-time processing and communication capability, make it possible for students to focus on critical conceptual issues and to quickly and iteratively examine modeling approximations and hypotheses, identify dominant processes, assess data worth and uncertainty, calibrate and validate the numerical representation, and experiment in real-time with



Time Step (DT):	10.	day
Flow Time:	0.0e0	day
Plume Time:	0.0e0	day
Particle Time:	0.0e0	day

X	715.986	m
Y	187.074	m
Aq_Top	-10.	m
Aq_Bot	-50.	m
n	0.3	
Kx	50.	m/day
S	0.0004	
SY	0.1	
Rech	0.0e0	m/day
Head	-2.0632	m
Vx	0.15056	m/day
Vy	-0.1378	m/day
Conc	0.0e0	ppm
RivLeak	N/A	1/day
RivHead	N/A	m
RivBotE	N/A	m
DrnLeak	N/A	1/day
DrnElev	N/A	m

Vertex Coordinates : 634.01 , 262.32 [m] --> Action accepted.

Flow Computations Converge in 1 Iterations

Figure 1 The IGW digital laboratory environment and a snapshot of a typical visual simulation. The palette on the left provides the tools and buttons for creating, running, visualizing, analyzing, and steering a model. The right pane displays the aquifer conditions and parameter values at the cursor location. The middle working area displays graphical conceptual model and animated visual simulation. The IGW website (http://www.egr.msu.edu/∼lishug/research/igw) presents extensive vivid dynamic simulations used in the classroom at Michigan State University (MSU) and Portland State University (PSU). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

environmental sampling, management, and remedial options.

IGW allows the students' thought processes to progress naturally and intuitively with the information visualized, overlaid, and compared at the instant it is required for analysis, providing a real sense of continuous active exploration and engaged problem solving. Being able to visualize subsurface flow, transport, and chemical processes as they evolve over time and visualize the complex interrelationships among hydrological and environmental variables sparks pivotal insights, giving rise to an intuitive grasp of the hydrogeological and chemical processes that cannot be readily obtained otherwise.

New Modeling Paradigm

The innovative interactive nature of IGW is derived from a new modeling paradigm that allows us to couple all the various models and solve them for conditions one time step forward from the current time. This allowed us to restructure and integrate the computations and modeling tasks into a single on-line application program—a program that permits the user to visualize the integrated behavior of the model system at every time step and evaluate its adequacy, so that the user can interrupt the computations, alter the model in significant ways, and restart computations as often as he/she deems necessary.

The basic concept is simple. Instead of treating flow and transport separately, we model them concurrently. Instead of treating regional-scale modeling, local-scale modeling, and site-scale modeling as different phases in a long sequential process, we couple the multi-scaled processes and model them simultaneously. Instead of relegating the graphical presentation of results and their analysis to the post-processing phase, at the end of a time consuming sequence of many steps, we incorporate them into a single on-line program with the simulator, to permit the interpretation of results as soon as they become available, at the end of each time step. To accomplish this, we employ the following new modeling paradigm.

At a discrete time level $t = t_n$ (the nth time step), perform the following:

(1) Flow modeling;
(2) Subscale flow modeling, if one or more sub-areas of detailed interest are specified;
(3) Particle tracking, if particles are introduced;
(4) Plume transport modeling, if contaminants are introduced;
(5) Subscale transport modeling, if defined sub-areas contain contaminants;
(6) Data and output processing and analysis, mass balance and water budget;
(7) Visualization;
(8) Repeat steps 1 through 7 for time step, t_{n+1}.

IGW Engine and Detailed Capabilities

IGW takes advantage of recent dramatic developments in computer technologies, software engineering, image processing, visualization software, geographic information system (GIS) technologies, as well as research in subsurface flow and contaminant transport processes and modeling. It provides an interactive, graphical environment for defining the aquifer framework, for inputting parameters, properties and stresses, for changing grid resolution, solvers, numerical schemes, and modeling methods, for controlling and managing program execution, and for integrating, overlaying, and visualizing data and results.

Groundwater modeling within such an environment is a process of high-level graphical conceptualization, as if one is drawing a picture of the site, and iteratively analyzing and improving the mathematical representation, making sense of the results, and solving problems. By pointing and clicking the mouse, the modeler can delineate areas of interest (e.g., the spatial extent of the modeled aquifer, its materials and properties; the spatial coverage of rivers, lakes, and wetlands; boreholes, wells; hydraulic stresses; and contamination sources) and immediately visualize the integrated dynamics and system interaction. The user is in control throughout the entire problem-solving process.

We employed object-oriented programming and designed the software environment so that students can, at any time—including during simulation or analysis—pause to edit and interact on-line with virtually any aspects of the modeling process—just like what a modeler can do offline at the beginning of the simulation. At any time, the students can (1) initiate transport modeling (e.g., particle tracking and/or plume simulation) to predict the fate and migration of spills at interactively specified locations, (2) subscale modeling that allows zooming into the detailed dynamics in real-time in areas of critical interest, and (3) stochastic modeling to examine the effects of subgrid variability and the associated model uncertainty. At any time, students can see the current results presented in an integrated and meaningful fashion, no matter how preliminary the model inputs or assumptions. The results displayed on the screen can then be used as starting conditions for continued ''instant'' incremental improvement. An incremental modeling capability proves extremely useful for groundwater investigation because of the inherently uncertain nature and the high cost of data acquisition.

The new software environment provides this unique, real-time interactive capability by writing the overall program in Visual Studio.net™ It controls the overall logic: the time stepping and nonlinear iterations, routing information across modeling components, tracking user action, providing visual feedback, accepting inputs and managing outputs, and processing and integrating results. In performing these tasks, the control program calls a number of embedded dynamic linking libraries (DLLs) (Fig. 2).

Flow and Transport Solver Library. A library of improved finite difference schemes for modeling groundwater flow and contaminant transport, in general, strongly heterogeneous aquifers with variable orientation of anisotropy [16]. These new schemes [16] allow students to construct aquifers of desired characteristics and complexity and provide accurate, efficient, and robust simulations of unsteady flow and contaminant transport and transformation (including advection, tensorial diffusion and dispersion, first-order decay, and linear equilibrium sorption) in saturated geological formations.

Sparse Matrix Solver (SMS) Library. A library of advanced matrix solvers including the algebraic multigrid solver [19]. These solvers have excellent

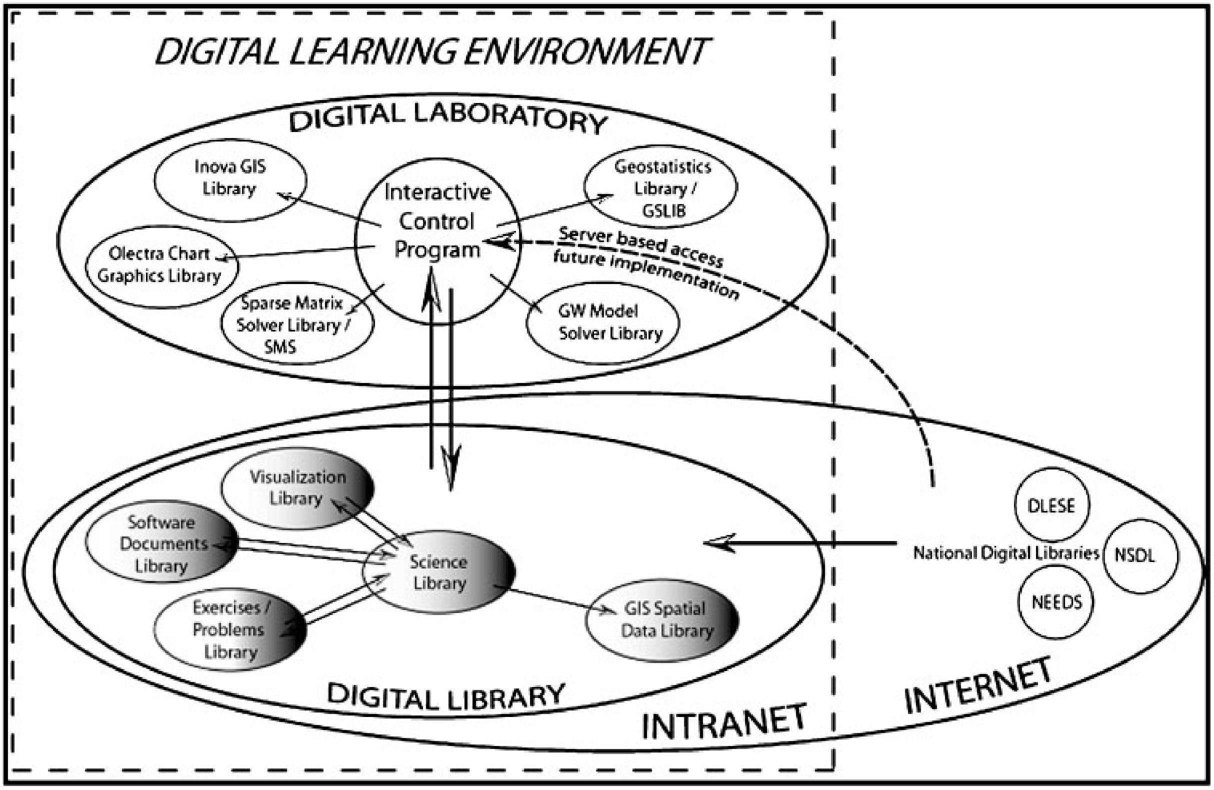


Figure 2 The underlying engine of the IGW Digital Laboratory. The arrows indicate the control capabilities of the various components. The shaded bubbles denote components that are still under development. DLESE, NEEDS, and NSDL are existing national digital libraries.

characteristics such as (1) being able to perform stable calculation of equation systems when solution process is not easily accelerated (e.g., in the presence of strong heterogeneity, anisotropy, variable orientation, singular stresses, or complex stratigraphy), and (2) being able to avoid rounding error accumulating with calculation iterations so that highly accurate solutions can be obtained.

Geostatistical Software Library (GSLIB). A library of advanced techniques and Fortran source programs for geostatistical interpolations and simulations [7]. These programs, combined with the new flow and transport solvers, allow modeling groundwater flow and pollutant transport in heterogeneous aquifers systematically.

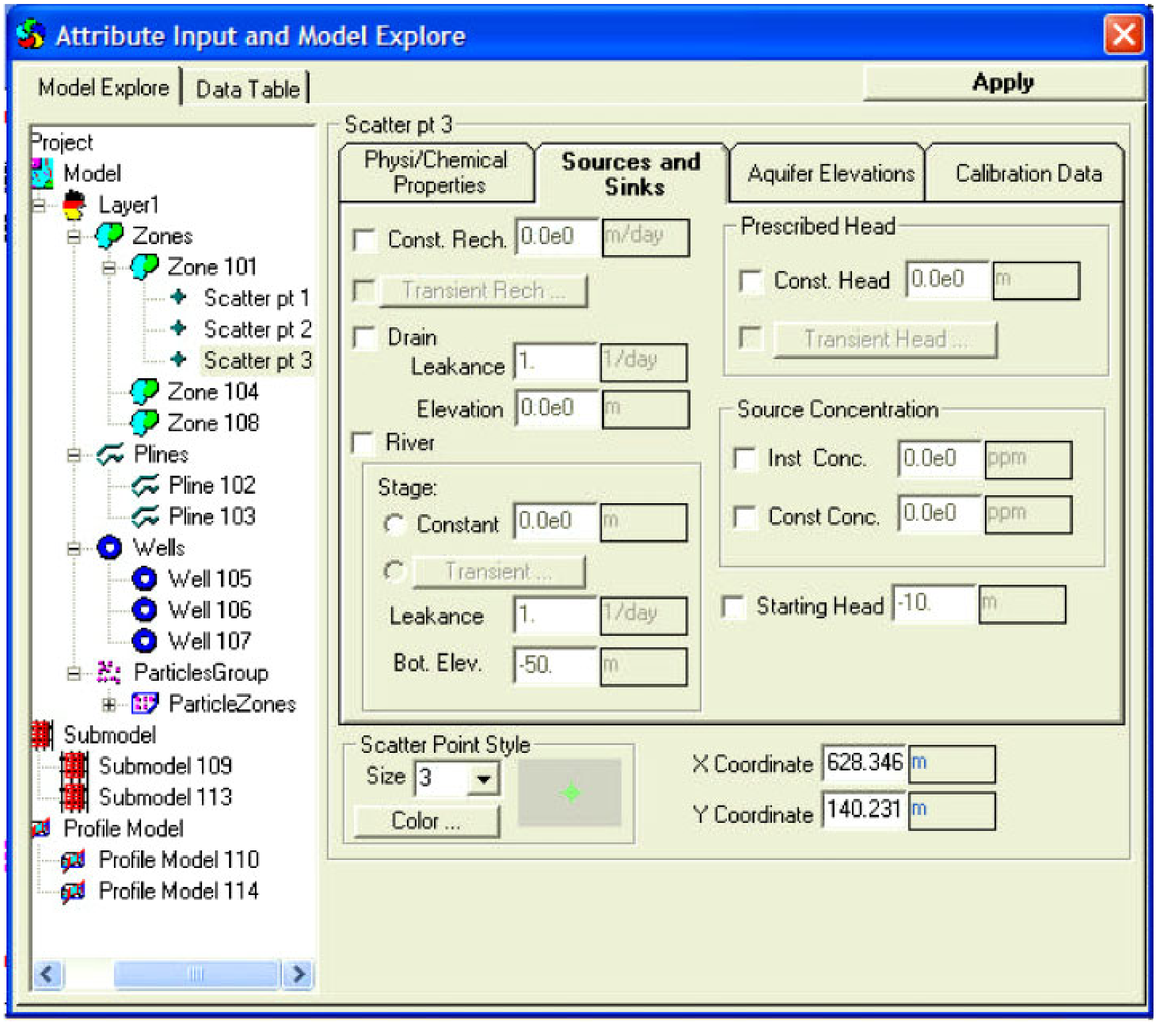
Inova GIS Library. A library that provides filters for GIS data and allows embedding GIS capabilities in windows applications. GIS represents a revolutionary tool for environmental, natural resources, and water resources planning, development, management, and protection. Inclusion of the GIS library into the IGW digital laboratory provides full fusion of some basic GIS capabilities and hydrogeology and makes it possible to bring a vast quantity of GIS data into the classroom. This provides a convenient means of addressing many important issues concerning the interactions of environmental, water resources, and land use planning and management.

Olectra Chart Library. A graphics library that allows for real-time animated visualization and analysis of system dynamics through displays ranging from simple bar charts to contour plots to complex 3D projections. With fast update capabilities and double buffering, the Olectra Chart library provides performance fast enough for real-time applications displaying changing data.

These computational, statistical, and graphical libraries are intelligently and seamlessly integrated into the object-oriented framework and the result is a complete point and click software environment that provides efficiency and maximum interactivity, transparency, accessibility, user control, and the capability of real-time visual simulation and analysis. Specifically, IGW offers the following unique "event driven" modeling capabilities.

Real-Time and Grid Independent Conceptual Modeling. Interactive and graphical specification and editing of model domain and aquifer properties and stresses over any arbitrarily shaped area at any time during model construction, simulation, and analysis. Interactive "model explorer" or a hierarchical graphical organization of model features (see Fig. 3). Copying of one conceptual model to multiple ones in the same working area for parallel visual sensitivity simulations. Automatic grid generation and conversion of conceptual representation to numerical models.

Real-Time Flow and Reactive Transport Modeling. Interactive simulation and real-time visualization and animation of flow in response to deterministic as well as stochastic stresses (e.g., induced by recharge, wells, streams and lakes, general head dependent flux, and steady or transient prescribed heads). Interactive, visual, and real-time particle tracking, random walk, and reactive transport modeling in both systematically and randomly fluctuating flow. Graphical release of particles in a polygon, along a polyline, and around wells, real-time forward and backward particle tracking, particle tracking with diffusion and dispersion, real-time conversion of particle plumes to and concentration plumes and vice versa, real-time capture



Scatter pt 3

☐ Const. Rech. 0.0e0 m/day

☐ Drain
Leakance 1. 1/day
Elevation 0.0e0 m

☐ River
Stage:
○ Constant 0.0e0 m
○ Transient ...
Leakance 1. 1/day
Bot. Elev. -50. m

Prescribed Head
☐ Const. Head 0.0e0 m

Source Concentration
☐ Inst. Conc. 0.0e0 ppm
☐ Const Conc. 0.0e0 ppm

☐ Starting Head -10. m

Scatter Point Style
Size 3

X Coordinate 628.346 m
Y Coordinate 140.231 m

Figure 3 The "Attribute Input and Model Explorer" window. The left-hand pane (Model Explore pane) is a hierarchical visualization of the model. The right-hand pane (Attribute Input pane) is where attributes (e.g., aquifer elevations, physical and chemical properties, and sources and sink characteristics) are entered for the features of the model. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

zone modeling and well-head delineation. Real-time modeling and visualization of aquifer transition from confined to unconfined to partially de-saturated or completely dry and rewetting.

Real-Time Hierarchical Modeling. On-line initiation of multiple submodels or hierarchies of submodels that allow ‘‘zooming’’ into the areas of critical interest without having to solve large matrix systems; real-time dynamic coupling of the ‘‘parent’’ model and its ‘‘children’’; automatic patching of a submodel to its parent model; interactive submodel detaching. Real-time visualization of multiple subscale flow and transport models.

Real-Time Cross-Sectional Modeling With Approximate “Lateral” Influx. Approximate modeling of steady and transient vertical flow patterns on multiple arbitrarily shaped cross-sections. Dynamical coupling with 2D areal model that provides an estimate of the net ‘‘cross flow’’ into the cross-sections. Real-time visual overlays of vertical flow dynamics and the aquifer stratigraphy, properties, hydrological features (rivers, lakes, wells, drains, surface seeps), and dynamically adjusted surface flooding area.

Real-Time Stochastic Modeling. Interactive and visual conditional simulation of hydrogeologic and geochemical spatial fields (e.g., conductivity, effective porosity, recharge, partition coefficient, decay coefficient); conditional and unconditional simulation; exploratory statistical data analysis (e.g., H-scatter plots, probability histograms); on-line variogram modeling with automatic or manual fitting; interactive scattered data interpolation, advanced regression, trend analysis, spatial smoothing/filtering, and Kriging; Gaussian and nonGaussian simulation techniques (e.g., FFT-based spectral algorithm, turning band method, sequential gaussian simulation, simulated annealing technique, multi-indicator simulation); multi-scale random field generation; real-time conditional flow and transport simulations. Interactive, real-time Monte Carlo and conditional Monte Carlo simulation. Real-time results processing, recursive computation of the means, variances, covariances, probabilities, and other statistics. Real-time visual stochastic capture zone delineation.

Real-Time GIS-Like Model Presentation. Automatic and customizable GIS-like overlays of model inputs (e.g., conductivity, transmissivity, porosity, partition coefficients, aquifer elevations, thickness, etc.), outputs (e.g., head, velocity, particles, plume concentration, standard deviations, capture zone, reservoir flooding areas, seepage and wetland delineations, etc.), computational grid, conceptual site features, built-in IGW drawings and text annotations, and multiple basemaps in mixed raster and/or vector formats (e.g., Bitmap, JPEG, AutoCAD DXF, and GIS Shapefile). Interactive adjustment of mapping sequence; automatic continuous screen capture of selected areas or windows at discrete time steps or user-specified time interval.

Real-Time Model Analysis. Real-time dynamic visualization of instantaneous and accumulative water and solute mass balance over any interactively specified zones. Visual and real-time monitoring of head, seepage flux, and solute flux hydrographs and concentration breakthroughs and comparison with observations. Real-time monitoring of model states (e.g., all model inputs and outputs and aquifer conditions) at cursor location; real-time visualization of means, standard deviations, and covariances. Real-time visual presentation of the probability distributions of state variables (e.g., of conductivity, head, seepage and solute fluxes, concentration) at user specified locations. Real-time presentation of the temporal processes (e.g., head, flux, and concentration) with confidence intervals.

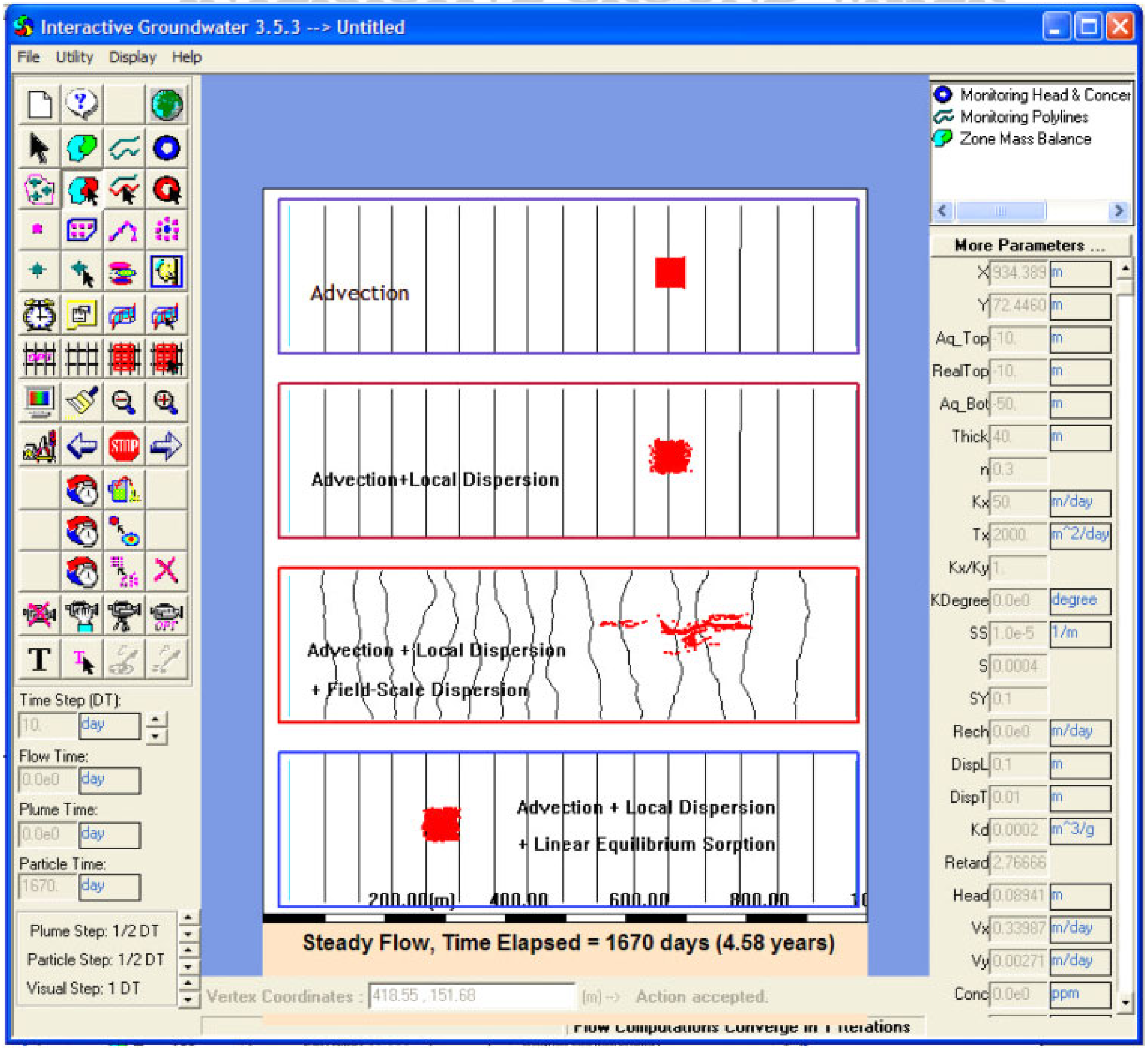
Real-Time Smart-Tutoring System. One-click, context sensitive, on-line help on software features, typical values of aquifer materials and contaminant properties, basic science concepts, and modeling techniques. Built-in frequently asked questions; online tutorials. Interactive wizard for beginners.

INNOVATIVE APPLICATIONS OF IGW

The unprecedented real-time capability transforms the way professors teach and students learn in water resources and environmental engineering and geosciences curricula related to groundwater.

Imagine conveying the concept of field-scale dispersion, retardation, effects of heterogeneity, capture zone, and dynamic interaction between groundwater and surface water and between physical and chemical processes utilizing vivid, real-time, and interactive simulations. Think about how much easier it would be to understand the invisible groundwater dynamics if students have an ‘‘interactive notepad’’ on which they can draw a sketch themselves and experiment interactively with the aquifer, the stress, the flow, the plume, the design, the numerical methods, and the different ways of visualizing the groundwater system. Consider the classroom in which students can learn groundwater monitoring and remediation by actually designing visually a sampling network and cleaning up the contamination with instant feedback. Envision teaching with an "interactive electronic chalkboard," the professor can draw a conceptual picture of a leaking waste disposal site and his/her students can immediately visualize how the water and contaminants move around and impact a nearby well-field. The professor can further modify the conceptual representation and evaluate alternative scenarios (e.g., different pumping strategies, different aquifer properties, or introduction of heterogeneity) on the plume migration in response to real-time student inquiries.

Over the years, we have applied extensively the new technology to innovate groundwater education and research. IGW is used by many universities as a digital laboratory or a visual thinking, modeling, and problem-solving environment that has benefited a significant number of courses in environmental and water resources engineering and geosciences curricula that have a groundwater or stochastic modeling component, such as the following:



Time Step (DT): 10. day

Flow Time: 0.0e0 day

Plume Time: 0.0e0 day

Particle Time: 1670. day

Plume Step: 1/2 DT
Particle Step: 1/2 DT
Visual Step: 1 DT

X 934.389 m
Y 72.4460 m
Aq_Top -10. m
RealTop -10. m
Aq_Bot -50. m
Thick 40. m
n 0.3
Kx 50. m/day
Tx 2000. m^2/day
Kx/Ky 1.
KDegree 0.0e0 degree
SS 1.0e-5 1/m
S 0.0004
SY 0.1
Rech 0.0e0 m/day
DispL 0.1 m
DispT 0.01 m
Kd 0.0002 m^3/g
Retard 2.76666
Head 0.08941 m
Vx 0.33987 m/day
Vy 0.00271 m/day
Conc 0.0e0 ppm

Steady Flow, Time Elapsed = 1670 days (4.58 years)

Vertex Coordinates : 418.55 , 151.68 (m) --> Action accepted.

Flow Computations Converge in 1 Iterations

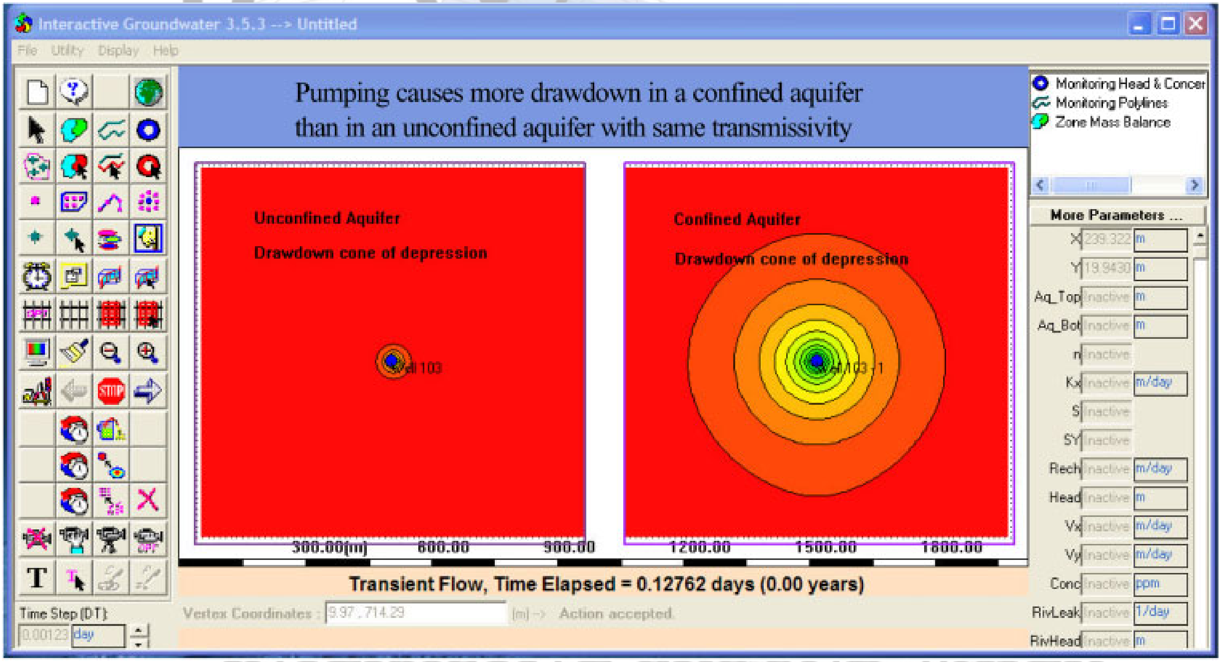
Figure 4 Students in Groundwater Modeling class at MSU and Groundwater Hydrology class at PSU interactively investigate transport processes in the subsurface. IGW allows students to visualize contaminant migration and "experience" the phenomena of "macrodispersion" associated with heterogeneity and "retardation" related to sorption. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

- Hydrogeology, Groundwater Hydrology, Groundwater Modeling, Geostatistics, Stochastic Groundwater Hydrology and Modeling.
- Contaminant Hydrogeology, Fate and Transport of Contaminants, Contaminant Transport Modeling, Groundwater Remediation.
- Computational Methods in Geosciences and Water Resources and Environmental Engineering, Geostatistics.
- Engineering Hydrology, Water Resources Engineering, Environmental Engineering.

Depending on the level and focus of the course, IGW is used in a variety of ways. It is used for real-time demonstration and visualization of basic concepts, processes, phenomena, (Figs. 4 and 5) as well as complex scale effects (Figs. 8–11), dynamic interaction among aquifers and among coupled physical-chemical processes (Fig. 12). It is also used to visualize and better understand the solution techniques and procedures—the numerics, statistics, geostatistics, and stochastics within a meaningful geosciences and engineering context (Figs. 13–15). Most importantly, IGW is used to provide integrated modeling exercises or a virtual field experience; for in-class live investigation with real-time feedback and student–instructor interaction; for individual, active, and engaged exploration and experimentation; and for out of class group-oriented problem-solving activities (Figs. 6, 7, 13–16). Finally, IGW is used to systematically implement a number of action-oriented instructional models, including collaborative learning, problem-based learning, and project based learning.

Active Learning of Fundamental Concepts and Processes

Within the IGW digital laboratory, a student investigator can freely explore. Students learn by doing, creative experimentation, and active research. IGW allows invisible processes and elusive concepts to actually be "experienced" and come to life. For example, by graphically generating an aquifer of desired configuration and characteristics and introducing a pumping well, students can immediately investigate, visualize, interact, and experiment with the well dynamics. In particular, students can examine the area of well influence and the area of contribution and



Pumping causes more drawdown in a confined aquifer than in an unconfined aquifer with same transmissivity

Transient Flow, Time Elapsed = 0.12762 days (0.00 years)

Time Step (DT): 0.00123 day

Vertex Coordinates : 9.97 , 714.29 (m) -> Action accepted.

X 239.322 m
Y 19.9430 m
Aq_Top Inactive m
Aq_Bot Inactive m
n Inactive
Kx Inactive m/day
S Inactive
SY Inactive
Rech Inactive m/day
Head Inactive m
Vx Inactive m/day
Vy Inactive m/day
Conc Inactive ppm
RivLeak Inactive 1/day
RivHead Inactive m

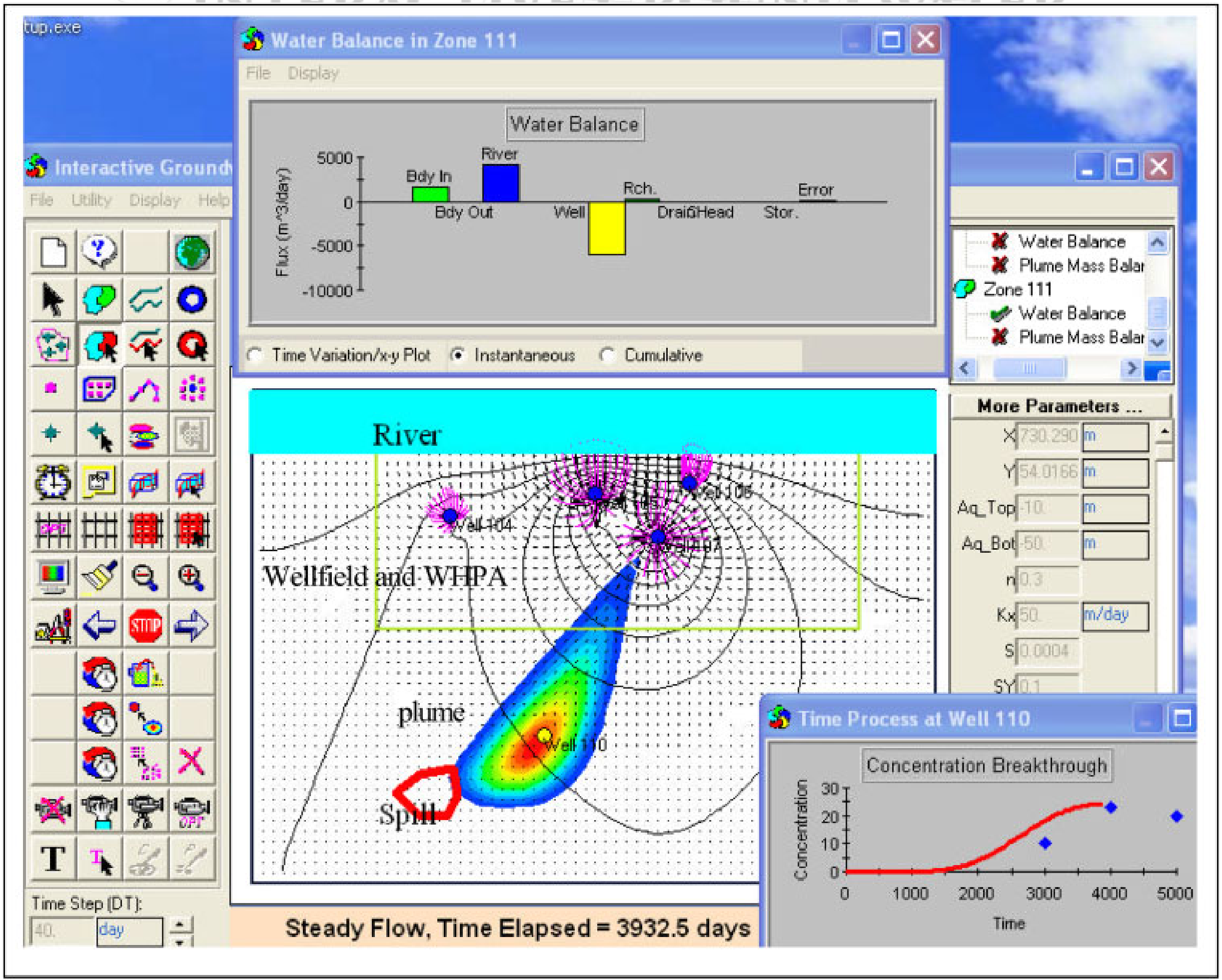
Figure 5 Students in Water Resources Engineering class at PSU and Engineering Hydrology and Groundwater Hydrology classes at MSU learn basic concepts and processes related to aquifer flow through real-time and visual explorations. Utilizing IGW as a "visual interactive notepad" students experiment with factors that affect the well dynamics. The visual environment allows them to appreciate the dramatically different drawdown response to pumping in a confined and unconfined aquifer because of their different storage mechanisms. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley. com.]

explore how different aquifer properties (e.g., conductivity, coefficient of anisotropy, or storage coefficient) affect the evolution of well-drawdown cone of depression (Fig. 5).

By introducing additional wells and a connected stream nearby, students can further investigate well interference and visualize aquifer–stream interaction. Students can interactively adjust the settings of the stream–aquifer interface, and/or add a recharge component to the model and can readily discern the changes in the head distributions and associated flow patterns as the results are immediately processed and displayed (Fig. 6).

By visually introducing a contaminant spill, a student can investigate and visualize in real-time contaminant transport and transformation processes including advection, diffusion, dispersion, sorption, retardation, and decay under different geological, hydrological, hydraulic, and chemical conditions interactively and graphically specified by them or an instructor (Fig. 6).

By installing sampling and extraction wells, students can learn how to characterize and remediate the



○ Time Variation/x-y Plot ● Instantaneous ○ Cumulative

X 730.290 m
Y 54.0166 m
Aq_Top 10. m
Aq_Bot -50. m
n 0.3
Kx 50. m/day
S 0.0004
SY 0.1

Time Step (DT): 40. day

Steady Flow, Time Elapsed = 3932.5 days

Figure 6 Utilizing IGW as an "visual interactive blackboard," professor in MSU groundwater modeling class and PSU groundwater hydrology and water resources engineering classes leads a live investigation on the fate and transport of an organic solvent found downstream of an industrial site and the impact on a nearby community well-field. The professor iteratively improves the conceptual model and investigates different hypothetical scenarios in response to real-time student inputs, inquiries, and discussion. The visual and open-ended explorations promote hands-on and discovery learning and foster higher-order thinking skills. The live investigations energize students and completely change the classroom dynamics. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley. com.]

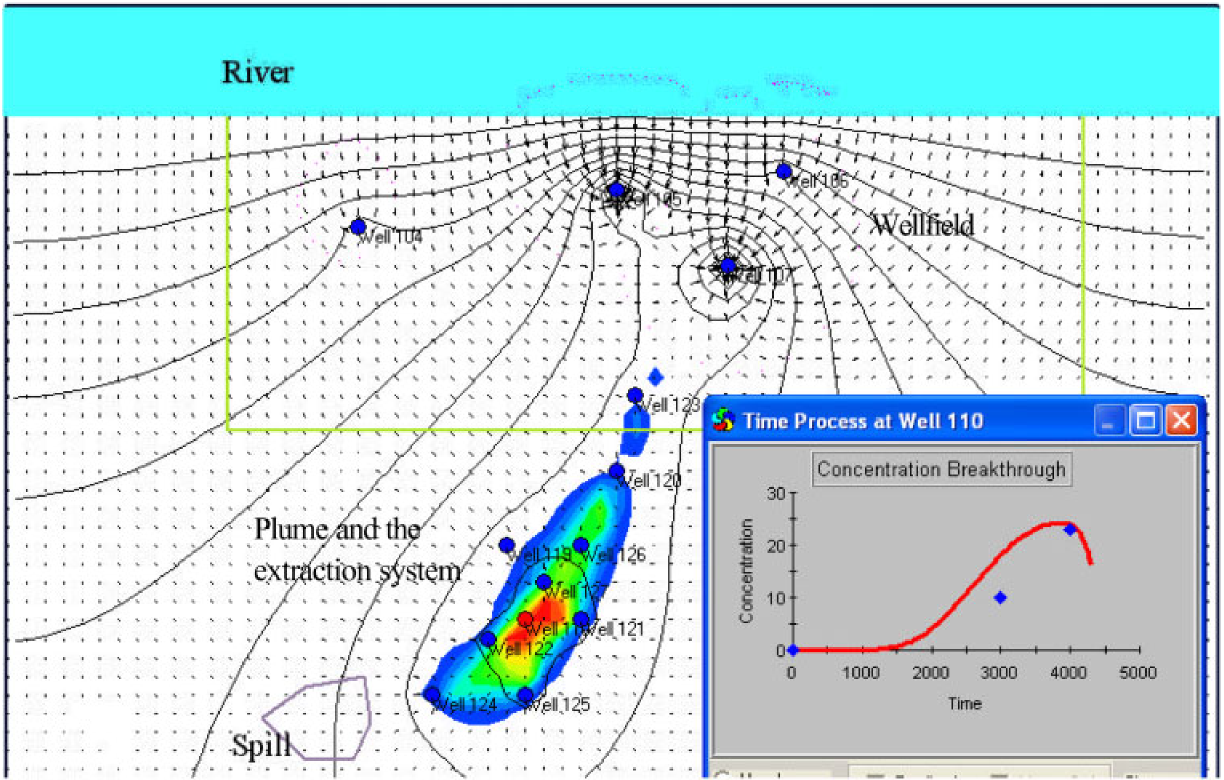


Figure 7 Students in Groundwater Modeling classes at MSU and PSU and in Groundwater Remediation class at Oregon State University (OSU) learn groundwater remediation and monitoring by actually designing extraction and sampling networks and cleaning up the aquifer. Utilizing IGW real-time capability, students interactively and graphically experiment with the different extraction networks and sampling alternatives and immediately visualize the plume response and evaluate the performance of remediation design. IGW complements theoretical instructions and provides students with much needed hands-on experience in remediation and monitoring design. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

contamination. They can visually experiment with the various cleanup schemes (with respect to, e.g., pumping patterns, rates, and scheduling) and monitor instantaneously the plume response (Fig. 7).

Bringing Cutting-Edge Research Into the Classroom

IGW allows bringing new contents and cutting-edge research into the classroom. For example, by generating a heterogeneous aquifer (e.g., introducing zones of different properties or random variability), students can examine the effects of heterogeneity on flow and plume migration and investigate ways to model the heterogeneous transport [9] (Figs. 8–12). In particular, students can investigate the impacts of low and high permeability zones, the tailing and channeling effects (Figs. 8 and 12), the macrodispersion, the relationship between dilution and dispersion (Fig. 9), the effects of heterogeneity on cleanup efficiency (Fig. 10), the different ways of representing heterogeneity (e.g., Gaussian or nonGaussian models), and the validity and range of applicability of the various effective models and representations (Fig. 9), and how heterogeneities may significantly complicate site characterization, monitoring network design, and groundwater remediation [9].

By invoking IGW stochastic modeling capability, students can investigate how heterogeneity, because of data limitation, translates into uncertainty in a systematic probabilistic framework. Student can generate plausible aquifer realizations consistent with the limited data and make a probabilistic prediction of the aquifer flow and contaminant transport (Figs. 11 and 15). Students can further investigate the impact of data collection on uncertainty reduction through ‘‘conditional simulation’’ [7,9].

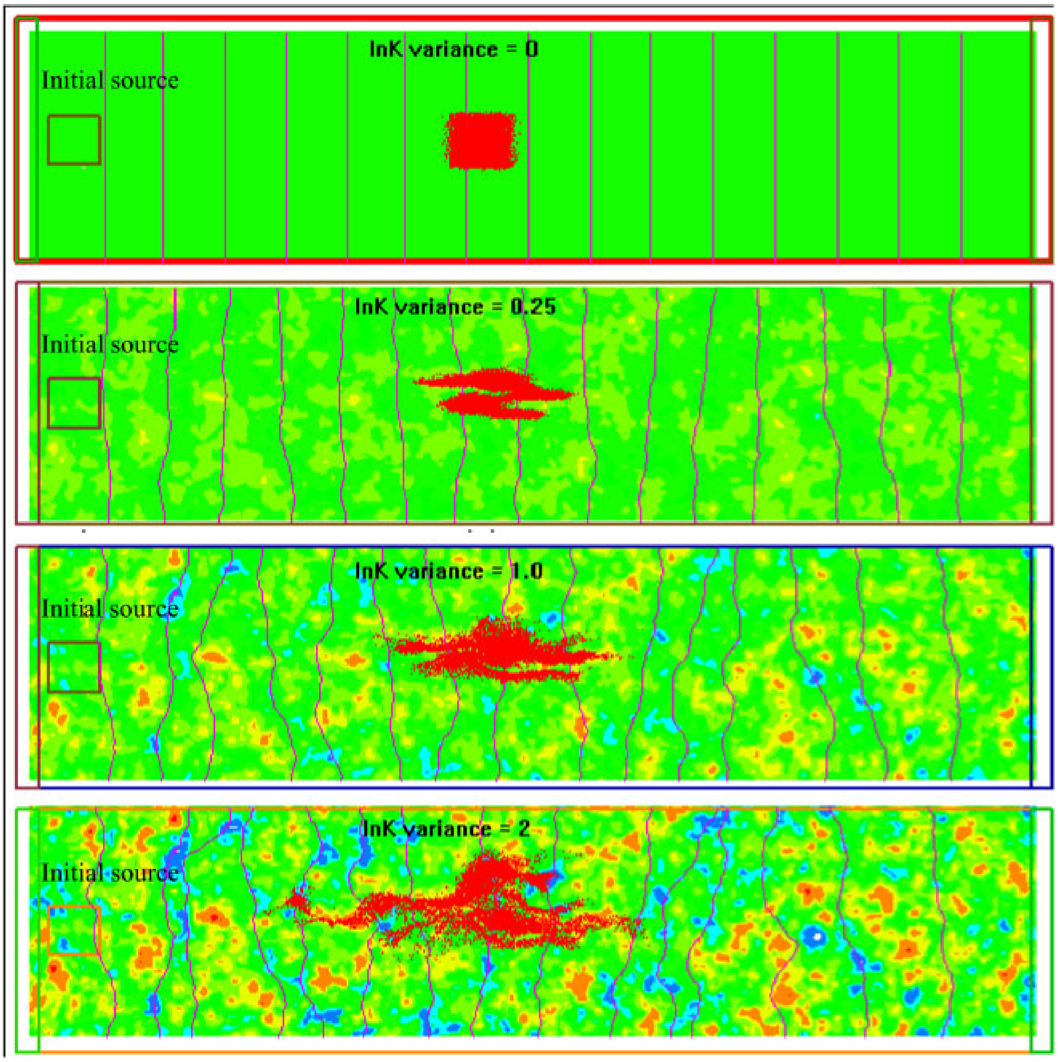


Figure 8 Utilizing IGW as a virtual research laboratory, students in Stochastic Subsurface Hydrology class at MSU and in Advanced Topics in Subsurface Flow and Transport class at PSU investigate the effects of heterogeneity on contaminant transport. Students visually create aquifers of desired configurations and characteristics, interact in real-time with the conceptual representation and site features that affect heterogeneous transport. The high impact real-time visualizations of IGW allow students "experience" the complex scale effects in the subsurface. Students develop a deep understanding of the dramatic impacts of small-scale heterogeneity on field-scale transport. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

By generating an aquifer with "random" variability in multiple spatial parameters and/or temporal stresses and boundary conditions characterized by different statistical correlation and cross-correlation models, students can examine the interactions among geological, hydrological, and chemical heterogeneity (Fig. 12), the effective hydraulic and biochemical properties, and the effect of the different correlation models on the flow, transport, and transformation. One can also investigate "nonideal transport" associated with the "trapping effects," the preferential channels, and the interacting chemical and physical heterogeneity (Fig. 12), and their implications on site characterization and remediation.

By generating an aquifer that exhibits multiple scales of variations in its properties, students can study the impact and significance of scale interaction, the interaction between large-scale nonstationarity and small-scale dynamics, the interaction of regional and site-scale flow and transport processes through a

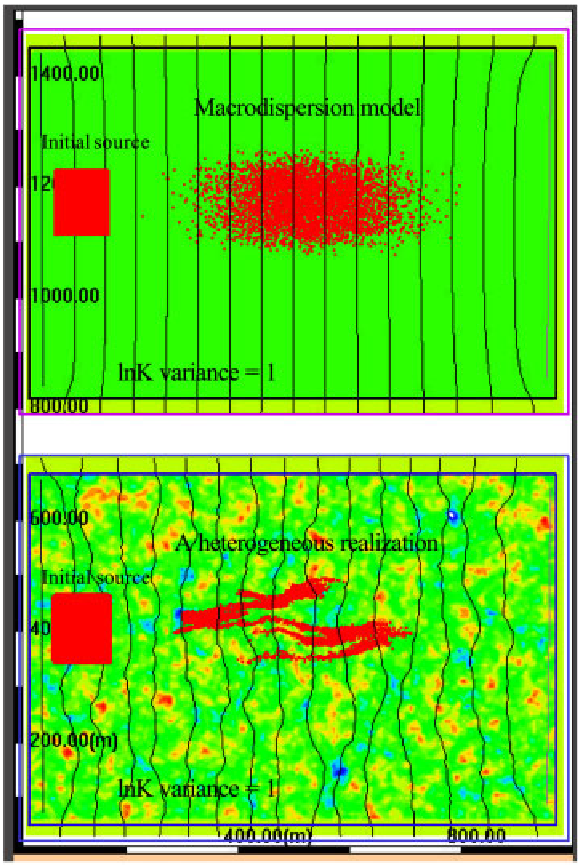


Figure 9 Students in Stochastic Subsurface Hydrology class at MSU investigate ways to model solute transport in heterogeneous aquifers. In particular, students examine the validity and range of applicability of the effective macrodispersion models. Through extensive explorations and interacting with a range of factors that control field-scale dispersion, students found that effective macrodispersion models, though popular in theoretical literature, provide a poor representation of field-scale transport in most practically meaningful situations. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

cascade of intermediate-scales of variability. Utilizing the new interactive hierarchical modeling capabilities, one can further explore ways to realistically model multi-scaled processes and to assimilate data across multiple spatial scales under realistic conditions (Fig. 13). Students can also investigate the effectiveness and implications of different ways to scale up and scale down a cascade of variabilities.

Making Mathematics Meaningful

IGW makes mathematics transparent. Abstract numerics, statistics, and stochastics come alive! IGW allows students to take a more "behind the scenes" approach to examining results. They can interact and experiment hands-on with the model solvers, algorithms, and solution techniques for a concrete and physically meaningful situation and instantly visualize the practical implications of their choices. Comparisons of the different results encourage students to seriously consider the implications of their chosen solution methods and the assumptive framework that apply when developing solution schemes.

For example, students can visualize the impact of solver selection on the rate of contaminant plume spreading (Fig. 14). They can visualize on-line the matrix solution process and the iterations of nonlinear differential equations. They can compare different methods for solving sparse matrix systems and how aquifer heterogeneity and/or anisotropy may potentially cause slow solution convergence. Students can also visualize the effect of different discretization schemes for approximating elliptic, hyperbolic, and parabolic partial differential equations. They can visually observe the numerical error or inaccuracies and their evolution—the effect of grid spacing and time step size on the solution accuracy and visualize the phenomena of numerical dispersion and spurious oscillations [14,15].

Students can interactively learn, investigate, and visualize statistics and probability and conditional probability within a meaningful geosciences and engineering context (e.g., what is the probability that the advancing TCE plume may hit the community wells with a concentration exceeding the EPA standard?) (Fig. 15). They can interact with and visualize the techniques of numerical integration (particle tracking), spatial interpolation, statistical regression and interpolation, spatial data analysis, histogram and correlation and variogram modeling, random field generation, conditional geostatistical simulation, Monte Carlo simulation, and conditional Monte Carlo simulation.

The students thus use the IGW environment to learn computational mathematics and statistical and probabilistic methods in water resources and environmental engineering and geosciences. This is extremely important because teaching fundamentals and quantitative theory has always been a major challenge in an applied engineering discipline. Theoretical equations are often deemed abstract and numerical schemes dry. Students do not often see how solving differential equations can be related to cleaning up groundwater contamination. Within the environment, mathematics becomes concrete and differential equations more meaningful.

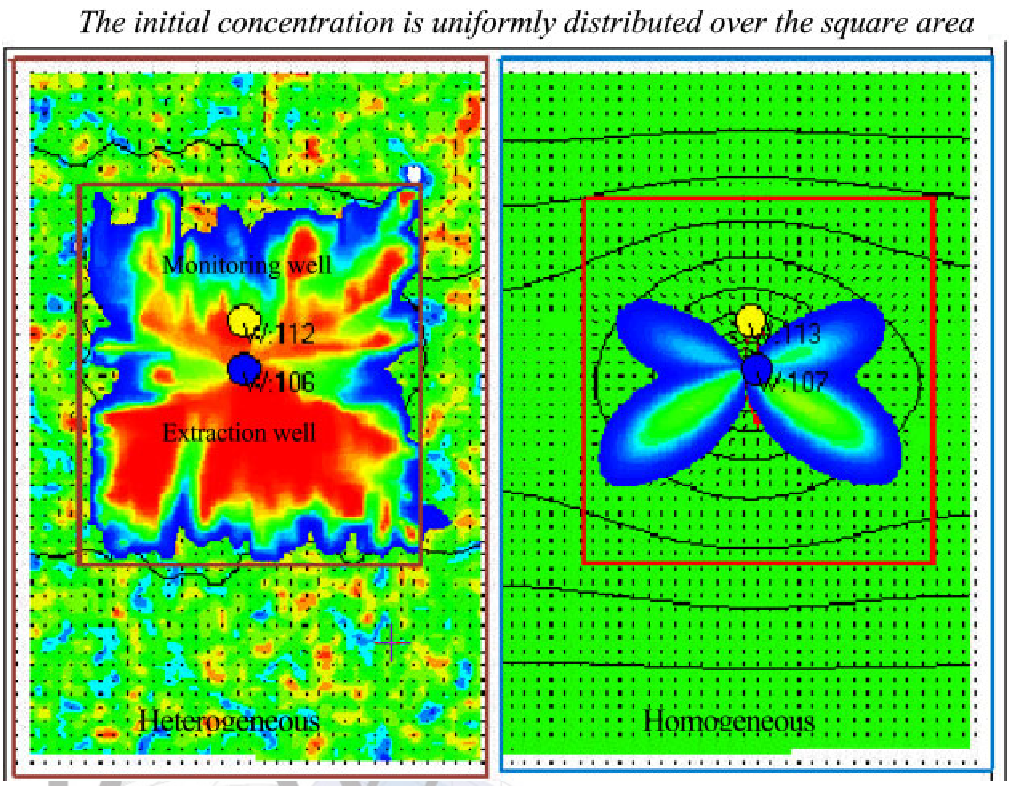


Figure 10 Students in Stochastic Subsurface Hydrology classes at MSU and PSU investigate the effect of heterogeneity on groundwater cleanup. By creating virtual contaminated aquifers with and without small-scale heterogeneity, students found what practitioners empirically discovered in the field that cleaning up groundwater contamination using "pump and treat" is often much more difficult than originally expected because of the "trapping" effects and remediation designs based on traditional deterministic models substantially underestimate the cleanup time. Students develop a deep understanding of what they discovered themselves. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Bring Real-World Investigations Into the Classroom

Finally, IGW allows bringing integrated and interdisplinary site investigations into the classroom. The IGW environment is transformed into a virtual experimental field site or "testing ground" (Fig. 16).

By providing instantaneous feedback, and making a student's thinking explicit, visible, and understandable to all in a naturally expressive manner, the environment is ideal for effective collaborative learning, interdisciplinary interactions, and communication, for involving others with different skills and cultural backgrounds in sharing information, brainstorming, and developing ideas.

Performing site investigations simultaneously nurtures and expands both problem-solving strategies and disciplinary knowledge bases by placing students in the active role of a researcher/problem-solver confronted with ill-structured problems that mirror real-world situations. Students can get a true feel for real-world group work through instructor mediated cycles of interaction, feedback, class discussion, skill development, and oral and written reporting. The instructor can teach the concepts, principles, and skills within this engaging context using real situations to stimulate and invite the students to participate in the experience on their own terms. Such techniques provide for active learning and the opportunity to integrate diverse elements, such as case studies (the problem), group work (student teams), problem solving (vocational learning-by-doing), instructor interaction with groups, and class discussion. Thus the classroom becomes a knowledge building, learning community.

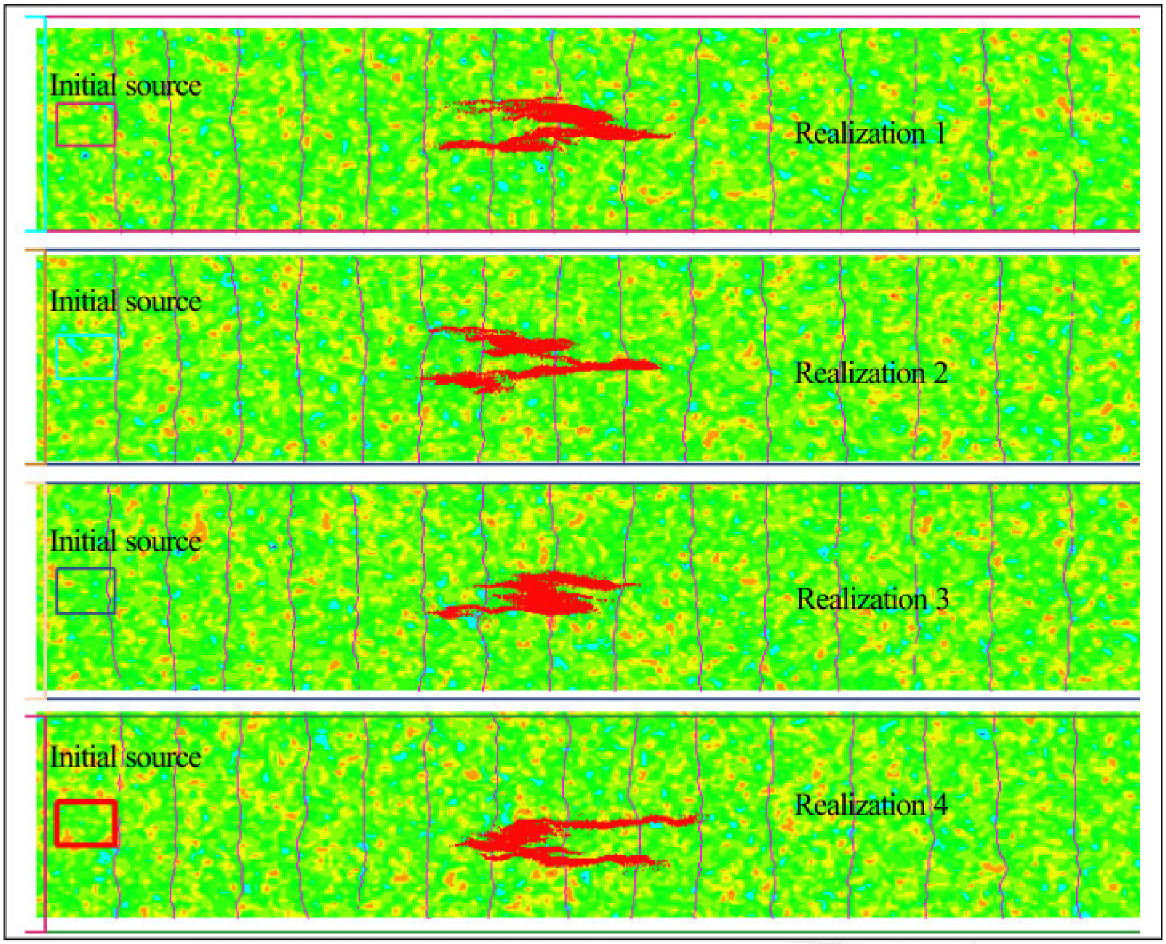


Figure 11 Students in Groundwater Modeling and Stochastic Subsurface Hydrology classes at MSU investigate the relationship between spatial variability and uncertainty and how data collection can be used as a systematic way to reduce uncertainty in site characterization. Students learn, because of data limitation, heterogeneity translates into uncertainty in the subsurface properties which, in turn, cause the nonuniqueness in the predicted flow and plume dynamics. Students also find that likely plume realizations are often quite different even after the plume travels tens or even hundreds of correlation scales. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Acting as investigators and working in teams, students can confront tangible practical problems, for example, cleaning up an accidental contamination spill, evaluating the environmental impact of a leaking landfill, developing a wellhead protection program for a municipal well-field, conducting a remedial feasibility study for a hazardous waste site, or providing expert testimony in a legal dispute. Students learn by conducting guided site investigations and solving authentic problems. Since the students lack significant information and experience, they will ask questions. When adopting the new instructional model, we expect the stock queries, "Why do we need to know this?" or "Which equation should we use to solve the problem?" to be replaced by new and more relevant questions such as:

- Where is the plume of contamination and what is in it?
- What data do we need to collect to find the plume and characterize it?
- Where is the optimal place to install a monitoring well?

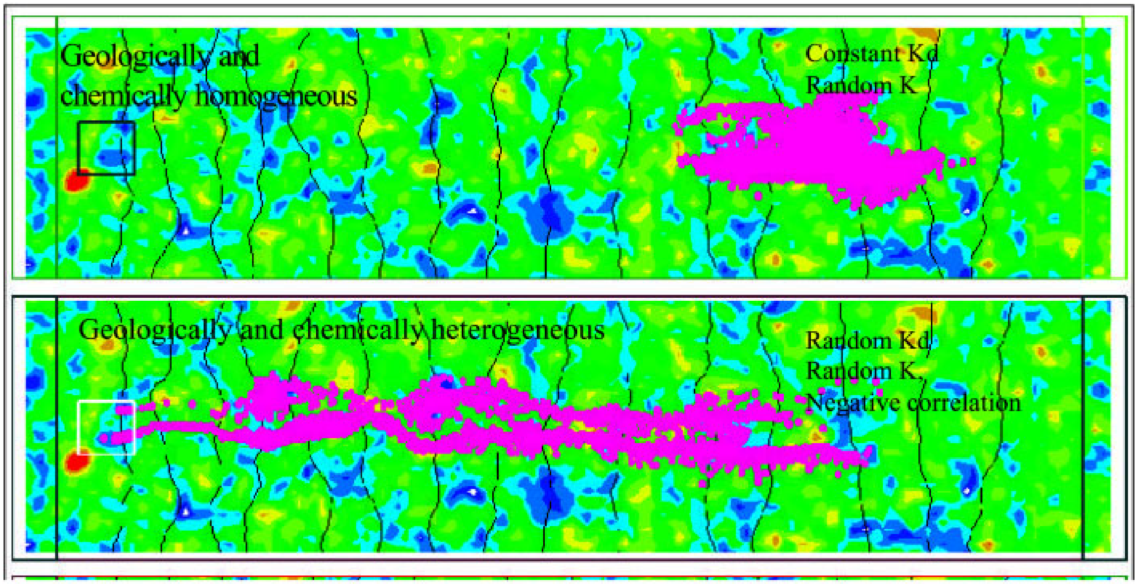


Figure 12 Students in Stochastic Subsurface Hydrology investigate reactive transport in heterogeneous aquifer. IGW allows students to "feel" the strongly nonlinear interaction between physical and chemical heterogeneity. In particular, students find that a typical negative correlation between the conductivity and partition coefficient has the effect of significantly increasing the overall velocity variability, creating the strong tailing and channeling effects that are often observed in the field. [Color figure can be viewed in the online issue, which is available at www. interscience.wiley.com.]

- Why is our model inconsistent with our observations?
- How can we modify our conceptual representation to explain the data and improve our understanding?

Through these questions, called "learning issues," students become responsible for their own learning. The students tap into their creative resources and they develop direction and focus. Working in groups, they discuss the monitoring issues, report back, present findings, challenge and debate each other, explain their points of view, and search for cleanup strategies that build on the strengths of all the group members. In this setting, the instructor becomes a mentor, a facilitator, a co-learner, and a co-investigator with the student. The instructor moves among groups, directing students' discussions and energies when appropriate. The instructor provides coaching and support. At critical times, the instructor teaches students the skills, strategies, and links they need to complete the tasks they define for themselves. Rather than simply lecture, the instructor instead cultivates skills, focuses effort, fosters resourcefulness, and maintains an interactive climate of learning, exploration, and discovery.

"Open Mode" Visual Investigation Versus "Closed Mode" Virtual Investigation. Students can utilize the environment in an "open mode" format. This is the natural functioning environment of the software and corresponds to the systematic way that modeling software packages are implemented in the professional world. The full range of software tools are available and the student has full control to adjust all model parameters with the end goal being to develop a model that sufficiently represents the real-world situation.

IGW also allows students to engage in virtual site investigations that utilize its "closed mode" format capabilities. In contrast to the open mode format, the closed mode format presents the problem in terms of the software, is not transparent, and limits the tools that are available to the students. The software allows the instructor to limit access to certain information, disable software features, and thus keep the students largely "in the dark" in terms of what is actually happening in the aquifer. The students' subsequent

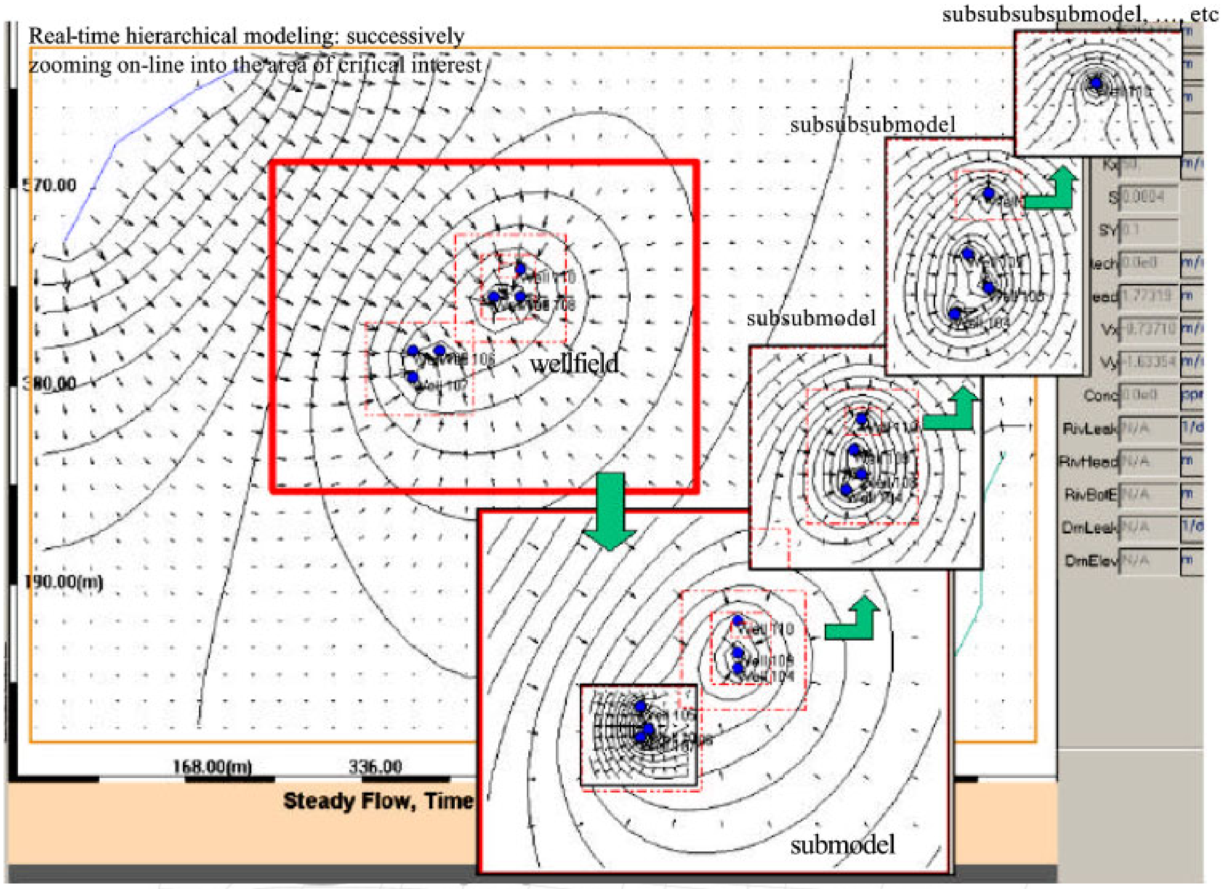


Figure 13 Utilizing IGW real-time hierarchical modeling capability, students in Groundwater Modeling class at MSU investigate a complex groundwater system across multiple spatial scales. Students obtained high-resolution dynamics in areas of critical interest (e.g., around wells) by developing a hierarchy of groundwater models of increasingly higher resolution and smaller domain. IGW automatically couples on-line the model hierarchies, with the parent model dynamically providing the boundary conditions for its "children" which, in turn, provide the boundary conditions for their own "children." The unique hierarchical modeling capability of IGW eliminates a major computational bottleneck in large-scale groundwater modeling and allows bringing complex problem solving into the classroom on a routine basis. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

explorations must be their "candle in the darkness." For example, the students cannot "see" the extent of a contamination plume visually but must make scientific determinations, and thus "illuminate" the hidden environment, based on data extracted from monitoring wells. The closed mode format allows instructors to present a site that the students can monitor, investigate, and analyze in real-time without being able to adjust its intrinsic parameters or artificially visualize it (which adds to the tenability of the virtual site as representing a real-world site in the minds of the students).

Thus students mimic the steps taken during a real-site investigation and cleanup effort: (1) investigating the site to determine its geologic, hydrologic, chemical, and physical characteristics, (2) designing and implementing a monitoring and remediation program, and (3) providing overall project management by having to work within a specified budget and time frame. The environment

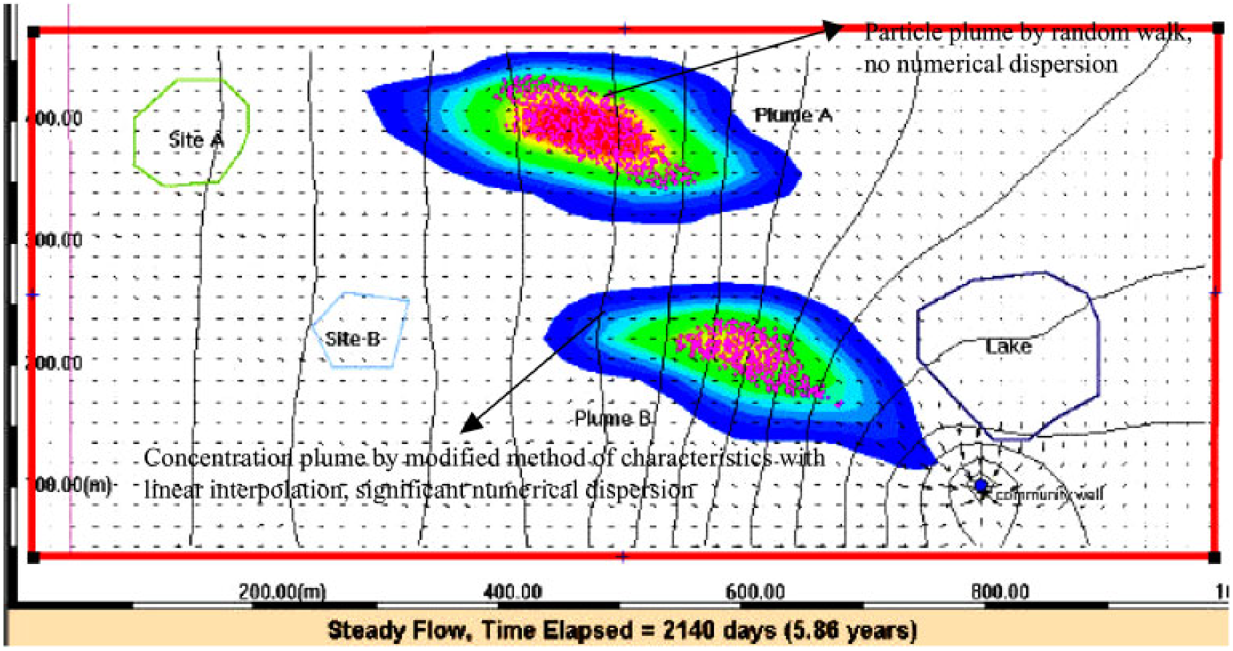


Figure 14 Students in Numerical Methods in Environmental and Water Resources Engineering class at PSU and Groundwater Modeling class at MSU investigate the phenomena of ''numerical dispersion,'' a common numerical error in model-based site investigation. Guided by the numerical theories learned in the classroom, students interact with the numerical representation, for example, grid resolution, time step, and discretization schemes. Students develop a deep understanding of the implication of ''numerical dilution'' and the critical importance of numerical methods in practical groundwater modeling. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

allows instructors to tweak the exact implementation details. These details can be customized according to the content and the level of the course in which it is used.

SUMMARY OF INSTRUCTIONAL BENIFITS AND NATIONAL DISSEMINATION

In a nutshell, we have presented a unique multi-intelligent, multi-modal, and multi-sensory digital learning environment that allows an instructor to implement an action-oriented curriculum that emphasizes learning by doing, conceptual modeling, real-time interaction, creative experimentation, and critical thinking.

The innovative environment produces a number of practical benefits. The new software system:

- fosters hands-on problem-solving skills and critical reflection and creative thinking abilities;
- promotes a ''constructivist'' view of learning that capitalizes on what we know of how students learn best;
- motivates student interaction, creative experimentation, cooperation, and collaboration;
- provides seamless integration of education with research and theory with application and introduces in a substantial way cutting-edge research into engineering education;
- promotes ''nonlinear inquiry'' of knowledge and facilitates ''storylines'' or thematic learning, where a pathway for exploration is woven around particular project dynamics;
- facilitates student-centered learning, allowing choice in the pathways for learning and the location and rate at which material is introduced;
- improves the delivery of advanced engineering education to women and minorities by addressing different learning styles and modalities and facilitating individualized learning and independent studies; and

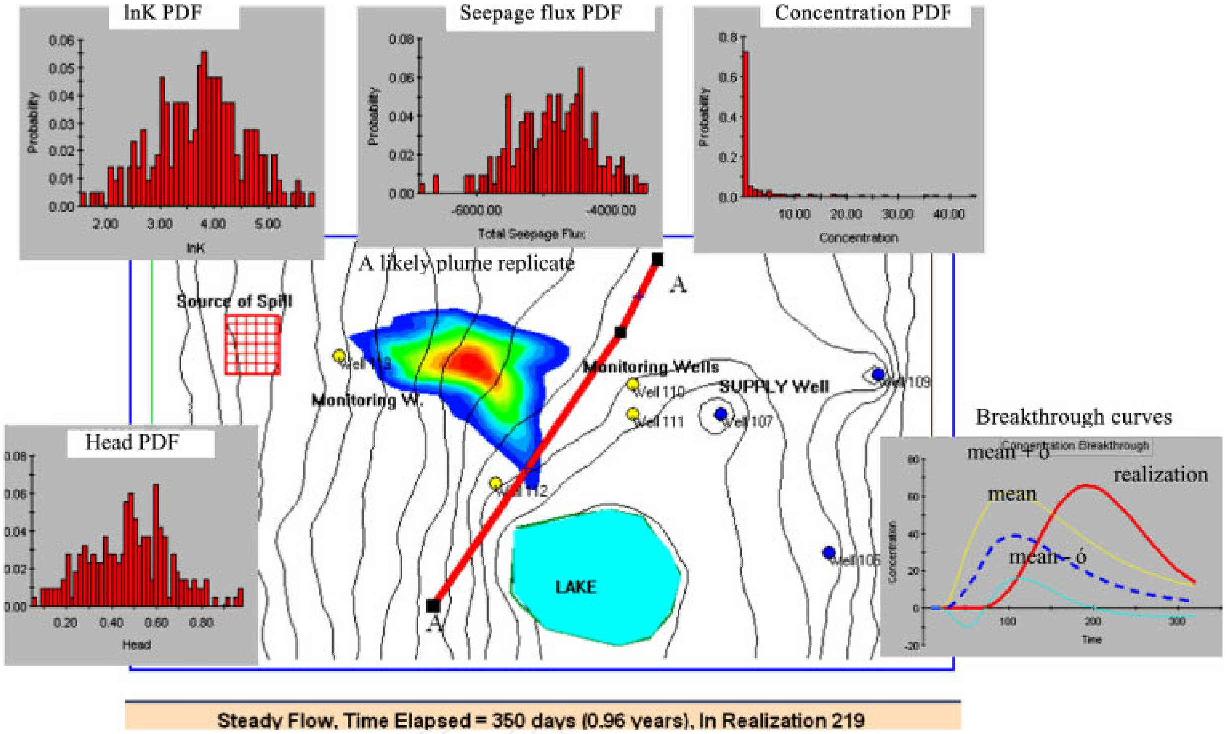
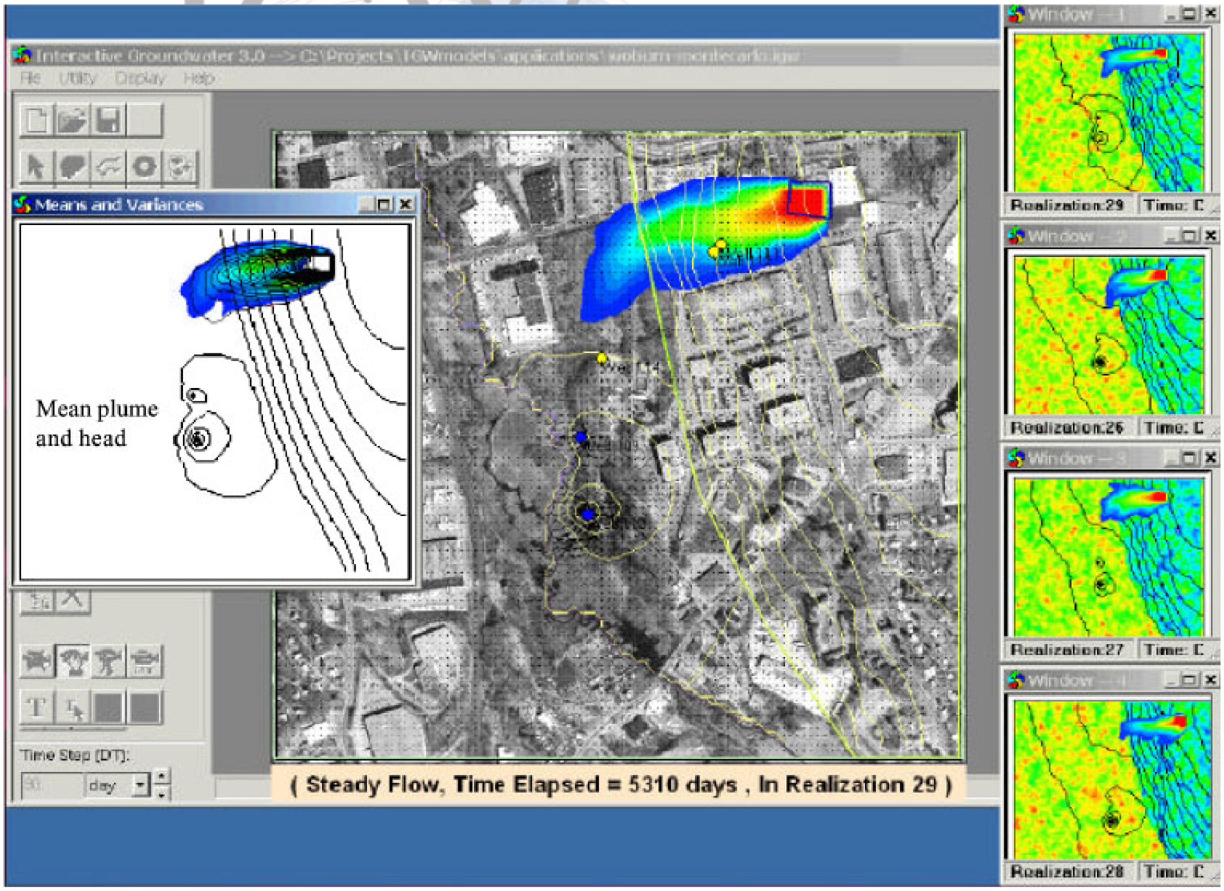


Figure 15 (*Caption on page 200.*)



`Aquifer conditions modified for educational purpose`

Figure 16 (*Caption on page 200.*)

- enhances career opportunities for students by giving them advanced experience in practical problem solving.

NATIONAL DISSEMINATION

IGW is distributed through a number of channels. The Premier Award Committee provides copies of the software on the 'Premier Courseware of 2002' CD to engineering schools nationwide and at major educational conferences. They are also providing copies of the CD to those who request one through the National Engineering Education Delivery System (NEEDS) website. In addition, the latest version of the software, documentation, and associated presentations are available through the IGW website at http://www.egr.msu.edu/~lishug/research/igw/.

ACKNOWLEDGMENTS

The authors thank Bill Gray of the University of Notre Dame, George Pinder of the University of Vermont, George Yeh of the University of Central Florida, Albert Valocchi of the University of Illinois at Urbana Champaign, and Claire Welty of Drexel

---

Figure 15 Students in Stochastic Subsurface Hydrology class at MSU use probabilistic approaches to predict the impact of an industrial spill on the environment. Students discover that while the log conductivity, head, and seepage flux are often normally distributed, the probability distribution of the concentration is strongly skewed and the concentration standard deviation, the focus of many recent theoretical studies, does not provide an adequate measure of uncertainty under most practically meaningful situations. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Figure 16 Utilizing the practical and engaging context documented in the best seller and movie "A Civil Action," students in Groundwater Modeling classes at MSU and PSU investigate the high-profile superfund groundwater contamination site in Woburn, Massachusetts. The courses integrate the student's education and research roles, and stress active, hands-on, and collaborative learning and practical problem-solving skills and critical thinking abilities with less dependence on traditional lectures. The courses develop simultaneously students' problem-solving skills and disciplinary knowledge bases by placing them in the active role of researchers and problem solvers confronted with ill-structured real-world situations. Students learn applied groundwater modeling by actually conducting a comprehensive model-based characterization study of the Woburn site. The class is divided into teams who act as consultants representing, respectively, the victims/local community and the potential responsible parties and provide expert witness for their respective "clients." Using IGW, each student "consultant" team develop and calibrate a groundwater flow and contaminant transport model that is used to characterize the complex groundwater contamination site and address a series of focal problems surrounding the controversy regarding the fate and transport of the groundwater contaminants at the various industrial sites in the vicinity of the city drinking wells. The courses involve group work, class debate, brainstorming, written report, and final oral defense on the groundwater flow and solute transport issues at the Woburn site. The instructor organizes and pilots this cycle of activity, and teaches groundwater modeling concepts, principles, and skills within that context. The courses adopt performance-based evaluations that take as the object of assessment the final product or the groundwater model that students develop. Specifically, students are evaluated based on how well they can characterize the site given the limited data available and on how effectively they communicate and defend their results, findings, and the decision-making process to their client and the public (in this case, it is the instructor and their peer students) both orally and in a formal technical report. The assessment tests the whole-system learning that emphasizes such activities as defining problems, making assumptions, testing hypothesis, developing strategies, trial and errors, evaluating data and data worth, dealing with heterogeneity and uncertainty, detecting "signal" from seemingly random measurements, integrating sciences, constructing arguments, and debating conclusions. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

University for their letters in support of IGW for the 2002 Premier Award. The authors also thank the Premier Award selection committee for their valuable comments and detailed evaluation on the software. Kyle Paulson and Roger Wallace, Michigan State University, and Bill Fish, Portland State University, edited parts of the materials used in this manuscript and their contributions significantly improved the presentation of this paper. The development of *Interactive Groundwater* is a collaborative effort. Shu-Guang Li is the chief architect of the overall software system, the new modeling paradigm, numerical methods, and algorithmic innovations. Qun Liu is the chief software engineer. Other authors of the software system include Huasheng Liao and Qingsheng Huang. David Ni contributed to the implementation of the algebraic multigrid matrix solver, geostatistical data analysis and simulation, and stochastic modeling. Kyle Paulson is the primary author of the IGW tutorials and users manual [21−23]. Huasheng Liao is the primary author of the preliminary IGW reference manual [16]. Steve Wesley provided responses to frequently asked questions. Soheil Afshari performed IGW code testing against known analytical solutions. Andreanne Simard provided assistance in software testing and documentation.

REFERENCES

[1] M. P. Anderson and W. W. Woessner, Applied groundwater modeling—Simulation of flow and advective transport, Academic Press, San Diego, CA, 1992.

[2] A. Benney, Creating an active learning environment using digital video—What I did and how I did It, World Conference on Educational Multimedia, Hypermedia and Telecommunications (EDMEDIA). Vol. 2001, Issue 1, Fairfield Univ., USA.

[3] J. S. Brown, A. Collins, and P. Duguid, Situated cognition and the culture of learning, Educ Res 18 (1989), 32−42.

[4] E. G. Cohen, Restructuring the classroom: Conditions for productive small groups, Rev Educ Res 64 (1994), 1−35.

[5] A. Collins and J. S. Brown, The computer as a tool for learning through reflection, In: H. Mandl and A. Lesgold, editors, Learning issues for intelligent tutoring systems, Springer-Verlag, New York, 1988, pp 1−18.

[6] R. Denning and P. Smith, A case study in the development of an interactive learning environment to teach problem solving skills, J Interact Learn Res 9 (1998), 3−36.

[7] C. V. Deutsch and A. G. Journel. GSLIB: Geostatistical Software Library and User's Guide, 2nd ed., Oxford University Press, New York, 1997.

[8] T. M. Duff, J. Lowyck, and D. H. Honassen, editors, Designing environments for constructive learning, Springer-Verlag, Heidelberg, 1993, pp 231−247.

[9] L. Gelhar, Stochastic subsurface hydrology, Prentice Hall, Englewood Cliffs, NJ, 1993.

[10] M. M. Griffin, You can't get there from here: Situated learning, transfer and map skills, Contemporary, Educ Psychol 20 (1995), 65−87.

[11] S. Harley, Situated learning and classroom instruction, Educ Technol 33 (1993), 46−51.

[12] P. C. Honebein, T. M. Duffy, and B. J. Fishman, Constructivism and the design of learning environments: Context and authentic activities for learning, In: T. M. Duffy, J. Lowyck, and D. H. Jonassen, editors, Designing environments for constructive learning, Springer-Verlag, Heidelberg, 1993, pp 87−108.

[13] J. A. N. Lee, Interactive learning with a web-based digital library system, in Ninth DELOS Workshop on Digital Libraries for Distance Learning, Brno, Czech Republic, 15−17 April, 1999.

[14] S. G. Li, F. Ruan, and D. B. McLaughlin, A space-time accurate method for solving solute transport problems, Water Resour Res 28 (1992), 2297−2306.

[15] T. Lowry and S. G. Li, A characteristic-based finite-analytic method for solving the two-dimensional steady-state advection-diffusion equation, Water Resour Res 38 (2002), 1123, doi: 10.1029/2001WR000518.

[16] H. Liao, K. J. Paulson, S. G. Li, C. F. Ni, and R. Wallace, IGW 3 Reference Manual, Department of Civil and Environmental Engineering, Michigan State University, 2003.

[17] H. McLellan, Virtual environments and situated learning, Multimedia Rev 2 (1991), 30−37.

[18] W. S. Mehl and C. M. Hills, MODFLOW-2000, The U.S. Geological Survey Ground-Water Model—User Guide to the Link-AMG (LMG) Package for solving matrix equations using an algebraic multigrid solver: U.S. Geological Survey Open-File Report 01-177, 2001, 33 p.

[19] National Science Foundation, Restructuring Engineering Education: A Focus on Change, Report of an NSF Workshop on Engineering Education, NSF 95-65, Division of Undergraduate for Education and Human Resources, 1995.

[20] National Science Foundation, Geoscience Education: A Recommended Strategy, NSF 97-171, Arlington, VA, 1997.

[21] K. J. Paulson and S. G. Li. Interactive Groundwater Tutorial, Department of Civil and Environmental Engineering, Michigan State University, 2002.

[22] K. J. Paulson and S. G. Li. Interactive Groundwater Users Manual, Department of Civil and Environmental Engineering, Michigan State University, 2002.

[23] K. J. Paulson and S. G. Li, Interactive Groundwater Quick Tutorial, Department of Civil and Environmental Engineering, Michigan State University, 2002.

[24] T. C. Reeves, Evaluating interactive multimedia, In: D. M. Gayeski, editor, Multimedia for learning: Development, application, evaluation, Englewood Cliffs, NJ, Educational Technology Publications, 1993, pp 97–112.

[25] US Environmental Protection Agency, Cleanup the Nation's Waste Sites: Markets and Technology Trends, EPA-542-R-96-005A, 1997.

[26] M. F. Young, Assessment of situated learning using computer environments, J Sci Edu Technol 4 (1995), 89–96.

BIOGRAPHIES

Shu-Guang Li is an associate professor of civil and environment at Michigan State University and is a licensed professional engineer. Dr. Li received his PhD (1993) in water resources and environmental engineering from Massachusetts Institute of Technology and MS (1988) in Hydraulics and Computational Fluid Mechanics from the University of Iowa. Dr. Li is actively involved in teaching and research in the areas of groundwater hydrology, groundwater modeling, stochastic groundwater modeling, and numerical methods in water resources and environmental engineering.

Qun Liu is a research associate in the Department of Civil and Environmental Engineering at Michigan State University. He received his PhD (1993) in civil engineering and applied mechanics and MS (1990) in computational mechanics from Sichuan University, China. Dr. Liu's research is concerned with civil and environmental engineering informatics. His expertise cuts across multiple disciplines, including biofluid mechanics, structural engineering, information technology, and software engineering. His recent research focuses on real-time, object-oriented groundwater modeling and 3D visualization.