The Effect of Modeling and Visualization Resources on Student Understanding of Physical Hydrology

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ABSTRACT

We investigated the effect of modeling and visualization resources on upper-division, undergraduate and graduate students' performance on an open-ended assessment of their understanding of physical hydrology. The students were enrolled in one of five sections of a physical hydrology course. In two of the sections, students completed homework problems and projects using only Excel (Microsoft, Redmond, WA) or MATLAB (MathWorks, Natick, MA) as modeling resources, and in the other three sections, some of the homework exercises were replaced with modeling and visualization activities using the interactive modeling software COMSOL Multiphysics (COMSOL, Burlington, MA). Other aspects of the course (instructor, syllabus coverage, lectures, and textbook) remained the same throughout the study. We performed a repeated-measures analysis of variance, which showed that gains from pretest to posttest were statistically significant overall and were independent of the section in which students were enrolled for all but one component on the assessment. In that case, students who did not have access to the COMSOL modules marginally outperformed the others, but not to the required level of statistical significance. These results were complemented by a qualitative investigation of students' interaction with the modeling software. We interviewed a subset of students and assigned codes to themes that arose when we analyzed the resulting transcripts. This process allowed us to develop a theory of how students were interacting with the modeling and visualization resources. A significant theme was the issue of "scaffolding," or supports, with both positive and negative consequences for students, depending on their personal preferences and previous experience. © *2015 National Association of Geoscience Teachers*. [DOI: 10.5408/14-057.1]

Key words: hydrology, physics, modeling, COMSOL

INTRODUCTION

Need for Modeling and Visualization in Physical Hydrology

In their call to action, Wagener et al. (2010) described the enormous challenges facing hydrologic research and education today and the "unprecedented opportunity" to use advances in modeling and visualization, which are "prerequisites for detecting, interpreting, predicting and managing evolving hydrologic systems," (p. 8) to address them. Merwade and Ruddell (2012) clearly articulated the implications of modeling and visualization in hydrology education:

> *"Considering the extensive use of authentic data, integrated modeling, and geospatial visualization in research applications and in the professional world, training in these approaches is becoming necessary for a successful career in hydrology. For this reason alone, it seems reasonable to suggest a strategy of supplementing the traditional hydrology curriculum with the latest data and modeling approaches."* (Merwade and Waddell, 2012, p. 2398).

In alignment with these calls for incorporation of data modeling and visualization into hydrology instruction (Wagener et al., 2012), faculty at the authors' institution have developed a series of COMSOL Multiphysics[3] (COMSOL, Burlington, MA; Zimmerman, 2006) models of hydrological systems, which permit students to visualize, explore, analyze, and predict the consequences of changes to a hydrologic system and its inputs. These modules complement lecture-based instruction and other tools for data modeling and manipulation, e.g., spreadsheet software, such as Excel (Microsoft, Redmond, WA) and open-ended programming, and computational environments such as MATLAB (on which COMSOL was originally based; MathWorks, Natick, MA).

During the past five years, the modules have been implemented in a colisted, upper-division, undergraduate- and graduate-level physical hydrology course. The goals of this course are for students to (1) develop a quantitative, process-based understanding of hydrologic processes; (2) gain experience with different methods in hydrology; and (3) enhance their learning, problem-solving, and communications skills. Developing an "... awareness of the totality of interconnected (mainly physical) processes involved in the hydrological cycle" (Nash et al., 1990, p. 606) has been identified as first among the goals of hydrology education, and there is increasing recognition that geoscience education requires a quantitative focus (Manduca et al., 2008). The hydrology community also acknowledges the need to connect this quantitative, theoretical understanding with knowledge of the methods and practices within the field (Wagener et al, 2012). The contents of the course in this study matched quite well to those of the largest subset of

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[3] See http://www.comsol.com.

hydrology courses, i.e., civil engineering hydrology and groundwater hydrology, in a study from several decades ago (Groves and Moody, 1992). Thus, the hydrology-specific goals of the course aligned with those identified by the broader community, and the course cannot be considered atypical in that regard. What distinguishes this course is the development and addition of the COMSOL Multiphysics modeling and visualization modules to the curriculum. The homework exercises involving these modules are documented in the online supplemental materials.[4] The syllabus for the course is also included in the online supplemental materials.[5]

To test the efficacy of the curriculum modules in meeting the stated learning goals, the authors developed an open-ended assessment of student understanding of physical hydrology (Marshall et al., 2013). The assessment consisted of three questions, mirroring course goals. The first asked students to describe the important physical processes in hydrology and how they affect hydrological systems, the second asked students to describe the relevant physical laws that govern hydrology and how they relate to hydrological processes, and the third asked students how they would assess the effects of a drought and urbanization on a local spring and to predict what the effects would be in the future.

Regarding the first question, important components of the water cycle are precipitation, runoff, evaporation, and transpiration, which are also related to solar radiation and soil-and-groundwater flow (or infiltration). In colder areas, snowfall and snow melting, sublimation, or evaporation would be included. *Precipitation* is any moisture input from the atmosphere to the land, including both rainfall and snowfall. Evaporation and transpiration comprise the moisture return to the atmosphere, which requires an input of energy, coupling the water cycle to the energy cycle. *Transpiration* is moisture uptake by plants from roots and released to the atmosphere. Soil-and-groundwater flow is the redistribution of water underground, which is due to gravity, pressure, and capillary forces.

Regarding the second question, the relevant physical laws that govern hydrology are the conservation laws of mass and energy and the conservation of momentum. Fundamentally, these are the laws of thermodynamics and Newton's second law. There are multiple forms of the equation showing *Flux* = (*Resistance or conductance coefficient*) × *Gradient*. Examples of this include Darcy's law for groundwater flow in saturated porous media or the Richards equation for unsaturated flow of moisture through soils, equations for mass and energy transfer or evaporation and transpiration from soil and water surfaces, Manning's equation for open channel flow, Fick's law for solute diffusion, and Fourier's law for heat transfer.

For the third question, to predict the effects of continued drought and urbanization, a hydrologist would collect historical data, especially during nondrought years and before urbanization, then continue to monitor for the same information. These data would primarily include rainfall and spring discharge and, perhaps, water quality. Based on the historical data, either a statistical model or a process-based model (e.g., a groundwater flow model) would need to be built, calibrated to the historical data. Urbanization can be represented by the amount of impervious cover from maps or population data (but that isn't really hydrology). Once a model is calibrated, it can be used to analyze what might happen under different forcing conditions that are not represented in the data, such as extreme and prolonged drought or continued growth of the city.

This article reports results of a 3-y study to compare precourse and postcourse responses of students (both graduate and upper division undergraduate) in the physical hydrology course. Depending on the semester in which they took the course, students were tasked with modeling hydrologic phenomena using either Excel and/or MATLAB alone or with the application of COMSOL Multiphysics as part of the assigned homework. During the course of the study, the instructor remained the same, and other aspects of the course (lecture, exams, student projects, and presentations, etc.) were deliberately held as constant as possible. Examination of course grades and pretest scores indicated no systematic variation in the student population over this time; however, possible unidentified variation in the population constitutes a limitation of the study.

Specifically, we sought to determine

- How do different modeling utilities compare in terms of enhancing student mastery of course goals as assessed by before and after tests?
- How do students describe their interactions/experiences with different approaches to modeling and visualization?

STUDY DESCRIPTION

Setting

The study took place in five sections of a colisted, upper-division, undergraduate and graduate, physical hydrology class, offered in a department of geological sciences, over the course of 3 y. Each of the sections was taught by the same instructor, one of the authors (M.B.C.). The class is based on, and closely follows, the textbook *Physical Hydrology* by S. L. Dingman (2008), a later edition of the most often used textbook cited by Wagener et al. (2007). The semester-long class is targeted toward upper-division, undergraduate students and new graduate students studying hydrology or hydrogeology. The class covered the following broad topics, which included all aspects of the hydrologic cycle: (1) atmospheric and climate processes; rainfall; (2) snow and snowmelt; (3) unsaturated zone and infiltration processes; (4) evaporation and transpiration; (5) runoff processes, streamflow, and watershed hydrology; and (5) groundwater hydrology. Roughly 2 to 3 weeks are devoted to each topic. (A sample syllabus is included in the online supplementary materials[5]).

The topics are presented such that a molecule of water is essentially tracked through the hydrologic cycle, beginning in the atmosphere, where it condenses to form rainfall or snow, then as rain and snow (with snow potentially accumulating on the ground), with some water going back to the atmosphere (evaporation and transpiration). Infiltration across the soil surface and soil moisture flow are then discussed, with water that did not infiltrate becoming runoff on the land surface and eventually forming streamflow. Finally, water that infiltrated through the unsaturated soil

[4] The homework exercises can be found online at http://dx.doi.org/10.5408/14-057s1.

[5] The syllabus can be found online at http://dx.doi.org/10.5408/14-057s2.

reaches the water table of aquifers. At this point, groundwater hydrology is covered, the last topic of the class. At each step, the pertinent physics, and to a certain extent, thermodynamics, are taught.

The class grading is heavily weighted toward assignments, with homework comprising 50% of the final grade. One homework assignment is assigned approximately every two weeks with a total of six homework assignments throughout the duration of the semester. The modeling and visualization activities, discussed in detail below, were integrated into the third and sixth (final) homework assignments (see online supplemental materials[4]), when the instructor felt that modeling and visualization would particularly help in the students' learning and appreciation of the topic.

Participants

In all, 80 participants, out of a total enrollment of 95, consented to participate. We were able to match preassessment and postassessment scores for 51 students. Some students completed only the pretest (and were not present for the posttest or had dropped the course), and others were not present at the beginning of class on the first day and completed only the posttest or did not label their assessments in such a way that they could be matched. Assessments that could not be matched were used for summary statistics only. Additionally, 14 students consented to be interviewed. Because not every student consented to participate and completed both the pretest and posttest and the numbers of participants were too small to disaggregate the data by gender or student status, there is a limitation on the generalizability of the study results.

The participants were either upper-division, undergraduate or graduate students enrolled in a section of a physical hydrology course, cross-listed as undergraduate/graduate and offered in the geological sciences, over a 3-y period. The course is a requirement for undergraduate students majoring in geology with a hydrogeology emphasis or geosystems engineering and hydrogeology (a hybrid program between petroleum engineering and hydrogeology) and is an elective for general geology and environmental science students. Calculus and a previous introductory hydrogeology course are prerequisites. Graduate students taking the course might be from the geosciences or engineering, occasionally other areas, and for them, there were no prerequisites, and enrollment was based on instructor consent. The difference in prerequisites for the undergraduate and graduate versions of the course tended to yield overlapping distributions in terms of preparation, particularly mathematical preparation, for the undergraduate and graduate students. In other words, graduate students were not, on average, likely to be better prepared technically than undergraduates in terms of physical hydrology.

Modeling and Visualization Resources

During the first year (two sections of the course), students were required to use Excel spreadsheets or MATLAB to manipulate data and produce graphs/plots through which trends in hydrologic interactions could be visualized and analyzed. Arguably, Excel presents only the crudest modeling capability, but using it, students might, for example, plot the Darcy flux (described below) versus head gradient by entering the equation corresponding to Darcy's Law into Excel. They could then identify trends from the resulting graph of pressure versus output flow, arguably performing rudimentary modeling and analysis.

During the second 2 y (three sections of the course), students were given access to, and required to use, COMSOL Multiphysics to model some of the same hydrogeological phenomena. COMSOL Multiphysics is a generic, finite-element, numerical modeling software. Its origin can be traced back to the partial-differential equation numerical solver toolbox for MATLAB, which then evolved into independent modeling software with a user-friendly, Windows-based, graphical user interface. The COMSOL Multiphysics user interface integrates all modeling aspects, from choosing which governing differential (conservation) equations to solve, setting boundary conditions and internal domain parameters or coefficients, building structured or unstructured finite-element meshes, to postprocessing and visualization of results, including generation and viewing of animations. The workflow from model conceptualization, domain and geometry setup, finite-element mesh generation, solution (or actual model run) to postprocessing is all tightly integrated and sequentially arranged.

The assigned homework problems that use COMSOL are included as part of the online supplemental materials.[4] Figure 1 shows screenshots from a COMSOL Multiphysics exercise modeling a Darcy tube and allows students to discover Darcy's Law for themselves. The model shown was created for students using COMSOL Multiphysics, and students were asked to modify the inputs and interrogate the results, i.e., a rudimentary sensitivity analysis. Figure 1 also illustrates the COMSOL Multiphysics workflow (left side of the screenshot); the user would have to go sequentially through all the tabs from top to bottom, but in this case, these have already been prepopulated. This example shows groundwater flow through a tube packed with sand, i.e., a Darcy tube. Darcy's law—the fundamental equation describing fluid flow through porous media—was empirically derived through experiments by Henry Darcy with these tubes. The students were essentially made to replicate Darcy's experiments computationally and digitally using COMSOL Multiphysics. In Fig. 1, water is injected from the left into the tube and comes out on the right end (arrows indicate the flow). The flow is driven by a linear pressure drop; the pressure field is indicated by shading in the circular cross sections.

Figures 2 and 3 illustrate two other examples of assigned problems that use COMSOL Multiphysics. Figure 2 shows a screenshot of a model for unsaturated flow through a two-dimensional vertical cross section of soil with a root serving as a macropore (i.e., a fast-flow path, or "wormhole"). It shows the saturation of the soil (1 being saturated) some time after infiltration from the top started. This model solves the Richards equation, which is a nonlinear, partial-differential equation. The students were introduced to the equation in class lectures, but such a numerical model simulation using the Richards equation is far beyond what the class would normally cover. For example, writing their own programs to solve this would require many semesters of courses in mathematical modeling. The idea of this exercise, as with other COMSOL Multiphysics problems, is to investigate how the system works when certain parameters are changed. The modeling aspects, for the most part, remained as a black box for the students, although the

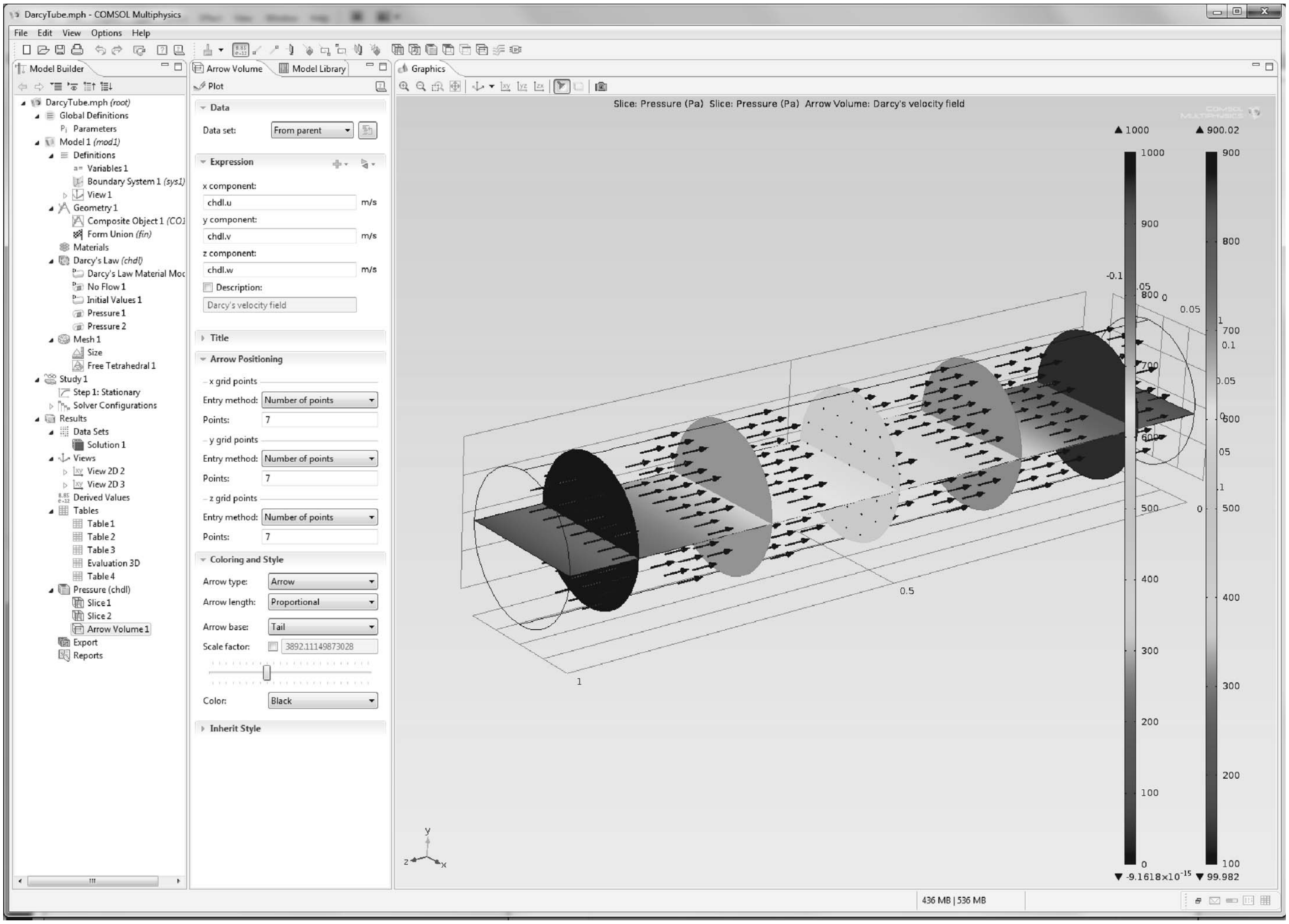

FIGURE 1: Screenshot of a three-dimensional COMSOL Multiphysics model of saturated groundwater flow through a tube filled with sediment, i.e., a Darcy tube. The model solves the steady-state groundwater flow equation, i.e., the Laplace equation, with flow described by Darcy's Law.

instructor gave a very brief discussion of what the software was doing, i.e., that it was numerically solving the governing differential equations.

The third example shown (Fig. 3) models two-dimensional groundwater flow through a regional aquifer where flow through the aquifer is driven by sinusoidal pressure (or head/water table) variations at the top of the domain or land surface. This is a typical, if not classical, configuration for so-called topography-driven regional groundwater flow. The screenshot (Fig. 3) shows one output for such a model, showing the pressure field driving the flow (black flowlines). The actual solution or calculation of such a flow field is again far beyond the expectation for the students in the class. However, they were shown conceptual cartoons of these flow fields in class lectures. In this assignment, the students interrogated the flow and pressure fields based on varying model inputs.

Despite the capabilities of COMSOL Multiphysics, in this study and for the classes we investigated, the modeling was kept mostly opaque. The students were taught and expected to know the underlying physical processes and corresponding equations inherent in the models, but minimal modeling background was expected or introduced. The COMSOL Multiphysics models were designed to be virtual canned, i.e., recipe-driven, experiments. During semesters when COMSOL problems were not assigned, no directly corresponding questions replaced these problems, as this would not have been possible. However, problems that required hand calculations that could also be implemented in Excel or MATLAB were sometimes assigned in lieu of the problems involving COMSOL.

ANALYSIS

The authors used both quantitative (before and after tests) and qualitative (student interviews and observations) methods to assess the effectiveness of the various methods of implementing modeling. Students in all sections of the course were informed about the study on the first class day and asked for informed consent to participate in the study, following an approved institutional review board protocol. Most students gave consent; however, not having every student participate may represent a selection bias and is a limitation of the study.

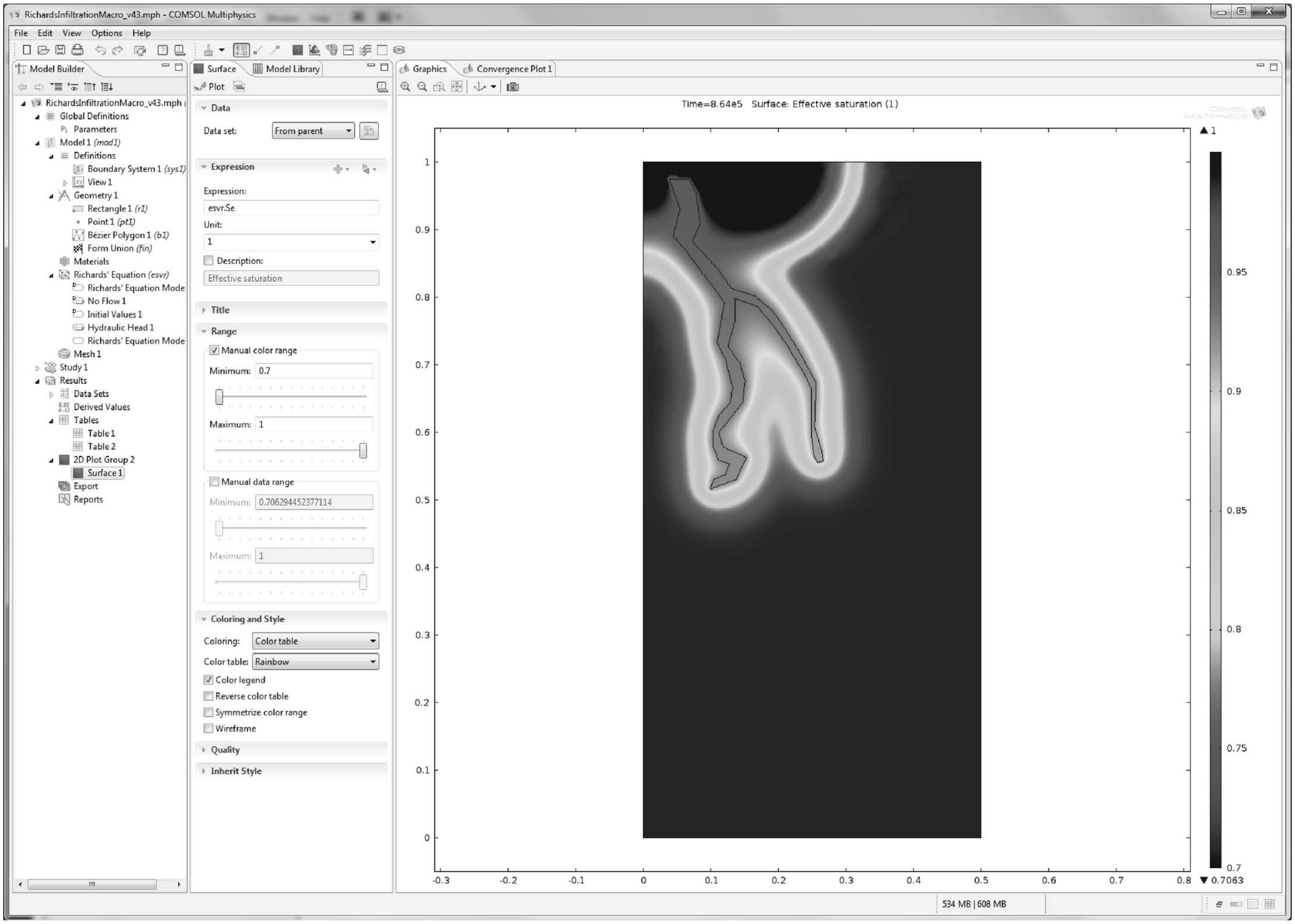

FIGURE 2: Screenshot of a vertical two-dimensional COMSOL Multiphysics model of unsaturated soil water flow due to infiltration from the surface and affected by a root macropore representing a preferential flow path. The model solves the transient Richards equation, a nonlinear partial-differential equation.

Quantitative Assessment of Understanding

The quantitative design involved two groups that were enrolled in different semesters during which different modeling resources were used by students (i.e., Excel/MATLAB or manual calculations versus COMSOL Multiphysics). The same instructor taught all the classes analyzed here, using the same syllabus, lecture files, and format. Class assignments that included the COMSOL Multiphysics exercises were graded by graduate-student teaching assistants. The same dependent variable (gain score on a physical hydrology assessment developed for this study) was measured at the beginning and end of each semester. Students completed the pre/post assessment, yielding scores ranging from 0 (blank or no relevant response), 1 (some recognition of concepts, knowledge from precollege curriculum), 2 (basic understanding, college level), and 3 (full understanding, what might be expected of an advanced hydrology graduate student). Development of the instrument and the rubric is detailed in Marshall et al. (2013).

Typical responses are described in detail in Marshall et al. (2013). In general, responses that scored a 1 on the first question—hydrologic processes—mentioned components of the water cycle as it might be presented in precollege courses, i.e., precipitation and evaporation but not infiltration or transpiration, and focused on the sun as the driver. Reponses that scored a 2 contained a complete list of processes, and responses that scored a 3 contained a complete list of processes and related them to the presence, movement, and storage of water. Typical responses that earned a 1 on question 2—laws that govern hydrology—listed only the name of a law (often Darcy's law). Responses that scored a 2 gave some indication of the conservation laws and mentioned that drivers (thermodynamics, gravity) and resistive elements determine flow. Responses in the 3 category gave a clear description of how Darcy's law, conservation of mass, and thermodynamics govern the processes controlling the storage and flow of water. Responses that scored a 1 on the third question—how to predict the effect of drought and urbanization—simply mentioned comparing present conditions to previous (non-drought) conditions. Responses garnering a 2 listed appropriate measurements and a plan to categorize the present and compare the present conditions to input/output trends in historical data. Finally, responses earning a 3 described a plan to develop a model based on physical laws and historical data and to use it to predict future outcomes.

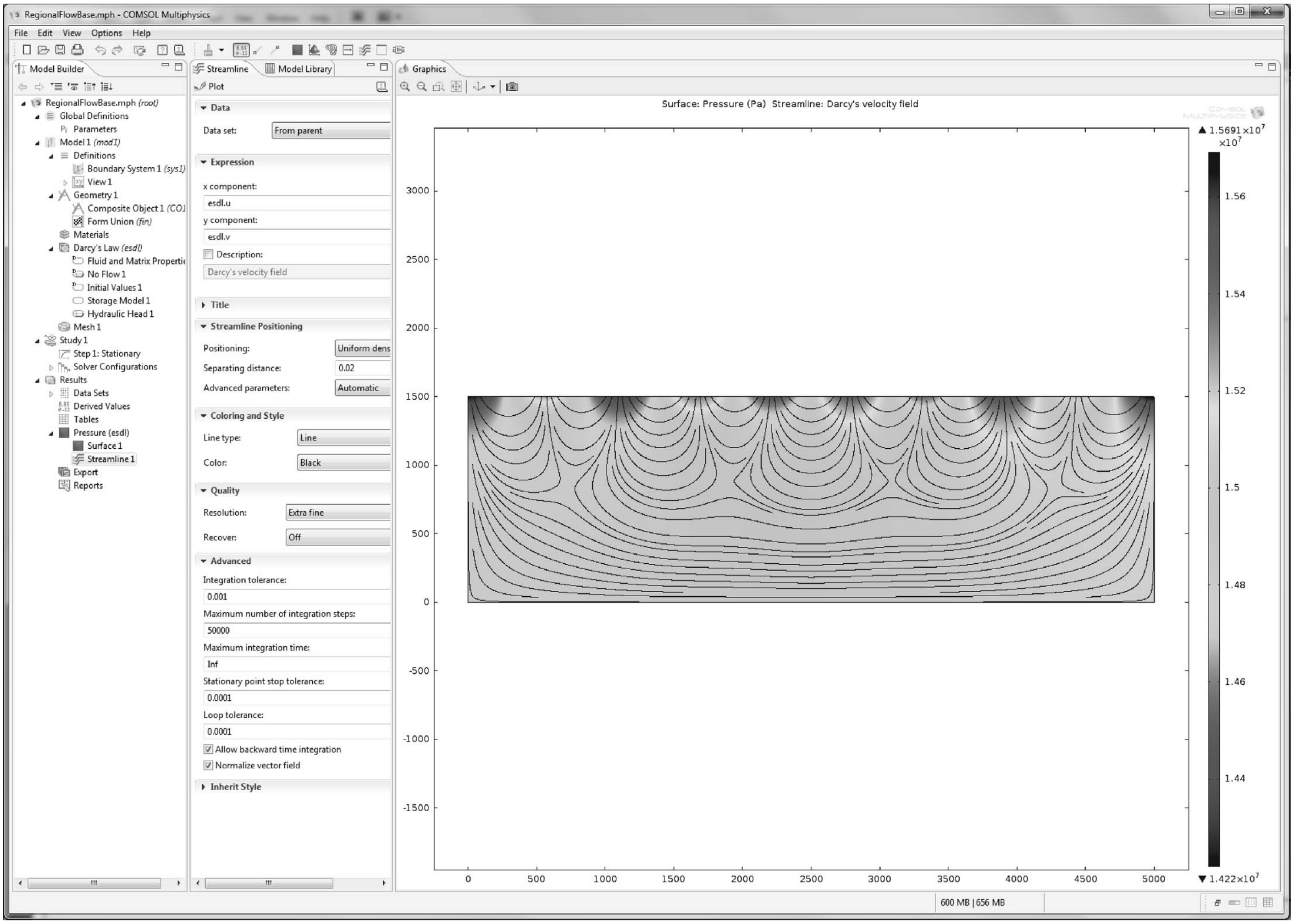

FIGURE 3: Screenshot of a two-dimensional COMSOL Multiphysics model of topography-driven regional groundwater flow through a rectangular aquifer with the top boundary representing periodic sinusoidal variations in pressure. The model solves the steady-state groundwater flow equation, i.e., the Laplace equation, with flow described by Darcy's Law.

Participants' modeling knowledge was assessed indirectly by the third item on the preassessment and by general awareness of the population enrolling in this course, that is, students enrolling in this class are not likely to have an extensive knowledge of COMSOL Multiphysics modeling. No student mentioned using COMSOL Multiphysics to make predictions on the preassessment.

All responses were blind coded (i.e., coders had no knowledge of whether they were assessing a pretest or a posttest response, or what modeling resources students had experienced in the classroom) by at least four independent reviewers who had been trained in using the instrument. An initial comparison of the independent coding results yielded greater than 90% agreement between coders. All discrepancies were negotiated, and a consensus rating was assigned by the entire team. The pre/post scores were matched and pretest, posttest, and gain scores (difference between pretest and posttest scores) were tabulated in a file using SPSS (IBM Statistics for Macintosh, Armonk, NY) software. Each score record was assigned a value for the semester enrolled, which correlated with modeling resources used, i.e., whether students engaged only with Excel/MATLAB/hand calculations to meet course requirements ($n = 22$) or were required to use COMSOL Multiphysics ($n = 29$).

Our goal was to determine whether there were significant pre/post differences in the scores on the physical hydrology assessment for students with access to different modeling resources, that is, whether the modeling resources that students used made a difference in their learning, as measured by the preassessment and postassessment.

We compared the pretest and posttest scores between the two groups using a one-way analysis of variance (ANOVA). This test compares the medians of two distributions and calculates the probability that they in fact came from the same population, i.e., that the null hypothesis (that there was no difference between the two groups) is valid. For this purpose, we considered the three assessment items to be independent (orthogonal) measures; that is, familiarity with hydrological process did not necessarily correlate with familiarity with the laws of physics or the experimental methods of hydrology. Therefore, we performed a separate ANOVA for each of the three assessment items. To minimize the chances that repeated testing might result in a Type-I error (that we might reject the null hypothesis even though there was in fact no true difference between the groups), we required a more-stringent level significance, $p < .01$, as opposed to the $p < 0.05$ level typically accepted. (Note that a typical approach to the issue of repeated testing is to use the Bonferroni correction, i.e., to divide the required significance level by the number of tests, in this case, three.)

In addition, because the number of subjects was small for the different groups, we were careful to check that our data met the requirements for ANOVA. For an ANOVA to be valid, (1) there must be no outliers in either group, (2) each group's data must be normally distributed. and (3) each group must have equal variance (homogeneity of variances).

To test for outliers, we created box plots in SPSS, from which we identified one gain score as an outlier. That score resulted from a case in which a student had a clear, well-articulated pretest but left portions of the posttest substantially blank, possibly due to time restrictions. This data point was eliminated from the set, leaving a total of 50 matched pretest and posttest scores for further analysis.

Because our sample size was large enough, we used graphical methods to determine whether the data met the normality assumption for ANOVA. The box plots used to check for outliers indicated a normal distribution of gain scores for each question, once the lone outlier was removed. We also created Q-Q plots (plot of expected versus observed distribution of scores), and data values appeared to follow the 45° normal line; therefore, we judged that the dependent variable was normally distributed for both groups.

Finally, we tested for homogeneity of variances in the gain scores because the one-way ANOVA assumes that the population variances of the dependent variable are equal for all groups. If the variances are unequal, the Type-I error rate is affected. There was homogeneity of variances of the gain scores for the process assessment component ($p = 0.63$), the law assessment component (0.57), and the methodology assessment component ($p = 0.47$), as assessed by Levene's test of homogeneity of variance, meeting that requirement.

Qualitative Assessment of Interactions With Modeling Resources

In addition to the statistical analysis of student learning, a volunteer sample of students were interviewed about their experiences in the course, in particular, their interactions with whichever modeling and visualization resources they had been required to use during the semester. In all, 14 students were interviewed, representing a sampling of undergraduate and graduate students, male and female participants, and students enrolled in each of the sections. Interviews were recorded and transcribed. In addition, students were observed as they interacted with a teaching assistant for the course during help/study sessions for the course. All the resulting artifacts (interview transcriptions and observation notes) were then independently open coded for concepts related to modeling and visualization and for their interaction with learning and other aspects of the course (see, for example, Mann [1993] for an explanation of the coding process in grounded analysis). The interviewed students presented both positive and negative perspectives on different aspects of the course, making it seem unlikely that the students who were interviewed, albeit a volunteer sample, presented a systematic bias.

The concepts identified in the open coding were compared, common themes were identified, and common terminology and coding schemes were negotiated. Interviews were independently coded using this scheme, and a subset of the independently assigned codes were compared yielding agreement at the 98–99% level. After all interviews had been coded, a common categorization scheme for the codes was developed by negotiation, and a theory of student interaction with the visualization resources was developed.

QUANTITATIVE RESULTS

As a first step in comparing the results of the posttest to those from the pretest, we created before and after histogram plots for each of the three components of the assessment in each semester. In comparing the frequency histograms for scores on each of the three assessment questions, a shift toward more positive scores from the pretest to posttest on each component of the assessment was evident for each semester the course was taught, i.e., both for the students who used Excel/MATLAB (year 1) and for those who used COMSOL (years 2 and 3). Figure 4 shows the before histogram (top row) and after histogram (bottom row) for each of the three assessment components for students who had access to COMSOL (white bars) and those who did not (gray bars).

To test for the significance of this difference, we examined the main effect of time using a repeated-measures (within-subjects) ANOVA, which compares the mean of the pretest scores to the mean of the posttest scores and determines the probability that the pretest and posttest results might have come from the same distribution (i.e., that there was no change in the scores from the pretest to the posttest). Table I shows the results for the process, laws, and methodology questions, respectively. Each indicates a difference between pretest and posttest scores on all three questions that is significant at the $p < .001$ level, meaning that, overall, student scores improved from pretest to posttest. There was statistically significant learning in each case.

Table II shows the interaction between the semester a student was enrolled in the course, indicative of the modeling and visualization resources that were available to him or her, and the main effect of time (pre/post) on scores for each component of the assessment. There was no statistically significant interaction between the semester a student participated and the process component [$F(1, 48) = 0.84$, $p > 0.05$] or the physical laws component of the assessment [$F(1, 48) = 0.03$, $p > 0.05$] meaning that pre-post difference did not depend on the semester in which the respondent was enrolled, i.e., which modeling resources they used, for these two questions.

The interaction between semester and the methodology component of the assessment, however, approached significance [$F(1, 48) = 6.08$, $p < 0.05$ (but not <0.01)] leading us to investigate a possible difference on this component between the two groups. Inspection of the means plots for the two groups shows that group that used Excel, showed a larger improvement (mean = 0.77, SD = 0.65) on the methodology component of the hydrology assessment than the group that used COMSOL Multiphysics (mean = 0.29, SD = 0.73). Although this result is

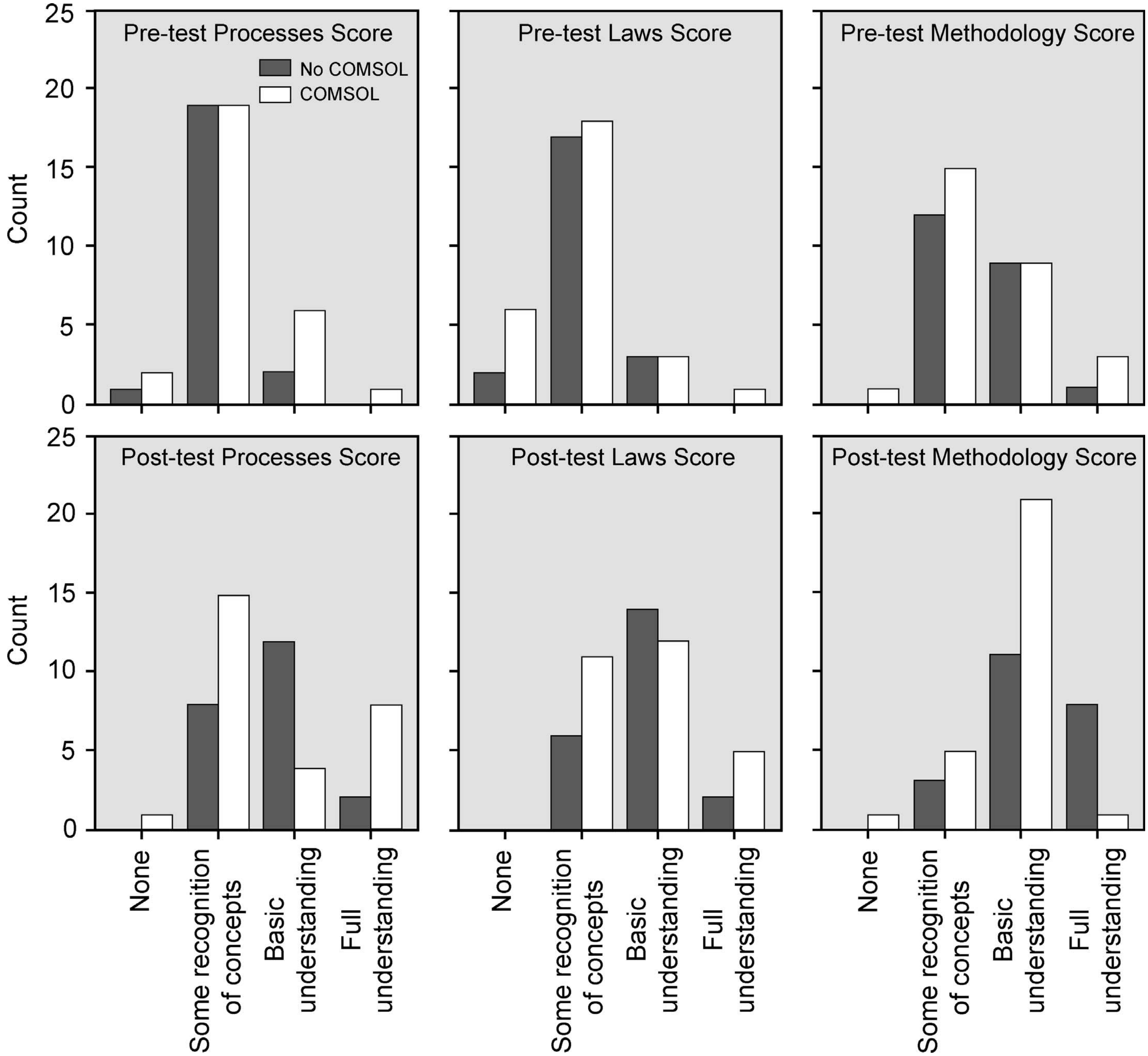

FIGURE 4: Histograms of scores on the processes, laws, and methodology components of the pretest (top row) and posttest (bottom row) for students who used COMSOL Multiphysics as a computing resource (white) and those who did not (gray).

only marginally significant, it indicates that COMSOL Multiphysics appears to be no more effective, and possibly less effective, in raising scores on this one component of the assessment.

QUALITATIVE RESULTS

Concepts that arose in the initial independent coding of the qualitative data (interviews and observations) included time, instructions, visualization, deriving equations, linking equations to concepts, fundamental physics, identifying trends (in hydrological data), manipulating data, instructions, expectations, satisfaction, familiarity, software operation and syntax, acquiring skills and tools (in hydrology and hydrology education), and specific topics (soil mechanics, snow melt, etc.) and course elements (homework, lecture, instructor, COMSOL). Upon reviewing these themes, three major categories emerged from the data: affordances, barriers, and preferences. Of these, the first two pertained directly to students' interaction with modeling resources, and the third served to situate the students' experiences. Table III documents the categories and the themes that emerged under each.

TABLE I: ANOVA results showing the main effect of time (pre/post) for the three components of the assessment: hydrological processes (process), physical laws (law), and methods of hydrology (method). Note that the effect of time is highly significant ($p < .001$) in each case.

Source	Type-III Sum of Squares	df	Mean Square	F	Significance	Partial η^2
Process						
Sphericity assumed	7.840	1	7.840	22.718	0.000	0.317
Huynh-Feldt	7.840	1	7.840	22.718	0.000	0.317
Law						
Sphericity assumed	14.822	1	14.822	50.782	0.000	0.509
Huynh-Feldt	14.822	1	14.822	50.782	0.000	0.509
Method						
Sphericity assumed	6.250	1	6.250	23.558	0.000	0.325
Huynh-Feldt	6.250	1	6.250	23.558	0.000	0.325

Affordances

Components or characteristics of the modeling resources (and instruction in general) that students cited as helping them learn were characterized as *affordances*. As noted in Table I, visualization was a major concept in the category of affordances (all student responses are identified by initials).

> *"We're talking like orthographic effect and when you can see like a picture of a mountain and then how the air moves up it. That really helps like with the visualization and then the remembering and understanding…"* (A.B.)

> *"I like [the COMSOL modules]. They're cool. The first one was really interesting to see… It's just—I'm a visual learner… It had 3D models for, it was infiltration, and it showed the different conductivities of soil and stuff, so it was cool. There was a block that wasn't as permeable as the one above, so it was interesting."* (U.G.)

Students also noted visualization as an affordance in terms of video of actual physical phenomena as well as laboratory demonstrations.

> *"Even though I read a lot of times beforehand about the eddies, the concept, and the papers about eddies, but I really cannot understand how, um, the eddies looks like [sic] in nature and, uh, he shows some experiments on dye, uh, how it's heated and then it propagates, and then I can understand better about the concept."* (P.L.)

Students cited opportunities to identify trends, to synthesize the "big picture" and analyze real data, as affordances that helped them to learn:

> *"You could find, or like these temperatures, okay, what/how does this temperature change with elevation? And then, how does this pressure change?"* (A.B.)

> *"What I learned how to do was put it all together and not just schematically, but put it all together with some sort of physically derived equation."* (A.J.)

> *"When you analyze it, it helps you like think about it and [to] make sure so if you have it right and [to] help it set in, like you're understanding in your mind better."* (A.B.)

Students also noted acquiring skills or tools as an affordance:

TABLE II: ANOVA results showing the interaction of the main effect of time (pre/post) with the semester in which students were enrolled in the course, indicative of which resources they were required to use.

Source	Type III Sum of Squares	df	Mean Square	F	Significance	Partial η^2
Process × semester						
Sphericity assumed	0.291	1	0.291	0.842	0.363	0.017
Huynh-Feldt	0.291	1	0.291	0.842	0.363	0.017
Law × semester						
Sphericity assumed	0.008	1	0.008	0.026	0.872	0.001
Huynh-Feldt	0.008	1	0.008	0.026	0.872	0.001
Method × semester						
Sphericity assumed	1.461	1	1.461	6.078	0.017	0.112
Huynh-Feldt	1.461	1	1.461	6.078	0.017	0.112

TABLE III: Categories and themes arising from qualitative analysis of interviews.

Barriers	
	Instructions/examples (lack of)
	Time
	Lack of clear expectations
Affordances	
	Visualization
	Identification of trends
	Synthesis
	Analysis of data
	Relating concepts to equations
	Acquiring tools/skills
Preferences	
	Appreciation/satisfaction
	Difficulties/challenges
	Familiarity

> *"We did a lot with MATLAB, and I think it was good experience to learn how to use it."* (A.B.)

> *"I knew nothing about Excel Spreadsheets. Even if I didn't get to where I wanted to go, I've come a long way."* (P.B.)

> *"I think that could be really useful, especially with COMSOL being something that would be very important to anyone in this room (um) at one stage or another, maybe more so to some than like geomorphologists or geographers, but for the hydrologists that would be very, very important."* (A.J.)

Barriers

Things that stood in the way of learning, or made learning difficult for students, were characterized as *barriers*. This included things that were needed, e.g., instructions, but lacking.

> *"There were some idiosyncrasies in the [COMSOL] program that didn't come across in his walk-through. For instance, if you clicked out of tab and clicked back into it, it didn't save your changes, and I never could figure out why or if it was actually running what I wanted it to. So, things like that… trial and error."* (S.C.)

> *"They're just very lengthy a lot of the time, and it's very easy to just do [i.e., put] extra parenthesis or missing one parenthesis, and then it's just like the whole thing's wrong."* (J.P.W.)

> *"Whereas with COMSOL, because it was, the whole interface was unfamiliar, and the way [the instructors] wrote up the instructions for the COMSOL, I found sort of difficult to follow … so I found myself sort of more wrapped up in that than in actually interacting with the software and thinking about what was going on."* (A.W.)

The length of time to complete assignments was also given as a barrier to learning:

> *"It's definitely going to be different because you have to go out and find your own data set, apply concepts that we're learning in the class to a real-world application, and try to make paper material out of it, which is going to be helpful; it's just going to be time intensive. It's going to be helpful but very painful."* (N.M.)

> *"But, like I said, those first couple of homeworks took me 20-plus hours for one homework assignment. It's not like this is all I have to do. You know, so it's a little, at times, it's been a little frustrating."* (M.K.)

Preferences

Many concepts that arose in the coding fell into the category of preferences, and students' preferences clearly moderated their interactions with the modeling resources in the course. In the interviews, students uniformly expressed appreciation for the efforts of the instructor, regardless of whether they felt the course had been a successful experience for them, e.g.,

> *"One thing is that I'm really glad he's [including modeling]. The fact that he did that shows that he's real interested in teaching and also in the classroom… I really appreciate being able to be in a class like that."* (P.B.)

However, students also cited difficulties and challenges, often linked to their personal capabilities and skills:

> *"Empirical equations always feel a little bit more arbitrary to me, and it's more to memorize, and I am not good at memorizing equations, so they always feel a little more challenging to me in that sense as well."* (A.W.)

> *"I don't, like, that kind of programming situation is something I can do, but I already knew that's not one of my strengths. Like, it's not something that comes very easily to me."* (M.K.)

> *"There's one problem on one of the assignments that did require some doing (a little bit) of calculus that did require some derivation. That was great, and I think I would be willing to do twice (or three times) as much homework if they were like that."* (D.S.)

A related theme was familiarity. Students expressed comfort (or discomfort) in dealing with familiar (or unfamiliar) topics or software:

> *"So, I didn't know MATLAB before I had taken this course. I understood what it was and what it could do, so that has*

been kind of a start-up curve, and I don't think that my MATLAB codes are very good, I just think they like get the job done.'' (K.L.)

''It's just because like I've been using Excel since like middle school or whenever you first learn it.'' (A.B.)

''Right now we're dealing with stream runoff and that is one topic I'm really not familiar with. All the other topics so far I've probably been pretty familiar with or I'm doing my thesis on so I understand most of the concepts up until now.'' (N.M.)

DISCUSSION

How Different Modeling Utilities Compare in Enhancing Student Mastery of Course Goals

Overall, the statistical analysis showed that all implementations of modeling in this physical hydrology course were effective. The difference between pretest and posttest assessments was highly significant ($p < .001$) each semester. It was expected, based on previous studies, that COMSOL Multiphysics would be effective in enhancing student understanding of hydrology. Singha and Loheide (2011) reported that 3 h of exploration with a COMSOL Multiphysics model improved students' estimates of groundwater velocities for a sand-and-gravel aquifer compared with their estimates made after 4 h of lecture and 1 h of hands-on exploration with a physical (sand tank) model. That was a small study, involving only eight students in one class; however, it indicated that the use of a numerical model, in addition to standard lecture and ''ant-farm'' experiments, might enhance student understanding of groundwater rates, mechanisms, and the parameters controlling groundwater flow and contaminant transport.

What was unexpected was that both types of modeling and visualization resources, Excel and/or MATLAB versus COMSOL Multiphysics, would be equally effective. The only statistically significant difference in the mean of the distributions of gain scores between semesters (those in which students were required to model hydrology phenomena using only Excel/MATLAB and those in which they employed COMSOL Multiphysics models to study hydrological systems) was on the methodology portion of the assessment, and that was significant only at the $p < .05$ level.

This result runs counter to the expectation that the manipulation and, in particular, visualization, capabilities of the COMSOL model would enable students to achieve insights into hydrological phenomena that they would not be able to otherwise and problematizes the intuitive call to ''supplement [...] the traditional hydrology curriculum with the latest data and modeling approaches'' (Merwade and Ruddell, 2012, p. 2398). In this case, the newer tools were not shown to be more helpful than older technologies, such as Excel (which, as noted in one interview, these students had been using since middle school), at least within the limitations of this study.

To investigate the possible reasons for this finding, we turned to qualitative analysis of students' experiences with the modeling resources as described in interviews.

How Students Describe Their Interactions/Experiences With Different Approaches to Modeling and Visualization

In piecing together the major categories arising from the qualitative analysis (coding of the interviews), we developed a theory of modeling resources as *scaffolding. Scaffolding* is a term commonly used in education to characterize instructional strategies designed to help students in learning. In its broadest sense, all teaching is scaffolding, but the common connotation is those temporary supports (''training wheels'') that teachers implement to move students toward greater comprehension and independent problem-solving capability. The notion of instructional scaffolding is rooted in the assumption that what students can do today with help of a more experienced collaborator, they will be able to do tomorrow by themselves (Vygotsky, 1978). Here, the actual assistance comes from software that encapsulates the knowledge and capabilities of more-experienced others, as well as from the instructor and teaching assistants. The instructors provide scaffolding in the form of access to appropriate modeling resources, predeveloped models, directions for exploration tasks that will help the students develop appropriate skills and conceptual understanding, and finally, assistance with the tasks as needed.

For some students, the scaffolding software clearly provided an affordance, i.e., it enabled them to do and see things that they would not have been able to do or see without it. As noted above, for some students the modeling resources facilitated identifying trends over time and visualizing relationships.

''And once I got the graphs in Excel right, I could see what he was trying to display in class, and I figured it out for myself, so that really helped me concentrate on it, learn the material.'' (N.M.)

''...and then it's a more visual output there and then, you know, running it through there and then saying, you know, 'Okay, so what are we getting? What effect is this having?''' (M.K.)

''Like, I didn't know anything about COMSOL, but I really didn't have to know, because the homework was... it was funny 'cause it was very straightforward in many senses. It was just like 'click on this, click on that.''' (R.F.)

''And, you know, instead of just being an equation or a line graph, you actually got to see in 2D [in COMSOL] what that would look like as the contour plot.'' (S.C.)

For others, however, the scaffolding actually provided a barrier, preventing them from ''seeing'' the fundamental concepts in the same way that a painter's scaffold or construction scaffolding might obscure the view of a mural or monument, as opposed to providing a perspective or access unobtainable without it. Although the scaffolding might help in construction or updating of a model, it did not help some students in developing an understanding of the concept(s) on which it was based:

"The reason I would take a physical hydrology course is to see things come from first principles, to come from physics, and the course material itself is often very encapsulated…. We're provided with like Excel spreadsheets and all these things, at least for me, the perspective I want out of the class, these are all barriers to the fundamental, sort of fluid dynamic processes that I'm trying to understand." (D.S.)

The student quoted above clearly did not see the fundamental physics in the outputs of the software. For him, the closed-form equations themselves correlated with the concepts in a way that that the graphs and images produced by the software could not. He would have preferred "time and space to engage with the equations alone, at a level of rigor that I don't find in class or certainly in assignments" (D.S.).

Another way in which the scaffolding software created an unintended barrier for the students was in terms of the time and detailed procedures necessary to produce a result. Students cited this barrier for each of the forms of software used:

"But for me, because of my not knowing Excel—not knowing how to do spreadsheets very well, and not remembering all the math and physics—it took me probably twice that amount of time, and I just found that excessive." (P.B.)

"So I think the easiest parts for me on the homework have been like conceptual questions, because a lot of the rest has to do with figuring stuff out in MATLAB and plotting it in MATLAB and things like that." (K.L.)

"When I was using the COMSOL, I felt like I was just struggling with the interface in trying to figure out how I need to do what I was suppose to be doing and wondering if I was doing the right thing. So, I wasn't thinking much about the science that was going on. Um, it was more about, 'did I click the right buttons?" (A.W.)

The means to remove these two types of barriers may run counter to each other. Although the images and displays made possible by more-advanced modeling technologies might enable novice users to identify trends and synthesize concepts, the same technological affordances might hide (or at least not highlight) fundamental features of the physics of hydrological systems, allowing the user to be unaware of "the limitations and difficulties in developing numerical models that faithfully represent the system they are modeling."[6]

In some cases, even students who benefitted from the affordances of whichever modeling resources they used and the access those tools provided to solutions for the novice modeler, also faced the greatest barriers in using the software:

"Overall, after we can get the Excel to work and then we plot whatever we're looking at, that's definitely beneficial, and it definitely helps summarize certain processes or helps you learn the general trend of things, but getting to that point, often times, is somewhat difficult." (J.P.W.)

"That's where the science is… is like modeling and... So I think it is really useful; I think the hurdle (maybe) is (like) the technical, knowing the program, the start-up associated with (like) getting to know a program, but once you understand it and if you can actually relate it to physical processes, then yeah, I think it's helpful." (K.L.)

"I got a lot out of [COMSOL modeling], but it was too much effort and frustration, and too much time for what I got out of it." (P.B.)

"COMSOL, I kind of wondered at the time why we were doing it because most of us have never heard of it and will never use it. And so it was a little bit pointless for most of us in the class, and it took a lot of time. But the visualization was pretty neat." (S.C.)

The more powerful, versatile, COMSOL Multiphysics allowed students to do (and see) more, but was less familiar and more challenging. As noted on the COMSOL Web site:

"Finite element methods for approximating partial differential equations that arise in science and engineering analysis find widespread application. Numerical analysis tools make the solutions of coupled physics, mechanics, chemistry, and even biology accessible to the novice modeler. … But with this modeling power comes great opportunities and great perils." (emphasis added) (http://www.comsol.com/books/mmwfem).

Thus, despite the affordances provided, all three modeling resources explored in the course of this study also created barriers to learning, at least for some students. In the end, personal preferences and familiarity had the dominant role in determining the balance between the two effects.

CONCLUSIONS AND IMPLICATIONS

Although our quantitative results did not show a clear advantage for the incorporation of the COMSOL Multiphysics, the qualitative results indicate the value that students placed on the opportunity to learn to use this tool:

"I think that could be really useful, especially with COMSOL being something that would be very important to anyone in this room… for the hydrologists, that would be very, very important." (A.J.)

Even students who thought they would never use COMSOL in the course of their careers saw value in the ability to visualize phenomena, and our program remains committed to continuing to offer and expand activities with COMSOL Multiphysics as part of the instruction in physical hydrology and to make these tools available to the larger community. For more information about access to the modules, please contact one of the authors.

[6] http://www.comsol.com/books/mmwfem.

However, these results also indicate the need both to make the COMSOL Multiphysics modules more accessible and to ensure that they are used in such a way that students are "thinking... about the science that [is] going on" rather than thinking "did I click the right buttons" to justify the expenditure of effort on the part of students and instructors to include them in the curriculum. Perhaps not surprisingly, these results reiterate that the effectiveness of any tool will depend on the needs and abilities of the user, and how she or he uses that tool. A newer, more powerful technology will not necessarily provide a panacea. Developers need to be cognizant of the need to provide self-explanatory and intuitive interfaces, with entry points for more-novice users (training wheels), which still allow the user to inspect and consider the constraints and boundary conditions that might have been implemented on his or her behalf. A major step in this direction has been a new COMSOL release, called *COMSOL Server*, in which a user (in this case, the instructor) can create a model and "freeze" it for others to use, placing limitations on the changes that can be made to variables. This feature will be employed in future instantiations of the course to make the COMSOL manipulations more transparent to the students. Demonstrating that students learn more (or more efficiently) with the COMSOL modules as they exist would have been in some ways a more welcome result; however, solid evidence that more work needs to done to make the modules accessible to students is also of value.

At the same time, in giving students access to the latest data and modeling approaches, care needs to be taken that scaffolding provided does not obscure the physics, with modeling tasks supplemented by reflection, closing the loop back to the fundamental laws. No amount of modeling and visualization will substitute for thinking and articulating what the models are telling us. Therefore, open-ended, conceptual questions requiring students to describe the meaning of the simulation results will continue to be part of COMSOL-based homework exercises (see online supplement[4]). The ultimate goal is for students to "put it all together and not just schematically, but ...with some sort of physically derived equation," as A.J. did.

Finally, this study took place in only one course at one institution. Not all students consented to participate, and not all participants completed both the pretest and the posttest assessment, limiting the generalizability of the results. Further, participant numbers were not sufficient to be disaggregated by student status (undergraduate versus graduate), gender, or, perhaps more important, by the student's intended career path. Thus, another outcome of this study is the identification of the need for further research into the effectiveness of the COMSOL Multiphysics curriculum intervention described here with larger populations.

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