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An Interdisciplinary Guided Inquiry on Estuarine Transport Using a Computer Model in High School Classrooms

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Abstract

The National Science Education Standards *have highlighted the importance of active learning and reflection for contemporary scientific methods in K–12 classrooms, including the use of models. Computer modeling and visualization are tools that researchers employ in their scientific inquiry process, and often computer models are used in collaborative projects across disciplines. The goal of this project was to develop and field-test a module that used a computer model to teach marine sciences content in an applied, inquiry-based, and collaborative manner. Students used an estuarine transport model to explore the question of how circulation patterns affect planktonic organisms, demonstrating the interdisciplinary interaction of physics and biology. Our experience suggests that computer models, when used for inquiry, can help foster students' understanding of the nature of science and critical-thinking skills.*

Key Words: *Interdisciplinary lesson; environmental science; estuarine transport; STEM.*

○ Project Motivation

Calls from the National Research Council (1996) and National Science Foundation (2000) emphasized the importance of providing students with authentic science experiences through active inquiry. They also highlighted the importance of using and understanding the nature of models as conceptual representations that are developed and tested. Computer models and simulations are important tools in modern scientific inquiry and are cornerstones of many interdisciplinary, collaborative projects. Therefore, introducing students to computer modeling is an important component of understanding modern scientific techniques.

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Interactive illustrations are now available for a variety of topics, such as molecular genetics (Marbach-Ad et al., 2008) and chemical bonds (Frailich et al., 2009). These computer modeling tools have been shown to significantly improve students' understanding of abstract ideas by making them more tangible (Harris et al., 2009). However, these examples represent only one of the diverse ways that scientists utilize computer models.

Scientists conduct experiments with computer models to understand phenomena and to generate predictions. For instance, a circulation model of Chesapeake Bay helped scientists study variations in flow patterns (Li et al., 2005). This model also enabled scientists to test hypotheses regarding how changes in weather and/or land use would affect these flow patterns and how organisms are subsequently dispersed (North et al., 2010). Using computer models in an inquiry-based manner requires (1) understanding the concepts of variables and model limitations, (2) formulating testable hypotheses, (3) collecting and analyzing data (model output), and (4) drawing conclusions from the data (de Jong, 2006). Therefore, computer modeling can potentially equip students with scientific process skills essential to understanding scientific concepts.

In addition to being a tool for scientific inquiry, computer models can also provide students the opportunity to work collaboratively and across disciplines. Working collaboratively and in an interdisciplinary manner are essential skills for scientists (Sung et al., 2003). To date, several guided-inquiry activities that utilize computer models are available (e.g., TELS Center at http://telscenter.org; Linn et al., 2006). However, these models focus on a single discipline or subject (e.g., Marbach-Ad et al., 2008) and are often designed for individual, independent investigation (e.g., Frailich et al., 2009). Thus, there is an unmet need for well-designed, field-tested classroom modeling activities that are both collaborative and interdisciplinary.

We chose to model estuaries because they are good subjects for interdisciplinary learning. First, estuaries are semi-enclosed areas where fresh water and sea water meet, and therefore they are good case studies for physical principles on density and currents. Second, estuaries are important habitats and nursery grounds for many ecologically and economically important organisms (e.g., crabs and salmon) and, therefore, are places of ecological interest. The rich biological diversity in estuaries also provides a wide array of examples of how organisms adapt to their physical environment (interactions

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of physics and biology). Finally, because estuaries are often heavily populated and threatened by human activities, they illustrate how social sciences interact with natural sciences.

○ Module Development & Details

The module is based on an estuarine circulation model (MacCready, 2007) and a particle-tracking algorithm developed by Dr. Grünbum to study the role of behaviors in particle transport. We simplified and developed a graphical user interface for this model to allow students to investigate how changes in estuarine circulation would affect dispersal outcome. We also designed activities to provide students with background information on density, estuarine circulation, and plankton ecology. We consulted three NSF-OACIS (National Science Foundation-Ocean and Coastal Interdisciplinary Sciences) GK–12 doctoral fellows who have worked in high school classrooms to ensure content relevance and appropriate presentation format (for more information on this program, visit http://depts.washington.edu/oacis/). The module was designed to align with national and Washington state science education standards (Table 1).

The lesson was delivered in two periods of a marine biology class, the first lasting 50 minutes and the second 1 hour and 50 minutes (see the Discussion for how the lesson can be extended). The lesson plan roughly followed the learning cycle (engagement, concept introduction, application, and assessment). The instructors were two GK–12 doctoral fellows. Their research projects are not related to computer modeling or estuarine transport, so subject expertise is not necessary to teach this lesson. Lesson materials are available at http://www.ocean.washington.edu/people/faculty/grunbaum/education_resources.htm.

○ Engagement

The students were shown a physical model of an estuary, consisting of a clear box with salt water and fresh water, kept separate by a removable "flood gate." The flood gate is a piece of plexiglass with a slit about 1 × 1/2 inch cut in the middle. An acetate sheet held in place with Vaseline closes off this slit and, when removed, allows the water masses to interact. Details of how to construct the model can be found at http://fermi.jhuapl.edu/student/currents/waterfall_apparatus.htm (Figure 1). The students were asked to formulate a hypothesis regarding what would happen upon removal of the gate between salt and fresh water. They tested their hypothesis by removing the gate and were asked to draw a conclusion based on their observations. Instructors then led class discussion on students' observations, reviewing the concepts of density and circulation.

○ Concept Introduction

A 20-minute mini-lecture was presented to the students to introduce three major concepts: (1) the characteristics of estuaries, (2) variations in estuarine circulation patterns, and (3) the nature of plankton. For concept 1, the students studied aerial photographs and maps of estuaries and discussed similarities between geographic locations. We highlighted to the class that estuaries are coastal, semi-enclosed, well-protected areas that are often strongly influenced by human activities (as indicated by the number of cities and buildings). For concept 2, the students were asked to think about how the flow pattern within an estuary changed across different time scales, using different figures as clues (Figure 2A). We highlighted that in estuaries circulation patterns are affected by tides (daily–monthly variation), rainfall (daily–seasonal variation), and snowfall (seasonal–yearly

Table 1. List of national and Washington state science education standards met by this module.

National Science Education Standards	Washington State Science Education Standards
Grades 9–12: ***Science as Inquiry Standards*** Abilities necessary to do scientific inquiry Understanding about scientific inquiry ***Physical Science Standards*** Structure and properties of matter Motion and forces ***Life Science Standards*** Mass, energy, and organization of living systems Behaviors of organisms ***Science and Technology Standards*** Understanding about science and technology	Grades 9–12: ***EALR 2 ~ Inquiry (Conducting analysis and thinking logically)*** The essence of scientific investigation involves the development of a theory or conceptual model that can generate testable predictions ***EALR 3 ~ Application (Science, Technology, and Society)*** The ability to solve problems is greatly enhanced by use of mathematics and information technologies ***EALR 4 ~ Life Sciences (Maintenance and Stability of Population)*** Scientists represent ecosystems in the natural world using mathematical models
	Grades 6–8: ***EALR 2 ~ Inquiry (Questioning and Investigating)*** Models are used to represent objects, events, systems, and processes. Models can be used to test hypotheses and better understand phenomena, but they have limitations ***EALR 4 ~ Physical Sciences (Atoms and Molecules)*** Substances have characteristic intrinsic properties such as density, solubility, boiling point, and melting point, all of which are independent of the amount of the sample

Note: EALR stands for Essential Academic Learning Requirement. Core concepts are stated in parentheses.

Figure 1. Physical model of an estuary. (A) Salt water (left) and fresh water (right) were poured into each compartment. (B) When the flood gate was released, the denser, saline water sank to the bottom of the fresh-water compartment, displacing the fresh water on top. (C) A stratified water column was formed. (Photo credits: Elizabeth Tobin.)

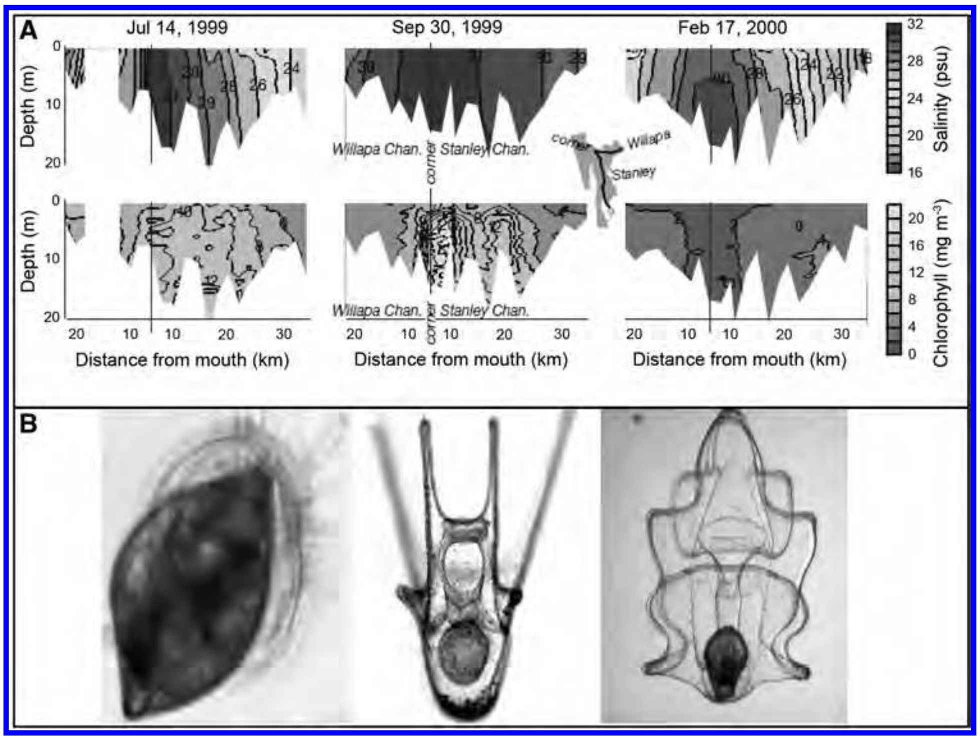


Figure 2. (A) Estuarine circulation and changes with time showing instantaneous vertical sections of salinity and chlorophyll along the Willapa (northern) and Stanley (southern) channels (in Willapa Bay, WA) from CTD transects on three dates. Students were asked to identify possible mechanisms that led to the observed differences in salinity and chlorophyll. Taken from Banas et al. (2007). (B) Images of meroplantonic invertebrate larvae (meroplankton are organisms that spend only a part of their life in the water column): (left) a geoduck veliger (© Karen Chan); (middle) a sea star bipinnaria (© Fernanda Oyarzun); and (right) a sand dollar pluteus (© Karen Chan).

variation). For concept 3, through a matching game to pair larval stages with adults, the students learned that some marine invertebrates spend part of their life in the plankton (Figure 2B). To provide context for the estuary model, we illustrated the concept that for weakly swimming larvae, timing and locations of release and their behaviors could significantly affect where they are dispersed. The study by North et al. (2010) provided an easy-to-understand example. Movies of North et al.'s computer model are available at http://northweb.hpl.umces.edu/videos_animations/Oyster_Larvae_Animations.htm.

○ Application

The students integrated the chemical (salinity), physical (density-driven flow), and biological (nature of plankton) concepts that they had learned by addressing the following problem: "When and where should an organism release its larvae if the larvae grow best within the nutrient-rich estuary?" In groups of two to three, the students formulated their own hypotheses to answer the stated problem, explained their rationale, and collected, graphed, and drew conclusions from the model data they collected (Figure 3B). They used the graphical user interface of the estuary model (Fig. 3A), a Matlab-based program, to investigate this problem.

This model simulates how density-driven currents transport passive particles within and out of an estuary. Model flow patterns are based on those of Willapa Bay, Washington. Students can manipulate three variables in this model, namely the volume of river flow (high, medium, and low representing different amounts of snow melt), the date of larval release, and the location of larval release (distance from the mouth of the estuary). Because the particles lack behavior, the distance transported is positively correlated to the duration of the larvae's exposure to high river flow (i.e., the overlap between the 14-day larval duration and the peak of river discharge) and to the volume of river flow. Not surprisingly, larvae released closer to the mouth of the estuary are more likely to be washed out of the domain.

○ Learning Assessment

To assess understanding, the students were asked to present to the class their motivating questions, their data in a graphic format, and their conclusions (Figure 4). The instructors guided the presentations

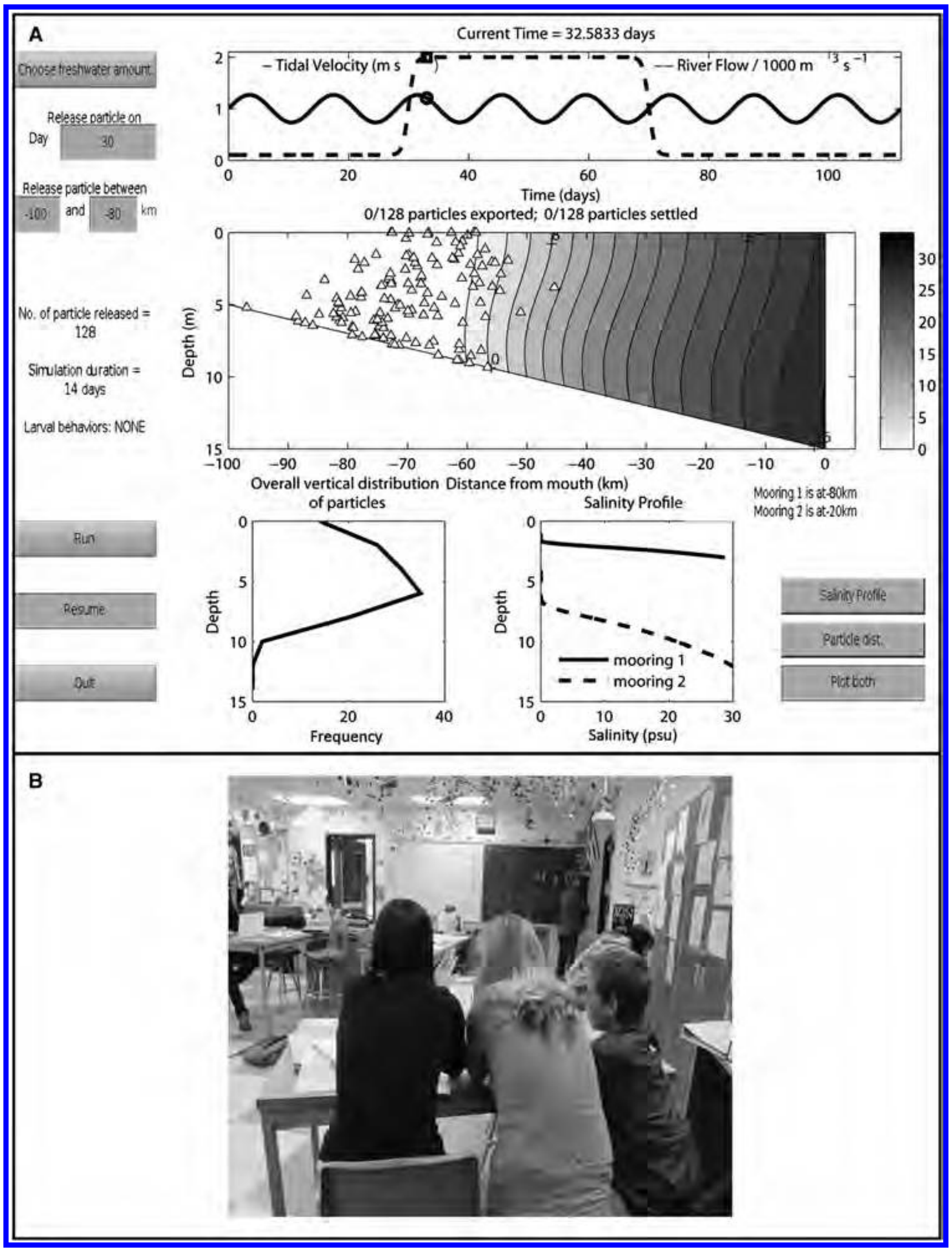


Figure 3. (A) Screen shot of the graphical user interface of the particle transport model used in this lesson. (Top panel) Volume of river flow (- -) and tidal cycle (-). (Middle panel) Cross section of estuary with contours showing salinity. Triangles represent transported particles (model larvae). (Bottom panel) Vertical distribution of transported particle (left) and vertical salinity profile (right). Students can manipulate three variables in this model: (1) volume of river flow (high, middle, and low); (2) location of particle release; and (3) timing of particle release. (B) In groups of two or three, students formulated hypotheses about how changes in one or more of these variables affect particle transport. They reported their findings in a graph and orally to their peers at the end of the lesson.

and final discussion in which the students reflected upon the lessons learned. In this discussion, the instructors provided real examples of organisms that migrate up and down estuaries that matched students' predictions (Forward et al., 2003). The instructors also encouraged the students to reflect on the limitations of this simple computer model and ways in which it might be enhanced.

○ Module Evaluation

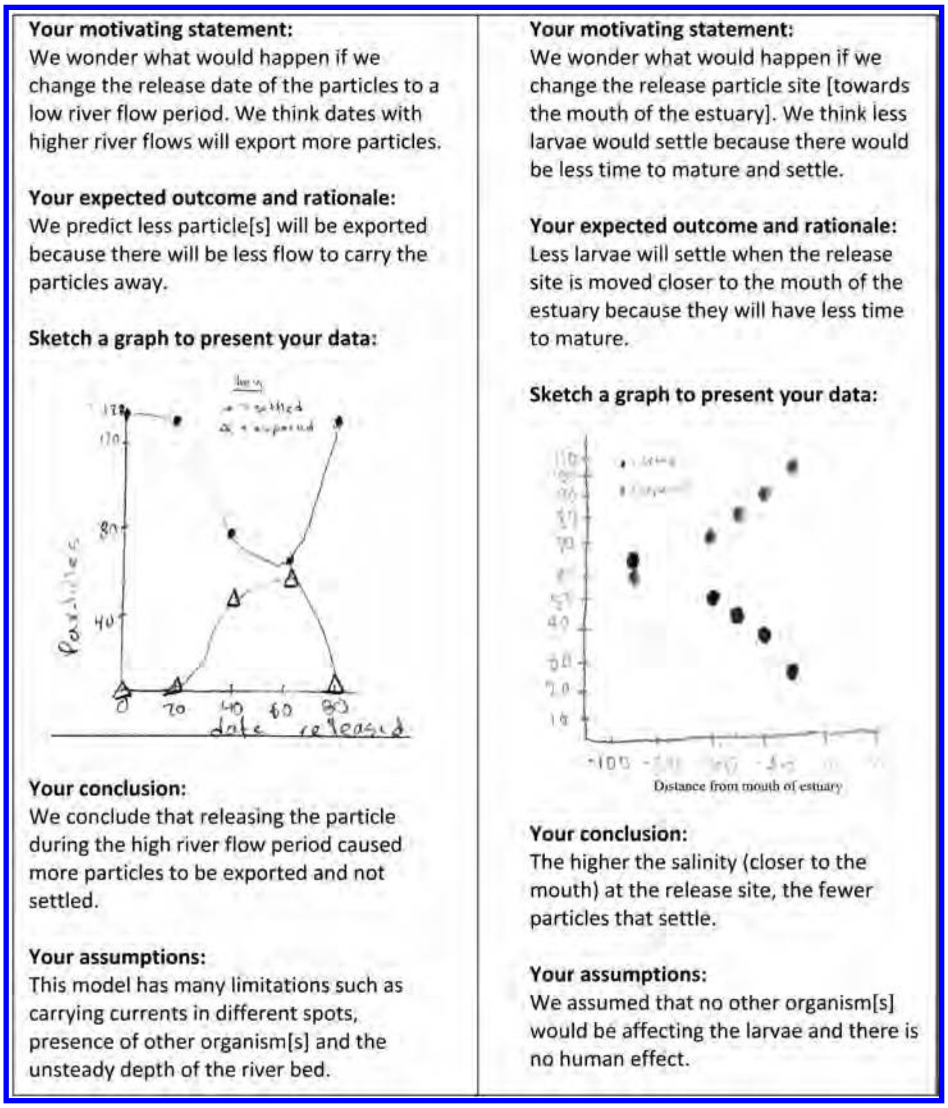
The lesson was first pilot-tested in a Marine Science classroom with 13 students in grades 10–12. Based on students' oral and written responses and teachers' feedback, we modified the worksheets and field tested the current version of the lesson in another high school.

The lesson was presented by a GK–12 doctoral fellow to a total of 107 ninth- through 11th-graders enrolled in four different periods of a Marine Science class. The students filled in worksheets in class before and after the lesson to gauge their learning gain. The two worksheets (hereafter "pretest" and "posttest") contained six paired questions that were identical. These consisted of multiple-choice, true-or-false, and short-answer questions (Figure 5). All short-answer questions were graded on a two-point scale. To gauge the students' preconceptions, the pretest contained a question asking them to name a plankton and explain how currents can affect plankton. The posttest had additional questions focusing on students' understanding of the estuary model and how currents affect particle transport. Identifiers were removed and replaced with randomly generated numbers, and the tests were graded by the same person in one sitting for objective assessment. Prior to administration, the tests were presented to five independent experts (doctoral candidates in oceanography at the University of Washington) for content validation. We did not have a control group that did not receive any instruction to confirm the reliability of the assessment. However, our goal was to assess whether the students' understanding improved after the module. Therefore, each individual's scores for each question on the pre- and posttests were compared with a paired t-test using the statistical package PSAW 18.0. Only students who turned in both the pre- and posttests in class were included in the statistics (n = 56).

○ Results

Students Lacked Prior Exposure to Computer Models

Of the 107 students in the marine biology class, 23.1% responded that they had used a computer model prior to this lesson. They



Your motivating statement:
We wonder what would happen if we change the release date of the particles to a low river flow period. We think dates with higher river flows will export more particles.

Your expected outcome and rationale:
We predict less particle[s] will be exported because there will be less flow to carry the particles away.

Sketch a graph to present your data:

Your conclusion:
We conclude that releasing the particle during the high river flow period caused more particles to be exported and not settled.

Your assumptions:
This model has many limitations such as carrying currents in different spots, presence of other organism[s] and the unsteady depth of the river bed.

Your motivating statement:
We wonder what would happen if we change the release particle site [towards the mouth of the estuary]. We think less larvae would settle because there would be less time to mature and settle.

Your expected outcome and rationale:
Less larvae will settle when the release site is moved closer to the mouth of the estuary because they will have less time to mature.

Sketch a graph to present your data:

Your conclusion:
The higher the salinity (closer to the mouth) at the release site, the fewer particles that settle.

Your assumptions:
We assumed that no other organism[s] would be affecting the larvae and there is no human effect.

Figure 4. Examples of students' responses on the guided-inquiry worksheet.

were asked in a follow-up question to describe the model. Four models were identified by the students: the star dome in physics, changes in carbon dioxide levels over time in biology, the relationship between temperature and respiration in biology, and natural selection/evolution in biology. Of these models, the first three were visualization of ideas; only the evolution model was used as a tool for inquiry (AVIDA is available at http://avida-ed.msu.edu/). In the evolution model, the students manipulated traits of model organisms (microbe color) and observed how the population changed over time. Our survey shows that the large majority of students have little understanding of applying computer models in an inquiry manner.

Students' Understanding of Estuary & Computer Models Improved Significantly

In the six paired questions, the students' scores significantly increased by the end of the lesson (Figure 6). We note that the students performed well, with averages of >1.5 out of 2, in the pretest survey in most areas (concepts on density, making and explaining predictions for the physical model, estuarine characteristics, and estuarine circulation patterns). The lessons nonetheless helped the students reinforce their understanding and, hence, obtain significantly higher scores.

The students' lowest-scored question on the pretest addressed their understanding of why scientists use computer models. A majority of students thought that scientists use computer models because "computers do not make mistakes" and "computers can give answers quickly." Responses like these indicated poor understanding of how computer models are designed and a lack of awareness of modeling limitations. After the lesson, the students provided much more sophisticated responses about why scientists use models, such as "Models can help create an idea of possible outcomes without affect[ing] the real system (e.g. oil spill)" and "Model[s] can be helpful to study places that [are] too difficult to reach or areas too large to sample."

In addition to better understanding the motivations for modeling, the students also improved their awareness of model limitations: they were able to identify missing biological and physical mechanisms that could potentially affect the model outcome. The students were asked in the posttest to suggest one feature to add to the model and to list questions that could be addressed using the proposed feature. Example responses include these: "How would temperature and rainfall affect particle transport?"; "I would add death rate because not all larvae survive in nature. Does the change in flow pattern still matter when organisms are dying?"; and "How would human interaction (e.g. pollution) and predator[s] affect larval transport?" In contrast to the novices' view that models are simply scaled-down replicas that accurately represent nature (Grosslight et al., 1991), the students developed a deeper understanding of modeling. They understood that models are often used to test ideas and phenomena; that models reflect the questions, intent, and assumptions of the modeler; and that models can change through time.

Students' & In-Service Teachers' Feedback

In addition to the pre- and posttests, we also asked a small subset of the students whether they found the lesson interesting and whether they believed they had learned from the experience (n = 23). On a Likert scale of 1–5, the students believed that the lesson was 3/5 interesting and 3/5 useful. One student commented that she or he liked this lesson and learned from it because it was very clear and simple. Another commented that the lesson helped him or her put concepts from different subjects together.

Because the lessons in both the marine science classrooms were taught by GK–12 fellows, their partner in-service teachers were able to observe the class. We held short debriefing sessions with the teachers to solicit their impressions of the lesson.

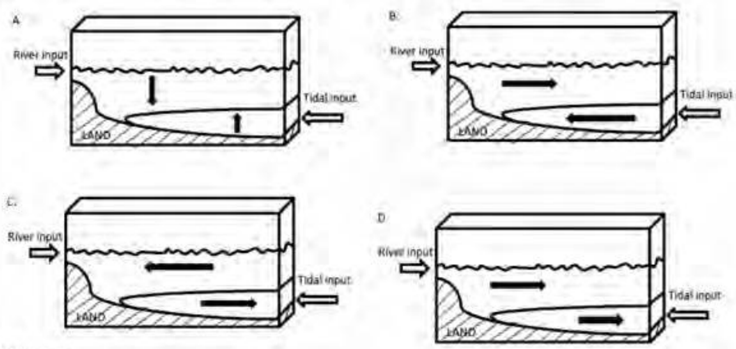
> "The students were really impressed by the dynamic model and were engaged

1. Water Density
Which the following things can make fresh water at room temperature denser?
Cooling the water ***Adding more salt*** ***Heating the water*** ***Adding freshwater***

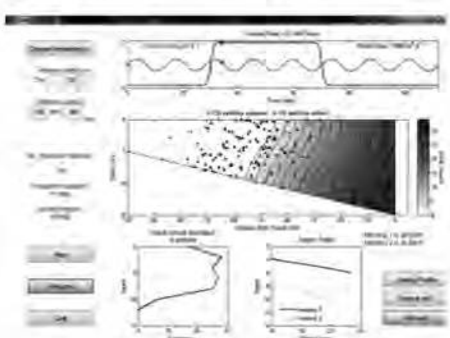
2. Applying density concepts to physical models
Based on your understanding of water density and density-driven water currents, what would you predict to happen in the model estuary shown? Mark on the following cross section (i.e. a slice of the box cut along the dotted line) using arrows of what will happen when the acetate is removed.

Explain your reasoning for the above prediction.

3. Characteristics of estuaries
The flow inside an estuary can be affected by the density of the freshwater input from the rivers and saline water from the sea. Based on your understanding of density-driven currents, which of the following pictures shows the overall direction of flow within an estuary most accurately?



4. Particle transport in estuary
One of the ways that scientists study estuary is using computer models to simulate flow patterns within the estuary. These models are also used to study how changes in flow patterns affect organism living in the estuary. Below is a screenshot of a model estuary within a normal year.



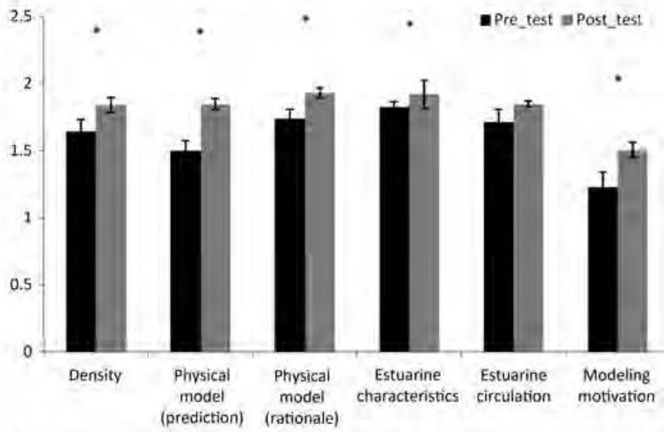
a) *What do you think will happen to the* ***amount of freshwater input*** *to the estuary in a year with intense rainfall such that the river flow doubled between Day 30 and 70?*
b) *What do you predict would happen to the* ***water flow within the estuary*** *in the wet year described in part a) of this question? You can use drawings or describe in words.*
c) *What would happen to* ***the number of particles swept out of the estuary*** *if the release date, location, and simulation duration remain unchanged? Give your reasons.*

5. Modeling motivation and limitations
One of the ways that scientists study estuaries is using computer models to simulate flow patterns within an estuary and how these patterns would affect organisms living in the estuary.
a) Give two reasons why you think scientists use computer models in their research?
b) Name one limitation of modeling estuaries on a computer.

Figure 5. Example of assessment questions.

Scoring rubric for short answer questions (0-2 point)

Score	Criteria
0	No response
0.5	Incorrect answer
1	Correct answer but wrong logic
1.5	Correct answer with incomplete explanation
2	Correct answer with logical explanation



	Density	Physical model (prediction)	Physical model (rationale)	Estuarine characteristics	Estuarine circulation	Modeling motivation
$T_{1,55}$	-2.281	-4.172	-2.619	-1.992	-1.218	-3.716
P	0.013	>0.001	0.006	0.026	0.114	0.0002

Figure 6. Students' learning gain. Average scores and standard errors of students' responses in the pre- and postlesson worksheet. Short-answer questions were graded on a 2-point rubric. All questions are normalized to a 2-point scale. The table shows t and P values for paired t-test. Asterisk represents significant difference.

> in the activities.... I think this lesson is a valuable opportunity for my students to be exposed to and to conduct an experiment with an actual research tool that scientists use." – Marine science teacher 1

> "At first I was a little skeptical about this modeling lesson but now I think it is worth the effort. Students were really engaged and learned new concepts. This lesson provided a good transition between physical components and biological components in an environmental science class like ours. " – Marine science teacher 2

○ Discussion

The high school students we studied had had very little exposure to computer models – more than 70% of them stated they had never used a computer model. Of those who had used a computer model, very few of them had used a model as a tool to conduct inquiry. It is also possible that teachers have introduced computer modeling but that the activities did not make an impression. During our lesson, a student commented that "to win" they had to figure out the combination of parameters for which most particles were retained. Such comments indicated that students were treating the model as a computer game and failed to appreciate the scientific questions behind it. Despite widespread access to computers, the applicability of computers to developing and testing scientific ideas has not been conveyed to the vast majority of high school science students. Our survey results emphasize the importance of making user-friendly guided-inquiry computer models more available to teachers and students. Our modeling lesson is an example of how to move beyond using computer models as a visualization tool and encourage students to actively and collaboratively conduct inquiries.

Beyond introducing our students to using computer models for inquiry, our lesson also exposed them to interdisciplinary learning. Clay et al. (2008) pointed out that students failed to transfer their knowledge from one subject area to another, on the basis of field tests of their interdisciplinary biology/physics lesson on plankton. Similar to their approach, our module encouraged students to connect a large-scale physical phenomenon (estuarine flow) to a biological concept (maintaining population) through a real-life problem (larval dispersal in an estuary). In addition to biophysical interactions, estuaries can also be used to discuss human–nature interactions. For example, teachers can lead a follow-up discussion of human impacts on estuarine transport (e.g., how damming of rivers might interfere with river flow and the implications for larval transport). Alternatively, teachers could go more deeply into plankton biology by collecting plankton samples to illustrate diversity, by studying the morphology of plankton and understanding their life-history adaptations (see Clay et al., 2008), or by discussing how swimming behaviors such as vertical migration may affect dispersal patterns.

Although computer lab activities in the high school classroom require advanced planning (such as reserving computer labs or carts), we believe that conducting modeling activities in class could better facilitate group interactions and thus aid student learning. In our classes, the students were actively engaged in discussion and were able to help each other overcome technical problems very quickly. The students were initially unfamiliar with the computer model and the graphical user interface, yet within- and between-group interactions allowed them to make progress through the exercise. The students were also motivated to explore different aspects of the model so that they could compare and contrast their findings with those of their classmates. Different modeling outcomes and conclusions between groups also stimulated in-depth discussion of the modeled systems. Therefore, group exploration of a new computer model was an effective approach in our classrooms.

Students' understanding of estuary and computer models improved after our lesson, which suggests that we achieved our project goal of making a lesson available that effectively delivers specific content and skills knowledge. Our experience showed that computer models are teaching tools with great potential as means of inquiry, venues of interdisciplinary learning, and intellectual challenges for student groups. We encourage teachers to use computer models both for visualization and inquiry to supplement existing lesson plans, so that high school classrooms better emulate and stimulate students' interests in real-world scientific research.

○ Acknowledgments

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