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Review
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NEW APPROACHES FOR INFUSING QUANTITATIVE REASONING INTO UNDERGRADUATE MARINE SCIENCE EDUCATION

A recently introduced Marine Science course at Richard Stockton College focuses on modeling physical and chemical processes in closed seawater facilities. The course illustrates to the students mathematical concepts such as recursive expressions, linear equations with limits on the variables, and finding roots of higher order polynomials. This paper describes five topics covered in the course, and mathematical ideas and principles behind each topic. Quantitative reasoning and analysis of these topics is greatly enhanced by extensive and interactive use of computer technology in the course. The exercises described can be used in a variety of undergraduate curricula, as practical illustrations of the concepts that are being discussed.

Key Words: computer-aided instruction, modeling, applications of mathematics, interactive learning

INTRODUCTION

The vital importance of mathematics in undergraduate science education has been discussed in various settings (HHMI, 1993; Woolnough, 1994; NRC, 1997; Adms and Hamm, 1998). This paper describes how mathematical ideas and principles are used in a recently introduced course at Richard Stockton College. The course is offered in the Marine Science Program, and it focuses on quantification and analysis of chemical and physical processes in closed seawater facilities (aquaria, mariculture etc.). These facilities have been proposed in the past as excellent environments for development and application of quantitative reasoning skills (Hughes, 1993). Instead of using often simplistic textbook examples regarding closed seawater facilities, our course is based on empirical data from two of the largest seawater aquaria on the East Coast of the United States: the Living Seas in Orlando (Florida) and the New Jersey State Aquarium in Camden (New Jersey).

The primary target audience for the course are students in the Marine Resource Management Track of the Marine Science Program. This track is biologically oriented, yet there is no course quantifying the importance of water quality parameters to the rearing of organisms and ultimately the financial success of mariculture enterprises. In addition, the course is of interest to other Marine Science students, as well as to some students who are majoring in Environmental Studies or Chemistry. To the chemically oriented students, the course offers an opportunity to explore and compare thermodynamic equilibrium calculations with those involving chemical kinetics. Students interested in physical aspects of marine or environmental science gain first-hand experience in developing and using analytical and numerical models. Today, such models are the basis for analyzing the fate of atmospheric pollutants, predicting El Niños and determining the ocean role in global climate change.

The calculations involved in quantifying processes in closed seawater facilities can be tedious and time-consuming, so we decided to have students model their approaches to problems using a spreadsheet software (Microsoft Excel). This is facilitated by the weekly computer lab sessions in an electronic classroom, which provides the instructor with the capability to demonstrate models, and provides each student with their own workstation. As a result, student learning in the course occurs largely through their own development of, and experimentation with, mathematical computer models. This approach compels students to continuously revisit previously learned concepts in mathematics, and it also introduces them to new ones, all in an applied setting. The applied quantitative emphasis of the course has resulted in its designation as a "Quantitative Reasoning Across the Disciplines" course. Quantitative Reasoning Program is a College-wide initiative at Stockton, and every graduating student is required to complete three Quantitative Reasoning courses. The new course thus serves to fulfill an important College requirement by exposing students to the fundamental importance of mathematics in natural sciences.

Below are descriptions of five course topics that are covered in detail during the semester. The mathematical concepts and approaches to these topics are discussed afterward. Some of the topics can also be used in basic science courses such as physics or chemistry (Grgurić, 2000), where they provide excellent examples of "real world" application of mathematical ideas. In addition, these course topics are useful as practical illustrations when the concepts in question are being studied in "pure" mathematics courses.

THE COURSE TOPICS

Topic 1: Water Exchange Rates

In closed seawater facilities, most water tanks are subject to regular water changes, in order to prevent the build-up of toxic animal waste products. The extent of these water changes is typically expressed as the fraction of water replaced in a given time period, e.g. 10% a week. An important question in the aquarium/aquaculture industry is determining the total fraction of the original water that remains in the tank after a given time period. A practical application of this question can be seen in the following example:

> *A fish tank has been contaminated by 200 mg/L of a toxic chemical. Water replacement regime in this tank is 15% a month. How many months will have to elapse*

before a fish species, which can tolerate at most 150 mg/L of the chemical, can be safely placed into the tank?

Developing computational methods to answer this and similar questions is an important first exercise that students are given in the course. Their answers are compared in order to discover whether different computational approaches yield the same results. That typically prompts a more fundamental discussion of mathematical methods implicit in students' solutions to the problem.

Topic 2: Preparation of Artificial Seawater

An aquarium or mariculture facility that is located far from the ocean, or where uncontaminated seawater is not available locally, has to prepare its own, artificial seawater. Calculating the artificial seawater formulation (that is, determining what chemicals and how much of each to add to make the artificial seawater) is a tedious and time consuming process, even if one wants to balance only the six major seawater ions. The reason for this computational difficulty is that seawater must contain a specific concentration of every individual ion, but each ion can be added only in conjunction with its counterpart through a given salt. Therefore, a combination of salts has to be found that will produce a solution containing specific concentrations of every ion. The students are asked to develop such an artificial seawater formulation, by choosing which salts to use and calculating their amounts.

Topic 3: pH/Alkalinity

Acid-base equilibria are of fundamental importance in natural water systems, and students analyze those equilibria in their introductory chemistry courses. Most seawater facilities that host a large number of heterotrophic organisms exhibit a decreasing pH and alkalinity over time, and chemicals have to be added to maintain these parameters in their ambient seawater range. This provides an opportunity for revisiting acid-base equilibria from a water management point of view. The goal in this approach is twofold: (1) to determine the pH and alkalinity shifts when given amounts of chemicals are added, and (2) to determine the chemicals and their amounts needed to achieve a required shift in pH and alkalinity.

Topic 4: Denitrification

The class discussion of nutrients in closed seawater systems centers on the widespread problem of increasing nitrate concentrations in facilities where photosynthesis is limited or nonexistent. While the concentration of nitrate ion seldom exceeds 50 mM in open ocean water, an aquarium or mariculture facility can exhibit nitrate concentrations of up to 10,000 mM. Biological denitrification is one method for controlling high nitrate concentrations in such systems. Students in the course are asked to develop denitrification model based on the chemical reactions involved in this process. They use their models to predict future nitrate concentrations in aquarium tanks, and to quantify certain side effects of denitrification on aquarium water chemistry.

Topic 5: Disinfection

Seawater in closed facilities must be continuously disinfected in order to prevent the spread of pathogenic diseases emanating from animal excretion products. Discussion of seawater disinfection centers on ozonation - the most widely used method - and its main side effect, formation of hypobromite and bromate ions. While some production of hypobromite is desired due to its disinfecting capability, bromate production is undesirable in closed facilities, because the species has been shown to be a renal carcinogen (Kurokawa et al., 1990). The questions that students address center on optimizing the disinfection conditions (ozone dose, contact time, etc.) in order to maximize hypobromite formation, while minimizing bromate production.

MATHEMATICAL CONCEPTS INVOLVED IN THE FIVE COURSE TOPICS

Quantitative approaches to each of the five topics discussed above involve applying mathematical ideas and principles. Students are typically familiar with some of the mathematical concepts involved (e.g. systems of linear equations or simple polynomials), but not with others (e.g. differential equations). By analyzing, solving and discussing the problems in question, the course serves to strengthen the students' proficiency in mathematics. Table 1 shows the mathematical concepts associated with each Topic. A closer examination of how these concepts arise in connection to solving the particular problems is provided in the following paragraphs.

Water Exchange Rates

One common approach to quantifying water exchange rates in closed seawater systems is to express the cumulative fraction of exchanged water at any given time interval in terms of the same fraction at the preceding time interval. This, recursive approach to solving the problem yields rather intuitive, linear mathematical expressions. The second approach to the problem is based on expressing the cumulative fraction of exchanged water as an exponential function of time. In this exercise, the students realize that recursive expressions are often mathematically simpler than those involving functions, but they may require numerous iterations to evaluate. This translates into an added cost in either the computational capabilities or the time required to arrive at a numerical answer. In contrast, functional expressions are often less intuitive, but they do not require iterations to evaluate. The students discover the benefits and drawbacks of both of these approaches through their own analysis and experimentation.

Preparation of Artificial Seawater

The problem of balancing the six major seawater ions is one of solving six linear equations (one for each ion) with eight unknowns (one for each possible salt). Since there are more unknowns than equations, it follows that there are many possible solutions. However, the problem is constrained by the requirement that all unknowns have positive, or zero, values. This requirements reflects the fact that only positive answers have physical meaning, as amounts of salts to be added.

When attempting to solve this problem, the students discover that the same artificial seawater can be prepared using different combinations of individual salts. This is possible because, for example, sodium ions in solution may come from sodium chloride or from another sodium salt. As students learn that there is "leeway" in artificial seawater formulation, they are asked to explore this leeway by assigning each salt its price, and finding such combination of salts that makes the least expensive artificial seawater. This introduces the students to the Simplex method of optimization, through a practical application of the method.

pH/Alkalinity

The problem of adjusting pH and alkalinity is based on carbonate equilibria and mass balance principles. The carbonate system in seawater can be described by eight equations with eight unknowns. Expressing the other variables in terms of the final pH variable yields a forth degree polynomial whose correct root must be identified and quantified. Students use the bisection method (Hoffman, 1992) as a tool to find the desired root of this polynomial. The method requires determining the proper constraints on the variable in question (the final pH), which can be done using the initial conditions of the problem and employing chemical intuition. After the proper root of the polynomial is determined with sufficient accuracy, the values of other unknowns are calculated by back-substitution. This exercise thus illustrates to the students the sequence of steps required to find roots of higher-order polynomials.

Denitrification

Denitrification provides an opportunity for the students to use empirical data collected in aquarium facilities, in order to determine rates of chemical processes. These rates are then incorporated into a predictive model, where a future nitrate concentration in an aquarium tank is expressed in terms of time. The students also use stoichiometry and mass-balance principles in order to quantify side-effects of denitrification, such as the amount of methanol required or the resulting effects on pH and alkalinity of seawater. By employing the linear regression method and making judgements concerning rejection of outlying data points, the students become aware of the importance of statistical methods in validating empirical data.

Disinfection

Aquarium disinfection processes are controlled by chemical kinetics (Kalmaz et al., 1985; Grguric et al., 1994), and their rates can be quantified using differential equations. Many systems of differential equations lack simple analytical solutions: as a result, numerical approximation methods have to be employed in order to solve these equations. This topic provides students with practical examples of differential equations and serves to demonstrate to them one method for solving these equations. In the process, the students realize that, for example, decreasing the ozone dose in a seawater facility by half decreases the amount of bromate produced almost by a factor of four. This trend is not at all obvious from the original differential equations and yet, it is essential when one has to determine the optimum ozone dose and contact time for a given system. While working on this exercise, the students learn the importance of avoiding pitfalls in numerical approximation methods (e.g. divergence of results when the integration interval is not sufficiently small). They also realize how important differential equations are in describing many natural and human-controlled environments.

BENEFITS OF THE INTERACTIVE, COMPUTER-BASED APPROACH

Quantitative analysis of the five course topics is greatly enhanced by extensive and interactive use of computer technology. Specifically, computers provide the following benefits to the students in the course:

- By supplying instantaneous feedback, computers enable the students to test different approaches to a problem and evaluate whether the results are meaningful or not.
- Some course topics (e.g. preparation of artificial seawater) lead to relatively simple, but very repetitive mathematical expressions. The use of computers to help solve such problems enables the students to focus on problem fundamentals, and not become distracted by the tedium of the calculations.
- When exact analytical solutions are not possible, computers are a very powerful tool in obtaining approximations, to a high degree of accuracy.
- For those problems where both analytical and numerical methods exist, computers can be used to compare the two types of methods and investigate the benefits and drawbacks of each.
- Finally, properly programmed computer models can provide predictions about the behavior of a system well into the future. In particular, the *Water Exchange Rates* and *Denitrification* topics are suitable for such programming and predictions.

CONCLUSIONS

Figure 1 shows the results of Student Evaluation of Teaching for the new course. Combined data from two semesters when the course was taught are included in Figure 1. For the category of *stimulation of interest in the subject matter* (dotted bar), 86% of student responses have been "6" or "7", the two highest possible scores. In the category of *effectiveness of the computer lab sessions* (clear bar), 92% of student responses have been "6" of "7". Finally, in the category of *educational value of homework* (dashed bar), 93% of all responses have been "6" or "7" and there is only one lower response, with a value of "5". These numerical results clearly show the success of the course as a whole.

Student answers given to our written questionnaires show that most students felt they have learned or reinforced a lot of their quantitative reasoning skills through this course. The students indicated that the relatively long time spent doing the mathematics necessary to solve the problems helped them significantly in the development of their applied analytical techniques. In fact, most students preferred to arrive at solutions through their individual efforts, rather than through group discussions. The educational value of homework problems, where this individual approach is most emphasized, was regarded very highly as a result (Figure 1).

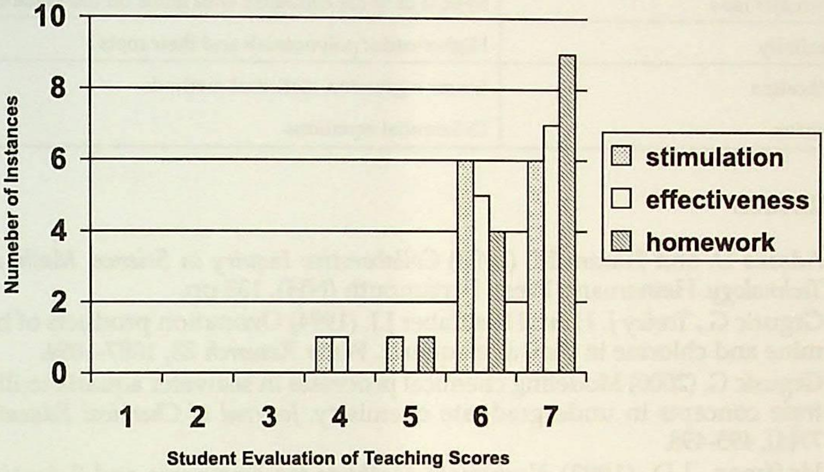

Figure 1. Distribution of Student Evaluation of Teaching Scores for three categories in the new course: (dotted bar) stimulation of interest in the subject matter; (clear bar) effectiveness of the computer lab sessions; (dashed bar) educational value of homework. Data from two semesters are included. Among the Student Evaluation of Teaching results, "1" represents the lowest score, and "7" represents the highest score.

The extensive use of computer technology in our course has been shown to have multiple advantages: their overall effect has been to enable the students to repeat calculations many times, using different input data. This has served as a powerful tool to increase the students' awareness and understanding of the mathematical relationships at work in their models. Another benefit of this approach has been that students became independent selflearners through the development and use of their own models. Many of these educational innovations are discussed as goals in the recent National Science Education Standards (NCR, 1996). The teaching approach in our course thus serves to help achieve some of the overall objectives in undergraduate science education.

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Table 1. Underlying mathematical concepts discussed during each Topic

Topic	Mathematical concept
Water exchange rates	Recursive expressions vs. functions
Salinity/major ions	System of linear equations with limits on the variables
PH/Alkalinity	Higher-order polynomials and their roots
Denitrification	Linear regression, statistical methods
Disinfection	Differential equations

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Sažetak

PRVI POKUŠAJI UVOĐENJA KVANTITATIVNOG ZAKLJUČIVANJA U DODIPLOMSKO OBRAZOVANJE IZ PODRUČJA ISTRAŽIVANJA MORSKIH RESURSA

Nedavno je na Richard Stockton College u New Jerseyju uveden kolegij Istraživanje morskih resursa, koji se temelji na modeliranju fizikalnih i kemijskih procesa u zatvorenim morskim bazenima. Kolegij objašnjava studentima matematičke pojmove kao što su rekurzivni izrazi, linearne jednadžbe s ograničenjima nad varijablama, te rješavanje algebarskih jednadžbi višeg reda. U radu je prikazano pet područja koja ovaj kolegij obuhvaća, uključujući matematičke ideje i principe koji pokrivaju svako pojedino područje. Kvantitativno zaključivanje i analiza tih područja znatno su prošireni velikom i interaktivnom upotrebom računalne tehnologije. Opisani zadaci mogu se koristiti i u velikom broju nastavnih programa dodiplomske nastave kao praktična objašnjenja koncepata koja su u ovom radu prikazana.

Ključne riječi: kompjutorski zasnovana naobrazba, modeliranje, primijenjena matematika, interaktivno učenje.