A Framework for Integrating Quantitative Geologic Problem Solving into Courses Across the Undergraduate Geology Curriculum

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ABSTRACT

Forging a link between quantitative skills and geologic problem solving is a valuable instructional approach that can guide the development of quantitative course material. A conceptual framework is presented that shows how various research tasks (for example, data collection and hypothesis development) employ certain combinations of quantitative skills (for example, graphical presentation and algebra). The framework shows how this "repertoire" of skills can be explored and strengthened by posing course assignments as research problems. An example problem, "What is the major source of nitrogen to the South Fork of the Palouse River?," illustrates implementation of all the tasks and skills in the framework via a four-week unit of coursework. Smaller units can focus on subsets of tasks and skills. Experience with units on structural geology, igneous petrology, hydrogeology, and isotope geochemistry suggests that the framework can be applied to virtually any geoscience topic at any level in the undergraduate curriculum.

Keywords: Education – geoscience; education – undergraduate; geoscience – teaching and curriculum; miscellaneous and mathematical geology.

Introduction

As geoscientists we recognize the increasing role and power of quantitative tools in our work. Therefore we want our students to obtain meaningful exposure to these tools as they are used in practice. Broader benefits should also be recognized; quantitative work builds math skills, helps students bridge intellectual gaps imposed by the division of academic disciplines, and generally enriches undergraduate education for both science and non-science majors.

In the struggle to act on this insight, one reflex has been to add numbers and/or number-crunching as adjuncts to existing exercises. Typically, students have been less than enthused by this approach, and we wonder whether the work really contributed to their geologic knowledge. These experiences have led us to adopt a more systematic and fruitful approach to including quantitative work in our courses. On reflection, we realized that, in our research practice, quantification is employed in various tasks:

1) grasping and articulating problems (hypothesis formulation),
2) gathering data by observation (data collection),
3) transforming raw data into results (data reduction and presentation),
4) describing data and results statistically (assessment of variability and uncertainty), and
5) evaluating results for consistency with hypotheses.

This simple representation of scientific method is not intended to imply that we strictly follow a predetermined task order; certainly in geoscience the interplay between experience and conception is rich and complex. The point here is that the tasks on this list are all integral to geoscience and that they require different kinds and combinations of quantitative skills (Table 1). Certain skills are used almost across the board; others are not. These skills, taken together, constitute a "repertoire" of quantitative skills for the geoscientist. Assignments in our classes, posed as research questions or problems, can emphasize this repertoire in its scientifically natural setting and sequence.

A research or "inquiry-based" approach holds several benefits for students. The assignments allow students to engage the material, building on what is already known and familiar, stressing "hands-on/minds-on" activities and thematic continuity, and improving grasp of the scientific method and its strengths and weaknesses (Dunkhase and Penick, 1991; Paul, 1992; Schweitzer and Tapp, 1994; AGU, 1994). Such an inquiry-based approach has been taken by many geoscience teachers before us (for example, Sanders, 1994; Smith and others, 1995, Soreghan and Soreghan, 1999, Carlson, 1999). Here we apply these ideas explicitly to coherent development of meaningful quantitative work in geology courses. We believe that this can be done at all collegiate levels in a wide variety of courses. To date, we and our colleagues have created material based on this approach with topical emphases in structural geology, igneous petrology, isotope geochemistry, and hydrology. Such units have been designed for and included in first- through fourth-year courses offered by our department.

This paper has two objectives: 1) to describe a conceptual framework for building quantitative work into geoscience course material (Table 1) and 2) to illustrate, by example, use of the framework to implement a unit of coursework based on a research problem. We also briefly report on our limited assessment to date of the success of the framework and

Task	What students do	Quantitative skill
1. Hypothesis development	Examine historic river hydrograph (literature) Learn about terrestrial N cycle Develop hypotheses for $[NO_3]$ response to different source scenarios	Graphical presentation Articulation of problem in terms of natural law (mass conservation)
2. Data collection	Design experiment – select sampling locations that allow determination of NO_3 flux for different sources Measure flow velocity, cross sectional area, stream water $[NO_3]$	Description of spatial variability Calibration, standardization, reporting
3. Data reduction	Calculate water and NO_3 discharges from stream cross-sectional area, velocity, and $[NO_3]$ Compare NO_3 mass flux across stream reaches of interest to assign source/sink (conserve N mass)	Algebra, dimensional analysis, graphical presentation Application of natural law (mass conservation)
4. Uncertainty analysis	Assign uncertainties to the computed NO_3 source/sink using mean and standard deviation	Descriptive statistics Error propagation
5. Hypothesis testing	Compare results of source/sink determinations to decide which source(s) are significant on the sample date Check for reasonableness – Compare annual stream-water discharge (literature data) to mass N applied to watershed annually – is the source large enough?	Algebra, dimensional analysis, graphical presentation

Table 1. Geoscientist's repertoire of quantitative skills in the context of the research problem "Sources of N to the South Fork Palouse River."

discuss its flexibility and broad applicability across the subdisciplines of geologic instruction.

The example is a four-week unit in our third-year course, "Water and the Earth." One important goal of the course is to learn, improve, and apply quantitative problem-solving skills in geology. The three-semester-credit course meets for five hours per week and includes both lecture and laboratory components. The research-problem units are the focus of the course and occupy both lecture and lab time, thereby blurring the traditional separation of the two course components. The example unit described here addresses all the tasks listed in Table 1. Not all instructional units in geology courses need to utilize all of these tasks, nor need they target learning of all the skills. We hope that readers can use our framework to focus development of new quantitative course content.

Research Problem Unit

We pose the following question to the students: "What is the dominant source of nitrogen (N) in the South Fork of the Palouse River (SFPR)?" There are no existing data (aside from data generated by previous classes) that permit an unambiguous answer. Temporal data for the river exist for certain locations, and the students can make use of this information. Table 1 lists "What students do" in the context of tasks and skills.

Quantitative thinking about the problem begins with ***hypothesis development*** (Table 1). As background preparation for hypothesis development in this unit, students are given or learn about: a river hydrograph for a one-year period (Figure 1a), maps of land use in the region (see sketch map in Table 2 showing a dairy farm and sewage-treatment plant (STP) surrounded by cultivated fields), and key aspects of the terrestrial nitrogen cycle pertinent to the problem. They learn that nitrate (NO_3) is the dominant form of nitrogen pollutant in river water, and we quickly move to discussions focused on nitrate. The students draw graphs of hypothesized nitrate concentration for a one-year period for each of two scenarios: a) all pollutant N comes from agricultural runoff; b) all pollutant N comes from STPs (Figure 1b). As they draw these graphs, students naturally consider stream-nitrate mass discharge associated with each source (although they do not articulate their thoughts as such). Most students hypothesize that dilution of pollutant inflow explains the drop in nitrate concentration from sewage-treatment plants during periods of high stream discharge and that heavy runoff from agricultural land during periods of high stream discharge explains the peaking of agricultural nitrate concentations at those same times. (Figure 1b).

Data collection (Table 1) provides opportunities for students to consider what data and observations are needed to address the question. In this example, students need to think through and decide about two aspects of the problem: a) where to sample to obtain the needed data; and b) what parameters to measure. Part (a) is not completely straightforward because there are two tributaries joining the main stem of the river in town (see sketch map, Table 2). The instructor sets limits on the testing plan by setting a practical limit on the number of stream transects to be sampled. The class must come to consensus on a plan; groups and individuals debate the best choice of locations, and in the field they decide exactly what and where to sample. The field-sampling trip provides many other opportunities to consider quantitative aspects of the problem. In this example, spatial variability is an important issue, both at the basin scale and at the scale of stream measurements. The variability of the stream cross section can be quantified by the students. Students are encouraged to investigate chemical variability either by collecting replicate samples for

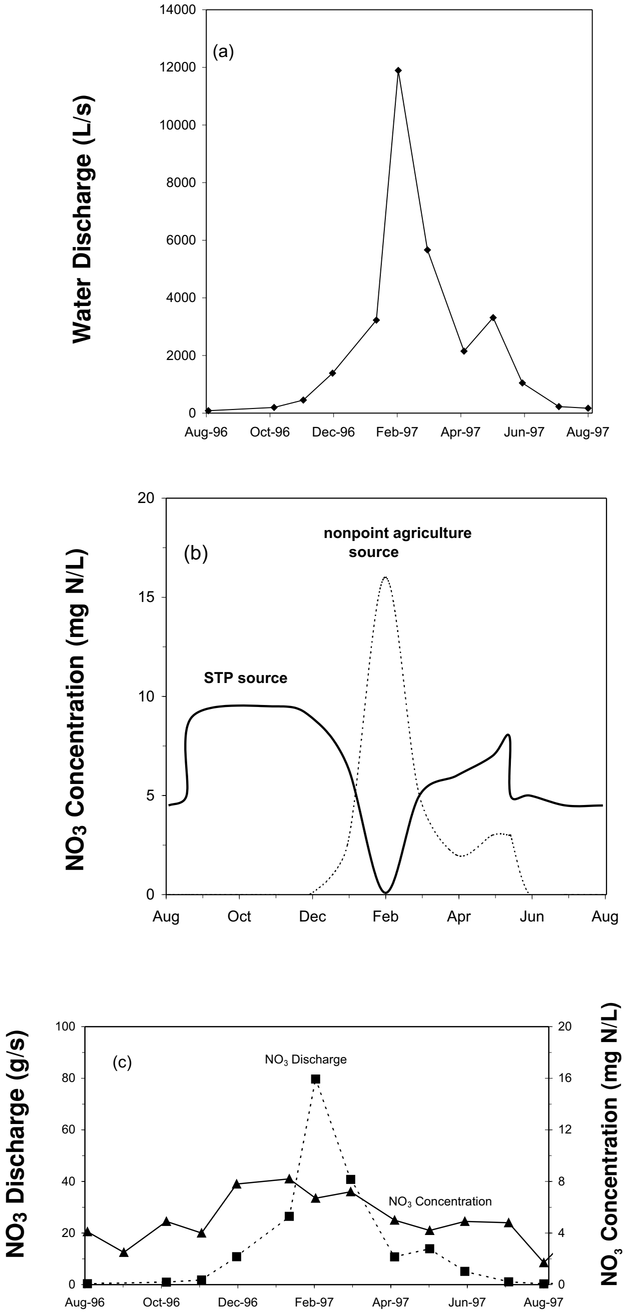
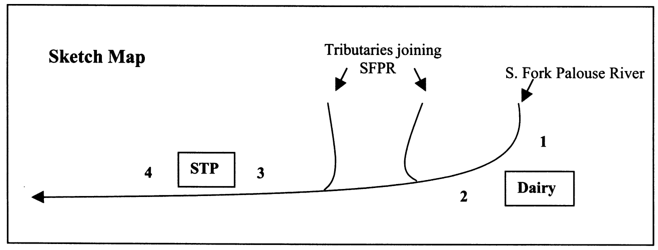


Figure 1. Changes through time of various stream properties. (a) Stream hydrograph for the SFPR (DOE, 2000), (b) typical hypothetical nitrate concentration ([NO_3]) graphs produced by students, (c) observed nitrate concentration (DOE, 2000) and estimated nitrate discharge from historic data. Typical features of student hypotheses shown in part (b) include: high [NO_3] with peak runoff and no [NO_3] during summer for the nonpoint agriculture source, and very low [NO_3] with peak runoff due to dilution for the STP source. Students predict the summer [NO_3] decrease for the STP source based on University students (>50% of the city population) leaving the area from June-August. Students work with (c) after collecting their own data.



(A)	Sample location			
	1	**2**	**3**	**4**
Q_w (m^3/s)[a]	15.7	15.3	37.1	37.9
[NO_3] (mg N/L)[a]	8.0	8.0	7.5	8.5
$Q_N \pm S_{QN}$ (g N/s)[b]	126±30	122±29	278±31	322±36

(B) Nitrate discharge by source[c]:

$Q_{N,\ STP}$	$= Q_{N4} - Q_{N3}$	=	44 ± 48 gN/s
$Q_{N,\ D}$	$= Q_{N2} - Q_{N1}$	=	− 4 ± 41 gN/s
$Q_{N,\ Ag}$	$= Q_{Total}$	=	320 ± 36 gN/s

[a] Water discharge relative error (ε_{QW}) was 0.23 (locations 1 and 2) and 0.10 (locations 3 and 4). Nitrate concentration relative error (ε_{NO_3}) was 0.05 (all locations). Relative errors were estimated as the standard deviation divided by the mean value (S_{QW}/Q_W or $S_{[NO_3]}$ / [NO_3]) for replicate measurements.

[b] $Q_N = Q_W[NO_3]$; the error term (S_{QN}) is estimated using standard error propagation techniques for a product (Meyer, 1975) and assuming the errors are independent and uncorrelated.

[c] Error on nitrate discharge ($Q_{N,j}$) for each source (j=STP, dairy (D) or nonpoint agriculture (Ag)) is determined using the standard error-propagation rule for a sum/difference (Meyer, 1975) and assuming the errors are independent and uncorrelated.

Table 2. Example nitrate discharge results used for hypothesis testing. Results from each sample location (A) are used to calculate nitrate discharges for sources associated with land use (B). The sketch map shows numbered sampling locations relative to the point sources. Nonpoint, agricultural sources of N are upstream of the dairy and the tributaries joining the river between locations 2 and 3. The calculations shown demonstrate the importance of considering uncertainty in arriving at a defensible answer. Because the nitrate discharges from the STP and dairy sources are not significant, all nitrate discharge (Q_{Total}) is attributed to the nonpoint, agricultural source.

analysis of nitrate concentration or by measuring a surrogate parameter. In this example, we suggest the latter, that is, that students measure the electrical conductivity of the water – a quick and easy field measurement – to assess dissolved chemical variability. Building in the collection of replicate or spatial data can provide opportunities for practice with statistical analysis techniques.

The ***data reduction phase*** (Table 1) involves transforming measurements into information that addresses the research question. A graphical cross section of the stream channel is prepared for each sampling location. Stream width and multiple stream-depth measurements are used to divide up the cross-sectional area of the stream channel. Discrete areas and velocities are multiplied, then summed to produce total water discharge (Q_w). Water discharge is multiplied by nitrate concentration ($[NO_3]$) to obtain nitrate mass discharge (Q_N) for each sample location (Table 2A). Our students use spreadsheets for all of these computations, for any necessary unit conversions, and to produce a schematic stream cross section showing their measurement locations. (For several of our students, this exercise is their first introduction to data analysis using a spreadsheet.) The final data-reduction step entails identifying the nitrate sources/sinks associated with each of the land uses by assessing a nitrate mass balance for particular stream reaches, as shown in Table 2B. Students compare nitrate mass discharges above and below the dairy, above and below the STP, and then estimate nitrate discharge associated with agriculture by the difference.

Hypothesis testing and consideration of ***uncertainty*** (Table 1) are closely linked in the example problem. Nitrate presence in the river during the wet season (about late fall, winter, and early spring) in our area (Pullman, Washington) is primarily attributable to agricultural runoff. Students find that contributions from each of the other two land uses are small (Table 2B) – prior to accounting for uncertainty, one source (the dairy) often appears to be a sink for nitrate. However, once students account for the uncertainties on the nitrate mass-discharge differences (Table 2B), they find that the apparently small sources or sinks associated with the dairy and the STP are not significant on the date of their sampling (winter). The students conclude that the only unambiguous source of nitrate in the wet season is agricultural runoff.

An important aspect of ***hypothesis testing*** is checking results for reasonableness (Table 1). In the example problem, students are asked to make two comparisons to check their answers. They use the Palouse River $[NO_3]$ and flow-monitoring data, posted on the World Wide Web by either the US Geological Survey or the Washington State Department of Ecology, to make the necessary computations. First, they compute the proportion of nitrate discharge that occurs during the wet season. The finding that 90+% of annual nitrate mass discharge occurs during the wet season helps to put their results, collected on one day during the wet season, into context. Furthermore, it allows them to conclude that their samples are representative of the high-nitrate discharge season. Second, they compare annual nitrate mass discharge (computed as N) normalized by watershed area to average N application (per unit area) for our region. They find that N mass discharge is less than N applied. This finding is essential *if* the conclusion that most N is derived from agricultural runoff is to be supported. Comparisons to literature data allow the students to reflect on their findings. These comparisons generally require additional quantitative work and can be designed to emphasize practice of key computational steps.

Discussion

Assessment. We have begun assessment of the success of this framework as applied in our course "Water and the Earth." Pre- and post-course testing and student surveys were used to gauge student learning. Through the testing process, students demonstrated significant improvement in their understanding of and ability to use the law of mass conservation. This law was used to solve hydrologic problems in every unit of the course. In answering the pre-course quiz question (given on the first day of class), about two-thirds of the class demonstrated that they had a correct, but vague, notion of the concept, and only one student could give a concrete and correct example. No student was able to write an equation showing how the principle could be used to solve a geologic problem. On the final exam, all but one student correctly wrote a mass-conservation equation and identified specific inputs, outputs, and storage terms within the context of hydrologic problem solving. Many students were able to add another level of detail (and complexity) to the problem beyond the basic mass-conservation statement. This accomplishment indicated that there was substantial improvement in the students' comprehension of the key concept and their ability to utilize quantitative work in geologic problem solving.

Student surveys provided additional insight. In response to the question, "What types of exercises have been the most helpful to you in learning the material so far?," 75% of students identified the field and/or lab activities and explanations. Two examples of student remarks in the course evaluations were: "The instructor...expected the student to think his way through every concept in the course." and "Breaking into groups, and having us try to figure things out before you showed us, helped us think for ourselves and understand the material more." Such comments, taken together with the improvements in performance, suggest that the inquiry-based approach can successfully engage students in quantitative work.

Flexibility and application to other courses. The conceptual framework we describe here can be used to design assignments ranging from modest problem sets to multi-week problem-based units within a course. In the context of the example given here, a smaller unit focusing particularly on problem formulation and hypothesis development (Table 1) could explore various hypothesized scenarios using available or even synthetic data to work the mass balances in Table 2B. Another smaller unit could focus on data collection (Table 1): measuring stream cross sections, velocities, and/or nitrate concentrations, with or without a focus on issues of precision and possibly uncertainty. Such a unit could easily be expanded to include data reduction (calculating the nitrate discharges Q_N, Tables 1 and 2A), at which point it becomes possible to think semi-quantitatively about sources – even if the idea of mass conservation is never explicitly introduced. Data collection by the students themselves (task 2) is always preferable in principle but is unrealistic for certain kinds of problems. In our experience, using synthetic or literature data is less problematic if students have had their "hands on" task in a previous problem, earlier in the course.

The framework can also be used to selectively emphasize certain tasks and quantitative skills in overall course and/or curriculum design. Collaboration with our Department colleagues has convinced us that quantitative material can be applied to virtually any geologic topic at virtually any course level. Our introductory-level course still follows a traditional lecture format, but we are using the framework to redesign inquiry-based lab exercises that introduce quantitative skills (Table 1, tasks 2 and 3). We constructed a general second-year course entirely out of research units which treated topics in structural geology, igneous petrology, and isotope geochemistry. The structural-geology unit involved students using inexpensive physical models to quantitatively describe simple shear, with considerable attention to measurement error (Table 1, tasks 2, 3, and 4). The igneous-petrology unit involved fitting Rayleigh-fractionation models to MORB trace-element data, obtained from the literature, to investigate the hypothesis that the mantle is heterogeneous (tasks 1, 3, 4, and 5). In the isotope-geochemistry unit, students plotted $^{87}Sr/^{86}Sr$ ratios of marine carbonates, again from the literature, and explored hypotheses – constrained by mass conservation – as to what geologic processes caused variation of these ratios through the Phanerozoic (tasks 1, 3, 4, 5). More generally, wherever measurements are made, we can ask whether natural variability is evident or if all variation might be due to measurement uncertainty (Table 1, task 4).

Concluding remark. For purposes of designing material, it may be useful to tentatively construct a table like Table 1 for each assignment in a course. The instructor will find that some assignments can address many or all of the tasks and skills, while other assignments may involve only one or two tasks and associated skills. If tables for all assignments contain the same small subset of task entries, this might call for modification or development of additional material to emphasize the range of tasks and skills in the geoscientist's quantitative repertoire.

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Associate Professors Keller and Allen-King and Assistant Professor O'Brien are all hydrogeologists. Collectively, their research interests cover a broad range of physical, chemical, and contaminant ground-water topics. Recent projects have examined the fate and transport of organic contaminants, geochemical and physical heterogeneities of aquifer systems, local watershed hydrology and biogeochemistry, and hydrogeologic controls on the geochemical carbon cycle.