Attempts at Improving Quantitative Problem-Solving Skills in Large Lecture-Format Introductory Geology Classes

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ABSTRACT

We have used a variety of approaches to introduce quantitative concepts into our introductory geology classes, some of which rely on using case studies of local rivers to improve student interest and appreciation of quantitative methods in scientific problem solving. Fortunately, there are rivers in most parts of the country, so these approaches are easily transferable and applicable in many areas. A simplified form of the continuity equation applied to stream flow serves as the starting point for developing a discussion of how and why local rivers are channelized for flood control. Students also analyze the recurrence interval of flooding along a local river of interest.

Keywords: Education – geoscience; education – science; education – undergraduate; education – special clientele; hydrogeology and hydrology; surficial geology – geomorphology; miscellaneous and mathematical geology.

Introduction

The Physical Geology course taught at the University of Houston is a traditional, freshmen-level course designed in part to satisfy a state-mandated core-distribution requirement for all undergraduates. Although geoscience majors take the course, over 95% of the students who enroll are non-science majors. Most sections are taught in large lecture classes of 100-200, and optional labs are taken by approximately 25% of the students. College algebra is a co-requisite for the course, providing our students with an opportunity to apply the math skills the University deems important enough to be required of all graduates.

We believe one of the prime goals of science is to solve problems, and math is a fundamental tool in scientific problem-solving. Also, some basic understanding of mathematics is requisite for scientific literacy (AAAS, 1994). If students can use basic math to solve (or at least understand) simple real-life problems, they will ultimately develop a better appreciation for how science works, how it affects their lives, and how math-based misconceptions can cause serious problems to both individuals and society as a whole. In short, math provides some of the tools with which students can learn science by doing science (National Research Council, 1996; deCaprariis, 1997).

The math skills needed to understand the quantitative aspects in our course are relatively modest and are routinely taught in middle and high school (TEA, 1999; TIMSS, undated). They include:

- Interpretation of x-y and pie graphs,
- Variables expressed as algebraic equations,
- Concept of rates (for example, erosion, sea-level rise, geothermal gradients, stream gradients, and evolution),
- Fractions, ratios, and percentages (for example, porosity, specific gravity, radiometric decay, and scale), and
- Probability concepts (for example, recurrence interval).

We have used a variety of approaches to apply these skills and concepts in our classrooms; however only a few are described here. In particular, we find that the use of case studies of local rivers aids both in developing student interest (Dupré, 1997) and in improving their appreciation of quantitative methods in scientific problem solving. Fortunately rivers are present in most parts of the country, so these approaches described here are easily transferable and applicable in many areas.

Flooding: An Issue-Based Approach

The large class size, combined with time constraints, require that we develop the ideas outlined in this paper by engaging the class in question-and-answer exercises to allow the students to see how arguments and information can be marshalled to develop a better understanding of a potentially complex topic. We begin a week-long discussion of rivers with an overview of the benefits and hazards associated with rivers, particularly focusing on hazards related to flooding and erosion.

We start with a question – *"how can a few inches of rain cause so much flooding?"* Students are used to seeing rainfall amounts reported on TV, yet they have a problem mentally transforming the rainfall to runoff. We continue by asking, *"what is the volume of runoff passing through nearby Brays Bayou [located a block off campus], if an average of 1 inch of rain falls upstream?* At that point some students recognize that it depends on the area being drained by the river. The class "discovers" the concept of the drainage basin.

We then ask, *"is the volume of rain equal to the volume of runoff?"* Some will respond no, as some water is lost due to infiltration into the ground. In that case, *"what are the variables that determine the rate at which water infiltrates?"* The students develop a list, which can include soil type, rate of rainfall, ground slope, soil moisture content, vegetation, and land use. They can then develop the following relationship:

(average rainfall – average infiltration)
× drainage area = volume of runoff.

We then do a simple calculation showing that, for the actual drainage area of Brays Bayou of 95 square miles (246 square kilometers), a one-inch rain with an average infiltration of 0.2 inches results in 2.6 billion cubic feet of runoff. The students are surprised by the large volume produced from such a small rain.

The discussion then turns to how volume of runoff translates to an elevation of flood waters. Upon reflection, the class realizes that it isn't the volume of water that's important to most flood issues, it's the rate at which that volume passes a single point. We have now introduced the concept of discharge (=volume/unit time), as well as the closely related parameter stage (= stream surface elevation). If time allows, we discuss rating curves, which plot discharge against stage, and how stage, as measured at gaging stations, is actually used as a proxy for discharge in most cases. Hydrographs, which plot discharge (or stage) against time, are an important graphical tool in describing runoff. Hydrographs of real-time stage and discharge can be downloaded from the Internet (U.S. Geological Survey, 2000) and used to illustrate points made in the previous day's discussion. Use of real hydrograph data is extremely effective in generating student interest. Several freshman textbooks use hydrographs to show the lag time between rain fall and runoff, and to illustrate the increased peak discharge (and stage) with urbanization of the drainage basin by increasing the speed by which water flows out of the drainage basin (for example, see Plummer and others, 1999; Tarbuck and Lutgens, 1999). We also note that urbanization, by replacing more permeable soils with impervious structures, also increases the volume of runoff, further accentuating the increased peak discharge. In short, upstream development can result in increased downstream flooding.

> ***...on any given day, approximately 40% of the students are likely to be absent.***

Channelization and the Continuity Equation

We give an overview of the various structural and non-structural responses to floods, focusing on channelization. Channelization often involves modification of a segment of a stream to increase its flow velocity, thereby decreasing the cross sectional area and lowering flood stage so that the discharge can be contained in the channel without overbank flooding. A simplified form of the continuity equation (equation 1) applied to stream flow can be the starting point for developing a useful discussion of how and why a local river is channelized for flood control.

$$Q = VA \quad , \qquad (1)$$

where:

Q = Discharge (volume/unit time, (for example, cubic feet/second or cubic meters/second)),
V = average stream velocity, and
A = cross sectional area of the stream.

Equations are rare (and in some cases completely absent) in most introductory geology textbooks (for example, see Shea, 1990, 1994). One advantage of using the continuity equation is that it is included in most recent textbooks, even if it is poorly stated in many cases (Wampler, 1997). This equation is typically used in textbooks only to show how discharge can be calculated, yet it can also provide the basis for analyzing why local streams are channelized, and how such channel modifications reduce local flooding. Such an approach is usually restricted to more advanced textbooks (for example, see Dunne and Leopold, 1978; Manning, 1987; Dingman, 1994), however it can also be used quite effectively at the introductory level.

We ask the students *"How do you increase the velocity of water flowing through a hose?"*, and they reply "by putting your thumb over part of the nozzle" (that is, by decreasing the cross sectional area). We then ask them *"How can you reduce cross sectional area (hence stage) without reducing discharge?"*, and, using the continuity equation, they respond "by increasing velocity." A class discussion generates the following ways to increase stream velocity: 1) decrease resistance to flow, 2) increase the efficiency of the channel, and 3) increase the slope of the channel.

Given these relationships, we help guide the students to develop a hypothetical algebraic relationship similar to equation 2:

$$V = k\,\frac{(\text{Efficiency})^{y}\ \&\ (\text{Slope})^{x}}{(\text{Resistance})^{z}} \quad . \qquad (2)$$

This approximates the Manning Equation (equation 3), which provides a framework for discussing various aspects of channelization.

$$V = \frac{1.49R^{2/3}S^{1/2}}{n} \quad , \qquad (3)$$

where:

V = average flow velocity (in ft/sec),
n = Manning's roughness coefficient (a dimensionless measure of the resistance to flow),
R = hydraulic radius (a measure of channel cross section efficiency), and
S = slope of the energy gradient (approximated by slope of the channel).

To illustrate the effect of channel roughness (or resistance to flow), we show pictures of two urban streams (Figure 1 A and B). Virtually all students recognize that the concrete-lined channel has the lower roughness coefficient, hence the fastest flow. This provides the engineering rationale for replacing riparian vegetation with concrete, thereby increasing flow velocity and decreasing stage. We have an overabundance of such concrete-lined waterways near the campus and throughout Houston to serve as examples, as do most urban settings.

Velocity can also be increased by making the channel cross section more efficient. This is done by

A B

Figure 1. Comparison of natural (A) and concrete-lined (B) urban streams.

increasing the hydraulic radius (R) of the channel, as defined by equation 4:

$$R = A/P \quad , \qquad (4)$$

where:

A = Cross sectional area of the water in the channel, and
P = wetted perimeter (= the perimeter of the channel in contact with water).

The term "hydraulic radius" isn't used in freshmen texts; however, the concept of channel efficiency can be found in many textbooks (for example, see Thompson and Turk, 1994; Dolgoff, 1998; Monroe and Wicander. 1998; Tarbuck and Lutgens, 1999; Plummer, McGeary, and Carlson, 1999); one (Pipkin and Trent, 1994, p. 243) shows how this unnamed ratio can be used to predict change in velocity. We show the students two channels with the same cross sectional area – one wide and shallow and the other narrow and deep (Tarbuck and Lutgens, 1999, p. 235). Most students recognize that water in the wide, narrow channel has more contact with the channel margin (a greater wetted perimeter), thus more friction to slow it down relative to a channel with a more efficient (higher) hydraulic radius.

In discussing the influence of channel slope, we ask students how to slow down when skiing down a steep slope, and many answer, "by taking a less direct, 'zig-zag, course." This introduces the concept of sinuosity and its relationship to slope. The sinuosity of a stream is a dimensionless ratio describing how much the channel deviates from a straight line. It can be calculated by dividing the channel distance by the straight line distance between two points (equation 5).

$$\text{Sinuosity}=\frac{\text{channel length}}{\text{straight-line (valley) length}} \quad . \qquad (5)$$

We show the students topographic maps of Brays Bayou in 1916 and 1978 (Figure 2) and ask them how straightening the channel affected sinuosity and channel slope. Slope (S) is defined as:

$$S = \Delta Y/X \quad , \qquad (6)$$

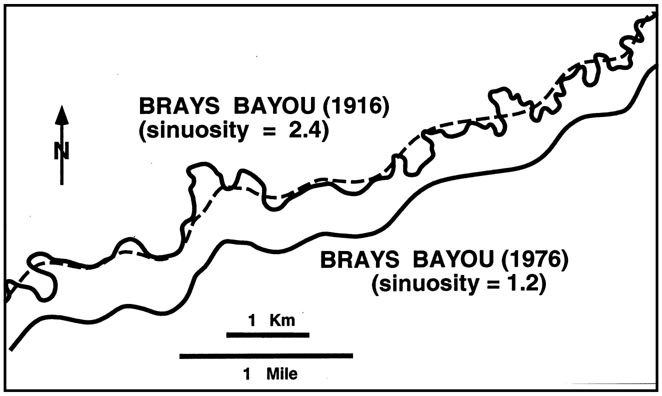

Figure 2. Comparison of channel shape and sinuosity of Brays Bayou before and after channelization (U.S. Geological Survey, 1920 and 1982).

where:

ΔY = change in elevation between two points, and
X = distance between two points measured along the channel.

Since straightening a channel reduces X without changing ΔY, it reduces sinuosity (from 2.4 to 1.2) and increases slope. In doing so, we have increased velocity and thus reduced local flooding.

At this point, it is important to discuss the fact that, although channelization may decrease flooding along a particular stream segment, it can result in increased flooding downstream. Other negative aspects of channelization include reduction in groundwater recharge, loss of riparian and aquatic habitats, aesthetics, and so forth.

What is the 100-Year Flood?

The local Houston newspaper quoted a flood survivor who was re-building his house in the floodplain as saying, "They say this is a 100 year flood. I don't guess I'll see the next one anyway." (Henderson, 1998). This illustrates the common misconception that the 100-year flood is a flood that occurs once every 100 years. This is reinforced when a local flood-management official states on TV that, "the longer it's been since we have had a 100 year flood, the more likely it is to occur

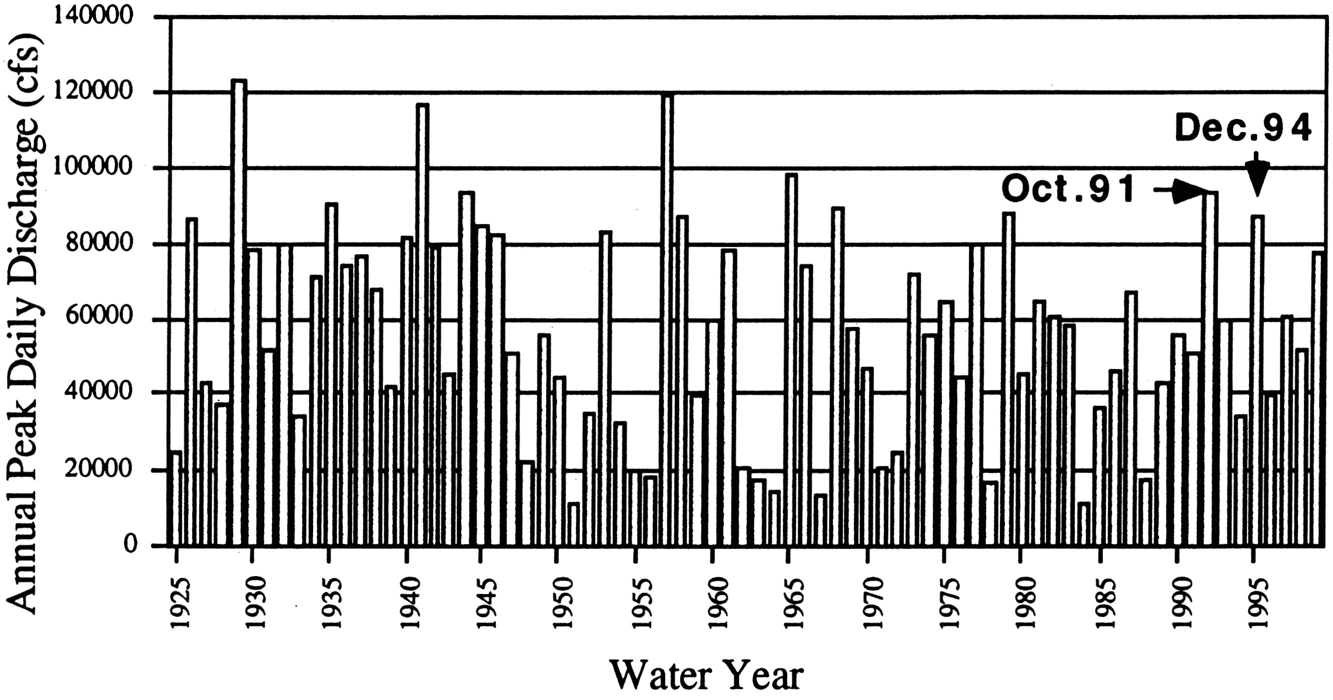

Figure 3. Flood record at the Richmond gaging station on the Brazos River.

in the future." We address these misconceptions head on in class using the coin toss as an example. The students demonstrate that "heads" does not come up once every two times you flip a coin, even though, on the average, it will come up 50% of the time. They also see that the coin has a 50% (or 1 in 2) chance of being heads on any given flip, regardless of the previous "flip history."

Similarly, the 100-year flood does not occur exactly once every hundred years, but is a flood with an annual recurrence interval of 100 years. The annual recurrence interval (RI) of an event of a particular magnitude is the average number of years between events of similar or greater magnitude. Annual recurrence interval is calculated as:

$$RI=\frac{N+1}{M} \quad , \qquad (7)$$

where:

N = number of years of record, and
M = relative rank of the event (M=1 for largest magnitude event of record).

The annual exceedence probability (P) of an event of a particular magnitude being equaled or exceeded in any given year is the reciprocal of the recurrence interval (equation 8).

$$P=\frac{1}{RI} \quad . \qquad (8)$$

Thus a 100-year flood is also one that has a 1% (1 in 100) chance of being equaled or exceeded in any given year, regardless of the previous "flood history." Most introductory textbooks include a graph of recurrence interval versus flood discharge, and some even provide data sets and show how it is calculated (for example, see Chernicoff, 1999; Monroe and Wicander, 1998; Plummer and others, 1999; Press and Siever, 1998). In addition, on-line data sets of peak annual flood discharges for rivers throughout the country are available through the Internet (U.S. Geological Survey, undated).

To increase the interest of our students, many of whom have heard of 100-year floodplain maps and the related FEMA insurance program, we discuss an article from the local newspaper (Munk, 1997) describing the plight of a small town (Simonton) approximately 50 kilometers west of Houston. The town has been incorporated since 1979; however, only recently have floods along the Brazos River (October, 1991 and December, 1994) caused serious damage. The class concludes that any response to the flood problem (for example, levees, buyouts, floodproofing) must include an analysis of the probability of damaging floods in the future. As an extra-credit assignment we give the students a histogram (Figure 3) and a table listing the peak average daily discharges for each of the 75 years of record (1925-1999) from which they calculate the recurrence interval and exceedence probability of all flood events greater than 80,000 ft^3/sec (including the 1991 and 1994 floods). They realize on the basis of their calculations that the town has suffered serious damage from a flood with an eight-year recurrence interval, that is, one with a 12% chance of occurring any given year. A second part of the case study (not discussed here) illustrates that levees proposed to protect the houses from flooding can't be built because of the rapid erosion rates and impending meander cut off. It should be noted that the concept of recurrence interval as described here is based on the assumption that climatic variations over the period of record don't affect the probability of an event occurring in the future. Gosnold and others (2000) correctly question this assumption; however this is a complication which, depending on time, may or may not be appropriate for an introductory class.

Does Our Approach Work?

The effectiveness of this approach is difficult to measure. In part, this is because most of it is based on discussions in class, where, on any given day, approximately 40% of the students are likely to be absent. Only 50-60% of the students do the assignments, such as the recurrence-interval problem set, whether they are required or given as extra credit. This approach is more effective when integrated into major individual or group projects requiring students to use real data to make a report, complete with documented recommendations for future action. One of us (WRD) did this for one section of the optional freshman lab and for an upper-division geohazards course, and the student reports were, on the whole, exceptional. Unfortunately, limitations of class size, personnel, and space preclude our using projects with formal reports in the large introductory classes. Nonetheless, students generally do better on exam questions relating to the topics discussed in this paper than on questions on other topics. In fact, some of the best results on the exams are obtained on questions dealing with the more quantitative aspects of river behavior, flooding, and channelization.

Conclusion

- Local rivers provide a useful context to introduce more quantitative concepts to non-science majors, as well as to help motivate students by showing how geologic issues affect their local community.
- The continuity equation provides a focal point to develop a classroom discussion of how and why rivers are channelized. It allows class participation and builds on several quantitative concepts, some of which are discussed in textbooks.
- The concepts of recurrence interval and exceedence probability, though difficult to understand, can be better understood if students do calculations using real data to better define a real geologic problem.

Acknowledgments

This article has been significantly improved thanks to the efforts of LeeAnn Srogi, James Westgate, and two anonymous reviewers, as well as the editorial staff of the *Journal*.

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