Integration of Environmental Analytical Chemistry with Environmental Law: The Development of a Problem-Based Laboratory

ARTICLE *in* JOURNAL OF CHEMICAL EDUCATION · DECEMBER 2001

Impact Factor: 1.11 · DOI: 10.1021/ed078p1652 · Source: OAI

1 AUTHOR:

Devon Cancilla
University of Missouri - Kansas City

Integration of Environmental Analytical Chemistry with Environmental Law: The Development of a Problem-Based Laboratory

Devon A. Cancilla

Department of Environmental Science, Huxley College of the Environment, Western Washington University, Bellingham, WA 98225-9181; *Devon.Cancilla@wwu.edu*

Increasingly, science-based organizations such as the United States Environmental Protection Agency (U.S. EPA) and Environment Canada (EC) are moving away from regulatory-based environmental assessments using standard analytical methodologies. Instead, they are encouraging the use of assessments based upon ecological screening techniques following the principles of environmental-effects monitoring and performance-based analytical methodologies. The goal of this approach is to provide a more integrated method for understanding complex environmental systems.

Environmental-effects monitoring is the process of assessing environmental conditions on the basis of specific ecological indicators such as reproductive success, mortality, observed toxicity, species diversity, or some other biological endpoint (*1–4*). To complement the use of ecological indicators, performance-based analytical methods are used to measure the levels of both target and nontarget chemicals in the specific system. A performance-based analytical method is one in which the quality of the result (including recovery, detection limits, precision, and accuracy) is defined in the method. A performance-based method provides information on the steps required to obtain data of specific quality (*5–10*). This is in contrast to a prescriptive method, which describes the specific procedures that must be followed to obtain an analytical result. A performance-based method describes what the outcome should be relative to the data quality, whereas a prescriptive method describes how an outcome is obtained through specific procedures.

Environmental-effects monitoring and performance-based analytical methods incorporate a fundamentally different way of thinking about environmental analyses. Traditionally, target lists of chemicals are used for screening; if these chemicals are present above defined levels, then a system is said to be contaminated. If the target chemicals are not present, a site is said to be clean, despite the fact that other chemical contaminants may be present, that low levels of target chemicals may interact synergistically to affect the ecosystem, or that other ecological indicators suggest a stressed ecosystem.

Within this context, environmental chemists must now be prepared to address specific issues relative to the measurement of chemicals in environmental systems. Rather than focusing solely on the question of whether a chemical is or is not present at target levels, they must be able to address a range of questions: What is it? How much is there? Is it going to hurt me or the environment? These questions require environmental chemists to be able to integrate knowledge from a wide variety of disciplines. In fact, experience in such diverse fields as analytical chemistry, environmental law, and environmental toxicology are all necessary to address these fundamental questions.

Environmental chemists therefore face difficult challenges related to generating, interpreting, and communicating complex chemical data in a manner understandable by nonchemists. Often, however, the language commonly used by chemists cannot be easily translated into the language of another discipline. The concept of scientific versus legal uncertainty is a classic example of an area where common terms do not have common meaning. Legal uncertainty is based upon a reasonable doubt, whereas chemical uncertainty is usually based on the concept of probability.

For these reasons, it is essential that environmental chemistry students develop the skills necessary not only to collect and interpret complex data sets but also to communicate their findings in a credible manner in nonscientific forums. Key to this requirement is an understanding of the quality assurance/quality control (QA/QC) elements used to support specific findings. The U.S. EPA, Environment Canada, and a number of other national and international organizations have prepared guidance documents describing the necessary level of QA/QC to support specific environmental projects (*11–16*). Guidelines for developing Quality Assurance Project Plans (QAPPS) and Data Quality Objectives (DQOs), as well as documents describing data verification and validation, are all easily available through the Internet (*16*). A variety of environmental chemistry courses have been described that introduce students to these various QA/QC elements (*17–24*). However, none incorporate the concepts of environmental-effects monitoring or performance-based methods.

This paper describes the development of a problem-based environmental analytical chemistry laboratory and its integration with an undergraduate environmental law course. The course is designed to introduce students to the principles of performance-based analytical methods and the use of environmental indicators to perform environmental assessments. In addition, the course introduces students to specific QA/QC elements necessary to support analytical results and to explain these concepts to nonchemists. The primary goals of the course are:

1. To give students experience with a variety of common analytical methods ranging from screening to quantitative analytical methodologies.
2. To give students experience in developing and interpreting quality control elements to support analytical results.
3. To link toxicological and chemical methodologies to address broad environmental problems.
4. To demonstrate the relationship between analytical variability, scientific uncertainty, and legal uncertainty.
5. To give students experience in communicating scientific data in policy and legal contexts.

Structure of the Course

Upper-division undergraduate courses in environmental law and environmental chemistry are offered once a year by Huxley College of the Environment at Western Washington University. Environmental Chemistry is part of a program in environmental toxicology and chemistry within the Department of Environmental Science. It is also approved as an upper-division elective course for chemistry majors by the Department of Chemistry within the College of Arts and Science. The Environmental Law course is offered as part of the program in environmental policy and planning within the Department of Environmental Social Studies at Huxley College.

Students taking the environmental chemistry course are junior- and senior-level environmental science or chemistry majors. The prerequisites for environmental chemistry include one year each of general and organic chemistry and the introductory course in environmental chemistry. Although it is strongly recommended that students have completed a course in analytical chemistry and instrumental methods, environmental chemistry is the first, and usually only, laboratory-based analytical chemistry course for many of the environmental science students. Students in the environmental law course are junior and senior level environmental planning and policy majors. These students have typically completed a course in U.S. environmental policy. In situations where programs lack an environmental law course, linkages with courses such as landuse planning, environmental politics, or introductory environmental studies would be possible.

The entire 10-week laboratory is dedicated to resolving legal and scientific questions related to the question "What's Flowin' through Rowan?". Students are asked to investigate chemical and legal issues related to the possible presence of environmental contaminants under the Clean Water Act (CWA) and/or the Safe Drinking Water Act (SDWA). In one scenario, the hypothetical City of Rowan is facing an administrative hearing by the U.S. EPA for continued violations under the Safe Drinking Water Act. In particular, the City has been cited for violations related to the presence of atrazine in its finished drinking water.

In this exercise, the law students are divided into groups representing either the City of Rowan, the U.S. EPA, the state Department of Health, or a citizens' group. Depending on class size, additional groups such as the state Department of Ecology can be added to the hearings, or there can be two sets of groups, with hearings scheduled on separate days. Each group is assigned a chemist who acts as a consultant and who performs a series of chemical and toxicological tests designed to assess the quality of Rowan's drinking water. Typically, approximately 12 students take the environmental chemistry course. This means that each chemistry student is paired with between two and five students from the environmental law class to form a group.

At the beginning of the course, both the law students and the environmental chemistry students are given information packets containing chemical and toxicological monitoring data covering the previous two-year period. Included with the environmental data are supporting quality assurance/quality control data such as control charts, blanks, and duplicate samples. The package contains testimonials from individuals from the U.S. EPA, City of Rowan, citizens' group, and the Department of Health, providing each group's perspective on the alleged problem. It also contains maps showing landuse patterns in the Rowan watershed. For the chemists, the introductory information includes readings and material on quality control and quality assurance practices. Information from the Canadian Association of Environmental Analytical Laboratories (*13*), the laboratory accrediting body of Canada, the U.S. EPA Quality Assurance Project Plans (*14*), and the U.S. EPA Functional Guidelines for Organic Data Review (*15*) provide students with background material on quality assurance/quality control principles and documentation. Readings on the development of performance-based analytical method and environmental-effects monitoring are also included.

One of the complicating factors presented to the students in the information packet is the fact that two separate laboratories were involved in the assessment of Rowan's watershed during the previous two years. Data from these two laboratories during the two-year period showed atrazine levels to range between 1.2 and 5.6 ppb (µg/L) (Fig. 1). As stated in the information packet, it is the City's claim that analytical variability makes the data unreliable for use in determining whether the running quarterly average of 3 ppb for the maximum contaminant limit (MCL) for atrazine has in fact been exceeded. As a result, the City claims that it should not be fined for noncompliance under the SDWA. Other groups claim the data *do* provide evidence of violations and that the City should indeed take corrective actions and/or face fines.

During the course, students are given additional information in the form of memos, correspondence, or newspaper reports. For example, each student receives a copy of the *Rowan Roundup*, Rowan's newspaper, which contains a number of articles relevant to resolving the problem of "What's Flowin' through Rowan?" In particular, hints buried in the articles suggest that Rowan is facing a far larger environmental problem than atrazine contamination. For example, Arntzen Enterprises, Fred's Fish Farm, the Happy Hollow subdivision, and the cemetery are implicated as sources of non-atrazine contamination (Fig. 2). These hints become evident as students work through the chemical and toxicological analysis of water samples collected in and around Rowan.

The chemistry students, using the historical information as a starting point, must conduct a series of chemical and

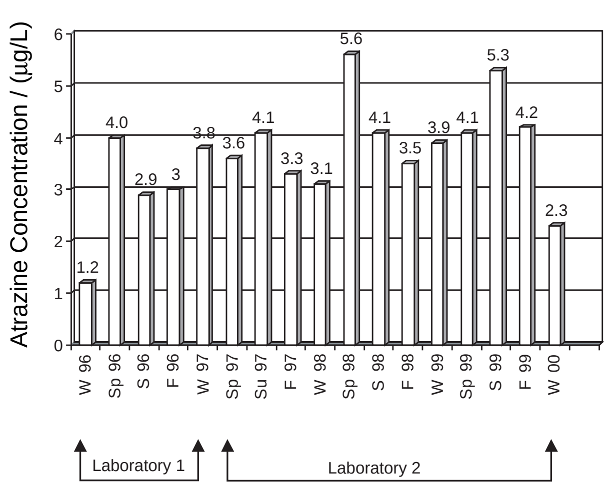

Figure 1. Laboratory 1 and 2 results for two-year atrazine concentrations in finished water samples from the City of Rowan.

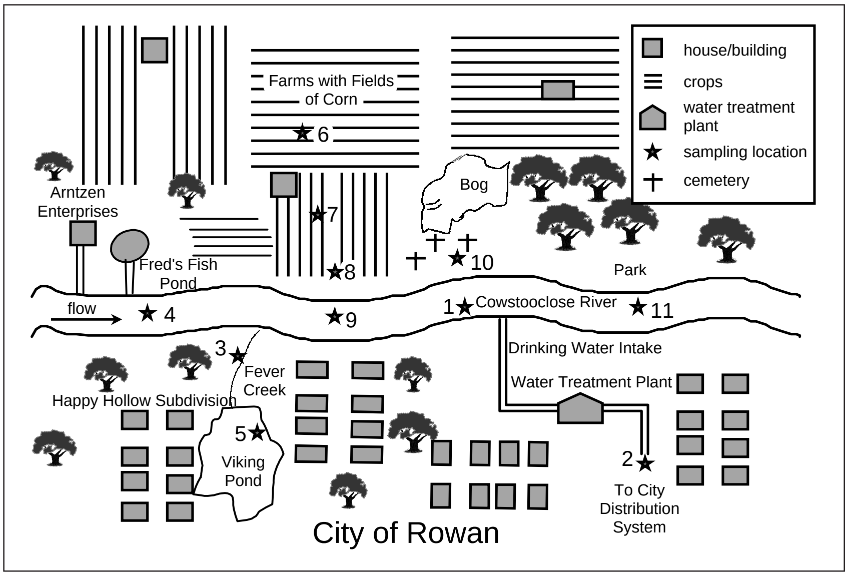

Figure 2. Map of the City of Rowan showing surrounding landuse patterns and sampling locations.

toxicological studies on the waters collected in and around the City of Rowan (Fig. 2). Their ultimate goal is to determine whether the City is out of compliance with the SDWA. In addition, the exercise shows that environmental impacts can often not be related to simple "target" analysis. In this case, throughout the exercise, evidence is developed indicating that effluents from a number of sources that do not contain atrazine, such as Fred's Fish Farm, are impacting Rowan's water supply.

Analytical results generated by the chemistry students during the course are used by the law students to develop and support arguments concerning whether the City should be cited and fined under the SDWA. The law students are allowed to use any legal device to support their arguments and have used such tactics as obtaining subpoenas to view laboratory notebooks and records of the opposing group's chemists. The final examination is a mock agency hearing in which each group has an opportunity to argue its case in front of a hearing board. The board is made up of faculty members and representatives from state or federal agencies that have experience with compliance issues. Students must follow specified federal administrative procedure requirements in presenting facts, evidence, and arguments during the hearing. As is the case with real hearings, a "no surprise" rule is in effect and each side must allow for a period of discovery. Discovery is defined as the process by which one party obtains facts and information from the other party to assist in the preparation for the hearing. In general, each group must formally request specific information from the opposing group. One class period before the hearing is set aside for discovery, at which time the requested information can be exchanged. Information usually requested from the chemists includes laboratory records, quality control data, raw data, and methods.

The Background Information

The primary purpose of the background information, other than to provide historical information, is to introduce students to the principles of QA/QC and the use of these techniques to assess the reliability of analytical data. Students are given data generated from each of two laboratories for the previous two years (Fig. 1) for the City of Rowan's finished drinking water (site 2 in Fig. 2). They also receive a series of control charts showing the analytical performance of specific quality control types from each laboratory (Fig. 3), specific

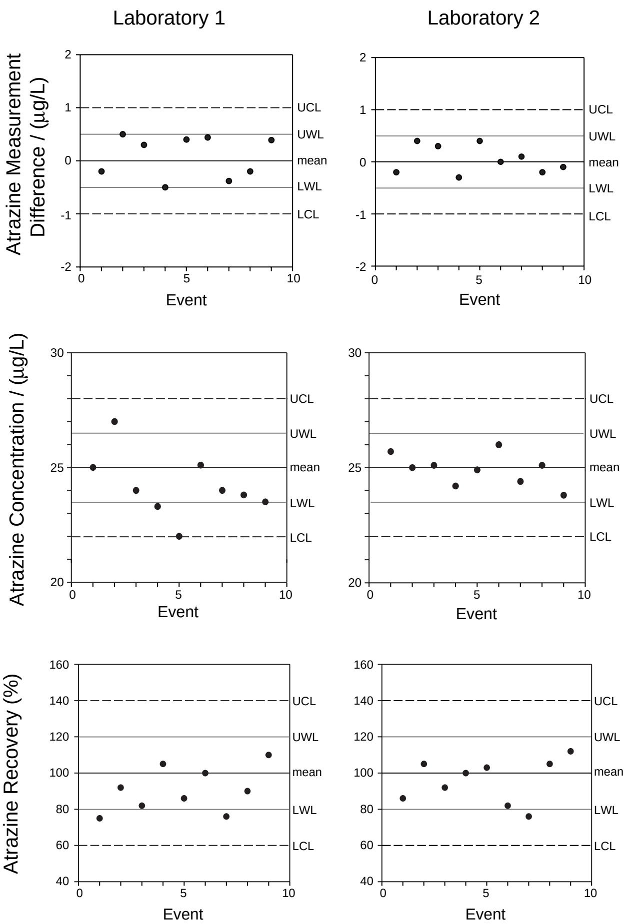

Figure 3. Quality control charts from laboratory 1 and 2 showing method precision, accuracy, and recovery.

Table 1. Atrazine GC–MS Analytical Results

Sample	Laboratory 1: Fall '96[a]			Laboratory 2: Winter '00[b]		
	Value/ (µg/L)	Target Value/ (µg/L)	Result	Value/ (µg/L)	Target Value/ (µg/L)	Result
Travel blank	<MDL	<MDL	Pass	<MDL	<MDL	Pass
Travel spike	5.0	10.0	Low	8.2	10.0	Pass
Method blank	0.8	<MDL	Flag	<MDL	<MDL	Pass
Method spike 1	8.2	10.0	Pass	10.2	10.0	Pass
Method spike 2	8.5	10.0	Pass	9.9	10.0	Pass
Location 1	12.5	—	—	11.0	—	—
Location 2	3.0	—	—	2.2	—	—
Calibration check	—	10.0	Pass	9.6	10.0	Pass

[a]MDL = 0.1 µg/L.
[b]MDL = 0.4 µg/L.

Table 2. Winter 2000 Chemical and Toxicological Survey Data, Laboratory 2

Sample Location	Results				
	Immuno-assay[a]	GC–MS/ (µg/L)	Mung Bean Assay[b]	Γ_5 Value[c]	
				Microtox	Phenol
1	+	11	+++	2.5	0.8
2	+	2.2	+	1.2	1.1
4	+	0.6	–	0.32	0.9
5	–	<MDL	+	0.12	1.6
6	+	<MDL	–	0.35	1.1
8	+	58	+++++	42	1.4

[a]+ indicates atrazine detected by immunoassay.
[b]+++++ is very toxic, +++ moderately toxic, and + mildly toxic.
[c]The greater the Microtox Γ relative to the phenol Γ, the more toxic the sample.

laboratory reports from each of the laboratories (Table 1), and data from a chemical and toxicological survey of the Rowan watershed conducted by laboratory 2 (Table 2).

Using this information, the chemistry students are introduced to the types of analyses they will perform in the laboratory and the principles of QA/QC used to support these analyses. As these methods are not prescriptive in nature, students learn to evaluate data from performance-based methods through the development of specific quality-control elements. They are introduced to the requirements of environmental laboratories to show ongoing statements of the *p*recision, *a*ccuracy, *r*ecovery, *c*ontamination, and *s*ensitivity of the method (PARCS statements) through the use of an analytical tray pattern. The analytical tray pattern is the sequence, type, and frequency of samples analyzed to demonstrate the performance characteristics of the analytical method.

These requirements are reflected by national and international standards developed for the performance of analytical laboratories by groups such as the U.S. EPA (*14*), the International Standards Organization (ISO) (*11*), and the Organization for Economic Cooperation and Development (OECD) (*12*). Each of these organizations has developed specific guides for good laboratory practice, which contain significant QA/QC elements for the generation and interpretation of analytical data in support of specific programs. For example, U.S. EPA has established National Functional Guidelines for Organic and Inorganic Data Reviews (*15, 16*) related to the analysis of contaminants in the environment.

The required use of the PARCS statements in support of the data is designed to demonstrate that the analysis of a single sample, such as a single laboratory value reporting atrazine at a concentration of 3.8 µg/L, is essentially meaningless. The types of samples typically used in an analytical tray pattern to generate the PARCS statements and the decision rules associated with each statement are presented in Table 3. Using the control charts and the results from the specific analyses, the chemistry students provide the law students with a memo summarizing their interpretation of the results and recommendations for the types of analyses they propose to resolve the issue of "What's Flowin' through Rowan?"

The students' understanding of the QA/QC elements and PARCS statements is reflected in their memos to the law students. The primary interpretation should show the correct evaluation of actual data and control charts. As can be seen from the data (Table 1, Fig. 1), students should find that Laboratory 1 appears to be biased low in its measurements of atrazine. Laboratory 1 also appears to have laboratory contamination, as seen from the presence of atrazine in its method blanks,

Table 3. Sample Types and Decision Rules Used to Evaluate PARCS Statements

Sample Type	Use	Decision Rules
Continuing calibration verification	Ensures integrity of calibration curve; low-level samples used to assess instrument sensitivity	Within 20% of target value
Method blank	Laboratory-related contamination	c-Line control chart
Field blank	Field-related contamination	c-Line control chart
Field spike	Recovery, sample integrity	Within 20% of target value
Travel blank	Travel-related contamination	c-Line control chart
Travel spike	Recovery, sample integrity	Within 20% of target value
Method spikes (at least 2)	Precision, accuracy, recovery	Precision: within 20% difference; accuracy: within 20% of target value; recovery: within 80–120% of target value
Sample duplicate	Precision	Within 20% difference
Sample (matrix) spike	Accuracy, recovery	Accuracy: within 20% of target value; recovery: within 20% of target value
Sample spike duplicates	Precision	Within 20% difference
Standard reference material	Accuracy, recovery	Accuracy: within 20% of target value; recovery: within 20% of target value

Table 4. Samples Analyzed by Environmental Chemistry Class

Sample	MB	MT	IA	SPME	SPE	AA
1	X	X	X	X	X	X
2	X	X	X	X	X	X
3	X	X	X		X	X
4		X	X		X	X
5		X	X		X	X
6		X	X		X	X
7	X	X	X		X	X
8	X	X	X		X	X
9	X	X	X		X	X
10		X	X		X	X
11		X	X		X	X
Method blank	X	X	X	X	X	X
Method spike 1					X	
Method spike 2					X	
Travel blank	X	X	X		X	X
Travel spike		X	X		X	
Duplicate site 7	X	X	X		X	X
Duplicate site 2	X	X	X		X	X
Atrazine standard, 3 ppb		X				
Atrazine standard, 20 ppb	X	X				
Calibration			X		X	X
Calibration check					X	X
Positive control	1 mM $PbCl_2$	5 mM phenol	Atrazine standard			
Detection limits					X	X

that would affect the results. Laboratory 2 appears to have adequate method performance to support its findings that high levels of atrazine are present in Rowan's water supply. In addition, toxicity assays (mung bean and Microtox) indicate a general level of toxicity at a number of locations, including the finished water.

The Laboratory Analyses

The laboratory experiments are designed to take students from qualitative screening methods to specific quantitative methods. General toxicological screening is also used to allow students to assess possible environmental effects through the concept of environmental-effects monitoring. Specific tests, including samples used to generate the PARCS statements, are shown in Table 4. Samples are prepared to show specific trends in atrazine concentrations throughout the watershed. Samples for toxicological testing are prepared to show a pattern of toxicity unrelated to atrazine concentrations. The purpose, once again, is for students to recognize that compounds other than atrazine may be present and responsible for the observed toxicity of the samples. These tests include:

Mung bean germination (MB) experiments (*25*). Samples collected from different locations are screened for general toxicity through a mung bean germination assay. These tests assist in the development of an environmental-effects monitoring strategy. Relative toxicity is measured as a percent difference (growth) of treated mung beans against positive and negative controls. The positive control is lead chloride, used at a 1.0 mM concentration, which is known to cause a 50% reduction in growth relative to the negative control (distilled deionized water).

Microtox (MT) experiments (*26*). Samples collected from different locations are screened for general toxicity through a bacterial bioluminescent assay. These tests assist in the development of an environmental-effects monitoring strategy. Relative toxicity is measured as a percent inhibition (reduction of emitted light) of treated bacterial samples relative to positive and negative controls. The gamma value is defined as the ratio of light lost to light remaining after exposure of the test organism (*Vibrio fisheri*) to a sample. The positive control is a 0.05 mM aqueous solution of phenol, a concentration that causes a 50% reduction in bioluminescence and would represent a gamma value of one. The negative control is distilled deionized water. The greater the gamma value, the greater the toxic effect; gamma values above the phenol standard are considered the most toxic and gamma values near the negative control are considered nontoxic.

Immunoassay (IA) experiments (*27*). An immunochemical screen is used to detect the presence of atrazine at specific locations throughout the Rowan watershed. This information is used to develop a comprehensive sampling plan. Commercial immunoassay kits are used in the class. Suppliers of these kits usually provide a significant discount to educational institutions, making them affordable for classroom use.

Solid Phase Microextraction (SPME) experiments (*28*). A semiquantitative analytical method is developed and used to estimate the levels of atrazine and other compounds in a sample. Gas chromatography combined with a flame ionization detector is used for analysis.

Solid Phase Extraction (SPE) (*29*). A quantitative method is developed using performance-based methods criteria that rigorously determine the level of atrazine in a sample. This method is also capable of detecting other organic contaminants. Gas chromatography–mass spectrometry is used for analysis.

Atomic Absorption (AA) Spectroscopy (*30*). This method screens for the presence of specific metals as possible contributors to toxicity. Zinc, lead, and copper are usually the target analytes.

Samples are not actual environmental samples and are prepared in bulk to be as homogeneous as possible. Atrazine was selected as the analyte of interest because it is regulated under the SDWA, is used extensively, is fairly easy to analyze, and has been extensively studied. In addition, commercial reference standards and immunoassay kits are readily available. Samples are prepared at three concentration levels: 300, 600, and 900 μg/L. Calibration curves are presented to the students so that these values represent 3, 6, and 9 μg/L respectively. Samples used for immunoassay are actually 3, 6, and 9 μg/L and are prepared using the calibration standards that come with the immunoassay kits. The only samples containing atrazine are those used for the SPE, SPME, and IA experiments. For example, atrazine is present at site 2 (finished drinking water) at the 3 μg/L level in the SPE, SPME, and IA samples given to the students but not in the samples for MB, MT, or AA analysis for that location. This obviously artificial situation makes it easier to prepare samples in bulk and minimizes the students' exposure to these chemicals.

Students are given samples "collected" from specific locations around Rowan. Each student or group receives a set of samples and every test has its own sample bottles. In most cases students receive only enough material to conduct each experiment once (SPME and AA are the exception). The samples come with chain-of-custody forms showing time and date of collection and other general observations of the sites. Once in the laboratory, students are required to document the storage and handling of each sample. Improper documentation by the chemists has sometimes been uncovered when the law students request specific evidence related to the samples. This has ultimately led to motions to disallow the use of opposing groups' data during the hearing phase of the class.

General Laboratory Results

Students receive identical samples for a given location. It is their responsibility to generate and interpret the analytical results supported by the appropriate PARCS statements. Experience has shown that laboratory technique is a significant cause of analytical variability, which in turn leads to a wide range of final values for the City of Rowan. The challenge students face is to report their data in a scientifically defensible manner and to articulate the extent to which they are confident in their interpretation. It is important for them to define the boundaries of their data and whether they are willing to stand by their interpretation in a public hearing.

Figure 4 shows the typical chromatographic peaks associated with the solid-phase extraction analysis of atrazine in Rowan's finished drinking water (map, site 2) from four groups of two students each. In determining the final concentration, all groups used the same calibration curve. As can be seen in Figure 5, significant variability existed among groups, resulting in a wide range of reported atrazine results. The supporting PARCS statements for the groups also showed a wide range of results (Table 5). Overall, the performance of the Blue group appears to be the most reliable according to the PARCS

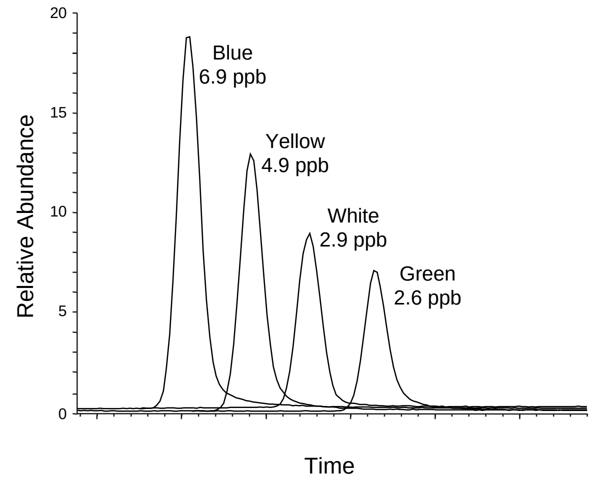

Figure 4. Chromatographic results for atrazine for site 2 from of laboratory groups Blue, Yellow, White, and Green. Retention times are offset to allow easier comparison of response.

Table 5. PARCS Statement for Groups Relative to Atrazine Analysis at Site 2

Group	Atrazine/(µg/L)[a]	Precision (%) Based on Duplicates	Precision (%) Based on Method Spikes 1 and 2[b]	Accuracy (% error)[c]	Recovery (%)[d]	Contamination[e]	Sensitivity/(µg/L)[f]
Blue	7.3, 6.5	12	78	–0.40	99	0	1.9
Yellow	2.9, 4.9	50	61	123	223	0	0.23
White	3.5, 2.5	27	79	24	124	0	1.7
Green	2.9, 4.1	37	19	165	265	0	0.1

[a]Reported for duplicate samples.
[b]Target was 2 µg/L.
[c]Based on method spike 1; target was 2 µg/L.
[d]From method spike 1; target was 2 µg/L.
[e]Based on method blank.
[f]Calculated from 7 replicate spikes at 1 µg/L.

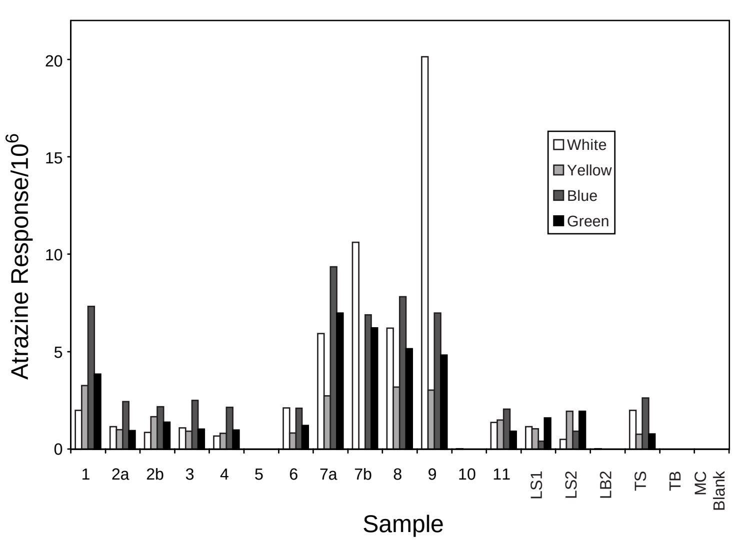

Figure 5. Variation in GC–MS atrazine results for the Rowan watershed by laboratory groups Blue, Yellow, White, and Green.

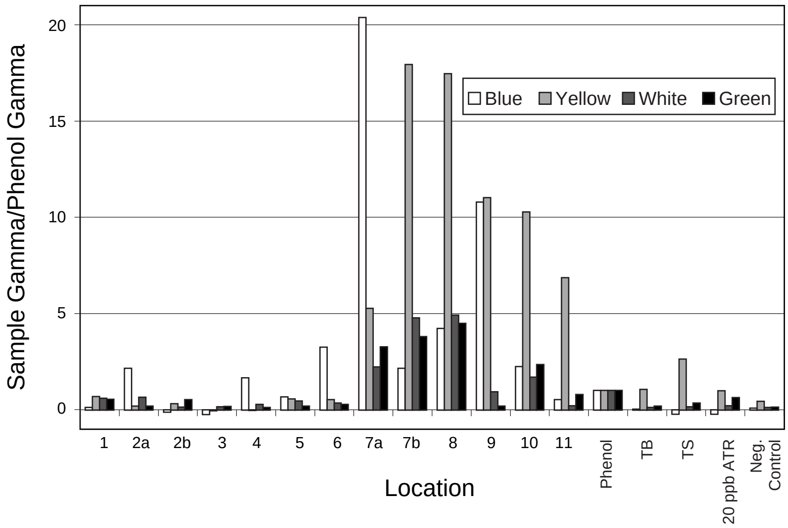

Figure 6. Relative gamma values from laboratory groups Blue, Yellow, White, and Green, based on Microtox acute toxicity evaluation.

decision rules. Only the precision statement using replicate method spikes appears to pose a significant problem to this group. It is obvious from the data that the other groups had significant problems with many of the PARCS statements, particularly with method precision and recovery.

Similar variability was observed for all of the laboratory methods. One group generally produced data of better quality than the others, as demonstrated through the PARCS statements, but not necessarily the same group in each case. This fact was often raised during the hearings in an attempt to discredit other groups.

Environmental effects were evaluated using mung bean germination and Microtox assessments. Once again, significant variability was observed in the data obtained by the various groups. Figure 6 shows the Microtox gamma values of each of the four groups, and Figure 7 shows the results of the mung bean germination assay. As can be seen, a 20 ppb atrazine standard (a concentration significantly higher than that found in Rowan's finished drinking water) had no significant toxic effect on the test organisms. This suggests that atrazine is not responsible for the level of toxicity observed in the samples. Significant variability exists in toxicity data for each of the locations. The Blue and Yellow groups appeared to have the poorest precision, as seen in replicate sampling at sites 2 and 7. These results require the students to determine a level of confidence in their results to develop a defensible interpretation of their data, knowing the results of the other groups. This requirement is demonstrated through the students' final consulting reports and performance at the public hearing.

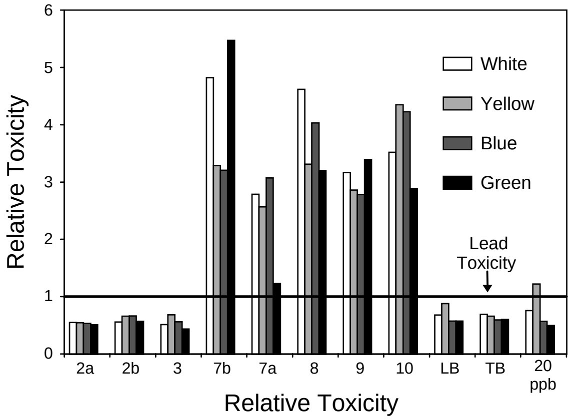

Figure 7. Relative toxicity values from four laboratory groups using the mung bean germination evaluation.

Laboratory Structure, Student Evaluation, and Safety

The environmental chemistry laboratory at Western Washington University has eight computers that are networked through the university system. All of the analytical instruments used by the class (GC, GC–MS, AA) are located in a centralized university instrumentation center and are networked through the university system. The instruments used in the course have automatic samplers capable of operating 24 hours a day. This allows the large number of samples prepared by the students to be analyzed. Data from each of the instruments are placed on a central server and are accessible from the environmental chemistry laboratory and a number of computer laboratories throughout the university. Through negotiations with instrument vendors, no-cost stand-alone copies of specific instrument software are loaded onto each of these computers. This allows students to manipulate all of the output from each of the instruments as if they were using the instrument itself. Plans are currently being developed to permit access to data over the Internet, allowing students to access data from remote locations.

The class meets two days a week for three hours each time. A class size of eight allows students to perform each of the experiments individually. With more than eight students, space and resource limitations require the students to work in pairs. A typical schedule with eight students is outlined in Table 6. The first class meeting is devoted to safety and general laboratory orientation. During this laboratory period, students are required to attend the university-developed safety orientation, which includes information on safety equipment, procedures for handling chemicals, accident prevention, chemical disposal, fire safety, and the proper use of laboratory equipment. Students are required to wear safety glasses and lab coats in the laboratory at all times and to wear appropriate protective gloves when conducting experiments.

Table 6. A Typical Laboratory Schedule

Week	Lab	Individual							
		A	B	C	D	E	F	G	H
1	1	Safety and check-in							
2	2	Introduction to experiments and background to problem							
	3	SPE	SPE	IA	IA	AA	AA	MT	SPME
3	4	SPE	SPE	MB	MB	AA	AA	IA	SPME
	5	SPE	SPE	MB	MB	SPME	SPME	AA	MT
4	6	IA	IA	SPE	SPE	SPME	SPME	AA	AA
	7	1st joint meeting with law class							
5	8	MB	MB	SPE	SPE	MT	data	SPME	AA
	9	MB	MB	SPE	SPE	data	MT	SPME	data
6	10	MT	data	AA	AA	SPE	SPE	MB	MB
	11	data	MT	AA	AA	SPE	SPE	MB	MB
7	12	2nd joint meeting with law class							
	13	SPME	SPME	data	MT	SPE	SPE	data	data
8	14	SPME	SPME	MT	data	MB	MB	SPE	SPE
	15	AA	AA	SPME	SPME	MB	MB	SPE	SPE
9	16	AA	AA	SPME	SPME	IA	IA	SPE	SPE
	17	Discovery and hearing preparation							
10	18	Hearings							
	19								
11	20	Final report due (final exam week)							

NOTE: Laboratory meets for 3 hours on Tuesdays and Thursdays. MB stands for mung bean germination; MT is Microtox assay; IA is immunoassay; SPME is solid-phase microextraction; SPE is solid-phase extraction; AA is atomic absorption spectroscopy. Initial MB dosing is conducted on Monday and toxicity assessment is done on Thursday. Deadlines: week 3, memo to law students (50 points); week 5, 1st draft of consulting report (100 points); week 8, 2nd draft of consulting report (150 points); week 11, final consulting report (250 points). Consultation with law class and participation in hearings and laboratory count 100 points.

The second laboratory meeting is used to outline the course, review the background information and basic concepts, describe critical points in each of the experiments, and handle administrative details. After the second meeting, the students begin conducting the experiments according to the specified schedule (depending on the size of the class, either individually or in groups). All experiments are conducted in a round-robin manner so that only two individuals or groups are conducting the same experiment at any one time—although if necessary, the mung bean, immunoassay, and atomic absorption could be done with greater numbers of students. The only experiment requiring outside time is the mung bean experiment. Because this is a 72-hour exposure study, students must come in for approximately one-half hour during non-laboratory days to dose the beans. An important aspect of this schedule is that specific laboratory time is reserved for each individual or group during the quarter to process data. This gives the instructor time to review the students' data and answer specific questions that arise related to data interpretation, instrumentation, and legal issues. Additional time is set aside for the chemistry students to meet with the law students. These data processing and meeting times are essential to the success of the course. Once the experiments are underway, the students are inundated with a vast array of data. The opportunity to think about how the data are related to the overall problem "What's Flowin' through Rowan?" elevates the students from mere data generators to data users.

The primary basis of student assessment is the final consulting report that each student must prepare. In this report, students provide and support their professional opinion on the problems faced by Rowan. Examples of actual consulting reports commissioned by government and private groups are available to them. During the quarter students produce two draft reports in addition to the final report. They use these during their meeting with the law students and during the final hearings. When the class size precludes a final hearing, there are negotiation exercises during which, once again, the chemistry students act as advisors to the law students. The other mechanisms for evaluating students' understanding of the material are the required memo to the law students explaining the background information and their performance during the public hearing.

A primary focus of the course is developing the students' understanding of how data quality is evaluated. This understanding becomes apparent in the evaluation of their memos and draft and final reports. Students are not penalized for generating poor or variable data; rather, they are assessed on their ability to recognize how data of differing quality may be used to address specific environmental issues. They learn that throwing away data as "no good" can be as detrimental to understanding a situation as relying unquestioningly on data of questionable quality.

Because the chemistry students generate diverse laboratory results, the results generated by each group's consulting chemist may not support the group's position. Therefore, law students are allowed to form alliances and use data from other groups if the use of that data can be supported. They must, however, be able to explain and support why they chose not to use their consulting chemist's data. Once produced, all data become part of the public record. What is considered unusable by one group may represent supporting evidence by another. The students' ability to distinguish between unusable data and poor data is an important element of the course.

Conclusions

The integration of an environmental laboratory course with an environmental law course has given students a unique opportunity to utilize laboratory results in a real-world context. The use of environmental-effects monitoring, performance-based analytical methods, and QA/QC principles gives students a common terminology with which to interpret and assess chemical and toxicological data. Using these principles, students assess their data as well as data generated by other groups in a context that either supports or refutes specific legal and policy outcomes. In this manner, they come to realize that multiple, equally-defensible interpretations of data are often possible. Additionally, they learn the importance of keeping adequate records to support their laboratory activities. Having outside groups evaluate their data with the specific intent of discovering errors or evidence for alternative interpretations appears to provide significant motivation for students to keep detailed and current records.

The development of the course around the theme "What's Flowin' through Rowan?" allows course materials to be easily modified so that specific environmental issues other than the Safe Drinking Water Act can be highlighted. For example, issues related to the Clean Water Act, Total Maximum Daily

Loads (TMDLs), and permitting under the National Pollutant Discharge Elimination System (NPDES) can be addressed by changing the scenario to have a variety of potential pollution sources along the Cowstooclose River. For example, Arntzen Enterprises has been used as a pesticide mixing facility. This allows a library of problems to be developed, along with the supporting classroom materials such as newspapers and memos. In the event that class size precludes the use of a final hearing format, negotiation exercises have also been developed. Examples of these materials are located on our Web site (*31*). In these exercises, students must negotiate a settlement with the other interested parties, again using data generated by the chemistry class.

It has been my experience that a problem-based course in environmental chemistry greatly improves the presentation of chemistry in the undergraduate curriculum. Students have the opportunity to apply fundamental chemical concepts in a real-world context. When applying for jobs, many students have used their final consulting report as an example of their writing and critical thinking skills related to the application of chemistry to environmental problems. Student reviews of the course have provided positive feedback for this approach. For many students, this course was the first opportunity to use chemistry in an applied manner. A number of students have contacted me after graduating to comment on how well this class prepared them for their current positions in the environmental field.

Acknowledgments

The Camille and Henry Dreyfus Foundation provided support for the development of this course though its Special Grant Program in Chemical Science. Funding was also received through Western Washington University's Bureau for Faculty Research.

Literature Cited

1. Hodson, P. V.; Munkittrick, K. R.; Stevens, R.; Colodey, A. *Water Qual. Res. J. Can.* **1996**, *31*, 215–224.
2. *Aquatic Environmental Effects Monitoring Requirements*; National EEM Office, Science Policy and Environmental Quality Branch, Environmental Conservation Service, Environment Canada: Ottawa, ON, 1997.
3. Environment Canada. *Environmental Effects Monitoring*; *http://www.ec.gc.ca/eem/* (accessed Oct 2001).
4. Moran, T.; Lines, M.; Getty, K.; Kierstead, T. *In-Situ Multispecies Approach to Environmental Effects Monitoring of a Major River Ecosystem*; *http://www.pollutech.com/papers/p4.htm* (accessed Sep 2001).
5. Federal Participation in the Development and Use of Voluntary Consensus Standards and in Conformity Assessment Activities; *Fed. Regist*. **1998**, *63* (33), 8546.
6. U.S. Environmental Protection Agency. Performance Based Measurement System; *Fed. Regist*. **1997**, *62* (193), 52098–52105.
7. Kinney, A.; Caliandro, B. *Today's Chemist at Work* **1998**, *7*, 79–84.
8. Intergovernmental Task Force on Monitoring Water Quality. *The Nationwide Strategy for Improving Water-Quality Monitoring in the United States*; U.S. Geological Survey, Office of Water Data Coordination: Reston, VA, 1995.
9. USEPA Office of Solid Waste. *Performance-Based Measurement System*; *http://www.epa.gov/epaoswer/hazwaste/test/pbmsa.htm* (accessed Sep 2001).
10. U.S. Environmental Protection Agency. Performance Based Measurement System; *Fed. Regist*. **1997**, *62* (193), 52098–52105.
11. *ISO/IEC Guide 25: General Requirements for the Competence of Calibration and Testing Laboratories*, 3rd ed.; International Organization for Standardization: Geneva, Switzerland, 1990.
12. *Guides for Compliance Monitoring Procedures for Good Laboratory Practice*; Environment Monograph No. 46, (ICDE/GD92-33); Organization for Economic Co-operation and Development: Paris, 1992.
13. *Program Description Laboratory Accreditation Program*; Canadian Association of Environmental Analytical Laboratories: Ottawa, Ontario, 1998.
14. U.S. EPA Quality Staff. *USEPA Guidance for Quality Assurance Project Plans*; EPA QA/R-5; U.S. Environmental Protection Agency: Washington, DC, 1999.
15. *USEPA Contract Laboratory Program National Functional Guidelines for Organic Data Review*; EPA-540/R-94-012 (PB94-963501); U.S. Environmental Protection Agency: Washington, DC, 1994.
16. U.S. EPA, Region 10. *Quality Assurance References and Guidances*; *http://www.epa.gov/region10/offices/oea/qaindex.htm* (accessed Sep 2001).
17. Mishalanie, E.; Ramsey C. *Nat. Resources Environ*. **1999**, *13* (4), 519.
18. Libes, S. M. *J. Chem. Educ.* **1999**, *76*, 1642.
19. Spiro, T. G. *Crit. Rev. Anal. Chem*. **1998**, *28* (2), 46–49.
20. Lantz, J. M.; Feindt, J. E.; Lewellyn, E. P. B.; Walczak, M. M. *J. Chem. Educ*. **1999**, *76*, 1671–1672.
21. O'Hara, P. B.; Sanborn, J. A.; Howard, M. *J. Chem. Educ*. **1999**, *76*, 1673–1677.
22. Libes, S. M. *J. Chem. Educ*. **1999**, *76*, 1649–1656.
23. Kelter, P. B.; Grundman, J.; Hage, D. S.; Carr, J. D.; Castro-Acuna, C. M. *J. Chem. Educ*. **1997**, *74*, 1413–1421.
24. Juhl, L., Yearsley, K. Silva, A. J. *J. Chem. Educ*. **1997**, *74*, 1431–1433.
25. Shen, Z.; Fenquin, Z.; Fusuo Z. *J. Plant Nutr*. **1998**, *21*, 1153–1162.
26. *Standard Test Method for Assessing the Microbial Detoxification of Chemically Contaminated Water and Soil Using a Toxicity Test with a Luminescent Marine Bacterium*; American Society for Testing and Materials: Philadelphia, PA, 1995.
27. U.S. Environmental Protection Agency. *EPA Region 1—Immunoassay Guidelines QA Unit Fact Sheet 10/96*; *http://www.epa.gov/region01/measure/ia/iaguide.html* (accessed Sep 2001).
28. Boyd-Boland, A.; Pawliszyn, J. *J. Chromatogr*. **1995**, *704*, 163–172.
29. *National Field Manual for the Collection of Water Quality Data*; U.S. Geological Survey Information Services: Denver, CO, 1999. *http://water.usgs.gov/owq/FieldManual/chapter5/pdf/chap5.pdf* (accessed Sep 2001).
30. *Standard Methods for the Examination of Water and Wastewater*, 20th ed.; Franson, M. A. H., Ed.; American Public Health Association: Washington, DC, 1998; Method 3110.
31. Cancilla, D. A. Environmental Chemistry II (ENVR 451); *http://www.ac.wwu.edu/~cancilla/envr451.html* (accessed Sep 2001).