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Engaging Students through an Interactive Mass Balance Fundamentals Demonstration

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Abstract

Employing mass balance concepts is one of the fundamental approaches to address many of the National Academy of Engineering's Grand Challenges of the 21st century. Of the five stated grand challenges, the incorporation of mass balance principles is central to understanding and resolving four of the five technical challenges while it supports and informs decision making in the fifth. For burgeoning environmental engineers, the understanding of mass balance concepts is foundational for recognizing and solving the complex multimedia environmental problems they will face. Environmental engineering curricula therefore requires students to fully understand and demonstrate proficiency in the application of mass balance concepts. Unfortunately, many students struggle to initially visualize key aspects and understand assumptions used with the mass balance approach. A five-minute demonstration provides a visual, interactive classroom experience that improves understanding and learning for a broad spectrum of students' learning style preferences. The approach presented in this paper has been successfully used in an introductory environmental engineering course taught predominantly to non-engineering majors as part of a three-course environmental engineering sequence. Current data suggests that the incorporation of this demo improves student understanding of mass balance concepts evidenced by improved quantitative testing scores over the past two years. Though longitudinal data is forthcoming on the efficacy on long term retention, we strive for each non-engineering major in the sequence to be able to more broadly contextualize and solve complex problems using mass balance principles by incorporating a deliberate systematic approach. Indeed, for our students to tackle the grand challenges of this century, they must be able to understand the inherent interconnectedness of global and regional environmental systems.

Introduction

The environmental engineering discipline employs fundamentals of mass balance along with engineering design principles to develop solutions for environmental challenges. A number of these challenges are specifically addressed as grand challenges of the 21st century such as ensuring a sustainable supply of food, water, and energy to underdeveloped areas, curbing climate change while simultaneously adapting to its impacts, eliminating waste and waste-creating practices, and creating healthy and resilient communities [1]. In these four stated grand challenges, the application of mass balance principles is fundamental to understanding and developing solutions in natural systems. Therefore, we argue that undergraduate environmental engineering students must be proficient in the use of mass balance principles as is required for other fields of study, such as chemical engineering [2]. The population of students acquiring essential environmental engineering capabilities is eclectic at our institution. Every student graduates with a bachelor of science degree regardless of academic major. Therefore, non-engineering majors must take a three-course engineering sequence. There are seven engineering sequences from which students select with the environmental engineering sequence serving a population of about 200 students (or about 20% of the class population) each year. Students who study mass balance include those majoring in environmental engineering, environmental science, and numerous other majors associated with students in the environmental engineering sequence such as history, law, social sciences, psychology, and life sciences. Currently, 72 percent of students in our environmental engineering sequence are humanities majors while only 28 percent are in a STEM based major. Teaching environmental concepts over the three-course engineering sequence has been shown to increase environmental knowledge and positively influence environmental attitudes to a wide range of majors [3], [4], [5].

At our university, mass balances concepts are first introduced in EV301 (Environmental Science for Engineers and Scientists) in the context of understanding earth as a system and biogeochemical cycling of important elements (e.g., carbon and nitrogen). In subsequent courses within the curriculum, mass balance concepts are reintroduced in course content specific scenarios. For example, in EV401 (Physical and Chemical Treatment), students conduct reactors laboratory experiments in which they use material balances to compare the hydraulic characteristics of various reactors to concomitant ideal reactors. Students also use material balances to model the plug flow reactor as a series of complete mix reactors. Another example is EV402 (Biochemical Treatment), where students use material balances, Monod Kinetics, and engineering assumptions to develop models for suspended growth treatment systems. Further, in EV394 (Hydrogeology and Hydraulic Systems), students use the continuity equation and engineering assumptions to develop models for groundwater flow and contaminant transport in confined and unconfined aquifers.

Active learning is beneficial to the subject of mass and energy balances [6]. Additionally, the use of an in-class demonstration has the potential to increase student retention through seeing the link between what occurs in an equation via the demonstration [7] over other options such as optional on-line learning [8].

The prolific nature of mass balance principles in our courses along with the benefits of active learning led to the development of an in-class mass balance demonstration. The demonstration is focused on providing an interactive means to discuss mass balance with respect to the parent equation and three simplifying assumptions.

Mass Balance Principles

The fundamental mass balanced concepts are incorporated in Equation 1 [9].

$$\text{Accumulation Rate} = \text{Mass Flow Rate In} - \text{Mass Flow Rate Out} \pm \text{Transformation} \qquad \text{[Eq. 1]}$$

Equation 2 translates those concepts into commonly used parameters in mass balance analysis [10].

$$\frac{\mathrm{dM}}{\mathrm{dt}} = \sum \mathrm{Q_{in}C_{in}} - \sum \mathrm{Q_{out}C_{out}} \pm \mathrm{rV} \qquad \text{[Eq. 2]}$$

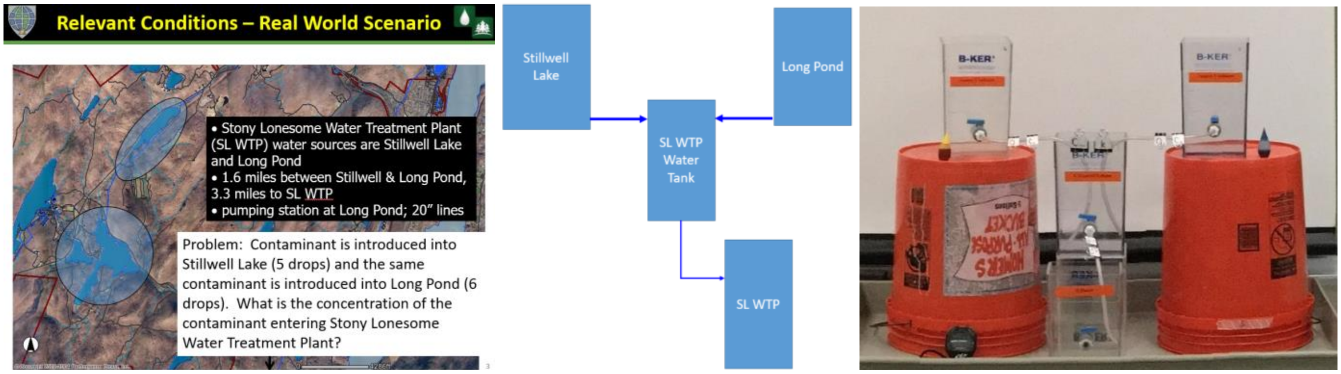
where $\frac{dM}{dt}$ is the change in mass over time, $\sum Q_{in}C_{in}$ is the summation of the flow rates in and influent concentrations, $\sum Q_{out}C_{out}$ is the summation of the flow rates out and effluent concentrations, and rV is reaction rate and volume. For the purposes of the introduction to mass balance, the reaction rate is assumed to be a first order reaction resulting in

$$r = kC_{mix} \qquad \text{[Eq. 3]}$$

where k is the reaction rate constant and C_{mix} is the concentration of this mix within the control volume. The control volume denotes the focus of analysis regarding the system of interest. Three simplifying assumptions applied to Equation 2 enables rapid analysis of complex systems through simplification. The assumptions include assuming the system is at steady state with respect to flow and concentration and that it is completely mixed. Steady state concentration implies that there is no accumulation of mass; therefore, $\frac{dM}{dt} = 0$. Assuming completely mixed refers to the concept that $C_{mix} = C_{out}$. The assumption of steady state flow implies $\sum Q_{in} = \sum Q_{out}$.

Background for In-Class Demonstration

The ability for students to connect to the information presented in the classroom through active participation in the in-class demonstration enables more interest and retention of information [6], [11]. The in-class demonstration is based upon considering mass balance associated with the source of drinking water for our institution. Stillwell Lake and Long Pond serve as the water sources for the Stony Lonesome Drinking Water Treatment Plant [12]. For the purposes of the demonstration model, the system of interest includes both sources as influents into a water storage tank with one effluent out of the water storage tank to the Stony Lonesome Water Treatment Plant. Figure 1 shows the link between the actual system, a sketch of the system, and the in-class demonstration set-up.



Relevant Conditions – Real World Scenario

- Stony Lonesome Water Treatment Plant (SL WTP) water sources are Stillwell Lake and Long Pond
- 1.6 miles between Stillwell & Long Pond, 3.3 miles to SL WTP
- pumping station at Long Pond; 20" lines

Problem: Contaminant is introduced into Stillwell Lake (5 drops) and the same contaminant is introduced into Long Pond (6 drops). What is the concentration of the contaminant entering Stony Lonesome Water Treatment Plant?

Figure 1. Correlation between the natural system (left), the diagram used to introduce mass balance principles (middle), and the in-class demonstration set up (right).

Scenario Driving In-Class Demonstration

A contaminant is introduced into "Stillwell Lake" (5 drops) and the same contaminant is introduced into "Long Pond" (6 drops). The students are tasked with determining the concentration of the contaminant entering "Stony Lonesome Water Treatment Plant" (SL WTP). This scenario and the conduct of the demonstration enables 16 different students the opportunity to participate. The specific conduct of the in-class demonstration is discussed below with the potential points noted where a student could participate.

Equipment Required for the In-Class Demonstration and Set-Up Required Prior to Class

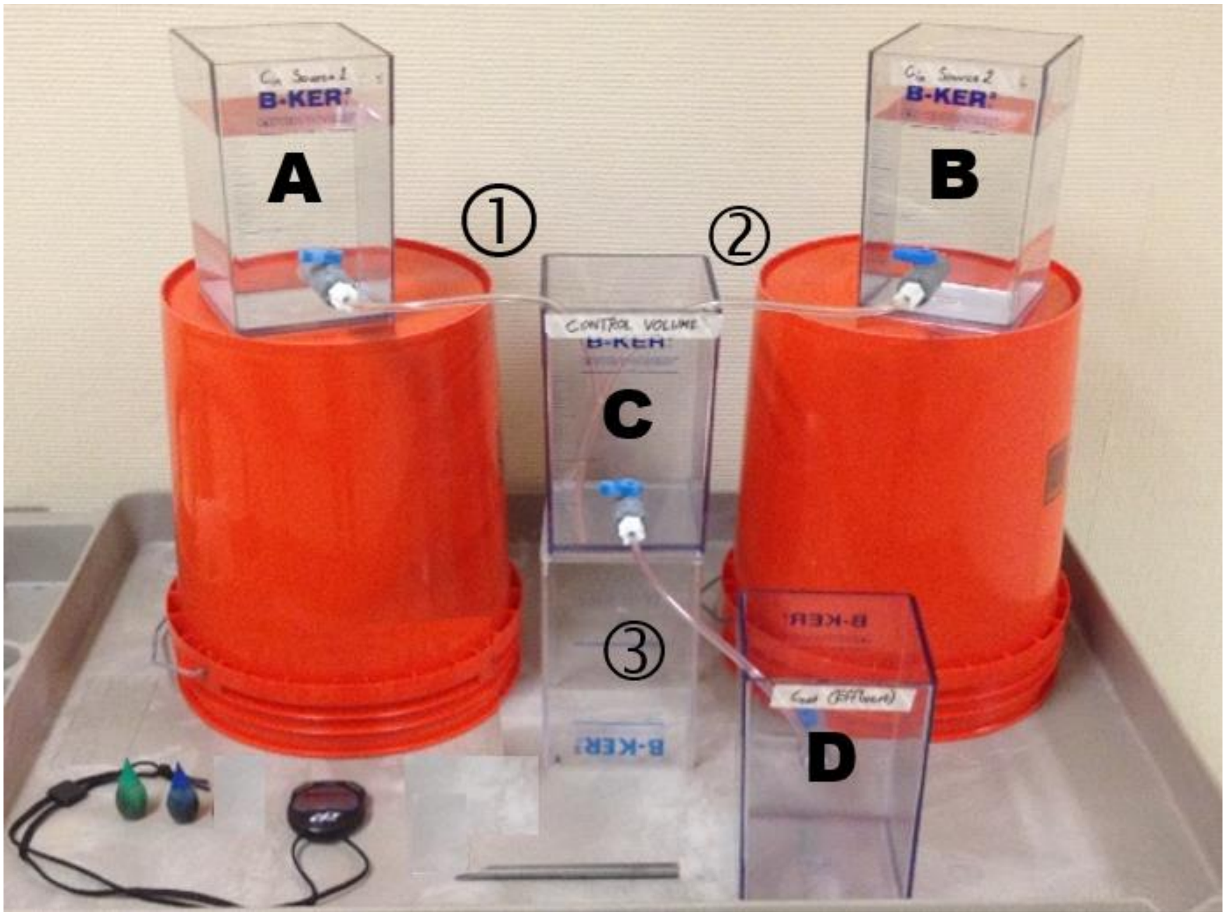


Figure 2. Equipment and materials needed to conduct the mass balance in-class demonstration. The letters (A, B, C, and D) denote the specific beaker for ease of future discussion. The circled numbers (1, 2, and 3) refer to the connection between the beakers (1 is the connection between A and C, 2 is the connection between B and C, and 3 is the connection between C and D).

The equipment needed to conduct the in-class demonstration is shown in Figure 2. The two orange 5 gal buckets provide elevation head for the two higher beakers (B-Ker^2 2000 mL square ¼ in thick acrylic jar, Phipps & Bird, Richmond, VA) representing Stillwell Lake and Long Pond. In the middle of Figure 2, one beaker is upside down to elevate the center beaker representing the Stony Lonesome Water Tank. The fifth beaker on the base elevation of the system set up serves to represent the Stony Lonesome Drinking Water Treatment Plant. Sampling valves (ball valve, PVC, 3/8-18 national pipe thread tapered male x ¼ compression ring, Phipps & Bird, Richmond, VA) with connected tubing (vinyl, flex, 3/16 inner diameter x ¼ outer diameter x 12 in long, clear, Phipps & Bird, Richmond, VA) enables flow from the top three beakers. Food coloring (McCormick® Assorted Food Color and Egg Dye, McCormick & Company, Inc., Hunt Valley, MD) serves as the contamination introduced within the system. A spatula (Fisherbrand™ Scoopula™ Spatula, 6 in, stainless steel, Fisher Scientific, Hampton, NH) enable mixing and a stopwatch enables evaluation of flow rates. Prior to class, both top beakers are filled with 2 L of tap water. The two top beakers have their tubing placed with the open end in the center beaker. The center beaker has its tubing placed in the lower beaker.

Conduct of the In-Class Demonstration

Throughout the demonstration, the students are taught through a multi-media presentation. Slides are used to relate the demonstration to formulas on a useful equation sheet, which the students have available for all graded events. Board notes are introduced at deliberate points in the demonstration to provide further background and enhance learning. The board set up to match the demonstration while working through the mass balance concepts also matches the problem set up included in the block guide which include reading assignments, lesson objectives, supplemental reading, and in-class problems. Table 1 outlines the steps for the specific conduct of the in-class demonstration.

With the completion of the in-class demonstration, discussion continues focused on the three primary simplifying assumptions previously mentioned in the mass balance principles section above. Keeping the accumulation of mass over time equal to zero in step 6, reinforced understanding of the steady state assumption that $\frac{\mathrm{dM}}{\mathrm{dt}} = 0$. The flow calculated from Beaker C to Beaker D which accompanied step 5 was discussed along with the impact of the assumption of the system being conservative with respect to flow. With this assumption ($\sum \mathrm{Q_{in}} = \sum \mathrm{Q_{out}}$), there is no need to calculate $\mathrm{Q_3}$ as $\mathrm{Q_3} = \mathrm{Q_1} + \mathrm{Q_2}$ for the system analyzed during the in-class demonstration. Comparison may occur between the experimentally measured $\mathrm{Q_3}$ from step 5 and a calculated $\mathrm{Q_3}$ based upon results from steps 4 and 5. Invariably, the values will not be the same due to factors such as resistance to flow within tubing 3 or differences in tubing diameters; however, the percent difference may be discussed and provide addition opportunities for the applicability of the assumption. Finally, the assumption of completely mixed is discussed through incorporation of visual inspection of Beaker B prior to mixing and a visual comparison between Beakers C and D. After the completion of the demonstration, a duplicate Beaker B prepared as described in step 2 still exhibits heterogeneous concentration (Figure 3). However, a visual comparison of the concentration in Beakers C and D (Figure 3) as represented by the color in each demonstrates the potential applicability of the completely mixed assumption ($\mathrm{C_{mix}} = \mathrm{C_{out}}$) where $\mathrm{C_{mix}}$ is the concentration within Beaker C and $\mathrm{C_{out}}$ is the concentration in Beaker D.

Figure 3. Visual representation of the concentrations with (left) Beaker B exhibiting heterogenous concentration conditions where the completely mixed assumption does not apply and (right) Beakers C and D exhibiting similar concentrations enabled more applicability of the completely mixed assumption.

Table 1. Steps followed to conduct the in-class mass balance demonstration to provide a visual learning experience which strengthens understanding of mass balance fundamentals.

Step	Item	Student Involvement
1	Add 5 drops of food coloring to Beaker A which was already prepared with 2 L of tap water. Students assume 1 drop = 0.5 mL and the density of the pollutant is the same as water (1 mL = 1 g).	1 student Class: calculates concentration in Beaker A
2	Add 6 drops of food coloring (a different color than used in step 1) to Beaker B which was already prepare with 2 L of tap water. Students make the same assumptions from step 1.	1 student Class: calculates concentration in Beaker B
3	Stir the food coloring in Beaker A; however, do not stir the food coloring in Beaker B. These conditions enable visual comparison between completely mixed versus heterogeneous concentrations. Then, stir the food coloring in Beaker B for applicability of assumptions discussed later.	1 student stirs Beaker A 1 student stirs Beaker B
4	Open the sampling valve completely on Beaker A to allow flow from Beaker A to Beaker C. Start the stopwatch when the valve is opened. Close the valve and stop the stopwatch once 0.5 L has flowed into Beaker C. The concentration calculated in step 1 is used as the concentration moving through tubing 1 (C_1) in mg/L. The point is made that the concentration in Beaker A is assumed to be homogeneous or completely mixed due to step 3.	1 student controls sampling valve 1 student controls the stopwatch and monitors the volume in Beaker C Class: calculates flow rate through tubing 1 (Q_1) in L/min
5	Open the sampling valve completely on Beaker B to allow flow from Beaker B to Beaker C. Start the stopwatch when the valve is opened. Close the valve and stop the stopwatch once 0.5 L has flowed into Beaker C which will now have a volume of 1 L. The concentration calculated in step 2 is used as a representative concentration moving through tubing 2 (C_2) in mg/L.	1 student controls sampling valve 1 student controls the stopwatch and monitors the volume in Beaker C Class: calculates flow rate through tubing 2 (Q_2) in L/min
6	Open the sampling valves on Beaker A, Beaker B, and Beaker C at the same time while initiating the stopwatch. These actions enable flow through tubing 1, 2, and 3. Ensure the volume in Beaker C remains constant at 1 L by adjusting the sampling valve to control flow. In so doing, steady state conditions are represented with no accumulation over time. Close all valves and stop the stopwatch once 1.5 min have elapsed. The volume of water in Beaker D provides essential information for the calculation of the flow rate from Beaker C to Beaker D through tubing 3 (Q_3).	1 student controls Beaker A sampling valve 1 student controls Beaker B sampling valve 1 student controls Beaker C sampling valve 1 student controls the stopwatch, dictates when all valves should be closed Class: calculates flow rate through tubing 3 (Q_3) in L/min

The final portion of the class involves incorporating all experimental data collected during the class period, applying the assumptions, and solving for the concentration of pollution entering Beaker D (see Figure 4). The demonstration occurs during lesson 2 and working through solving the environmental problem enables opportunities to further discuss proper steps in solving environmental problems, consideration of significant figures, and other problem-solving techniques.

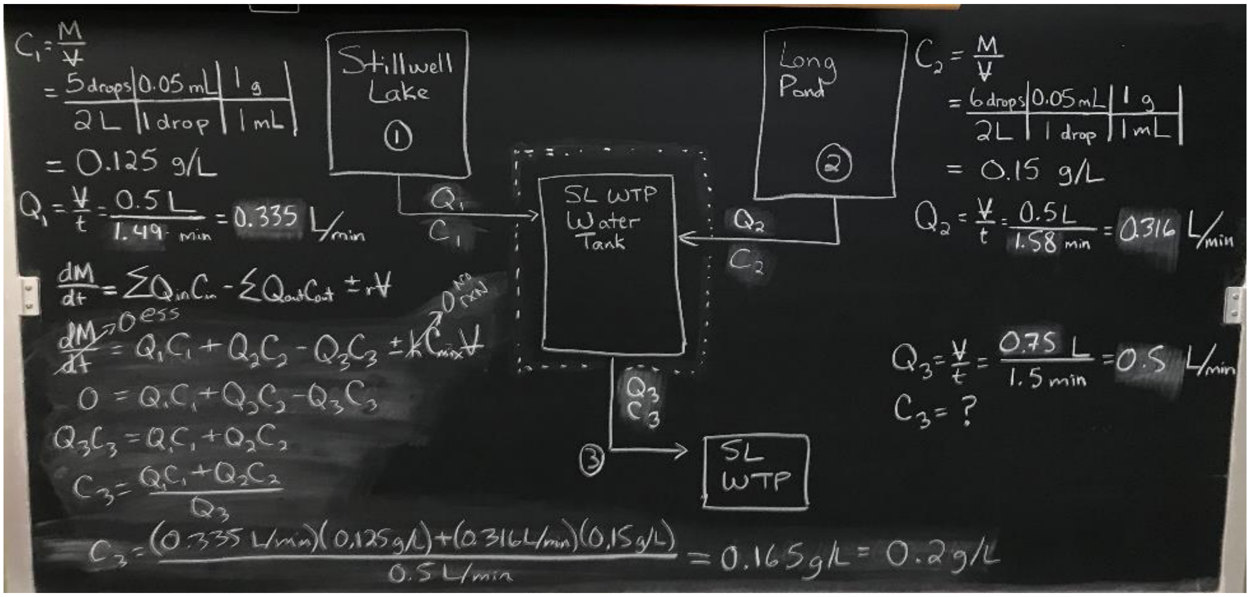


Figure 4. Board work completed throughout the conduct of the demonstration and culminating with solving for the concentration entering Beaker 4 which represents the Stony Lonesome Water Treatment Plant (SL WTP).

Analysis of the Effectiveness of the In-Class Demonstration

With a significant population within the environmental engineering sequence being non-STEM (72%), their desire and confidence with the use of mathematics and the equations above varies throughout the student population. The process of continual course assessment and refinement to remain relevant and work towards improving the educational experience of students led to incorporation of new methods of teaching topics for increased delivery of concepts and potential improvement in student retention of information depicted through increased performance. Examination of performance enables longitudinal analysis regarding students' abilities to retain information and the efficacy of modified teaching techniques for increased retention of material.

The in-class demonstration was incorporated into the second lesson of a 40-lesson course in 2017. Evaluation of performance on specific mass balance questions on the first exam of the semester and final exam of the semester occurred starting in 2018 with performance shown in Figure 5. The effective integration of the in-class demonstration increased each year through increased instructor familiarity and deliberate rehearsals. As the mass balance demonstration was incorporated for a second year in 2018 and further improved in 2019, the test performance on the mass balance questions during the first exam increased from an average of 81% to 87.5%. This improvement is statistically significant ($p = 0.0037$). Because there were no other significant changes to the study guide, mass balance homework, or useful equation sheet supplied for the test, it is plausible that incorporation and improvement of the mass balance demonstration for a second year significantly bolstered the success rate on the exam.

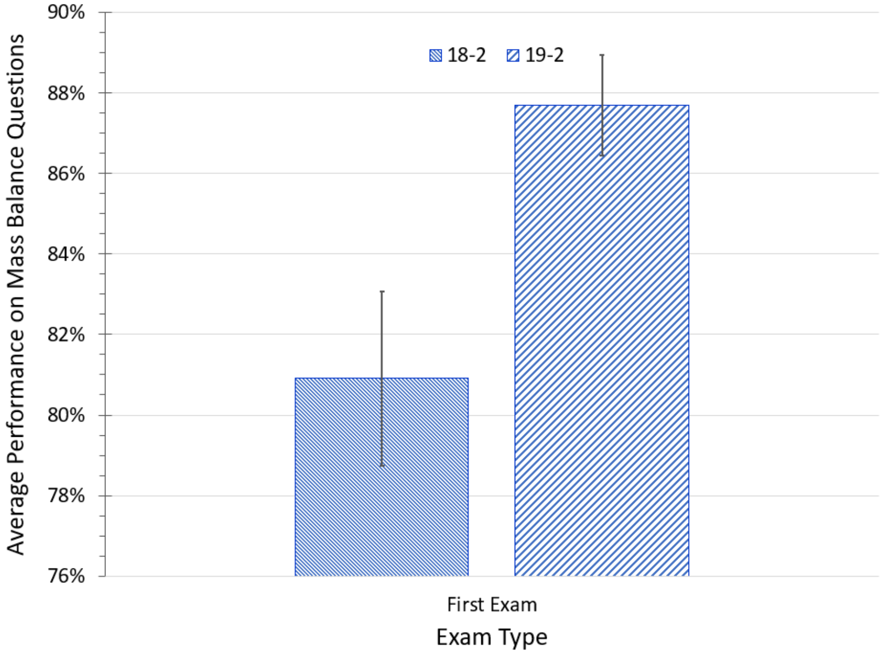


Figure 5. Performance on mass balance related examination questions near the beginning of the semester (first exam) for the previous two semesters. The error bars represent the 95% confidence interval for identification of the statistical similarities or differences among the populations shown.

Additional Resources

Enclosure A provides the full suite of slides used to capture the steps of the in-class demonstration. Slides are also provided that show the deliberate coverage of all aspects discussed in the course regarding fundamental mass balance concepts through the useful equation sheet which serves as a tool used on all graded assignments. Additionally, the board notes used for the demonstration are provided.

Best Practices with three Years of Refinement

Refinement of the conduct of the in-class demonstration and improved integration occurs each year through the process of a rehearsal of the class with the instructors teaching the material. During the rehearsal for this spring’s semester of 2020, a more deliberate rehearsal was conducted. In the previous three years, the general concepts regarding what to cover were discussed without walking through the entirety of methods to integrate the demonstration with the material required for coverage during the lesson. A recommendation for improved integration between the board work, class slides, use of the useful equation sheet, and conduct of the in-class demonstration involves creating a video of the entire 55-minute class for viewing by all instructors as part of the preparation for the lesson. After each year, the group of instructors should discuss any new methods incorporated for enhance delivery of the lesson material and update the video or capture the comments for use by future instructors.

Some of the specific changes made for the current semester included adding binder clips to place on the tubing to clearly mark the different flows and concentrations (e.g., Q_1, C_1, Q_2, C_2, etc.). Beakers were relabeled to more closely match the nomenclature used on the useful equation sheet. Classroom participation was refined to ensure all members within each class had the opportunity to participate in some activity associated with the demonstration to facilitate engaged, active learning. Finally, the study guide was refined so that the in-class problem matched the in-class demonstration configuration and helps students record information germane to the demonstration. The pace of the class was adjusted to ensure that students in each section had time to complete the entirety of the problem and solve for the final concentration of pollutant entering Beaker D.

Conclusion

The incorporation of an in-class mass balance demonstration which serves as a fundamental theme applicable to material taught throughout the course is essential to present at the beginning of the course. The inclusion of student participation with the conduct of the demonstration enables an active learning environment. The learning environment continues to become more effective through incorporation of recommendations for enhance integrating and smoothly linking the in-class mass balance demonstration to a real-world scenario, information provided on the student's useful equation sheet, and solving a mass balance problem in the manner expected of the students on future graded assignments. Incorporation of a well-rehearsed in-class demonstration does significantly improve student learning of material and enables increased retention through the duration of the course.

Future iterations of the in-class mass balance demonstration could correlate the dye concentration with a numerical value using a color measuring device (e.g., a spectrophotometer (Hach DR3900; visible spectrum 320-1100 nm; Loveland, Colorado)). These measured concentrations may be correlated with the calculated concentrations of the dye based upon the number of drops in a volume and dye density. These potential recommendations should be balanced with the additional time commitment for inclusion and the ability to provide coverage of the information determined essential to achieve the lesson objectives. Additionally, future research could evaluate the correlation between the student's performance on mass balance graded events and characteristics specific to each student such as demographics, field of study, and GPA prior to entering the course.

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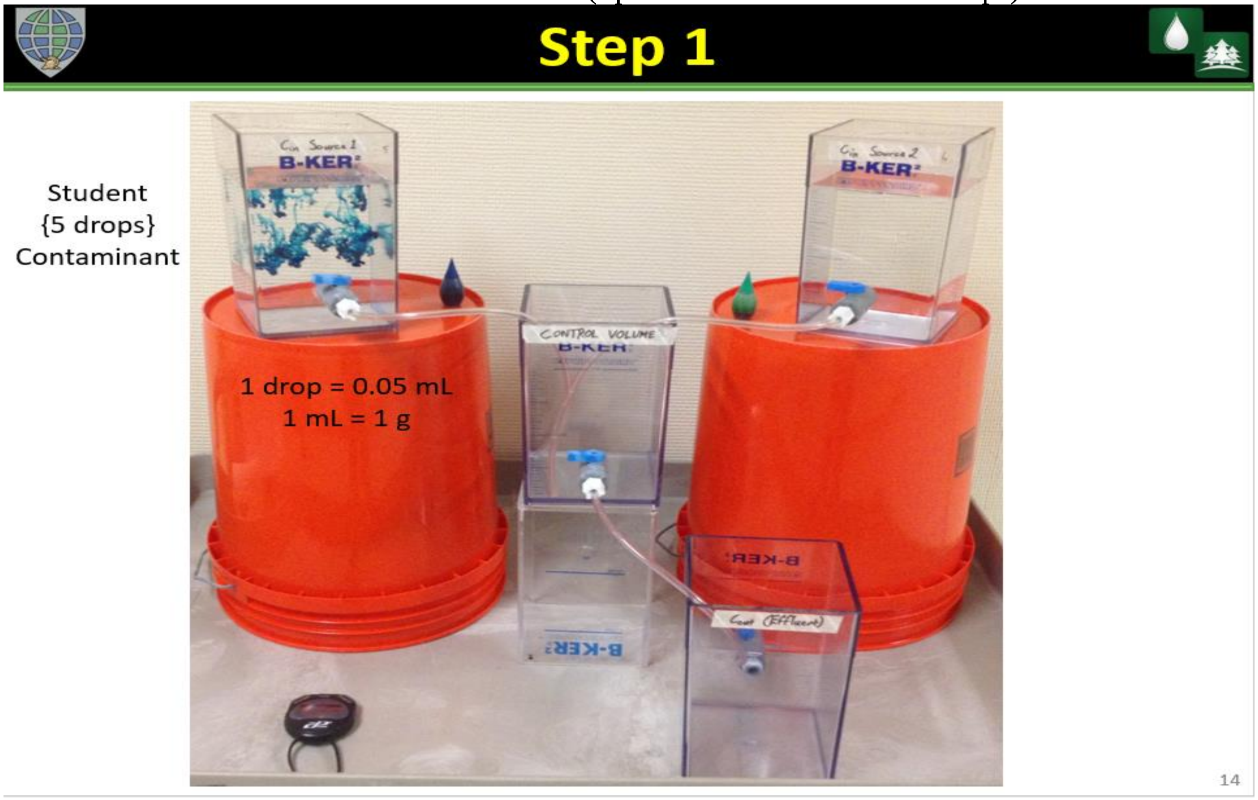
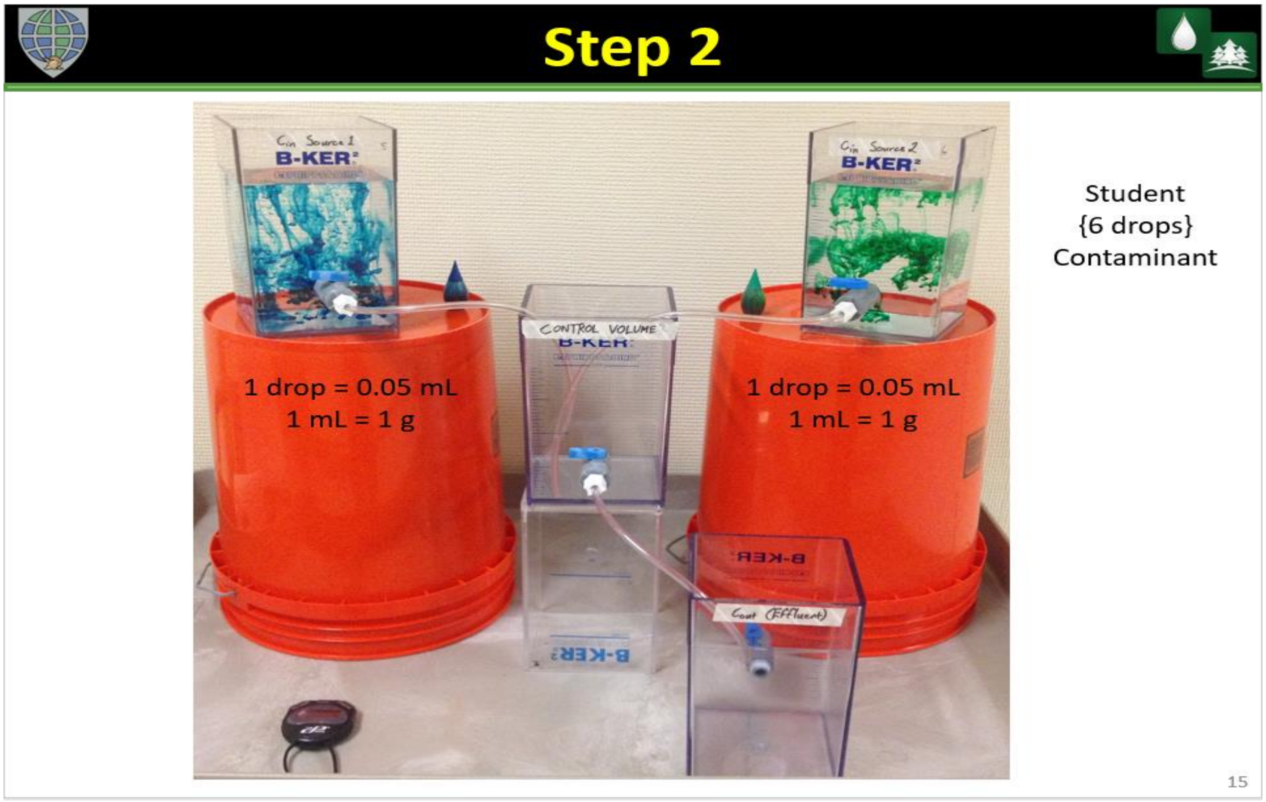
Enclosure A. In-Class Demonstration Slides (Specific to Demonstration Steps)



Step 1

Student
{5 drops}
Contaminant

1 drop = 0.05 mL
1 mL = 1 g



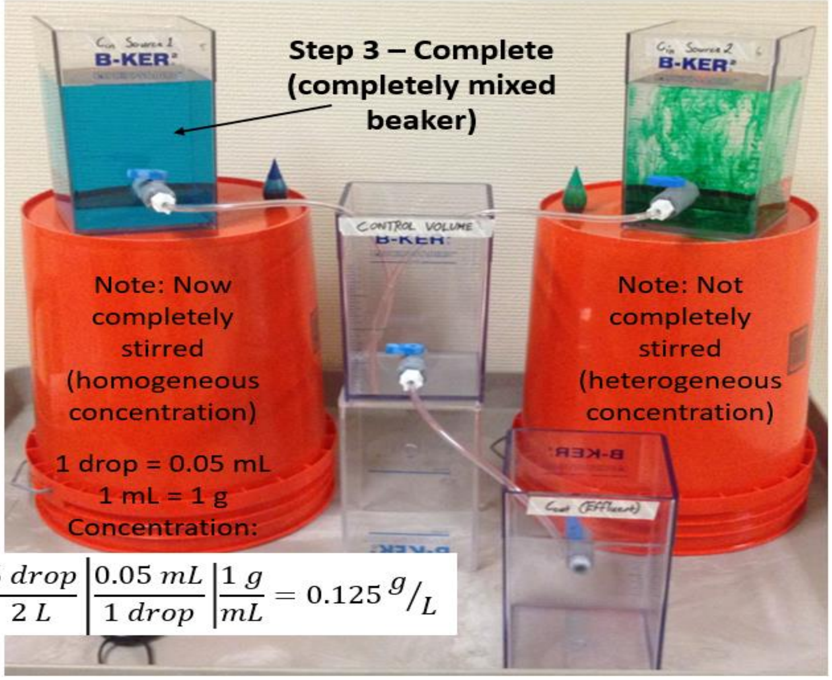
Step 2

Student
{6 drops}
Contaminant

1 drop = 0.05 mL
1 mL = 1 g

1 drop = 0.05 mL
1 mL = 1 g

Step 1 – Class Calculation



Student
{stir}

Step 3 – Complete (completely mixed beaker)

Note: Now completely stirred (homogeneous concentration)

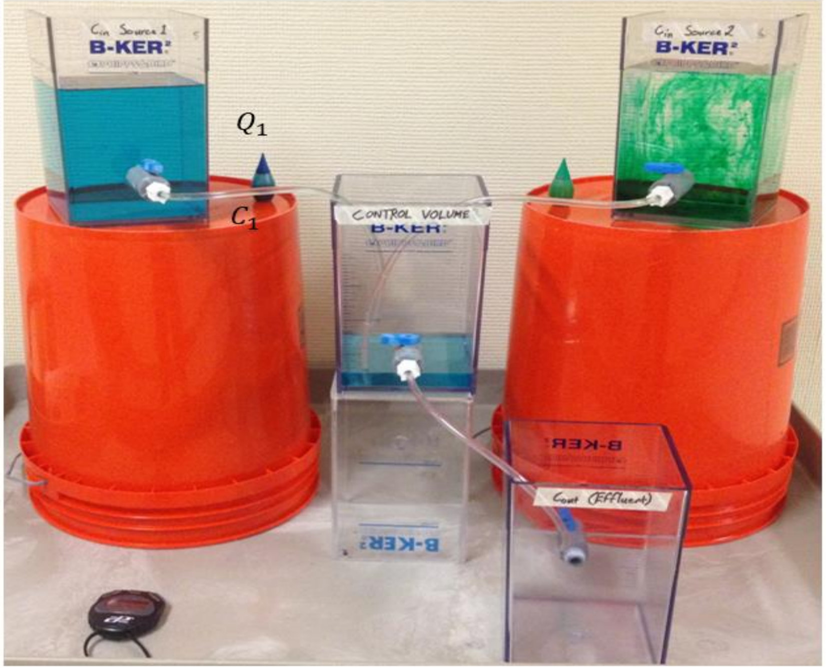
Note: Not completely stirred (heterogeneous concentration)

1 drop = 0.05 mL
1 mL = 1 g
Concentration:

Class
{Calculation}

$$C_1 = \frac{M}{V} = \frac{5\ drop}{2\ L}\left|\frac{0.05\ mL}{1\ drop}\right|\frac{1\ g}{mL} = 0.125\ {}^{g}/_{L}$$

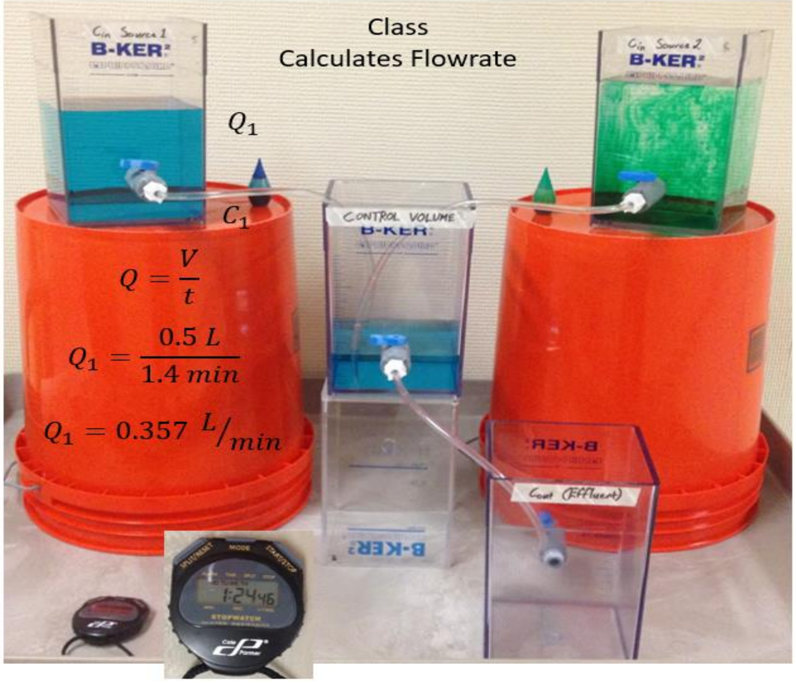
Step 2 – Class Calculation



Student
{open
nozzle
100%}

Student
{starts stop
watch}

Step 4 & Class Calculation



Class
Calculates Flowrate

$$Q = \frac{V}{t}$$

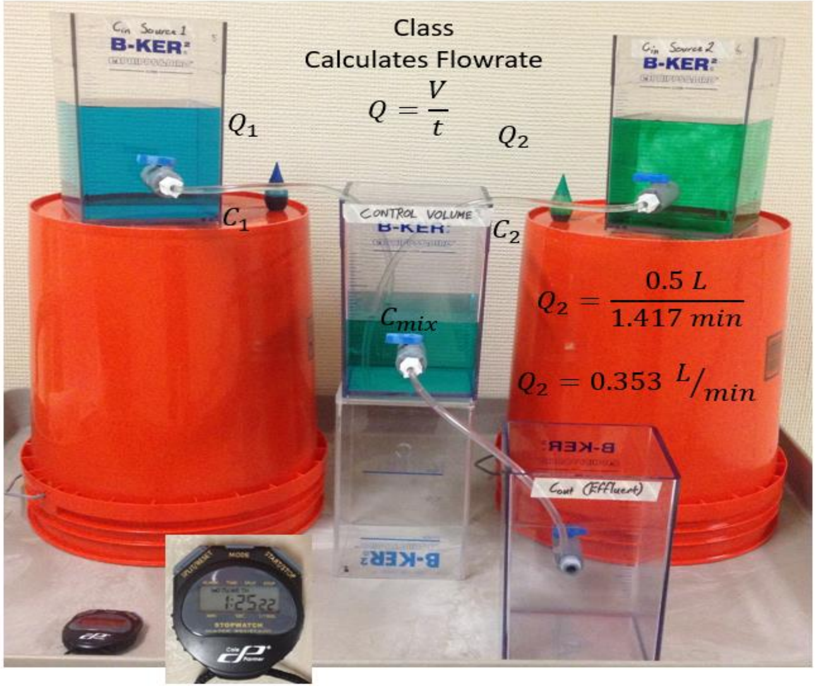
$$Q_1 = \frac{0.5\ L}{1.4\ min}$$

$$Q_1 = 0.357\ {}^{L}/_{min}$$

Student
{closes
nozzle once
“Control
Volume”
filled to
0.5 L}

Student
{stops stop
watch}

Step 5 & Class Calculation



Class
Calculates Flowrate

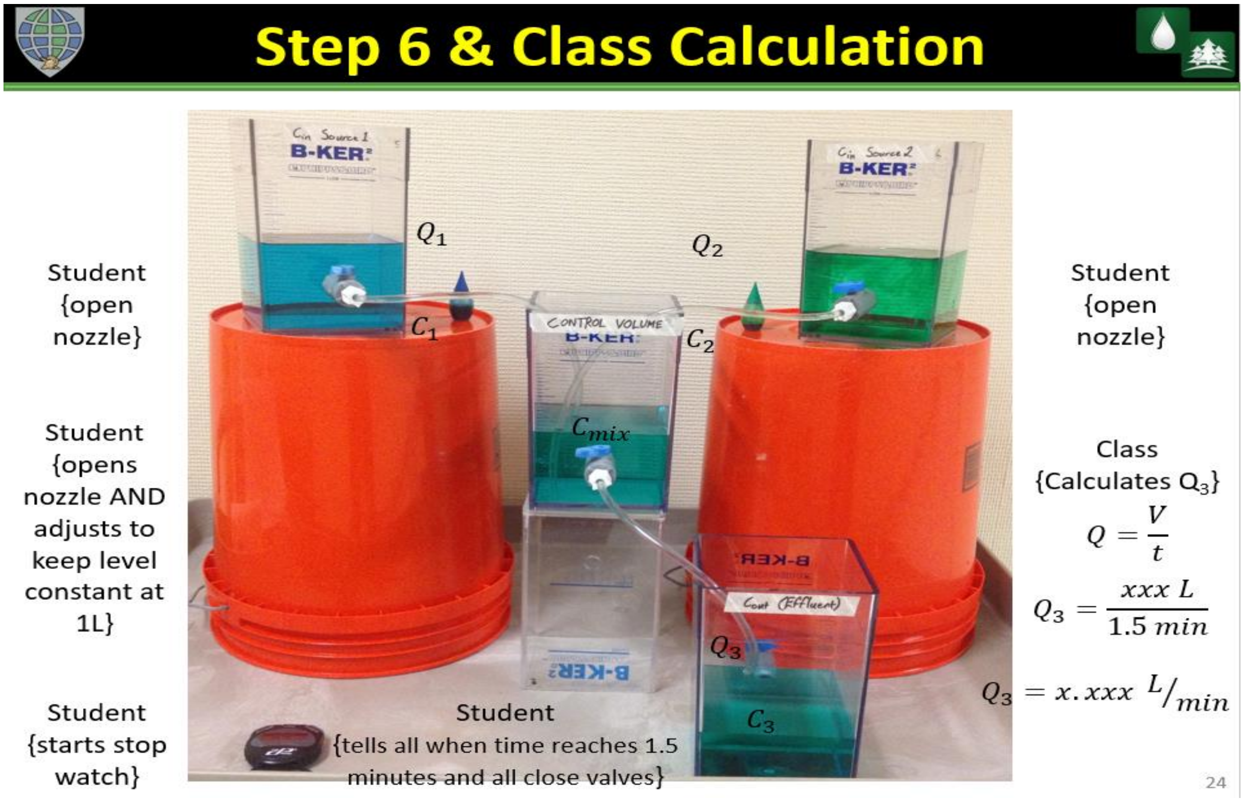
$$Q = \frac{V}{t}$$

$$Q_2 = \frac{0.5\ L}{1.417\ min}$$

$$Q_2 = 0.353\ {}^{L}/_{min}$$

Student
{opens &
closes
nozzle once
“Control
Volume”
filled to
1 L}

Student
{starts & stops
stop watch}



Step 6 & Class Calculation

Student
{open
nozzle}

Student
{opens
nozzle AND
adjusts to
keep level
constant at
1L}

Student
{starts stop
watch}

Student
{tells all when time reaches 1.5
minutes and all close valves}

Student
{open
nozzle}

Class
{Calculates Q_3}

$$Q = \frac{V}{t}$$

$$Q_3 = \frac{xxx\ L}{1.5\ min}$$

$$Q_3 = x.xxx\ {}^{L}/_{min}$$

In-Class Demonstration Slides (Complete Slide Deck available upon Request)