HANDS-ON STEM LAB · ENVIRONMENTAL SCIENCE & CHEMISTRY

Is Our Water Safe?
Investigating CO_2 Leaks in Groundwater

Students become citizen scientists!

Students simulate how injected carbon dioxide interacts with underground aquifers and learn how to help protect their community's groundwater.

2 class periods | Grades 9–12 | Groundwater aquifers | Real monitoring techniques

WHY THIS LAB MATTERS

Carbon Storage & Groundwater Safety

Carbon capture and storage (CCS) is a key strategy in the reducing greenhouse gas emissions. By capturing CO_2 from industrial sources and storing it deep underground — often in the same types of formations where we once extracted fossil fuels — we can reduce the amount entering the atmosphere. This process is increasingly being implemented across the Gulf Coast and other regions.

To ensure this technology is safe for people and the environment, the U.S. Environmental Protection Agency (EPA) regulates these storage activities through Class VI of the Underground Injection Control (UIC) program. These rules are specifically designed to protect underground sources of drinking water, defined as water <10,000 TDS, and include requirements to monitor groundwater near injection sites. But communities near these projects have important questions: **What happens if safeguards fail or someone makes a mistake, causing CO_2 to leak into drinking water?**

This lab lets students find out for themselves. By putting accessible, real-world science directly into the hands of high school students, it empowers them and their communities to better understand the environmental challenges that affect them. Students will build small-scale aquifer models, inject CO_2, and track chemical changes in the water using the same techniques that environmental scientists use in the field—transforming them from learners into investigators

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✅ **LAB TIMING**

This lab is designed for **two 50-minute class periods** to ensure adequate data collection. Day 1 covers field-style measurements (pH, conductivity). Day 2 covers lab-style measurements (calcium, alkalinity). The aquifer chambers can be assembled the day before to ease time constraints. If you are on a block schedule, the lab can be completed in one full class period with minor adjustments.

What students will learn

- Understand how CO_2 naturally fits into the carbon cycle, particularly in soil and groundwater systems, and explore its role in processes like respiration, dissolution, and mineral interactions — as well as its potential environmental impacts
- Discuss the role of CCS in the context of greenhouse gas sources and sinks
- Explore how groundwater is monitored to detect possible CO_2 leakage into drinking water aquifers, using real-world techniques and indicators
- Apply basic chemistry concepts to understand how CO_2 interacts with groundwater through
- acid-base reactions, pH buffering and changes, alkalinity, water hardness, and mineral
- dissolution and reactivity
- Practice groundwater sampling methods, including collection, measurement, and analysis of water quality parameters
- Get a better understanding of the potential environmental impacts of CO_2 leakage on aquifers

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BACKGROUND READING

The Science Behind the Experiment

How does CO_2 get into groundwater?

CO_2 is not just an industrial byproduct — it is a natural and essential part of Earth's carbon cycle. In fact, CO_2 is constantly produced in the shallow subsurface, especially in soils when plant roots and soil microbes respire. As they break down organic matter, CO_2 builds up in the air spaces (pores) between soil grains, generating far more CO_2 underground than is typically found in the atmosphere above.

When it rains, water moves downward through the soil (infiltration). As rainwater percolates through these CO_2-rich pores, it dissolves the gas into solution — governed by **Henry's Law**, which says the amount of gas that dissolves into a liquid is directly proportional to its partial pressure and solubility at a given temperature. Once CO_2 dissolves, it forms **carbonic acid (H_2CO_3)**:

KEY REACTION — CARBONATE SYSTEM MASTER EQUATION

$H_2O + CaCO_3 + CO_2 \leftrightarrow 2\ HCO_3^- + Ca^{2+}$

Water + Limestone + Carbon dioxide ↔ Bicarbonate + Calcium ions

More CO_2 pushes the reaction forward, dissolving limestone. If CO_2 decreases, the reaction reverses and minerals may re-form. This is **Le Châtelier's Principle** in action — when a system at equilibrium is disturbed, it shifts to reduce that disturbance.

Why does rock type matter?

The type of rock in the aquifer plays a major role in determining how groundwater chemistry changes when CO_2 is introduced. These reactions form the basis for interpreting monitoring results in real CO_2 storage projects. See a breakdown of the characteristics below:

Carbonate Aquifer

Limestone ($CaCO_3$) · White rocks

- CO_2 reacts quickly with limestone
- Limestone **dissolves**, releasing Ca^{2+} and HCO_3^- into the water
- This consumes H^+ ions, **neutralizing acidity — pH barely drops**
- Water hardness, alkalinity, and total dissolved solids all increase
- Acts as **nature's buffer**

Silicate Aquifer

Quartz / Feldspar · Brown rocks

- Silicate minerals dissolve much **more slowly**
- Buffering capacity is low — CO_2 acid is not neutralized quickly
- pH drops **more noticeably**
- Calcium and alkalinity show minimal change — rocks aren't dissolving quickly
- Acts as a **poor buffer**

Based on the characteristics listed above, we expect to see the following responses from each water monitoring parameter once the aquifers are introduced to carbon dioxide.

Parameter	Carbonate aquifer	Silicate aquifer
pH change	Small drop (buffered by rock)	Larger drop (unbuffered)
Calcium (Ca^{2+})	Increases as limestone dissolves	Minimal change
Alkalinity (HCO_3^-)	Increases	Minimal change
Conductivity (TDS)	Increases (more dissolved ions)	Small or no increase

BEFORE CLASS

Materials

SAFETY AND STANDARDS

Wear nitrile gloves and eye protection throughout this lab. Dispose of all chemical waste according to proper guidelines. Rinse containers and beakers with distilled water between samples when testing for fluid parameters. CO_2 under pressure can release quickly — always turn the regulator knob fully *off* (-) before inserting a cartridge. Test the assembled system by briefly opening the regulator and listening for hissing that could indicate a leak.

CHAMBERS & CONTAINERS

- 2 — 32 oz mason jars or standard 1000 mL beakers
- 2 — 50 mL beakers (one each for Silicate / Carbonate)
- 1 — 1000 mL beaker (waste disposal)
- Distilled water

ROCK MATERIALS

- Silicate rock pebbles (brown)
- Limestone / carbonate rock pebbles (white)

CO_2 INJECTION

- 2 CO_2 cartridges (20 g each)
- CO_2 regulator with knob
- Aquarium bubbler + ¼″ clear tubing
- Quick Connect adapter ⅜″ to ¼″
- 2–3 inch piece of ⅜″ clear tubing
- 2 binder clips (optional)

MEASUREMENT TOOLS

- pH sensor
- Conductivity sensor (μS/cm)
- Calcium hardness test kit
- Alkalinity test kit
- 2 large syringes + 12 filters (1 filter per sample)
- 12 labeled sample tubes with lids (enough for 3 time steps for both aquariums)

SAFETY & MISC

- Nitrile gloves
- Safety goggles
- Kimtech wipes
- Sharpie marker
- Data sheets and method to plot results (excel, google sheets, printed plots, etc)

✅ **DETAILED SUPPLY LIST**

A *Detailed Project Supply List* with direct purchasing links, current prices, and quantities is available in the Resources section. All materials have been selected for availability, and ease of ordering. Many are reusable across multiple classes or experiments, helping reduce cost over time.

Assembling the aquifer chambers

1. Fix a bubble stone to one end of the aquarium tubing and place it at the bottom of the jar.
2. Fill one jar completely **white carbonate rocks**; fill the other with **brown silicate rocks**. The more full a jar, the more reactivity you will observe; however, you may experience more difficulty pulling water samples. At minimum, at least 60-70% full is recommended.
3. Carefully add distilled water until there's just enough room at the top where the water will not overflow once the CO_2 bubbles through. Make sure the tubing stays submerged at the bottom. Each chamber holds approximately 1 liter total (450 mL of water and 550 mL of rock — about 45% porosity), allowing roughly 10 samples per chamber if 30-40 mL is collected per sample.
4. Secure free tubing ends upright with a binder clip attached to the top of the jar to stop flow between samples.
5. *Tip: If time allows, letting the system soak overnight before the experiment improves the quality of the baseline reading.*

DAY 1 & DAY 2

Step-by-Step Procedure

Setting the Scene

Look at the two chambers. In this model, the container represents the groundwater formation, the rocks are the geologic composition, and the tubing connected to the bottom of the chamber are our wells. In this experiment, this well is both our injection and monitoring well. This lab will simulate a simplified version of a real-world "huff and puff" test—a technique used by researchers to study how CO_2 behaves underground. In this method, CO_2 is injected into an aquifer, allowed to react with the surrounding water and minerals over time, and then the water is extracted and analyzed. By observing the resulting geochemical changes, scientists can determine what chemical processes occurred during the CO_2 exposure.

💡 **BEFORE YOU BEGIN — MAKE A PREDICTION!**

Before beginning, ask students to make predictions about how each aquifer type will respond to the CO_2 injection: *"How do you think pH, calcium concentration, and alkalinity will change in each aquifer type once CO_2 is added?"* Students should write down their hypotheses using key terms like **equilibrium shift, buffering, mineral dissolution**, and **ion formation (H^+, HCO_3^-, Ca^{2+}).**

🎬 **Lab Overview Video**
Watch a walk through of the full experiment for step-by-step guidance

Watch Video

📄 **Procedure Quick Guide (PDF)**
A condensed one-page reference for running the lab

Download PDF

Day 1 — Field Measurements

1. **Prepare the aquifer models**
   Construct the two aquifer models complete with monitoring and injection well as described in the Setup section above.

2. **Sensor setup & calibration**
   Calibrate the pH and conductivity sensors following the kit instructions before taking any readings. Set conductivity units to μS/cm.

3. **Prepare the sampling station**
   Label 12 sample tubes: C1–C6 for carbonate, S1–S6 for silicate. Label both 50 mL beakers and both syringes to match their chamber. Assign student roles: sampler, recorder, timer, tester, filter technician. Rotate when possible so students get a chance to try different things.

4. **Establish baseline (S1 & C1)**
   Before injecting CO_2, record the initial time of your first sample. Draw 30-40 mL from each chamber through the tubing. This may require a syringe to create enough suction. Pour into a 50 mL beaker. Take the baseline pH reading: insert the sensor all the way to the bottom and swirl slowly until the reading stabilizes, then record. Wipe the sensor with a Kimtech wipe. Take the conductivity reading. Repeat for the other chamber. Record pH and conductivity. Alkalinity and calcium are tested next from the filtered sample.

5

Filter & store baseline samples

Attach a filter to the syringe. Remove the plunger, pour in the sample from the 50 mL beaker, reinsert the plunger. Point tip up, remove filter, expel air, reattach filter. Push the plunger slowly to filter water into the clean, labeled sample tube. Seal and set aside for Day 2 lab-style testing. Use a fresh filter for each sample and dry all beakers, syringes, and tools between uses after rinsing with distilled water to minimize cross-contamination.

6

Inject CO_2 — simulate the "huff and puff" test

Begin by inserting the CO_2 cartridge securely into the regulator. Ensure the regulator knob is turned fully off before puncturing the cartridge. Connect the aquarium tubing to the CO_2 regulator with an adapter. Ensure all connections are tight (test by briefly opening and listening for hissing). Slowly open the regulator knob — bubbles will appear as CO_2 flows. Allow the entire 20 g cartridge to empty into the chamber. *Note: Each chamber must be injected with CO_2.*

7

Monitor changes — sample every 10–15 minutes for 1 hour

Once CO_2 injection is complete, begin taking water samples from each chamber every 10–15 minutes, depending on time constraints. Samples early on (within the first 30 minutes) helps capture the most dramatic changes — but changes will continue to happen for a few days. For each sample: collect 30-40 mL from each chamber into its labeled beaker, immediately measure pH and conductivity, wipe sensors between samples, then filter and store in a labeled tube for Day 2.

Note: If conducting the experiment in one day, other lab partners can run calcium and alkalinity tests while the field samples are pulled from the chamber.

Day 2 — Lab Measurements

8

Run calcium hardness test

Using the stored and filtered samples from Day 1, perform the calcium test following the instructions provided with the test kit for each sample (also detailed in the quick guide linked above. This is specific to the Salifert Calcium Kit). Record the result in mg/L on the data sheet.

9

Run alkalinity test

Perform the alkalinity test following the instructions provided with the test kit for each stored sample (also detailed in the quick guide linked above. This is specific to the Salifert Alkalinity Kit). Record the result in meq/L on the data sheet.

10

Graph your results & analyze

Plot pH, calcium, and alkalinity on the y-axis against time on the x-axis — one line for the carbonate system, one for the silicate system, on each graph. Compare how the two systems responded. Look for patterns and trends in the data that support or challenge your initial hypothesis.

👥 **EXAMPLE OF STUDENT ROLES**

Sampler — draws water from chambers | **Measurer** — operates sensors | **Recorder** — fills in data table | **Timer** — tracks 10–15 min intervals | **Filter technician** — filters and stores samples. Not everyone will get to do every job, but rotate when you can so students experience each role. Encourage them to watch and help each other to stay involved and learn from the whole process.

RECORDING RESULTS

Data Collection Table

Use the table below (or print it) to record measurements for each time point. Take baseline readings before CO_2 injection, then measure every 10–15 minutes. Keep in mind that results may vary depending on factors such as how long the chambers sit before the experiment begins, rock composition, and temperature.

Sample	Aquifer	Time	pH	Conductivity (µS/cm)	Calcium (mg/L)	Alkalinity (meq/L)	Notes
C1	Carbonate						
S1	Silicate						
C2	Carbonate						
S2	Silicate						
C3	Carbonate						
S3	Silicate						
C4	Carbonate						
S4	Silicate						
C5	Carbonate						
S5	Silicate						
C6	Carbonate						
S6	Silicate						

C = Carbonate aquifer | S = Silicate aquifer | Calcium and alkalinity columns are completed on filtered samples, make sure labels are correct.

Discussion Questions

After graphing results, use these questions to guide a reflective, student-centered discussion that encourages critical thinking:

> What are the key differences between carbonate-rich and silicate aquifers when CO_2 is introduced? Which parameters changed the most in each?

> How does Le Châtelier's Principle help us predict changes in groundwater chemistry? Which direction did the equilibrium shift when CO_2 was added?

> Why did calcium and alkalinity change in the carbonate aquifer but not the silicate aquifer? What does this tell us about mineral dissolution and reactivity?

> In what ways does understanding groundwater chemistry enhance CO_2 monitoring efforts? If you were a scientist monitoring a real storage site, which parameters would you watch most closely?

> How does the interaction of CO_2 with groundwater illustrate the broader carbon cycle?

> What are the potential risks and benefits of storing CO_2 underground in terms of climate change mitigation? Based on your results, do small CO_2 leaks pose a major risk to drinking water?

> How does the natural behavior of carbonate rocks — buffering acid — factor into the design of CCS safety monitoring programs?

What do these results tell us about CO_2 storage safety?

🔍 Small leaks are detectable

Even small CO_2 additions cause noticeable changes in pH, calcium, and alkalinity — especially in carbonate systems. These changes serve as clear geochemical fingerprints that can be used to detect and track leaks early.

💧 Groundwater reacts predictably

Carbonate aquifers buffer acid quickly, converting CO_2 to harmless dissolved forms like bicarbonate. Silicate aquifers respond more slowly but eventually stabilize. Aquifers are not passive — they naturally reduce the impact of CO_2 leaks.

📍 Risks are limited & local

Most changes are chemical — lower pH, higher calcium and alkalinity — but within safe ranges at classroom scale. Most changes are not directly toxic.

📊 Monitoring works

The same parameters measured here — pH, conductivity, calcium, alkalinity — are used in real EPA Class VI groundwater monitoring programs. Leaks are not invisible; they can be reliably detected before spreading or causing harm.

CURRICULUM ALIGNMENT

TEKS, Standards & Practices

AP Environmental Science — Practices

- **1.C** Explain environmental concepts, processes, or models in applied contexts.
- **4.D** Make observations or collect data from laboratory setups.
- **5.A** Describe patterns or trends in data.
- **5.D** Interpret experimental data and results in relation to a given hypothesis.
- **7.B** Describe potential responses or approaches to environmental problems.
- **7.C** Describe disadvantages, advantages, or unintended consequences for potential solutions.
- **7.D** Use data and evidence to support a potential solution.
- **7.F** Justify a proposed solution by explaining potential advantages.

AP Environmental Science — Standards

ERT-1.D Explain the steps and reservoir interactions in the carbon cycle.

> **ERT-1.D.1** The carbon cycle is the movement of atoms and molecules containing the element carbon between sinks and sources.
>
> **ERT-1.D.2** Some reservoirs in which carbon compounds occur in the carbon cycle hold those compounds for long periods of time, while some hold them for relatively short periods of time.

STB-2.A Identify the sources and effects of air pollutants.

> **STB-2.A.1** Coal combustion released air pollutants including carbon dioxide, sulfur dioxide, toxic metals, and particulates.

STB-2.G Explain how air pollutants can be reduced at the source.

> **STB-2.G.1** Methods to reduce air pollutants include regulatory practices, conservation practices, and alternative fuels.

STB-4.C Identify the greenhouse gases.

> **STB-4.C.1** The principal greenhouse gases are carbon dioxide, methane, water vapor, nitrous oxide, and CFCs.

STB-4.D Identify the sources and potency of the greenhouse gases.

> **STB-4.D.1** Carbon dioxide, which has a global warming potential (GWP) of 1, is used as a reference point for the comparison of different greenhouse gases and their impacts on global climate change.

STB-4.E Identify the threats to human health and the environment by an increase in greenhouse gases.

> **STB-4.E.1** Global climate change, caused by excess greenhouse gases in the atmosphere, can lead to a variety of environmental problems including rising sea levels resulting from melting ice sheets and ocean water expansion, and disease vectors spreading from the tropics toward the poles. These problems can lead to changes in population dynamics and population movements in response.

Chemistry TEKS

C.1(C) Use appropriate safety equipment and practices during laboratory, classroom, and field investigations as outlined in TEA-approved safety standards.

C.1(D) Use appropriate tools such as Safety Data Sheets (SDS), scientific or graphing calculators, computers and probes, electronic balances, and sufficient scientific glassware such as beakers, Erlenmeyer flasks, pipettes, graduated cylinders, volumetric flasks, and burettes.

C.1(E) Collect quantitative data using the International System of Units (SI) and qualitative data as evidence.

C.1(F) Organize quantitative and qualitative data using oral or written lab reports, labeled drawings, particle diagrams, charts, tables, graphs, journals, summaries, or technology-based reports.

C.2(B) Analyze data by identifying significant statistical features, patterns, sources of error, and limitations.

C.9(A) Interpret, write, and balance chemical equations, including synthesis, decomposition, single replacement, double replacement, and combustion reactions using the law of conservation of mass.

C.9(D) Describe the concept of limiting reactants in a balanced chemical equation.

C.12(C) Differentiate between strong and weak acids and bases.

C.12(E) Define pH and calculate the pH of a solution using the hydrogen ion concentration.

Environmental Systems TEKS

ES.10(D) Evaluate indicators of air, soil, and water quality — including chemical indicators like pH and electrical conductivity — against regulatory standards such as the Clean Water Act to determine the health of an ecosystem.

ES.10(E) Distinguish between the causes and effects of global warming and ozone depletion, including the causes, the chemicals involved, the atmospheric layer, the environmental effects, the human health effects, and the relevant wavelengths on the electromagnetic spectrum (IR and UV).

Biology TEKS

B.13.C Explain the significance of the carbon and nitrogen cycles to ecosystem stability and analyze the consequences of disrupting these cycles.

B.13.D Explain how environmental change, including change due to human activity, affects biodiversity and analyze how changes in biodiversity impact ecosystem stability.

19 Tex. Admin. Code § 112.50 — Environmental Systems, Adopted 2021 (One Credit)

The full regulatory text for this course standard is available via the link above. Key knowledge and skill areas relevant to this lab include:

> **Scientific and engineering practices (§ 112.50(c)(1)):** For at least 40% of instructional time, students ask questions, identify problems, and plan and safely conduct classroom, laboratory, and field investigations to explain phenomena or design solutions using appropriate tools and models. Applicable tools include pH meters or probes, water quality test kits or probes, rock and mineral samples equipment, and various data-collecting probes.

> **Carbon and biogeochemical cycles (§ 112.50(c)(5)(B)):** Students explain the cycling of water, phosphorus, carbon, silicon, and nitrogen through ecosystems — including sinks — and the human interactions that alter these cycles using tools such as models.

> **Sources of emissions (§ 112.50(c)(10)(A)):** Students identify sources of emissions in air, soil, and water, including point and nonpoint sources.

> **Emissions vs. pollutants (§ 112.50(c)(10)(B)):** Students distinguish how an emission becomes a pollutant based on its concentration, toxicity, reactivity, and location within the environment.

> **Effects of pollutants (§ 112.50(c)(10)(C)):** Students investigate the effects of pollutants such as greenhouse gases, chlorofluorocarbons, pesticide runoff, aerosols, and metallic ions, as well as thermal, light, and noise pollution.

> **Water quality indicators (§ 112.50(c)(10)(D)):** Students evaluate indicators of air, soil, and water quality — including chemical indicators like pH and electrical conductivity — against regulatory standards to determine the health of an ecosystem.

> **Global warming and ozone depletion (§ 112.50(c)(10)(E)):** Students distinguish between the causes and effects of global warming and ozone depletion, including the chemicals involved, the atmospheric layer affected, environmental and human health effects, and relevant wavelengths of the electromagnetic spectrum (IR and UV).

DOWNLOADS & LINKS

Resources

All materials below are available for download.

Teacher Manual — AP Environmental Science

Full facilitation guide including objectives, background, setup instructions, discussion prompts, and standards alignment.

Download PDF

Teacher Manual — Chemistry

Full facilitation guide with chemistry-specific context, pre-lab reading, step-by-step instructions, and TEKS alignment.

Download PDF

Student Lab Manual

Student-facing handout with pre-lab reading, safety notes, procedure, data table, and analysis questions.

Download PDF

Detailed Supply List

Itemized list with purchasing links, current prices, and quantities needed for one class.

Download PDF

Student Data Sheet (Printable)

Printable one-page data collection table for in-lab use, with room for all time points, parameters, and notes.

Download PDF

Procedure Quick Guide

Condensed one-page reference card for students to keep at the bench during the experiment.

Download PDF

Lab Overview Video

A step-by-step video walk through of the experiment, including setup, CO_2 injection, sampling, and measurement techniques.

Download PDF

EPA Class VI — Underground Injection Control

Official EPA program page on the regulations governing CO_2 geological storage and groundwater protection.

Visit EPA

GCCC factsheets and CCS info

Find GCCC factsheets based on our research, short stories on scientific concepts, and other supplementary materials.

Visit GCCC

Access to all files

Find all files in a single box folder, including the links within this page and other supplementary materials within the GCCC outreach page.

Box Folder