

Build a Better Filter: Can Sand and Gravel Do a Watershed's Job?

Investigation question: Using only gravel, sand, cotton balls and coffee filters and a \$10 classroom budget, how can a team design a filter that makes muddy runoff clear enough and fast enough, and how does the best filter compare with the filtering a forested watershed does for free?

Engineering design challenge

Groups of 4

2 sessions

Setup 10 · Activity 90 · Cleanup 10 min

MS-ETS1-3 · practice

MS-ETS1-2 · practice

MS-LS2-5 · practice

MS-ESS3-3 · supports

Scientific purpose

Teams design a layered filter in a cut plastic bottle, test it with simulated storm runoff, rate the cloudiness (turbidity) of the water they collect against a set of reference cups, measure how much flows through in three minutes, and track the cost. After a first round they study the whole class's results, borrow the best features of other designs and rebuild. The challenge mirrors the New York City case in the lesson: an engineered filter can clear water, but it costs money, clogs, and still leaves germs and dissolved substances behind, while the soils and roots of a healthy watershed do much of the straining continuously.

Why this helps students with this chapter

Students tend to assume that clear water is clean and that a filter is a simple fix. Building one shows the trade-off between clarity and flow, the price of every layer, and the way filters clog. Rating their own water against reference cups gives them a number to argue with, and comparing designs across the class is how engineers find features worth combining. Holding the bottle filter next to the idea of a forested watershed makes the value of a free, self-renewing filter concrete.

Standards connections

MS-ETS1-3 (practice, analyzing class test data to identify features worth combining): Every team posts its design and results; students use the class table to find which features gave the clearest water and which gave the fastest flow, and combine them in round 2 (q2, q3, q7). Only one redesign cycle is run and the materials are fixed, so this is practice.

MS-ETS1-2 (practice, comparing designs against a criteria table): Each test is checked against the same clarity, volume and cost criteria, so the competing designs in the class can be compared systematically.

MS-LS2-5 (practice, comparing an engineered filter with watershed protection as ways to provide clean water): In q9 and q10 students compare their filter with a protected forested watershed on cost, upkeep, what each removes and what else each provides. The comparison is qualitative and the watershed option is not tested, so this is practice toward the PE.

MS-ESS3-3 (supports, monitoring and minimizing a human impact on a creek): MS-ESS3-3 is a Grade 6 performance expectation in the California integrated sequence and is background only here. In q11 students propose a way to monitor and a way to reduce the mud a construction site sends into a creek, revisiting the Grade 6 idea.

Roles (rotate each session)

- **Builder:** Assembles the layers from the design sketch, levels each layer gently, and pre-wets the filter.
- **Tester:** Stirs and measures the runoff, pours it in one steady pour, runs the timer and measures the volume collected at 3 minutes.
- **Rater:** Pours 100 mL of the collected water into a clear cup, compares it with the reference cups on the X card, and reports the clarity rating.
- **Accountant:** Checks the design against the budget before materials are collected, records all results, marks each criterion met or missed, and posts to the class table.

Materials

Item	Quantity	Per	Note
Clear 2-liter plastic bottle, cut in half by the teacher, cut edges covered with tape, cap removed; the top half sits upside down in the bottom half as a funnel	1	group	Recycled bottles; 1-liter bottles also work with smaller test volumes.
Pea gravel or aquarium gravel, rinsed	600 mL	group	Classroom price \$1.00 per 100 mL scoop.
Washed play sand	600 mL	group	Classroom price \$2.00 per 100 mL scoop.
Cotton balls	10	group	Classroom price \$0.50 each.
Basket-style paper coffee filters	3	group	Classroom price \$1.50 each.
100 mL scoop (a cut-down cup marked at 100 mL)	1	group	
Simulated runoff: tap water mixed with bagged topsoil and crumbled dry leaves	about 1 L	group	Mixed by the teacher; see prep.
Identical clear plastic cups (9 to 12 oz)	3	group	
Measuring cup or 250 mL graduated cylinder	1	group	
Timer or stopwatch	1	group	
Plastic tray or dish tub and paper towels	1 tray, several towels	group	
Reference cup set R0-R5 and a white card printed with a bold black X	1 or 2 sets	class	Made by the teacher each day; see prep.
Disposable gloves	1 pair	student	Required for students with cuts, skin conditions or soil and mold allergies; optional for others.
Bucket for used water, sand and gravel	1	class	

Estimated cost: 15 to 30 per class (estimate) (an estimate; Play sand about \$6–8 for a 50 lb bag, pea gravel about \$5–8 a bag, cotton balls about \$2, coffee filters about \$2, a sleeve of clear cups about \$4, bagged topsoil about \$4–6; bottles are recycled, and measuring cups, timers and trays come from classroom stock. Sand and gravel can be rinsed, dried and reused. Estimated 2026 U.S. retail prices. The \$10 design budget is classroom money, not real cost.)

Safety

- The filtered water is not safe to drink and must never be tasted, even when it looks clear: sand, gravel and cotton do not remove germs or dissolved chemicals.
- Soil can carry bacteria and fungi. Use bagged topsoil, keep hands away from faces, cover cuts or wear gloves, and wash hands with soap after each session.
- Cut plastic edges are sharp. Only the teacher cuts bottles, and every edge is taped before students handle it.
- Spilled water and sand make floors slippery; work over trays and wipe spills at once.
- Pour used water, sand and gravel into the class bucket, never into the sink, where sand and soil can clog the drain; empty the bucket outdoors onto soil.
- Students with soil, mold or dust allergies wear gloves and can take the Rater or Accountant role.

Teacher preparation and setup

1. Cut each bottle in half about 10 cm below the shoulder with sturdy scissors or a utility knife (teacher only), and cover every cut edge with duct tape. Remove caps.
2. Mix the runoff: about 4 L of tap water, about 1 cup (240 mL) of bagged topsoil and a handful of crumbled dry leaves. Use bagged soil, not compost, manure-based products or soil from places where animals toilet. Stir well and let the coarse grit settle for a minute; stir again before every pour so each team gets the same mixture.
3. Make the reference cups, each holding 100 mL in identical clear cups. R0: 100 mL of well-stirred runoff. R1: mix 100 mL of runoff with 100 mL of tap water and pour 100 mL into cup R1. R2: add 100 mL of tap water to the other 100 mL and pour 100 mL into R2. Repeat for R3 and R4. R5: 100 mL of tap water. Each step halves the cloudiness, so R1, R2, R3 and R4 hold about 1/2, 1/4, 1/8 and 1/16 of the runoff's particles. Remake the set each day, because particles settle.
4. Rating method to demonstrate: set the student cup and the reference cups on the X card, swirl each gently, and look straight down through the water at the X. The rating is the number of the most similar reference cup; half ratings are allowed. Judge cloudiness, not color, since leaves can tint the water slightly.
5. Build and test one simple design yourself (for example a coffee filter, 300 mL of sand and 200 mL of gravel). If no design you try can reach rating 3, let the runoff's coarse grit settle longer before use or lower the clarity criterion to 2.5, and tell students why.
6. Post the price list and the criteria and constraints, and draw a class results table on the board: team, key features, round, rating, volume and cost.

Investigation design

Independent variable The filter design: which materials are used, in what order, and how much of each.

Dependent variable	Clarity rating of the collected water (0-5 against the reference cups), volume collected within 3 minutes (mL), and total cost (classroom \$).
Controlled	The same runoff mixture, stirred before every pour; 250 mL poured in one steady pour for every test; The same pre-wetting step (50 mL of tap water); The same 3-minute collection time; The same reference cups, 100 mL sample size and X card for every rating
Trials	Each team tests one design in Round 1 and a modified design in Round 2 (plus an optional clog test); the class table holds every team's results, so features can be compared across eight or more designs.
Comparison	Round 1 versus Round 2 within each team, and designs with and without a given feature across the class.

Student procedure

1. Session 1. Read the challenge, criteria, constraints and price list on the recording sheet. Answer q1: which criterion do you expect to be hardest to meet, and why?
2. Sketch your Round 1 design in the drawing box: every layer from top to bottom with its amount and cost, and the total. The Accountant checks that the total is \$10 or less before anyone collects materials.
3. Build. Set the bottle top upside down in the bottom half. Put any coffee filter or cotton plug in first, at the neck, then add the layers in your planned order, leveling each one gently without pressing it down hard.
4. Pre-wet the filter by pouring 50 mL of tap water through it; let it drain and empty the collector. Dry sand soaks up water, which would make the volume test unfair.
5. Test. Stir the runoff, measure 250 mL and pour it into the filter in one steady pour, starting the timer as you begin. At 3 minutes lift the filter out of the collector and measure the volume collected.
6. Rate. Pour 100 mL of the collected water into a clear cup and compare it with reference cups R0-R5 on the X card. Record the rating, volume, cost and whether each criterion was met, then post your design features and results on the class table.
7. Session 2. Study the class table and answer q2 and q3: which features appear in the clearest designs, which in the fastest, and is there a trade-off?
8. Redesign. Change at least one feature, borrowing from another team's design where the data support it. Add Round 2 to the drawing box with costs and a one-line reason for each change.
9. Rebuild with fresh or rinsed sand and gravel, pre-wet, and test again exactly as in Round 1. Record and post the results and answer q4.
10. Clog test, if time allows: without changing anything, pour a second 250 mL of runoff through the Round 2 filter and measure the volume at 3 minutes and the rating again.
11. Clean up: empty sand, gravel and water into the class bucket, rinse the cups, wipe trays and wash hands. Answer the analysis questions individually.

Expected observations

- These are predictions; the lab has not been run by the authors. Designs with a deep sand layer (300 mL or more) and a coffee filter or cotton plug at the neck should give the clearest water, likely ratings

of 2 to 4, because the finest clay particles in topsoil pass through even a good sand layer.

- Gravel-only or gravel-heavy designs drain fastest, often passing most of the 250 mL in well under a minute, but stay cloudy (ratings 0 to 1).
- A tightly packed cotton plug or several stacked coffee filters can slow the flow below the 150 mL criterion even when clarity is good.
- On the clog test the flow usually slows as mud builds up on top of the sand; clarity may stay the same or even improve slightly, because the clogged layer traps finer particles.
- Most teams improve at least one result in Round 2 by copying a feature from a clearer or faster design, and the class table shows a clarity-versus-speed trade-off.

Likely difficulties

- Pouring so fast that water overflows or runs down the inside wall of the bottle and bypasses the sand. Pour steadily onto the center of the gravel.
- Not stirring the runoff before measuring, so some teams get clearer water to start with and the comparison is unfair.
- Rating color instead of cloudiness, or rating without swirling the cups. Demonstrate the method once with the class watching.
- Spending the whole budget on sand and having nothing at the neck to hold it, so sand washes into the collector.
- Skipping the pre-wetting step, which makes the first test look slower than it is.

Structured debrief

1. Gather around the class table. Ask which features show up in the clearest designs (typically a deep sand layer, a coffee filter or cotton plug at the neck, and gravel on top to spread the pour so it does not dig into the sand) and in the fastest (more gravel, a thin sand layer, a loose plug). Name the trade-off between clarity and flow and ask which criterion each team sacrificed.
2. Run the clear-is-not-safe discussion from slide 26: list what a city would still need to do (disinfect, test) and what the filter cannot remove (germs, dissolved salts, nitrate, some pesticides).
3. Compare with a watershed: leaf litter and soil layers strain particles, roots and wetlands slow water so particles settle, soil microbes break down some wastes, and the system renews itself. Real slow sand filters in water plants depend on a living film of microbes that forms on top of the sand, so even engineered filters borrow from ecosystems.
4. Close with New York City's numbers: in the 1990s the city estimated a filtration plant for its Catskill and Delaware water could cost up to about \$6 billion to build and over \$300 million a year to run (an EPA-appointed expert panel argued it might cost as little as half that), against about \$1.5 billion over ten years for watershed protection. Ask students which constraint that comparison speaks to, and what other benefits the forest provides that the plant would not.

Recording sheet: what students fill in

Lab 2 recording sheet: Build a Better Filter

A town's creek turns muddy after storms. Your team must design a filter that cleans a sample of the runoff.

Criteria: the collected water has a clarity rating of **at least 3** (stretch goal: 4), and **at least 150 mL** comes through within 3 minutes of pouring 250 mL. **Constraints:** total cost **no more than \$10** in classroom money; only gravel, sand, cotton balls and coffee filters; every layer fits inside the top half of the bottle.

Never drink or taste the water, however clear it looks.

Price list (classroom money)

Material	Unit	Price
Gravel	100 mL scoop	\$1.00
Sand	100 mL scoop	\$2.00
Cotton ball	1 ball	\$0.50
Coffee filter	1 filter	\$1.50

Clarity scale

Rating	Most similar reference cup	Share of the runoff's cloudiness left (about)
0	R0 (runoff)	all of it
1	R1	1/2
2	R2	1/4
3	R3	1/8
4	R4	1/16
5	R5 (tap water)	none visible

1. Before you build: which criterion or constraint do you expect to be hardest to meet, and why?

Answer: Any choice with a reason. Many teams expect the clarity criterion to be hardest, because fine mud particles are tiny; others expect the 150 mL in 3 minutes to be hard, because sand that cleans well also slows the water.

Why: The point is to notice before building that criteria can pull against each other.

- Names a criterion or constraint
- Gives a reason linked to how filters work or to the budget

- Every layer labeled with material and amount
- Cost per layer and total shown, within \$10
- Round 2 changes marked with a reason

[illegible]

2. Look at the class table. What features do the designs with the highest clarity ratings share? What features do the fastest designs share?

Answer: Class-specific. Expected: the clearest designs share a deep sand layer and a fine barrier at the neck (coffee filter or several cotton balls), often with gravel on top; the fastest designs share mostly gravel, a thin sand layer and a loose plug.

Why: Students must cite features from the class table, not from their own design only.

- Names at least one shared feature of the clearest designs
- Names at least one shared feature of the fastest designs
- Refers to the class table

3. Is there a trade-off between clarity and speed? Use two teams' numbers as evidence.

Answer: Usually yes: designs with more sand or tighter plugs gave higher ratings but less volume in 3 minutes, and gravel-heavy designs were fast but cloudy. Example evidence format: Team 2 (400 mL sand) rated 3.5 with 160 mL, Team 5 (mostly gravel) rated 1 with 240 mL.

Why: The smaller the spaces between grains, the more particles are trapped and the more slowly water passes.

Also acceptable: If the class data show no trade-off, accept an answer that says so with numbers and suggests why (for example, one design got both).

- Answers yes or no
- Uses numbers from two teams
- Explains with spaces between grains or another physical reason

4. Describe your Round 2 change and the reason for it. Did the Round 2 results confirm your reasoning? Give the numbers.

Answer: Team-specific. A full answer names the change (for example, adding 100 mL of sand and a coffee filter), the class evidence that suggested it, and the before-and-after numbers (for example, rating 2 to 3.5, volume 200 to 170 mL).

Why: Iteration means a change justified by data and then checked by a new test.

- States the specific change
- Gives the reason from data
- Reports Round 1 and Round 2 numbers and whether they confirmed the reasoning

Analysis questions: answer key

5. Use the clarity scale. About what percent of the runoff's cloudiness did your best filter remove? (A rating of 3 leaves about 1/8, so it removed about 7/8.) Show your calculation.

Answer: Percent removed = $(1 - \text{share left}) \times 100$. Rating 3: $(1 - 1/8) \times 100 = 87.5$ percent. Rating 4: $(1 - 1/16) \times 100 = 93.75$, about 94 percent. Rating 2: $(1 - 1/4) \times 100 = 75$ percent. Rating 3.5 falls between, about 91 percent.

Why: Each reference cup halves the cloudiness of the one before, so rating r leaves about $1/2$ to the power r of the original.

- Correct share left for the student's rating
- Correct percent removed with work shown

6. What happened to the flow and the clarity on the clog test, and why? What would a real treatment plant have to do about clogging, and what does that cost?

Answer: On the second pour the flow usually slowed, because mud collected on top of and inside the sand and blocked the spaces between grains; clarity often stayed about the same or improved slightly, because the clogged layer traps finer particles. A real plant must clean its filters, for example by pumping clean water backward through the sand (backwashing) or scraping off the top layer, which costs energy, water, labor and equipment, and eventually the sand must be replaced.

Why: Clogging is the hidden running cost of engineered filtration that a watershed avoids by spreading the job over a huge area and renewing itself.

- Describes the change in flow (and clarity)
- Explains clogging by trapped particles
- Names a cleaning method and at least one cost

7. Name the best feature of two different teams' designs and explain how combining them could beat both. Use numbers from the class table.

Answer: Class-specific. Example: Team 3's coffee filter at the neck gave the clearest water (rating 3.5) and Team 6's thick gravel top layer kept flow high (210 mL). Combining a gravel top layer that spreads the pour and catches large debris with a sand layer over a coffee filter could keep the clarity while preventing the sand surface from clogging as quickly.

Why: MS-ETS1-3 is about finding the best characteristics of several tested designs and combining them; the answer must use test numbers.

- Names a feature from each of two different teams
- Quotes numbers that show each feature's strength
- Explains why the combination could beat both

8. Your best water may look clear. Name two kinds of things that could still be in it, and explain why sand, gravel and cotton cannot remove them.

Answer: Examples: germs (bacteria, viruses, parasites), dissolved substances (salts, fertilizer nitrate, some pesticides, metals), and fine clay too small to see. They pass through because they are far smaller than the spaces between sand grains or are dissolved in the water itself, so there is nothing to strain out.

Why: Clarity measures particles big enough to scatter light; safety requires disinfection and testing.

- Names two different kinds of contaminants
- Explains size or dissolving as the reason they pass through

9. Compare your filter with a forested watershed like the ones that supply New York City. Give one way they work alike and two ways the watershed is different (think about cost, upkeep and what else it provides). Then explain why New York still disinfects its water.

Answer: Alike: both strain particles as water passes through layers of soil, sand or gravel. Different: the watershed is huge, renews itself, and costs only what it takes to protect it, while the filter costs money to build and maintain and clogs; the watershed also slows water so particles settle, hosts microbes that break down some wastes, and provides habitat, recreation and flood control. New York still disinfects because neither forests nor sand reliably remove all germs, and disinfection is the safety step that kills them; the protected watershed replaces filtration, not disinfection.

Why: This is the key comparison between an engineered replacement and an ecosystem service.

- One similarity
- Two differences, including at least one about cost or upkeep
- Explains that disinfection is still needed because germs pass through

10. Suppose a filter like yours cost \$9 and cleaned 0.5 L of runoff before it clogged and had to be replaced. (a) What did it cost per liter? (b) A town uses 10 million liters of water a day. At that cost per liter, what would one day of water cost? (c) Real plants wash and reuse their sand. Why does that matter for this comparison?

Answer: (a) $\$9 / 0.5 \text{ L} = \$18 \text{ per liter}$. (b) $10,000,000 \text{ L} \times \$18 \text{ per L} = \$180,000,000$, or \$180 million for one day. (c) Real plants backwash and reuse their sand for years, so their cost per liter is far lower than a throwaway bottle filter's; the comparison shows why cleaning and reuse matter, but even a reusable plant costs money to build and run every year, which is why a watershed that does the job for free is so valuable.

Why: Unit cost and scaling show why engineered filtration is designed for reuse and why the replacement cost of a watershed is large.

- \$18 per liter
- \$180 million per day with work shown
- Explains that reuse lowers the real cost but does not make it free

11. A housing development is planned beside the creek that feeds a town's reservoir. During construction, bare soil will wash into the creek in storms. Propose one way to monitor the impact and one way to reduce it, and explain how each connects to this lab.

Answer: Monitor: measure the creek's turbidity (for example with reference cups, a clear tube or a white disk) upstream and downstream of the site after every storm, and compare with readings from before construction. Reduce: keep a strip of plants along the creek, cover bare soil with straw or mulch, put up silt fences, or build a small settling basin so runoff drops its mud before reaching the creek. Each connects to the lab: monitoring uses the same idea of rating cloudiness, and plant strips and settling basins do in the field what the gravel and sand layers did in the bottle.

Why: Revisits MS-ESS3-3 (Grade 6): design a method to monitor and minimize a human impact.

- A measurable monitoring method with when and where
- A practical way to reduce mud reaching the creek
- Connection to the lab for each

Individual evidence of learning

Each student submits the design drawing, the test and class tables, and individual answers to q5-q11. q7 is the evidence of analyzing test data to combine features (MS-ETS1-3); q8 and q9 show the difference

between clarity and safety and between an engineered filter and a watershed; q5 and q10 show the calculations; q11 revisits the Grade 6 idea of monitoring and reducing a human impact.

Assessment criteria

Criterion	Proficient looks like
Design and documentation	Labeled side-view drawing for both rounds with amounts and costs; both designs within the \$10 budget.
Fair testing	Runoff stirred, 250 mL poured, pre-wetting and 3-minute timing followed, and all results recorded with criteria marked met or missed.
Data-based redesign	The Round 2 change is tied to specific class data and the student states whether the new results confirmed it (q4, q7).
Science of filtering	Explains that clarity does not mean safety and names germs and dissolved substances (q8); compares the filter with a watershed on cost, upkeep and other services (q9).
Calculations	q5 percent removed and q10 cost per liter and daily cost are correct with work shown.

Accessibility adaptations

- Provide paper layer cards (gravel, sand, cotton, coffee filter) that teams arrange on the desk to plan before building.
- Students with limited fine-motor control can take the Rater or Accountant role; a wide-mouth funnel or a pre-cut bottle with a larger opening makes pouring easier.
- For low vision, use a high-contrast X card and an alternative card with five black lines of decreasing thickness, so clarity can be judged by counting how many lines are visible through each cup.
- Give multilingual learners a picture-labeled price list and frames such as 'Our filter met ___ but missed ___ because ___.'

Low-cost alternative

If bottles or sand are short, use paper or plastic cups as filter holders with five small holes poked in the bottom by the teacher with a pushpin, nested over a second cup, and halve every amount (125 mL pours, 50 mL scoops). Rate clarity only and drop the volume criterion. Clean bagged dirt or garden sand can replace play sand.

Model limitations

This activity has not been physically tested by the authors; the ratings and flow numbers in the expected observations are predictions. A bottle filter models only the straining part of what a watershed does. Real forested watersheds slow water over very large areas, let particles settle in wetlands and reservoirs, and host soil microbes that break down some wastes; real treatment plants add chemicals that clump particles, settling basins, sand filters that are backwashed and reused, and disinfection. The clarity scale measures cloudiness against one runoff mixture, not safety, and says nothing about germs, nitrate, metals or pesticides. Classroom prices are invented so that budget choices matter.

Teacher notes

Expected numbers are predictions because the lab has not been classroom-tested; adjust the clarity criterion after your own trial build (see prep). Check that each team's Round 2 cost is within \$10 before testing. For q3 and q7 accept any claims the class data actually support. Collect the class table on chart paper so the Lab 3 water decision (Decision 1) or Lesson 29 can refer to it. If only one session is available, skip the clog test and assign q6 as a prediction.