

Name: Nail and Silas

Leak alert:

Introduction and Research Question

Introduction/Literary review

Supplying clean drinking water is one of the most important jobs of any city or community. Before the water reaches its intended target, it is filtered, disinfected and pumped, which uses lots of money, energy and chemicals. However, a significant amount of this treated water never reaches the tap because it leaks out of pipes, valves and joints underground. These lost waters are called *non-revenue water* because the water company pays to treat and transport it but cannot even sell it (Wikipedia Contributors, 2019). In regions where water is already scarce or where the water system is fragile and old, continuous leakage can make shortages even worse and increase the cost of the water for everyone.

Leakage occurs for many reasons; underground pipes can crack as the soil moves or freezes and defrosts (*Fast Response Plumbing & Rooter, 2025*). Old pipes may corrode or wear thin over time, while poorly sealed joints and valves can allow a slow and constant trickle of water to escape. Usually, larger bursts are easy to notice, most of the time, and repair quickly because they flood the surface or cause obvious damage. In contrast, small leaks can be almost invisible at ground level, especially if the water soaks into the soil or even flows into drains. These small leaks may continue for days, weeks, and even years without getting detected, slowly wasting thousands of liters of treated water that could be used by people, businesses, or farms.

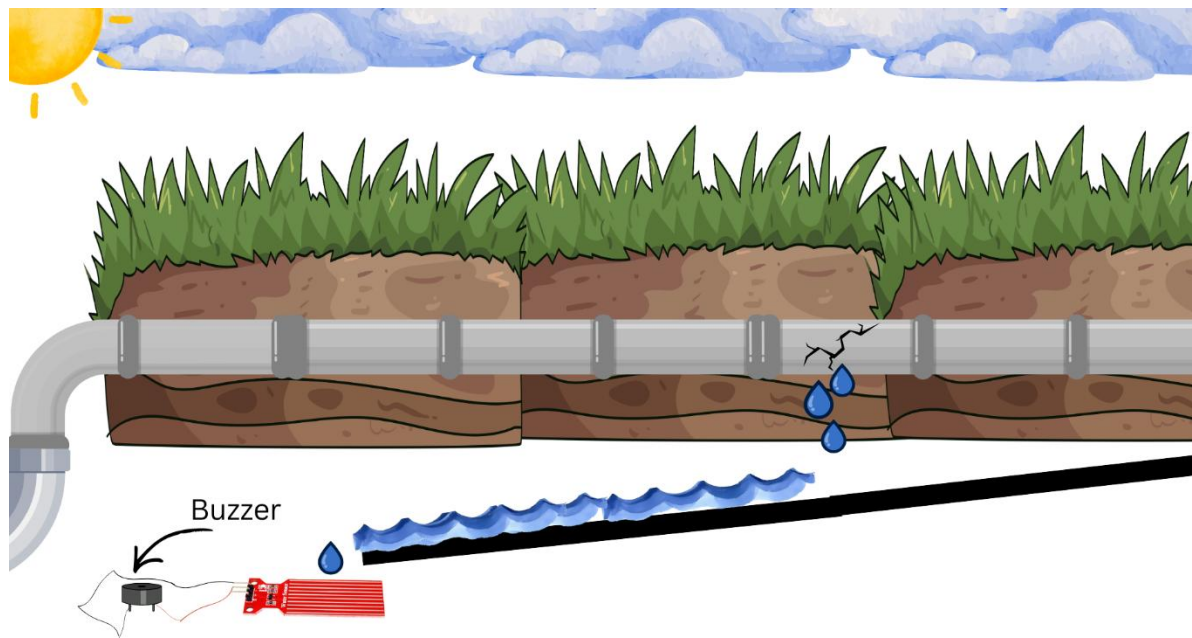
Water companies use several advanced technology-based systems to find those leaks. Some of these more common but expensive systems include acoustic listening devices that detect the vibrations and sounds of the water escaping under pressure. Companies might also use a system like a pressure and flow monitor along the pipe network, and smart systems that detect unusual patterns of water use (Energy.gov, n.d.). These technologies and systems can be very effective, but they often require very expensive equipment, specialist training, and regular maintenance. This can make them difficult to use in small towns, rural areas, and less-developed countries, where the technical support and money are limited. Even in well-resourced cities, existing methods can struggle to detect very small amounts of leaks early, before they grow and become larger breaks.

Globally, it is estimated that 346 million cubic metres of treated drinking water is lost every day and every year, which equates to 126 billion cubic meters per year, representing both a major environmental and economic issue, an issue that costs 39 billion USD per year, using a conservation value of about 0.31 dollars per cubic metre (Liemberger and Wyatt, 2018)

	Volume of NRW		Average level of NRW	Cost/value of NRW
	million m ³ /day	billion m ³ /year	Liters/capita/day	billion USD/year
Sub-Saharan Africa	14.1	5.2	64	1.4
Australia and New Zealand	1.0	0.3	36	0.1
Caucasus and Central Asia	8.0	2.9	152	0.8
East Asia	53.0	19.3	42	6.2
Europe	26.8	9.8	50	3.4
Latin America and Caribbean	69.1	25.2	121	8.0
Middle East and Northern Africa	41.2	15.0	96	4.8
Pacific Islands	0.5	0.2	211	0.1
Russia, Ukraine, Belarus	9.5	3.5	65	1.1
South Asia	63.4	23.2	93	6.0
Southeast Asia	18.4	6.7	81	2.0
USA and Canada	40.7	14.8	119	5.7
Total	346	126	77	39

This graph shows us that it is not just a minor problem we are trying to solve; it's a multibillion-dollar problem, something that's based on how developed a nation may be or how advanced a nation is. This is a unilateral global problem that needs a global solution, which we aim to solve by:

(SIMPFYED VERSION OF OUR MODEL)



Because of those challenges, there is a clear need for cheaper and simpler early warning systems that can react very quickly when a leak starts. Such systems could

be used as teaching tools in schools, as prototypes for future devices, or as practical solutions in places where advanced technology is not available. Basic electronic components such as breadboards, jumper wires, simple water sensors, and low-voltage buzzers are inexpensive and easy to assemble, which makes them suitable for building and testing.

Research Question

How does hole diameter (4, 7, 9, 12, 15 mm) affect the detection time (seconds from the first visible drop to the buzzer activation) in a model pipe at constant head (1.00m) when ramp angle (20 °), sensor height (15 mm above the cup base), pipe material (rigid PVC) and water temperature (20- 25 ° C) are kept constant?

Hypothesis

If the hole diameter increases from 4 → 7 → 9 → 12 → 15 mm while head height, ramp angle, water temperature and sensor height remain constant, then the detection time will decrease, because a larger opening will have a larger area, so more water reaches to the sensor each second

Scientific Reasoning (why this should happen)

In our setup, the buzzer turns on only after a fixed amount of leaked water has collected in the cup. That fixed amount is basically set by the sensor height, which we keep constant for every trial. We also start each trial with the reservoir at the same level, so the pressure (head) pushing the water is the same each time. Under those conditions, the key question is: *how fast does water leave the hole? That rate is called the flow rate*

Our first idea is that the speed of water as it exits a small hole depends on the height of water above it (the head of it). For a given head, this exit speed is constant (roughly). In physics, this is captured by Torricelli's idea, which is:

$$v = \sqrt{2gh}$$

In here, v is the exit speed of the water, g is gravitational acceleration, and h is the head height. Since we keep the h (head height) the same every trial, v has the same consistently every trial as well

The second main idea is that the flow rate Q (how much water comes out of the leak per second) depends on two main things: The exit speed v and the area A of the opening:

$$Q = v \cdot A$$

Since v is consistent in every trial (same head), this means the flow rate is essentially proportional to the hole's area: *bigger area = bigger Q*

The third main idea is how the area depends on the diameter (d) of a circular hole. The area of a circle is (found by the diameter)

$$A = \frac{\pi d^2}{4}$$

This means that when the diameter increases a little bit, the area increases a lot (it grows with d^2 , not only d). For example, if you were to double d , the area becomes about four times bigger.

All these put together: With the head fixed, $Q \propto d^2$. now link this to time. Let V^* be the trigger volume needed to touch the sensor. Because sensor height is fixed, V^* is the same for every trial. The detection time (t) is just the time it takes to collect the fixed volume:

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

Since the V^* here is constant and $Q \propto d^2$, we get the key prediction of:

$$t \propto \frac{1}{d^2}$$

In plain words, the greater the diameter, equates to much and faster the flow, meaning a much shorter time. As a simple illustration, if one hole's diameter were doubled, the area would be about four times larger, so the time to reach the same

trigger level would be about one quarter as long (because you are filling at around four times the rate)

And finally, there is a practical lower limit. For every small hole, the water may drip extremely slowly, or water drops may even cling to the edge due to surface tension or tiny burrs of the pipe from drilling. In that case, the cup may not reach the trigger level within our 5-minute window. This does not contradict the “larger hole = shorter time” trend; it simply shows the minimum detectable hole size for our model under the chosen head and sensor setting.

Assumptions and fair test conditions (so the prediction holds)

This prediction assumes that the ramp angle and the sensor height stays fixed (so V^* is constant), the head height is reset to the same level at the start of each trial, the water temperature stays similar so viscosity (how easy the water flows through) does not change too much, and the timing rule is identical: start at the first visible drop and stop at the first buzzer.

Possible deviations to watch (still consistent with the hypothesis)

At the smallest size (4mm), water may drip down very slowly or cling to the edge because of surface tension or a tiny burr, causing ND (>300 s). Small splashes missing the cup or a slight ramp misplacement can add random delay, but these do not change the overall trend and add scatter.

Variables

Independent Variable

Independent variable (unit)	The diameter in millimetres of the hole
Range of values	4 mm, 7 mm, 9 mm, 12 mm, 15 mm.
How the IV will be manipulated	We will cut separate PVC (Polyvinyl chloride) pipe sections, each about 20cm long, with the same inner diameter (~25mm). In the centre of each section, we will drill one hole using the correct drill bit (4,7,9,12, or 15 mm). Each of the pipe sections will then be tested one at a time in the same setup. The hole size can be checked with vernier callipers (± 0.1 mm) or by matching it to the

	drill bit that is used
Justification for choice if IV	The diameter of the hole directly controls the cross-sectional area of the opening and, therefore, the flow rate of water leaking from the pipe. A larger diameter has a larger area so that more water can escape per second, and the collection cup should be filling up faster. This should cause a measurable, clear change in detection time (the time until the buzzer sounds). This makes the hole diameter an ideal independent variable for testing our hypothesis that larger leaks are detected more quickly

Dependent Variable

Dependent variable (unit)	Detection time in seconds. The amount of time it takes from the first visible drop of water leaving the leak hole until the water sensor activates the buzzer.
Specific detail on how the DV will be measured	The dependent variable was the detection time (s). We measured detection time with a digital stopwatch (0.1 s resolution) under a fixed timing rule. Observer A watched the leak hole, and Observer B held the stopwatch for all trials. Timing started the moment the first droplet of water detached from the hole (Observer A called "Start", Observer B pressed the button) and stopped at the first continuous buzzer sound from the water sensor circuit (audible onset, not a brief chirp). Then we recorded times to the nearest 0.1 seconds directly into Table 1. Each of the diameters was tested three times, and the mean detection time (0.1 s) was calculated. If the buzzer did not buzz under 300 s, we recorded it as ND (>300 s) for that trial and did not include it as part of the mean. Between the trials, we always dried the ramp and the cup, reset the head to 1.00m, and kept the sensor at 15 mm, so the timing reflected only the hole diameter.

Control Variables

Control Variables	Target Value	How the variable will be controlled	Why it needs to be controlled
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Water pressure (head height)	1.00m ± 0.02m	Reservoir surface kept ~1.00m above hole, start level mark on bucket, refill to mark before each trial, measure with meter rule/tape. Head stability 50mL trigger lowers level ~0.7mm (<0.1% of 1m)	It needs to be controlled because water pressure directly affects the flow rate, changing height would cause the water to exit faster, so keeping it in a constant height ensures that differences are caused by only the hole size
Ramp angle 20 degrees	20 ° ± 1 °	The ramp is fixed at an angle of 20° using a clamp or strong tape. The angle is checked at the start of the experiment, and after any accidental bumps, using a protractor (± 1°). And the ramp position is not changed between the trials	The ramp angle controls how quickly the leaked water from the pipe is carried from the hole to the collection cup and the sensor. For example, a steeper or shallower angle would change the speed and path of the water drops, which would then change the detection time even if the hole diameter is the same. Keeping this variable constant means differences in detection time only comes from the hole size
Pipe material	Rigid PVC (uPVC), same inner diameter (~25mm), same batch\brand for all tests	All pipe sections are cut from the same length of rigid PVC, so they all have the same wall thickness and inner diameter. The same type of join fittings will be used for every set up. The inner diameter is checked	Different pipe diameters and materials can change the internal flow behaviour and the exact shape of the leak at the hole. This would also change how the water streams out or drips and could affect the detection time even if the hole diameter is the

		once with vernier callipers (± 0.1 mm) and each drilled hole is deburred, so the edge shape is similar	same. Keeping the pipe material and geometry constant prevents these factors from influencing the results
Ramp condition	Dry ramp at the start of every trial	At the end of each trial, the ramp is wiped with a towel, so it may be dry before we do the next trial. The same cleaning routine will be used for every trial, so the surface condition is consistent.	The wetness of the surface changes how the water drops behave on the ramp. For Example, a wet ramp can make the water spread out into a film and flow differently, which can change the amount of time taken for leaked water reach to the collection cup and sensor. Keeping the ramp condition the same ensures that differences in detection time come from the hole size, not from changes in the ramp surface.
Electronics supply and threshold	Single 9 V battery with a 1k OHM resistor in the circuit. (circuit kept exactly the same for all the trials)	Both the water sensor and the buzzer are powered from the same 9V battery for the whole experiment (or replaced with a 9V fresh battery if it becomes weak). A 1kilo Ohm resistor is kept in the same position in the circuit and the breadboard	If the supply voltage, the resistor value, or the sensor threshold changed, the sensor might trigger at a different water level or respond in a way that is weaker or stronger. That could make the buzzer turn on later or earlier for the same amount of leaked water, changing the detection time for

		wiring is not changed between the trials. If the water sensor module has an adjustable potentiometer (threshold), it is set once at the start of the experiment and then never changed again	reasons that are not really related to the hole diameter. Keeping the battery type, circuit settings and resistor identical makes us sure that differences in detection time are only caused by the leak size and not by changes in the electronics
Sensor position	15mm ± 1 mm above cup base	The chosen height (15 mm) was kept the same for all of our trials so that any change in detection time is due to hole diameter, not a shifting trigger level	We set the probe 15 mm above the cup base to avoid false alarms from residual moisture, splash back or humidity close to the bottom. This increases the specificity for real leak water while keeping the trigger level constant for all of the trials

Methodology

Equipment and Chemical List

- PVC pipe sections – 5 pieces, each around 20 cm long, 25 mm inner diameter (One whole will be drilled in each: 4,7,9,12, 15 mm)
- Drill with drill bits: 4mm, 7mm, 9mm, 12mm, 15mm
- Fine sandpaper or deburring tool to smooth the edges of drilled holes
- Small collection cup\ beaker (volume 100-250 mL for leaked water and sensor)
- A water reservoir
- Flexible tubing (to connect the reservoir to the pipe)

- Retort stand\clamp or other support to hold the pipe and ramp position
- Tray or a large plastic tub to catch the spills under the whole setup
- Meter ruler or tape measure to set the 1.00m head height
- Protractor to set and check the 20-degree ramp angle
- Stopwatch
- Marker pen labels for labelling pipe sections by hole diameter

Electronics

- Breadboard
- Water sensor module (typical low voltage rain\water) sensor and driver board
- Active buzzer – rated for low voltage use
- 9 V battery
- 9V battery clip
- 1k Ohm resistor
- Jumper wires (assorted male to male \ male to female as needed)
- Measuring cylinder, 250mL (-+ mL) for calibrating trigger volume
- Beaker or a jug, 500 – 1000mL for filling and transferring water
- Thermometer to check the room temperature water

Safety and clean up

Safety goggles – 1 pair per student near the experiment

Protective gloves for cleaning and handling rough pipe edges

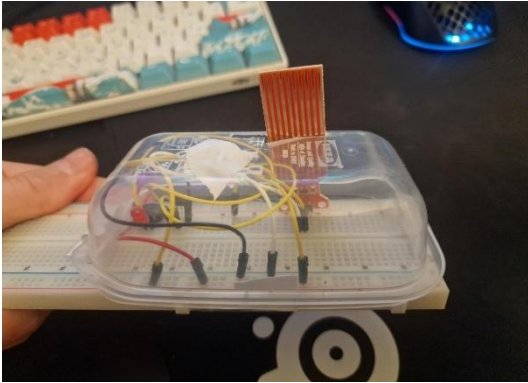
Paper towels or cloth towels for drying the ramp\cup and wiping spills

A vacuum cleaner for PVC shavings after drilling

These precautions ensured the experiment could be carried out safely

while keeping the method consistent across all trials

Safety, Environmental and Ethical Considerations

Hazard	Prevention
<p>Electricity near water (9V battery, wires, sensor)</p>	<p>Keep the breadboard, buzzer and sensor's control board inside of our super advanced, one of a kind, years ahead of its time, revolutionary, modular, tactical, dynamic, adaptive, next-gen, multi-theatre, transparent plastic splash guard (small clear bag or a box) mounted above the spill tray. The probe/sensing face remains outside of the cover. Position the opening facing down and route wires with a drip loop so the water cannot run inside. Dry hands before touching the circuit. Disconnect the 9V between trials and replace any wear covers before continuing</p> 
<p>Cutting tools and sharp edges (cardboard ramp, PVC, drill bits)</p>	<p>Cut on a stable surface with a cutting mat, keep fingers behind the blade. Also wear cut resistant gloves when trimming cardboard/tape and when deburring PVC. Clamp the pipe while drilling and deburr both sides of each hole to remove any left sharp plastic <i>(Added this after I cut my finger during the ramp construction)</i></p>
<p>Water spillage/spilling</p>	<p>Work over a tray and place towels under the setup. Wipe all the spills immediately and keep the floor dry and clear around the bench</p>
<p>Flying pieces/ eye</p>	<p>Wear safety gloves while cutting anything. Drill at a</p>

injury while drilling the PVC	moderate speed with the pipe clamped. Brush/ vacuum shavings, do not blow them. Check the bench for any fragments before testing
Battery misuse/disposal/overheating	Do not short the battery terminals. If the battery starts getting too weak or warm, stop it immediately and replace it. Recycle the used 9V battery in an approved recycling bin or store it in a terminal cover when not in use
Environmental, Water use	Use tap water only (around 20- 25 degrees), reuse the water between trials where possible and dispose the sink.

Procedure

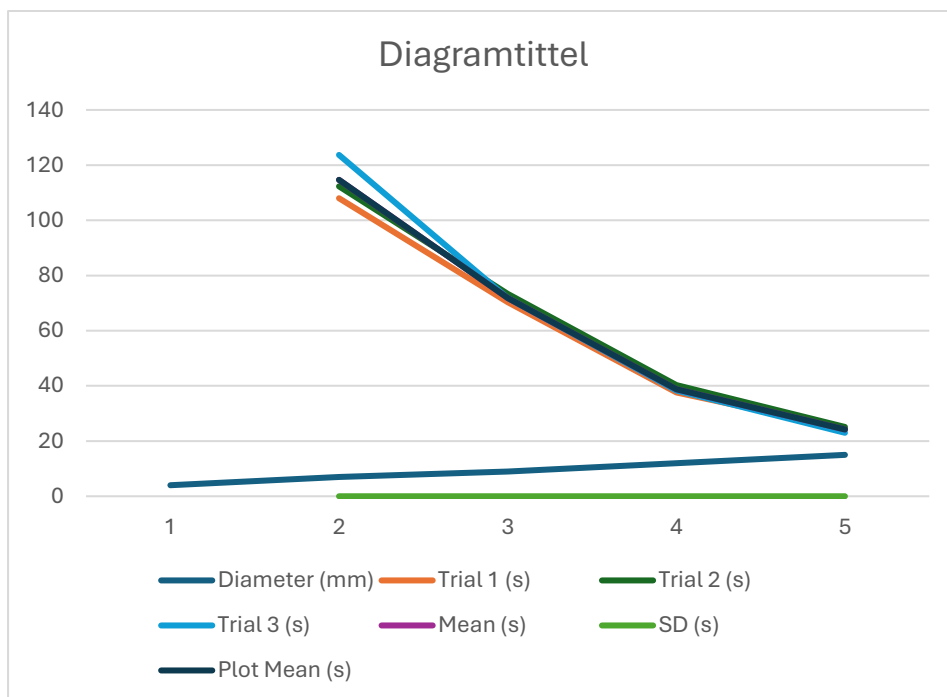
1. Prepare the five test pieces by cutting each of the PVC sections into about 20 cm long, inner diameter of 25mm, then drill one hole in the middle of each section using 4, 7, 9, 12, 15mm bits, then for safety purposes file down both sides so the lip is smooth, and finally, label each section with its intended diameter
2. Install the waterproof ramp and cup, then fix the ramp so the cardboard is fully covered with tape, so it makes a smooth and non-absorbing surface, then clamp/tamp the ramp at 20° (check it with a protractor). Position the cup so that all the water from the ramp runs into it, and leave a 2 cm gap between the hole and the ramp to avoid wicking
3. Set the head (pressure). Place a water reservoir that puts the water surface 1.00 m above the hole centre, then draw a start level mark on the reservoir. Before every trial, mark where the water line is and refill to this mark to keep consistency.
4. Mount the water sensor at a fixed level, then fix the probe tip 15mm above the base of the cup and mark the height. This is meant to avoid false alarms from residual wetness at the bottom and keep the trigger volume constant every trial
5. Wire and test the circuit. On the breadboard, connect the water sensor probe to its driver board. Then use a NPN transistor as a low-side switch for the active buzzer (collector → buzzer → +9 V, emitter → GND). Connect the sensor output

to the transistor's base through a 1 k Ohm resistor, share ground between sensor and the battery. Confirm by placing a drop on the probe (buzzer turns on). Keep the buzzer/ board inside the transparent splash guard, with the probe tip staying outside

6. Calibrate the trigger volume (3 pours). Slowly pour water into the cup until the water sensor circuit buzzes and the volume from the measuring cylinder. Empty and dry the cup to make sure the data doesn't get convoluted, then repeat this 3 times. Record the mean trigger Volume V^* . This confirms that the sensor height gives a consistent amount of trigger levels
 - a. Data collection (repeat for each diameter)
7. Select the pipe and insert the section of the chosen diameter, making sure the hole faces straight downward over the ramp.
8. Reset and check controls: Refill the reservoir to the start level, which was 1.00 m, and confirm that the ramp is angle of 20° , the sensor is 15 mm above the marked height, the ramp surface is clean and dry with a towel, and the cup is empty, dried, and fixed
9. Timing rule (two people): Person A starts the stopwatch at the first visible drop leaving the hole, then person B stops the stopwatch at the first buzzer sound. Record time to 0.1s for consistency
10. Repeat (3 trials per diameter): Empty and dry the ramp again and wait for around 10 seconds for drips to stop and then refill the reservoir to the start level and repeat until we have three trials for that diameter.
11. Non-detection rule. If the buzzer does not sound within the target range (300s), record it as ND (>300s) for that trial
12. Change the diameters: Swap to the next pipe section (7mm, 9mm, 12mm, and 15mm) and repeat the same steps from 8 to 11
 - a. After the data collection
13. Calculating the means: For each of the diameters, calculate the mean detection time from the three trials. If all the trials happened to be ND (>300s), write "No detection" for the mean
14. Graph and caption: Plot hole diameter (mm) (x-axis) and the Mean detection time (s) (y-axis). Caption, "Figure 1: mean detection time vs hole diameter" and add at 4 mm (No detection within 300s)
15. Keep the electronics above the water tray, dry our hands thoroughly before touching the circuit, and switch off the electronics between trials. Wear safety gloves and goggles when drilling the pipes and testing, and wipe spills immediately to prevent any slips

Data Collection & Processing

Hole diameter	Trial 1/s	Trial 2/s	Trial 3/s	Mean/s
4	ND (>300 s)	ND (>300 s)	ND (>300 s)	ND (>300 s)
7	108.0	112.3	123.7	114.7
9	70.3	73.3	71.8	71.8
12	37.6	40.3	38.3	38.7
15	24.5	25.1	23.0	24.2



The curve is non-linear (a bigger drop from 7 to 9mm than from 12 to 15mm), consistent with the prediction $t \propto 1 / d^2$.

Data Analysis and Conclusion

When the data shows (Table 1, Figure 1) for 7-15 mm, the mean detection time decreased as the hole got larger. 114.7 s (7mm), 71.8s (9mm), 38.7 s (12mm), 24.2s (15mm). We wrote 4 mm hole as ND (>300 s) for all trials, no buzzer within

the 5-minute window.

Why this pattern makes sense?

With the same head height and the same sensor height, the trigger volume is constant, so the time mainly depended on how fast the water escaped. A larger hole has a larger area, so more water per second reached the cup and the buzzer sounded sooner. This is exactly what we see in the means. The small standard deviations at 9- 15mm show that the pattern is reliable, the larger spread at 7mm is expected because longer times are more sensitive to reaction time and small drip differences

Anomaly/threshold

The 4mm hole shows ND (>300s). This does not mean “zero time”, it means our system did not trigger in 5 minutes. This suggests a lower detection limit for our setup. The flow was too small (or drops sticks to the edge) to reach to the sensor level in the time window. It does not contradict the trend for 7-15 mm

Conclusion

Under constant conditions, larger holes were detected faster. The results answer the research question: Detection time decreases as hole diameter increases for the sizes that produce visible leakage. The 4mm case indicates a minimum detectable leak size for this model within 300s

Evaluation of Hypothesis

Decision. Our hypothesis stated that the greater the hole diameter, the shorter the detection time under constant conditions. Our results support this for all the diameters that actually leaked which were 7 -15 mm. The mean detection time

gradually decreased from 114.7 s (7 mm) to 71.8 (9 mm) to 38.7 (12 mm) and finally to 24.2s (15mm) (Table 1, Figure 1). For 4mm, we recorded ND (>300s) in all three trials, which is inconclusive within our 5-minute window and indicates a detection threshold, not a reversal of the trend.

Validity of the data. The method held the head height at (1.00m), ramp angle at (20°), sensor height at (15 mm), ramp condition, pipe material and electronics constant. Timing used a consistent start/stop rule and three trials per diameter. Variation was small at 9- 15m, showing good repeatability. The larger spread at 7mm (SD = 8s) is expected and it is because long times magnify reaction time error. On this basis the data are sufficiently valid to evaluate the hypothesis for 7-15mm.

Reasoning link

In our setup the buzzer sounds when a fixed amount of leaked water reaches to the sensor. That fixed amount was set by the sensor height, which we kept the same each time. We also kept the head height the same, so the exit speed of the water in the hole is the same every trial. Therefore, the time mainly depended on how much water per second escapes through the hole. A larger circular opening has more area, so more water per second reaches the cup and the buzzer buzzes sooner. In symbols this is often written as $\text{time} \propto 1/(\text{diameter})^2$ (the symbol " \propto " just mean "goes like"). This is the exact pattern that we have observed

Quantitative checks

- Proportionality test. If $\text{time} \propto 1/(\text{diameter})^2$, then $t \times d^2$ should be roughly constant using the means:

7mm: $114.7 \times 49 = 5620.3$, 9mm, $71.8 \times 81 = 5815.8$, 12mm $38.7 \times 144 = 5572.8$, 15mm, $24.2 \times 225 = 5445.0$ (units $s \cdot mm^2$). These cluster around $\approx 5.6 \times 10^3$ ($\pm 4\%$), which is strong agreement for a school experiment

Boundary case (4mm) explained, not ignored. ND ($>300s$) means no buzzer has buzzed within 5 min, and not “zero”. A back of envelope prediction from the 7mm result gives $t_4 \approx 114.7 \cdot (7 / 4)^2 \approx 351$ s, it is already beyond 300 seconds, even before allowing for droplet clinging or tiny burrs. So, 4 mm naturally falls outside the detection window. It confirms a minimum detectable hole size for this design, and it does not contradict the decreasing time trend

Overall evaluation. Under constant head, sensor height, and ramp angle, the evidence is consistent and clear. Larger holes are detected faster, in the direction and approximate magnitude predicted by the simple area and flow reasoning. The 4mm one is inconclusive within 300 seconds time period and it identifies a detection limit of the current set up. This provides a clear and structured evaluation. Decision up front, numbers that proves it, anomaly handled, reasoning ling, and a final all up judgment.

Evaluation of Method

Strength	Data that supports this
Key variables tightly controlled Head = 1.00m, sensor 15mm, ramp = 20 °, same electronics and PVC	Smooth, monotonic decrease of mean time from 114.7 s to 24.2 with no reversals across 7-15 mm
Consistent timing rule and three trials per levels	Small scatter at 9 -15mm (SD = 1-2 seconds) shows good repeatability
Sensor height fixed, constant trigger volume	Quick 3 pour calibration gave a similar buzzer level each time and detection were stable once the flow has started
Ramp condition controlled (non	There were no random early buzzers,

absorbing cardboard, taped, and dry start each trial)	times followed hole size rather than surface soak up effects
Head stability addressed.	A 50mL trigger volume lowers the head by only around 0.7 mm (<0.1%), so the pressure was effectively constant during the trials, times changed with diameter, not head
Electronics configuration kept identical (9V + 1k Ohm)	No sudden, late or early triggers at the same diameter across trials.
Separate deburred pipe sections, one hole each.	No cross talk between the holes, edge shape was similar supporting fair comparison
Splash guard enclosure around electronics (probe tip left outside)	Zero also alarms from splashes. ND occurred only at 4mm, consistent with a real threshold
Two people timing (start stop roles)	For shorter times (12- 15mm) the measured values were very close (24.5 23.0, 25.1
Clear non detection rule (ND> 300s)	Honest recording of 4mm trials avoids inventing imagery values and reveals the detection limit of the design

Weakness/ limitation	Data that supports this
Human reaction time at long times	Largest spread at 7mm (108.0 -123.7 s, SD = 8.1s)
Sensitivity limit at the smallest diameter	ND (>300s) all of the 3 trials show that the setup could not detect the tiniest flow within the time window.

Power/ threshold stability (5V buzzer on 9V via 1k Ohm)	Works, but the supply is not regulated so the threshold could drift as the 9V battery weakens over time
Ramp material variability (taped cardboard)	Even with the tape, micro wetting can vary and slightly delay drops, especially for long times
Hole edge micro geometry at small sizes	Tiny burrs and wetting at 4 mm likely slowed drop release
Order effects (testing diameter in a fixed sequences)	If 7mm was always first, any early session drift (battery or ramp wetting) could bias that level
Only three trials and all of them in one day	We have within session repeatability, but no between day repeatability check.
Temperature not logged in each trial	We assumed 20 - 25 °C. A few degrees change can alter viscosity slightly
Hole size verification recorded qualitatively	Drill bit sizes used. Actual diameter may differ by very little (a few tenths) unless measured with calipers after drilling
ND is a right censored time, and not a numeric value	We cannot include the 4mm in numeric mean/ curve fitting without adjusting the design
Some water lost to splash or miss into cup is possible	Not observed at short times, but small misses would lengthen long times slightly
Head reset error between the trials	Manual refill to mark could give a few mm difference, affecting very long times even more.

Improvements or Further Investigations

Weakness as stated above	How would you improve this?	Why would this improve the investigation?
Human reaction time at long times	Record each trial on a phone at 60 fps from a fixed position, determine the start and stop by frame count and then convert it into seconds	Because It removes inconsistent start\stop clicking and reduces random errors, especially for long times (7mm). Increases reliability and accuracy of the DV
Sensitivity limit at 4 mm (ND> 300s)	Run an extension set only for the 4 mm hole with (a) head height increased to 1.20m (b) sensor lowered by 3- 5mm or (c) time window extended into 600 seconds	Allows measurement of a value instead of a censored “ND”, testing whether if the same trend will continue to very small leaks. Improves the validity of the conclusion near the detection limit
Power \ threshold stability (5 V buzzer on 9V via 1 kilo Ohm)	Use a regulated 5 V supply it could e a bench supply or a USB power bank and note the sensor threshold position) potentiometer turns) before\ after the session. Replace the 9V battery only for the sensor probe if needed	It keeps the trigger level constant so times change only because of the hole size and not drifting electronics This improves internal validity
Ramp material variability (taped cardboard)	Replace the current ramp with a rigid plastic/PVC sheet (same width/ length(set to 20°, keep the surface area smooth and non-absorbing (dry before each trial)	Removes soak up/ wetting differences and sagging. Reduces systematic error and it improves repeatability.
Hole edge micro geometry at small diameters	After the drilling, standardize deburring: 10 light turns with a countersink and 800 – 1200 grit sandpaper, verify diameter with vernier callipers (± 0.1 mm), photograph the edge once per pipe.	Ensures that droplet formation is comparable between pieces. Improves fair test control and precision

Order effects (testing diameters in a fixed sequence)	Randomize the order of diameters for each runs or use a balanced order (7-12-9-15-4, then 9-15-4-7-12, etc.)	It prevents drift in battery ramp wetting or operator fatigue from biasing one size and increases validity
Only three trials and all on one day	Increase to 5 trials per diameters and repeat it on two different days under the same conditions	More data decreases uncertainty of means and shows between day repeatability, higher reliability
Temperature not logged	Measure and log water/ room temperature in each trials, keep them within 20 - 25°C ($\pm 1^\circ\text{C}$) or note deviations	Viscosity changes as the temperature changes, logging/controlling it improves validity and comparability.
Hole size verification recorded qualitatively	Record actual hole sizes with callipers and report as 4.0, 7.0, 9.0, 12.0, 15.0 mm ($\pm 0.1\text{mm}$)	Confirms that the IV levels precisely and increases the accuracy of IV
ND is a right censored time and not a number	Present ND as ">300s" in the table and exclude from mean calculations, show ND on the graph with a special marker and an explanatory note.	Avoids distorting averages. Makes treatment of censored data transparent and valid
Possible splash/ miss into the cup	Add a short funnel/lip at the bottom of the ramp aimed into the cup, place a low splash guard behind the cup	Ensures that all leaked water reaches the sensor reservoir and this reduces random loss and improves accuracy
Head reset error between the trials	Use an overflow/ constant head reservoir (mark + overflow tube) so the water level returns exactly to the 1.00 m automatically. Confirm this with a ruler	Holds pressure truly constant (>0.1% change), strengthening internal validity.

Further Investigations

1. Test intermediate diameters (6mm and 10mm)

Why: Because it gives a smoother curve to evaluate whether time $\sim 1/\text{diameter}^2$ holds across more points

2. Sensor height series (10, 15, 20 mm above the cup base).

Why: Because it shows how trigger volume changes affect detection time, it is also useful for setting false alarm safe

3. Head height series (0.8 m, 1.0m, 1.2m) at one diameter

Why: Because it confirms the role of pressure in detection time, and checks if deviations at small holes are due to the insufficient head.

4. Automated timing with a microcontroller/ data logger

Why: Because it removes human reaction entirely and logs to 0.01 s, maximises accuracy.

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