

Clogged Gutter Detector

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1. Introduction

1.1 Problem

Residential gutters and downspouts direct rainwater away from roofs and building foundations. If water is not properly drained away from a house, soil near the foundation can become saturated, allowing moisture to enter the structure and contribute to problems including mold, rot, poor indoor air quality, and decreased building durability [1]. A clogged gutter or downspout can therefore become a maintenance problem before a homeowner notices visible overflow. Detecting the problem manually also commonly requires inspection of elevated gutters. Ladder use presents an additional safety concern; the U.S. Consumer Product Safety Commission estimated 228,875 emergency-department-treated injuries associated with ladders and stools in 2023 [2]. This statistic is not specific to gutter maintenance, but it demonstrates the broader risk associated with repeated ladder use.

1.2 Solution

The proposed Clogged Gutter Detector is an outdoor monitoring node installed near the primary downspout of a gutter zone. Instead of attempting to directly detect leaves or debris, the device compares two conditions: whether rain is actively occurring and whether water is flowing through the downspout. A precipitation sensor detects rainfall, while a Hall-effect flow sensor monitors water movement. If rain is detected but the downspout does not produce the expected flow signal, the system classifies the condition as a possible gutter obstruction. An ESP32-WROOM-32E processes the sensor measurements and sends an alert over a 2.4-GHz Wi-Fi connection to a test server or cloud dashboard. Between events, the main ESP32 processor remains in deep sleep, and a rechargeable 18650 lithium-ion battery is replenished using a small solar panel and charge-management circuit.

This approach improves on the team's original ultrasonic-debris design because it does not need to determine the shape, height, or composition of leaves inside the gutter. Instead, it detects the functional consequence of a blockage: rain is falling but water is not leaving through the monitored downspout. The device is intentionally described as detecting a possible obstruction rather than guaranteeing that a clog exists, since other abnormal conditions could also prevent expected flow.

1.2 Visual Aid

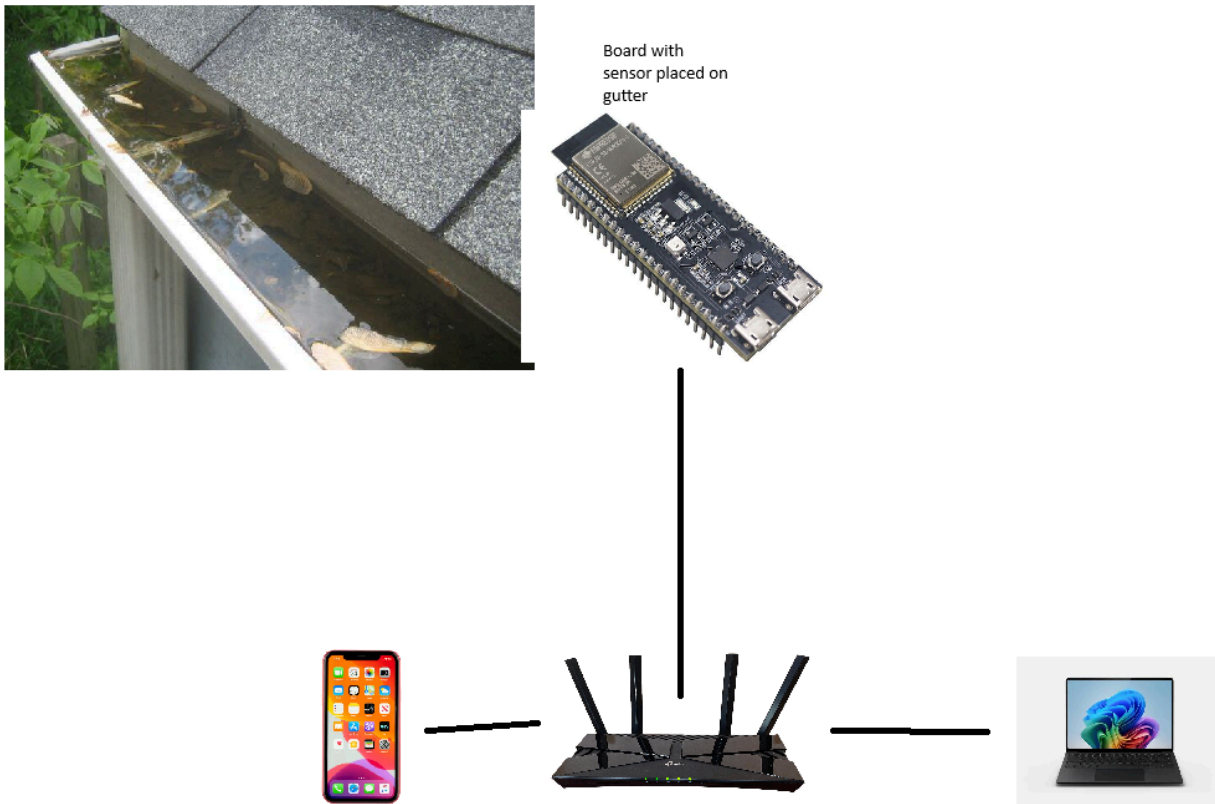


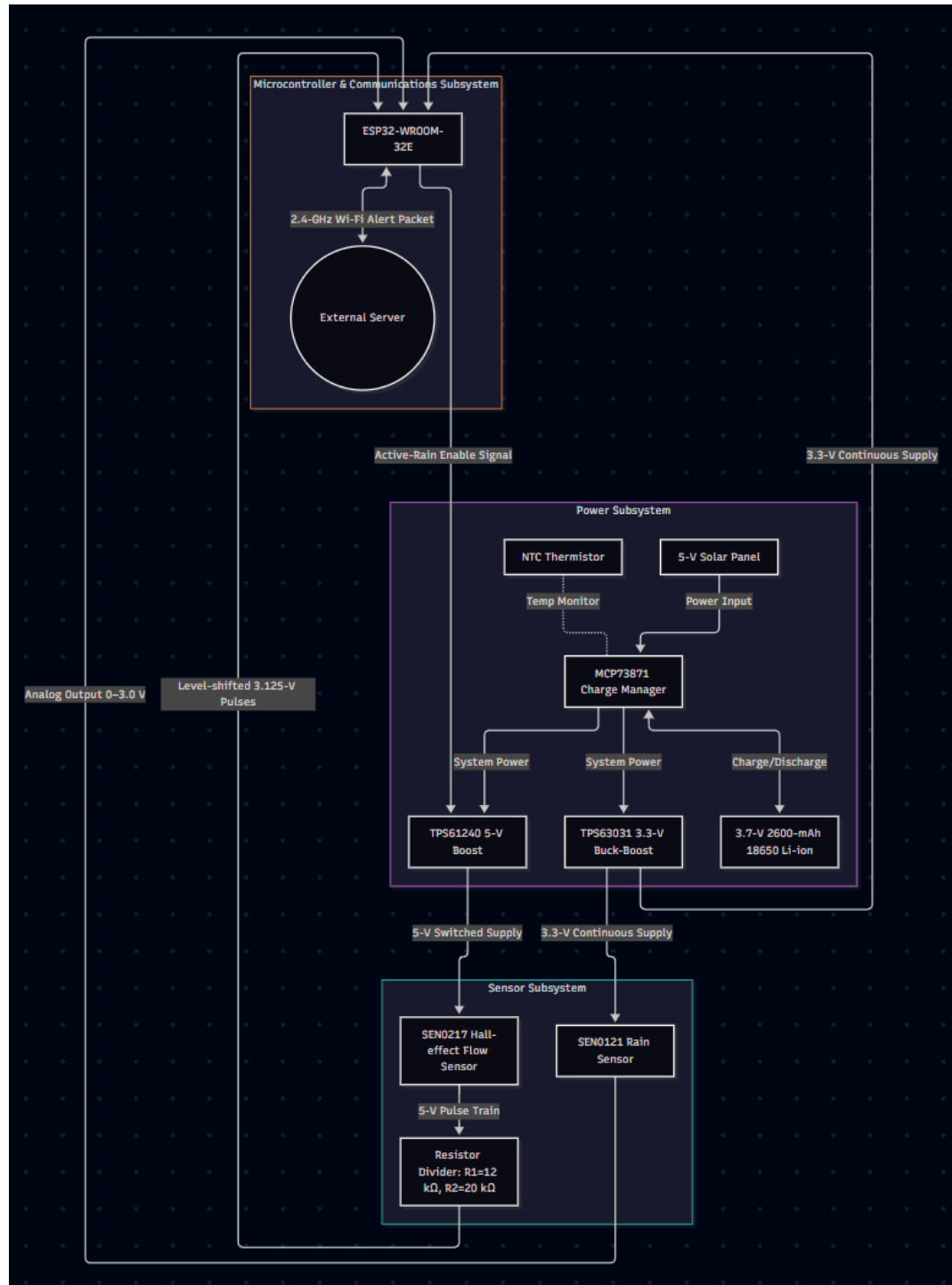
Figure 1. Intended use of the Clogged Gutter Detector. The outdoor monitoring node compares active rainfall with water flow through the primary downspout and sends a Wi-Fi alert when rainfall occurs without the expected flow.

1.3 High-Level Requirements

- The system shall detect active rainfall and begin evaluating downspout flow within 10 seconds of the onset of simulated rainfall in at least 9 of 10 test trials.
- During an active-rain condition, the system shall distinguish no flow from water flow of at least 1.0 L/min within a 10-second observation interval in at least 9 of 10 test trials.
- When active rain is detected and no corresponding downspout flow is detected, the ESP32 shall transmit a valid JSON alert packet over a 2.4-GHz Wi-Fi network and return the main processor to deep sleep within 10 seconds after the clog condition is confirmed.
- The power subsystem shall maintain the main system supply at 3.3 V $\pm$ 5% during sensing and Wi-Fi transmission and shall provide measurable positive charging current to the 18650 battery when the solar panel receives the defined bright-light test condition.

2. Design

2.1 Block Diagram



The design consists of three primary internal subsystems: sensor, microcontroller/communications, and power. The sensor subsystem determines whether rain and water flow are present. The microcontroller subsystem executes the rain/flow logic, controls sleep and wake behavior, counts flow pulses, and communicates with the external server. The power subsystem converts solar energy into battery charging current and generates regulated 3.3-V and 5-V supply rails. Each subsystem can therefore be bench tested independently before final system integration.

2.2 Physical Design

The main PCB, rechargeable battery, and power electronics will be housed in a weather-resistant polycarbonate enclosure approximately 120 mm × 90 mm × 45 mm. A Hammond 1554-series enclosure of approximately this size is available with IP66/IP67/IP68 ratings, making it appropriate as a reference enclosure for an outdoor prototype [28].

The enclosure will mount beside the monitored downspout rather than inside the gutter. The rain-sensing surface will be mounted on the upper exterior surface with its electrical connection protected inside or through a sealed cable entry. The solar panel will be mounted above or beside the enclosure where it has access to sunlight. The flow sensor will be installed vertically in the prototype downspout flow path; DFRobot recommends vertical mounting for its sensor and a tilt of no more than approximately 5 degrees.

Because the selected prototype flow sensor has an internal diameter of only 11 mm and a specified range of 1–30 L/min, it should not be represented as a full-size replacement for the cross-section of an unrestricted residential downspout. For the senior-design prototype, a controlled gutter/downspout test section will direct water through the Hall-effect sensor so the rain/no-flow detection concept can be quantitatively verified. A production version would require a larger-bore flow sensor or a nonrestrictive flow-detection mechanism.

2.3 Sensor Subsystem

The sensor subsystem provides the two physical measurements required by the high-level detection algorithm: precipitation and water flow.

2.3.1 Precipitation Sensor

The proposed precipitation detector is the DFRobot SEN0121 analog water sensor or equivalent resistive rain-detection board. The sensor can operate from either 3.3 V or 5 V and provides an analog output that rises as moisture accumulates on its sensing surface. When operated from 3.3 V, its published analog range is approximately 0–3.0 V, which allows it to interface directly with an ESP32 ADC input without exceeding the 3.3-V system domain.

The sensor will be mounted with its sensing surface exposed and its electrical connector protected from direct rainfall. Because the sensor is resistive, its absolute reading can vary with water coverage and surface condition. The system will therefore use a calibrated threshold rather than assume a universal raw ADC value. During setup, multiple dry measurements and

multiple wet measurements will be recorded, and a software threshold will be selected between the two distributions.

To retain low-power operation while still meeting the 10-second rain-detection requirement, the main ESP32 cores will remain in deep sleep while the ESP32's ULP coprocessor periodically samples the rain sensor using ADC1. Espressif explicitly supports using the ULP during sleep to monitor ADC/GPIO states and wake the main processor when a specified event occurs.

The ULP will sample the rain input approximately once per second. To reduce false triggers caused by a single droplet or electrical noise, the threshold must be exceeded on three consecutive samples before the main processor wakes.

2.3.2 Flow Sensor

The prototype will use a DFRobot SEN0217 / YF-S201-type Hall-effect water-flow sensor. Water passing through the device rotates a magnetic rotor, and a Hall-effect element produces a pulse train proportional to flow. The sensor is specified for approximately 1–30 L/min, draws approximately 15 mA at 5 V, and produces approximately 450 pulses per liter.

At the minimum project flow threshold of 1.0 L/min,

$$Q = 1/60 = 0.01667 \text{ L/s}$$

and the approximate pulse frequency is

$$f = 450 \times 0.01667 = 7.5 \text{ pulses/s.}$$

Over a 10-second observation period, this corresponds to approximately

$$N = 7.5 \times 10 = 75 \text{ pulses.}$$

Therefore, a healthy flow condition at 1 L/min should produce approximately 75 pulses during the 10-second measurement period. The verification requirement will conservatively use 70 or more pulses as positive evidence of flow.

A zero-flow condition should generate no legitimate pulses. When active rainfall has been confirmed but the measured pulse count remains below the validated flow threshold for the complete observation interval, the microcontroller will classify the event as a possible obstruction.

Flow-Sensor Logic-Level Interface

The flow sensor operates from the 5-V rail, and its published pulse output may rise above 4.7 V, so it cannot be connected directly to a 3.3-V ESP32 input.

A resistor divider will therefore use:

$$R_1 = 12 \text{ k}\Omega$$

between the sensor output and the ESP32 input, and

$$R_2 = 20 \text{ k}\Omega$$

between the ESP32 input and ground.

The nominal divided voltage for a 5-V input is

$$V_{_GPIO} = 5 \times (20 / (12 + 20)) = 3.125 \text{ V.}$$

This remains a valid HIGH for the ESP32 while providing margin below the 3.3-V input domain.

2.4 Microcontroller and Communications Subsystem

The system will use the ESP32-WROOM-32E because it integrates the microcontroller, ADC capability, pulse-counting peripherals, and 2.4-GHz IEEE 802.11b/g/n Wi-Fi communication required by the project. Espressif specifies a 3.0–3.6-V operating supply and recommends an external supply capable of at least 0.5 A. Wi-Fi transmit current can peak around 379 mA under the highest-power listed 802.11b condition.

The ESP32 will perform four primary functions:

- Remain in deep sleep while the ULP monitors the rain-sensor ADC value.
- Wake the main processor after the rain threshold has been satisfied.
- Enable the 5-V flow-sensor rail and count Hall-effect pulses during the defined observation window.
- If rainfall is present but the flow threshold is not satisfied, connect to Wi-Fi, transmit an alert, and return to deep sleep.

The ESP32 pulse-counter peripheral or GPIO interrupt logic will count pulses from the Hall-effect sensor. The firmware will not need to continuously calculate a precise volumetric flow rate because the primary system question is binary: is meaningful water flow present or absent?

A representative alert packet will have the following form:

```
{  
  "rain": true,  
  "flow_detected": false,  
  "flow_pulses": 0,  
  "possible_clog": true,  
  "battery_voltage": 3.87  
}
```

The external server will acknowledge receipt with a successful HTTP response. For the course prototype, successful receipt by a test endpoint is sufficient to demonstrate the communications subsystem; a production mobile application is outside the core scope of the design.

2.5 Power Subsystem

The power subsystem provides autonomous operation using solar-assisted charging and a single rechargeable lithium-ion battery.

2.5.1 Battery and Charge Management

A protected 3.7-V, 2600-mAh 18650 Li-ion cell will provide stored energy. For example, the Tenenergy 30016 includes protection electronics and is rated at 3.7 V nominal and 2600 mAh [26].

Charging will be managed by the Microchip MCP73871, a single-cell Li-ion/Li-polymer charge-management IC with system-load sharing. The device supports CC/CV charging, system-load priority, charge-current programming, thermal regulation, and automatic source/battery selection. The 4.2-V version will be used for the selected 18650 cell.

A nominal 5-V solar panel will feed the charger input. Because photovoltaic output varies with illumination, the MCP73871's VPCC feature is useful: if the input source begins to collapse under load, the charger can reduce battery charge current while continuing to prioritize system operation.

The target fast-charge current will be approximately 200 mA. The MCP73871 relationship is

$$I_{REG} = 1000 / R_{PROG1}$$

when I_{REG} is expressed in mA and R_{PROG1} in k Ω .

Choosing

$$R_{PROG1} = 5.1 \text{ k}\Omega$$

gives

$$I_{REG} \approx 1000 / 5.1 = 196 \text{ mA}.$$

This is appropriate for a small solar panel capable of roughly 200–240 mA under its rated illumination, while the charger's power-path management can reduce charging when the system load requires priority.

The MCP73871 THERM input will be used with an appropriate NTC thermistor placed near the battery so charging can be suspended if battery temperature leaves the permitted range. Microchip specifies an internal thermistor-bias source and charge suspension when the THERM voltage leaves the defined limits.

2.5.2 3.3-V System Supply

The original RFA listed a TLV70033 LDO. That component is limited to 200 mA, while Espressif specifies that the ESP32 supply should be capable of at least 0.5 A and documents substantially higher Wi-Fi peaks than 200 mA. Therefore, the detailed design replaces the TLV70033 with a Texas Instruments TPS63031 3.3-V buck-boost converter.

The TPS63031 accepts 1.8–5.5 V and automatically operates in buck or boost mode. TI specifies up to 800 mA at 3.3 V in step-down operation and up to 500 mA at 3.3 V in boost operation for suitable input voltage conditions. This allows the design to maintain a regulated 3.3-V rail as the single-cell Li-ion battery moves above and below 3.3 V during its discharge cycle.

The regulated 3.3-V rail powers the ESP32 and precipitation sensor.

2.5.3 5-V Flow-Sensor Supply

Because the Hall-effect flow sensor requires approximately 5 V, a TPS61240 fixed 5-V boost converter will generate a separate flow-sensor rail from the battery/system supply. TI specifies a 2.3–5.5-V input range, 5-V regulated output, output capability far beyond the approximately 15-mA flow-sensor load, and a shutdown mode consuming less than 1 μ A.

The ESP32 will enable this converter only during an active rain event. Therefore, the flow sensor and 5-V boost circuitry do not need to remain powered continuously while the system is idle.

2.6 Requirements and Verification

Subsystem	Requirement	Verification
Rain sensing	In at least 9 of 10 simulated-rain trials, the rain input shall cross its calibrated threshold and cause the main processor to wake within 10 s. During a 5-minute dry test, no false wake shall occur due to the rain threshold.	Place the completed sensor at its normal mounting angle. Record the dry ADC baseline for 30 s. Apply a repeatable water spray from the same height and flow setting. Measure time from first water contact until ESP32 wake using serial timestamp or oscilloscope GPIO marker. Repeat 10 times. Then dry the sensor and monitor for 5 min.
Flow sensing	Water flow of at least 1.0 L/min shall produce at least 70 valid pulses during a 10-s observation interval. No-flow testing shall produce no more than 1 spurious pulse in 10 s.	Use a controlled reservoir/pump and independently measure volume collected over time using a graduated container and stopwatch. Set flow to ≥ 1.0 L/min. Use the ESP32 pulse counter and oscilloscope to record 10-s pulse counts. Repeat 10 times. Repeat with zero water flow.
Flow interface	Flow-sensor HIGH pulses presented to the ESP32 shall remain between 2.70 and 3.30 V, and LOW pulses shall remain below 0.50 V.	Power the flow sensor from the regulated 5-V rail. Connect an oscilloscope to the sensor output before the divider and to the ESP32-side output after the divider. Run water through the sensor and record minimum HIGH, maximum HIGH, and maximum LOW voltages.

3.3-V supply	The ESP32 rail shall remain between 3.135 and 3.465 V for loads from idle through a 500-mA transient test load.	Power the regulator from a programmable supply representing battery voltages from approximately 3.0 to 4.2 V. Connect a DMM and oscilloscope to the 3.3-V rail. Sweep/load-step from light load to 500 mA and verify the output remains inside the $\pm 5\%$ range.
5-V supply	The flow-sensor rail shall remain between 4.90 and 5.10 V while supplying at least 15 mA.	Connect an electronic load set to 15 mA to the 5-V rail. Test using battery-input voltages representative of the operating range. Measure with DMM and oscilloscope.
Battery charging	With the battery below 4.1 V and the solar panel under the defined bright-light condition, battery current shall be positive and at least 50 mA after the system reaches steady state.	Insert an ammeter/current probe in series with the battery. Record solar input voltage, battery voltage, and battery current in darkness and under the defined bright-light source. Confirm charging polarity and current ≥ 50 mA.
Charge regulation	Battery voltage shall not exceed 4.2 V $\pm 1\%$ during controlled charge testing.	Charge the battery through the MCP73871 while monitoring battery voltage with a calibrated DMM. Verify that constant-voltage regulation occurs within 4.158–4.242 V and that charge current decreases near full charge.
Communications	For at least 9 of 10 clog-event trials, the ESP32 shall join the configured 2.4-GHz WLAN, send one valid JSON alert accepted by the server, and return the main processor to deep sleep within 10 s after confirmation of the no-flow condition.	Create Rain=True and Flow=False using the test fixture. Start a timer when the 10-s flow observation ends. Monitor serial output, server logs, and a GPIO sleep marker. Verify correct JSON and elapsed time. Repeat 10 times.
System logic	The prototype shall report no clog in at least 9 of 10 Rain=True/Flow=True trials and possible clog in at least 9 of 10 Rain=True/Flow=False trials.	Perform 10 trials with simulated rain plus normal water flow and 10 trials with simulated rain and zero downspout flow. Record the output classification for each trial and calculate classification success rate.

2.7 Tolerance Analysis

A critical electrical interface is the connection between the 5-V Hall-effect flow sensor and the 3.3-V ESP32 input. Direct connection risks applying excessive voltage to the ESP32, but excessive attenuation could prevent the ESP32 from recognizing a valid logic HIGH.

The design uses:

$$R_1 = 12 \text{ k}\Omega \pm 1\%$$

and

$$R_2 = 20 \text{ k}\Omega \pm 1\%.$$

The nominal output for a 5.0-V pulse is:

$$V_{_O} = 5.0 \times (20 / (12 + 20)) = 3.125 \text{ V}.$$

For the worst-case minimum HIGH output, use the flow sensor's guaranteed HIGH of 4.7 V, the minimum $R_2 = 19.8 \text{ k}\Omega$, and maximum $R_1 = 12.12 \text{ k}\Omega$:

$$V_{_OH,min} = 4.7 \times (19.8 / (12.12 + 19.8)) = 2.915 \text{ V}.$$

The ESP32 HIGH-input threshold is at most

$$V_{_IH} = 0.75 \times V_{_DD}.$$

At the maximum allowed project rail of 3.465 V,

$$V_{_IH,max} = 0.75 \times 3.465 = 2.599 \text{ V}.$$

Therefore,

$$2.915 > 2.599$$

and the pulse will still be interpreted as HIGH.

For the worst-case maximum divider output, assume the 5-V rail is at its +2% limit, or 5.10 V, with $R_2 = 20.2 \text{ k}\Omega$ and $R_1 = 11.88 \text{ k}\Omega$:

$$V_{_O,max} = 5.10 \times (20.2 / (11.88 + 20.2)) = 3.211 \text{ V}.$$

Even when the ESP32 supply is at the project's minimum 3.135 V, the datasheet's input upper bound of approximately $V_{_DD} + 0.3$ gives

$$3.135 + 0.300 = 3.435 \text{ V}.$$

Thus,

$$3.211 < 3.435$$

and the HIGH remains below the maximum permitted input level.

Finally, the flow sensor specifies a LOW of less than 0.5 V. Using the resistor tolerances that maximize the divider output gives

$$V_{OL,max} = 0.5 \times (20.2 / (11.88 + 20.2)) = 0.315 V,$$

which is safely below the ESP32 LOW threshold.

Therefore, the 12-k Ω /20-k Ω , 1% resistor divider provides adequate tolerance for both valid HIGH and LOW detection while protecting the ESP32 input.

3. Societal Impact, Engineering Standards, Ethics, and Safety

3.1 Societal Impact

The Clogged Gutter Detector is intended to improve building maintenance and reduce unnecessary exposure to elevated gutter inspections. Properly directing roof runoff away from a building helps protect the foundation from excessive water exposure and the moisture-related problems associated with it [1]. The system does not replace gutter maintenance; rather, it provides information that can help a homeowner decide when inspection or cleaning may actually be necessary.

The project can provide an economic benefit if early identification of abnormal drainage allows a user to address a blockage before prolonged overflow contributes to damage. Socially, the device reduces the need to repeatedly climb a ladder merely to check whether a gutter is obstructed. Environmentally, using a rechargeable battery, low-power operation, and solar-assisted charging reduces reliance on disposable batteries, although the electronics and Li-ion battery still require responsible end-of-life recycling. Globally and culturally, the product is not equally applicable to all structures: it is designed primarily for buildings that use conventional gutters and downspouts and that have access to compatible Wi-Fi.

3.2 Applicable Engineering Standards

Standard	Application
IEEE 802.11-2024	The ESP32 communicates using 2.4-GHz 802.11 Wi-Fi. IEEE 802.11-2024 is the active WLAN MAC/PHY standard.
47 CFR §15.247	Covers digitally modulated intentional radiators operating in the 2400–2483.5-MHz band in the United States. The design will use the ESP32-WROOM module and preserve the manufacturer's RF/antenna layout requirements.
IPC-2221C	Provides generic requirements and guidance for printed-board design and is applicable to the custom PCB layout.

IEC 60529	Defines ingress-protection classifications for electrical enclosures and is relevant because the electronics operate outdoors near water.
UL 1642	Addresses safety of primary and rechargeable lithium batteries with the goal of reducing fire and explosion hazards.

The prototype will not claim independent certification to IEEE, FCC, IEC, IPC, or UL standards. These standards are being used as engineering guidance, while certified components and manufacturer-recommended practices will be retained where possible.

3.3 Ethical Considerations

The most significant ethical issue is the accuracy of the warning provided to the user. IEEE ethical principles emphasize public safety and being honest and realistic about technical claims [17]. The system therefore will report a “possible gutter obstruction” instead of stating with certainty that a gutter is clogged. A rain-without-flow condition could potentially be caused by another mechanical condition, and the prototype's false-positive and false-negative rates must be recorded honestly rather than omitted.

This is especially important because both error directions can produce harm. A false negative could cause a user to assume the gutter is clear when it is not, while a false positive could cause an unnecessary inspection and therefore unnecessary ladder use. Verification results and known operational limitations should consequently be disclosed in the final documentation.

The system also communicates using a home Wi-Fi network. ACM Principle 2.9 emphasizes designing systems to be robustly and useably secure [18]. The project will therefore avoid transmitting Wi-Fi credentials as application data, will protect stored credentials, and will use authenticated/encrypted network transport such as HTTPS when supported by the test environment. Only information needed for system operation—sensor state, alert status, and optionally battery status—will be transmitted.

Finally, the project includes a rechargeable Li-ion battery and electronic hardware. Low-power design and solar-assisted charging reduce repeated battery disposal, but the team will not describe the system as environmentally impact-free. Batteries and electronics must ultimately be recycled or disposed of using appropriate procedures.

3.4 Electrical Safety

The primary electrical hazard is the 18650 lithium-ion battery. Although the system operates at low voltage and presents minimal electric-shock risk, a Li-ion cell can deliver significant fault current, and improper charging, short circuits, physical damage, or excessive temperature can lead to heating, fire, or cell failure. UL 1642 exists specifically to reduce fire and explosion hazards associated with lithium batteries.

The team will therefore use a protected 18650 cell and an integrated CC/CV charging controller rather than designing a battery charging algorithm from discrete components. Battery voltage and temperature will be monitored during charging, and the battery will not be charged above its specified 4.2-V limit.

Water is another electrical concern. Only the intended sensor surface and mechanically required flow-sensor portions will contact water. The battery, PCB, charger, regulators, and exposed electrical contacts will remain inside the weather-resistant enclosure. Cable exits will use sealed cable glands or equivalent strain-relieved penetrations.

3.5 Mechanical Safety

Installation of equipment around a roof gutter can create a fall hazard. No installation or adjustment will occur from a ladder during rain, snow, strong wind, or otherwise unsafe conditions.

The flow-sensor adapter must also be mechanically secure. A loose component could fall or obstruct drainage. The sensor and fittings will therefore be rigidly mounted during testing, and the test section will be inspected before water is introduced.

The selected 1/2-inch Hall flow sensor is inherently more restrictive than a normal residential downspout. This limitation will be clearly documented, and the prototype will not be represented as having the same maximum hydraulic capacity as an unrestricted residential downspout.

3.6 Laboratory Safety and Mitigation Procedures

For battery work, the team will follow the ECE 445 lithium-battery procedure. Before the 18650 cell is connected, the charging circuit will be simulated where practical and tested using a current-limited bench supply. The design will be reviewed by the TA and, when required, a power-focused TA. Battery testing will only begin after the charger and regulators have been verified without the cell connected. During senior-design laboratory charging/discharging tests, the lithium battery will be placed in an approved battery safety bag and applicable emergency equipment will be accessible. ECE 445 specifically calls for additional lithium-battery safety training, charge-circuit review, validation before battery connection, and use of a battery bag.

Outdoor water testing will be conducted separately from exposed bench electronics. Initial rainfall and flow experiments will use a ground-level fixture. An open PCB, exposed battery, laboratory power supply, or other non-water-resistant electronics will not be intentionally sprayed. If abnormal heating, battery swelling, unusual odor, or unstable charging behavior is observed, power will immediately be disconnected and testing will stop.

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