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RESEARCH ARTICLE

Chrono Aqua OSR (NIRI): A Real-Time Mechatronic System for Smart Urban Water Conservation with Customized Control

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ABSTRACT: Water scarcity is an increasing issue, which is standard across the globe, and compared to the present situation, especially problematic in rapidly urbanizing and developed cities like Bengaluru, where unsustainable consumption practices accelerate the crisis. This study presents the Chrono Aqua OSR, a mechatronics-based water conservation device designed for urban households to promote efficient usage through technological intervention. Powered by an ESP32 microcontroller and programmed in C++, the Device operates in five functional modes: Normal, Alert, Regulate, Eco, and Vacation, each tailored to monitor, alert, and regulate usage based on real-time consumption patterns. This research explores the device's design, development, and authentication through controlled experiments. Parameters, such as impurities and water temperature, were used to assess the device's functionality, along with controlled experiments to test the device's modes. Outcomes indicate that the Chrono Aqua OSR effectively reduces wastage without compromising user benefits. The system fosters awareness and sustainable habits among users by combining behavioral nudges with automated control systems. This research result suggests that the Chrono Aqua OSR is a practical and accessible solution for addressing household water overuse in urban areas, and its integration of innovative technology with user-friendly design offers a genuine path toward sustainable water use.

KEYWORDS: Arduino UNO, Chrono Aqua OSR, ESP32 Microcontroller, Mechatronic System, Urban Water Conservation.

Introduction

Water scarcity is an escalating global concern. Today, two-thirds of the world's population face some sort of water shortage, as per the World Health Organisation report (2023). Around 2.2 billion people globally lack access to safely managed drinking water.[1] As per the World Bank, if the current trend continues, the future is not even looking bright because global demand for fresh water is expected to exceed supply by 40% by 2030. As per the UNICEF 2023 report, by 2040, nearly 1 in 4 children worldwide will live in areas of extremely high water stress.[2] Coming to India, the challenges are more severe as India is home to 18% of the world's population, but it only has 4% of the world's freshwater resources. As per the Central Groundwater Board (CGWB), 2023, groundwater levels in India are declining by an average of 0.3 meters every year.[3] Water shortage, coupled with pollution, poor infrastructure for harvesting rainwater, urbanization, and inefficient water supply, is creating severe water stress.[4] As per the NITI Aayog report, nearly 600 million people in India face high to extreme water shortage.[5] With the current unchecked groundwater usage trends, major urban cities like Delhi, Bengaluru, Hyderabad, Indore, and Pune are projected to run out of groundwater by 2030.[6]

Urban centers like Bengaluru are facing severe stress on water resources due to rapid population growth, urbanization, and unregulated consumption design.[7] Even with investments in a supply-side framework, it constantly requires and surpasses accessibility, leading to chronic shortages.[8] A specific contributor to this crisis is the extreme water use in urban households, often driven by low awareness, ineffective consumption habits, and a lack of effective control mechanisms.[9] Existing literature highlights various scientific, technological, and behavioral approaches to water conservation. Smart water meters, automated irrigation systems, and leak detection tools have shown promise in improving efficiency.[10] However, many present solutions are expensive, difficult to implement, or fail to directly engage users in altering their consumption behavior.[11]

This research gives a new scientific introduction to the Chrono Aqua OSR, a mechatronics-based water conservation system designed to address these limitations.[12] Built on an ESP32 platform, the device offers five programmable modes: Standard, Alert, Regulate, Eco, and Vacation. These modes provide real-time monitoring, feedback, automated flow control, and leak detection.[13] Unlike conventional systems, Chrono Aqua OSR directly involves users in the conservation process while automating key control functions.[14] Future directions for Chrono Aqua OSR (NIRI) include integrating advanced AI algorithms for predictive analytics, enabling proactive water management.[15] Enhancing sensor networks for greater accuracy and expanding IoT connectivity will improve system responsiveness.[16,17] Incorporating renewable energy sources can make the system more sustainable.[18] Developing user-friendly interfaces and mobile apps will facilitate easier monitoring and control for users.[19] Additionally, adapting the system for diverse urban environments and scaling for large-scale deployment can maximize impact.[20] Research into data-driven decision-making will further optimize water conservation strategies, ultimately creating more resilient and intelligent urban water management solutions for sustainable cities.[21]

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This study found that sharing social norms helps homeowners save water more than just giving education. Factors like awareness, attitudes, and lawn knowledge also influence their willingness to conserve water. Ali, M. *et al.* [25] discussed that in Eastleigh, many households face water shortages. Most lack water-saving devices, but using them can reduce water use. The study suggests that low-income families should adopt water-saving tools, rainwater harvesting, and reuse grey water to help save water and manage shortages better.

Objectives:

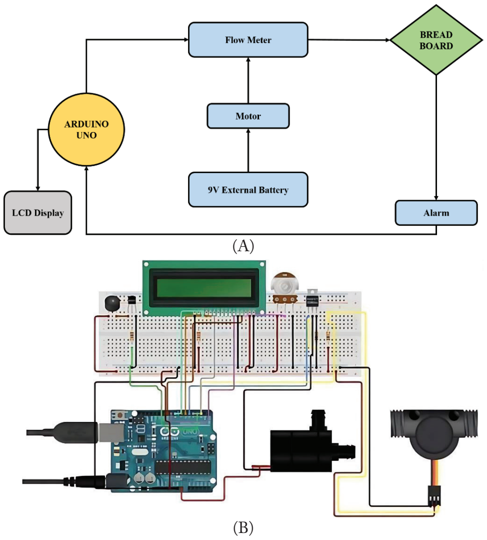
(1) To find water usage patterns at both household and appliance levels in urban settings.

(2) To design, develop, and validate the Chrono Aqua OSR device as an effective tool for reducing domestic water consumption. This research contributes a novel, scientific, and technological solution for urban water conservation by bridging the gap between behavioral and technological approaches.

■ Methods

Design:

Figure 1 presents the optimization of component selection and functional design in the Chrono Aqua OSR device prototype. Primary trials using Arduino UNO and a flow meter revealed issues such as fluctuating flow rates and incorrect readings due to a shortage of power supply and signal noise, necessitating code adjustments and recalibration. In Alert Mode, limitations in setting decimal values using the keypad were identified, leading to code modifications to enhance input accuracy and ensure practical usability during demonstrations. This block diagram shows a flow control system that uses an Arduino Uno powered by a 9V battery to regulate a motor, flow meter, and alarm. The Arduino shows the system status on an LCD display while processing flow meter data, controlling the motor, and setting off the alert. The breadboard links components for quick construction.



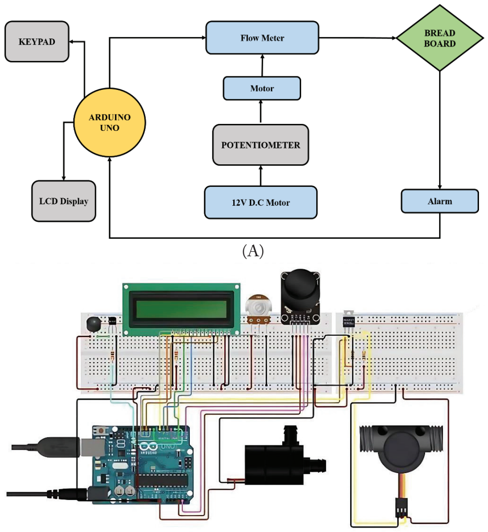
(A)

(B)

Figure 1: Shows the (A) is block diagram of the 1st iteration of the prototype with the Arduino UNO microcontroller, with Normal and alert mode functionality. Shows the (B) Circuit diagram of the 1st iteration of the prototype with the Arduino UNO microcontroller, with Normal and alert mode functionality.

Post-Trial Actions Trial 1:

Figure 2 system has been upgraded by integrating a 12V DC motor, which provides stable power and enhances water flow, ensuring efficient operation. Accurate calibration constant determination is crucial, and it has been experimentally calculated to improve the precision of flow measurements, with detailed calibration procedures to be documented later. On the software front, the code has been modified to accept decimal values for setting operational limits, allowing finer control and better customization. Additionally, new functionalities have been introduced, including regulation and eco modes, aimed at increasing the device's efficiency and promoting optimal energy use. These modes help in managing water flow more effectively, reducing wastage, and ensuring sustainable operation. Overall, these improvements contribute to a more reliable, precise, and energy-efficient water management system, ready for practical implementation and further optimization. Outlines the second round of testing, which demonstrated improved flow rate stability and accuracy in Normal Mode after switching to a 12V DC motor and recalibrating the flow meter (constant = 7.5). Meanwhile, alert and regulate modes show correct results, especially with manual potentiometer use as shown in Figure 2. An Arduino-based flow control system featuring keypad input, a flow meter, a motor, a potentiometer, an LCD, an alarm, and a breadboard for connections is depicted in this block diagram. The Arduino provides system monitoring and flow regulation automation by processing sensor data and controlling parts like the motor and alarm.



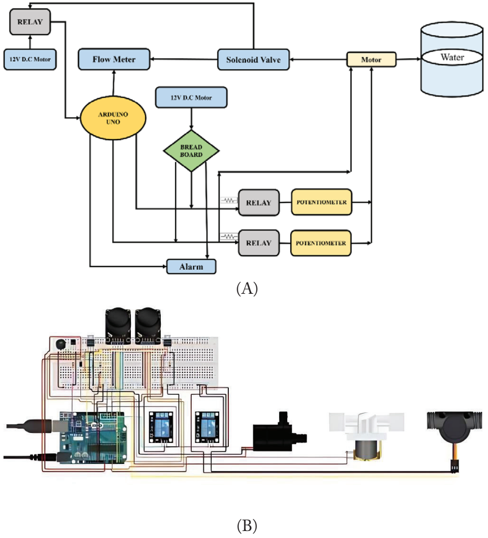
(A)

(B)

Figure 2: Shows that (A) the improved design integrates a 12V DC motor and keypad, enabling better power supply and alert system testing. It marked progress in flow accuracy and laid the groundwork for mode development. Shows the (B) circuit diagram of the 2nd iteration of the prototype with an Arduino UNO microcontroller with Normal, alert, regulate, and eco mode functionality.

Post-Trial Actions Trial 2:

Figure 3 project features an automatic regulation mode, created using a parallel circuit with a relay and potentiometers, enabling the system to adjust water flow automatically. The flow meter is connected to the valve via a half-inch collar with an inside diameter thread, addressing dimensional mismatches for secure attachment. Additionally, a vacation mode was developed to optimize system performance during extended inactivity, automatically blocking water flow to prevent wastage. This mode also includes leak detection, enhancing safety and efficiency. Overall, these advancements improve system automation, reliability, and energy conservation, making it suitable for practical and long-term use. Figure 4 shows the Image of the 3rd iteration of the prototype. An Arduino-based automatic water control system is shown in this diagram. It consists of motors, relays, solenoid valves, flow sensors, and relays for potentiometers. Using feedback from sensors and relays for automation, the Arduino effectively manages water flow by processing sensor data, controlling the valve and motor, and setting off warnings.



(B)

Figure 3: Shows the (A) block diagram of the 3rd iteration of the prototype with Arduino UNO microcontroller with Normal, alert, regulate, eco, and vacation mode functionality. Shows the (B) circuit diagram of the 3rd iteration of the prototype with Arduino UNO microcontroller with Normal, alert, regulate, eco, and vacation mode functionality.

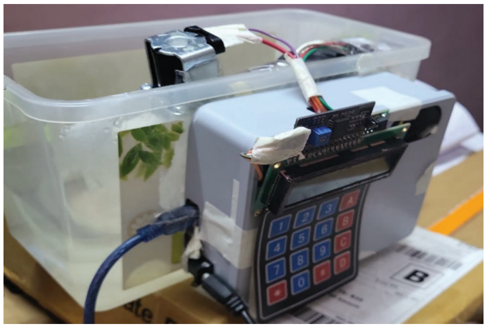
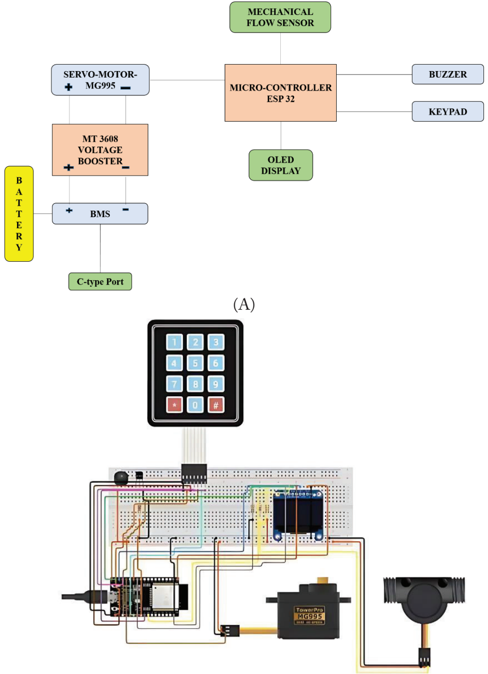


Figure 4: Shows the Image of the 3rd iteration of the prototype.

Post-Trial Actions Trial 3:

Figure 5 depicts the system uses various components for water management through different modes. In normal mode, a turbine flow meter and display monitor water flow. Alert mode uses a keypad and buzzer to warn when limits are crossed. Regulation mode employs a servo motor to control water flow by adjusting gears and levers. Eco mode also uses a servo motor to fully turn valves for water conservation. Vacation mode activates a servo motor to fully turn valves if a set time exceeds one minute, aiding in water savings during holidays. Battery management includes lithium-ion batteries, regulators, and charging modules to ensure a power supply. The IoT component connects the system wirelessly for remote monitoring and control. All components function well, and the system is ready for deployment in water conservation efforts. Figure 6 shows the Image of the 4th iteration of the prototype. This system receives input via a keypad, displays data on an OLED, and monitors a mechanical flow sensor using an ESP32 microcontroller. With the MT3608 module guaranteeing appropriate voltage levels for effective operation, it manages a battery-operated servo-motor, buzzer, and voltage booster.



(B)

Figure 5: Shows the (A) block diagram of the 4th iteration of the prototype with ESP32 microcontroller with Normal, alert, regulate, and eco mode functionality. Shows the (B) circuit diagram of the 4th iteration of the prototype with ESP32 microcontroller with Normal, alert, regulate, and eco mode functionality.

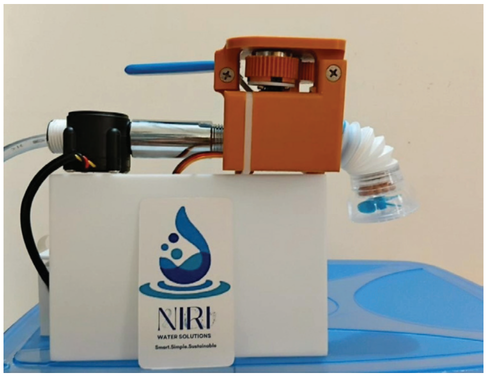


Figure 6: Shows the Image of the 4th iteration of the prototype.

Sample:

Table 1 summarizes key details of a survey conducted in Bengaluru, India, focusing on various living and institutional environments such as schools, apartments, individual houses, and hostels. The survey spans three time periods: May 2023, May 2024, and May 2025, allowing for a longitudinal study of changes or trends over time. Data collection employs both calls and in-person meetings, using structured questionnaires to ensure consistent and comprehensive information gathering. The target respondents are diverse, including resident owners, tenants, students, teachers, nurses, members of housing society governing bodies, hospital hostel administration officers, and utility managers. This wide range of participants ensures that multiple perspectives related to housing and institutional living conditions are captured. Overall, the survey design reflects a thorough approach to understanding the living environments and community dynamics in Bengaluru across different settings and time frames. The table describes a survey that was carried out between May 2023 and May 2025 in Bengaluru, India, with more than 100 participants from homes, apartments, and schools. Calls and meetings with residents, tenants, students, teachers, nurses, society members, and utility managers were used to gather data.

Table 1: Shows that the survey was conducted with more than one hundred (100) participants.

Field	Details
City, Country	Bengaluru, India
Places	Schools, Apartments, Individual houses, Hostels
Time period of the Survey	May 2023, May 2024, May 2025
Mode of survey	Call and physical meetings with a questionnaire
Target people	Resident owner, Tenant, Students, Teachers, Nurses, Housing Society Governing body members, Hospital Hostel Administration Officer, Utility managers

Instrument:

Table 2 outlines the key components and specifications of an embedded system design centered around microcontroller technology. The system utilizes either an Arduino UNO or ESP32 Wroom microcontroller, both popular choices for versatile and efficient processing. A mechanical turbine flow meter is included to measure fluid flow accurately. Visual output is managed through a compact 1.3-inch OLED display, providing a clear and low-power information display. Actuation is handled by MG995 servo motors and 12V solenoid valves, allowing precise control of mechanical movements and fluid flow. The power system includes a TP4056 battery management system (BMS), a rechargeable 18650 Li-ion battery, and an MT3608 voltage booster to ensure stable and efficient power delivery. User input is facilitated through keypad options (4×4 or 8×8) and a buzzer for audio feedback. Connectivity is achieved via IoT remote software supported by a chip-enabled microcontroller, enabling remote monitoring and control. Overall, the system integrates multiple components for robust, interactive, and remotely accessible operation. An Arduino UNO or ESP32 Wroom microcontroller, a mechanical turbine flow meter, a 1.3-inch OLED display, MG995 servo motors, 12V solenoid valves, power modules such as TP4056 BMS and 18650 batteries, a keypad, a buzzer, and Internet of Things (IoT) connectivity for remote control are all listed in the table.

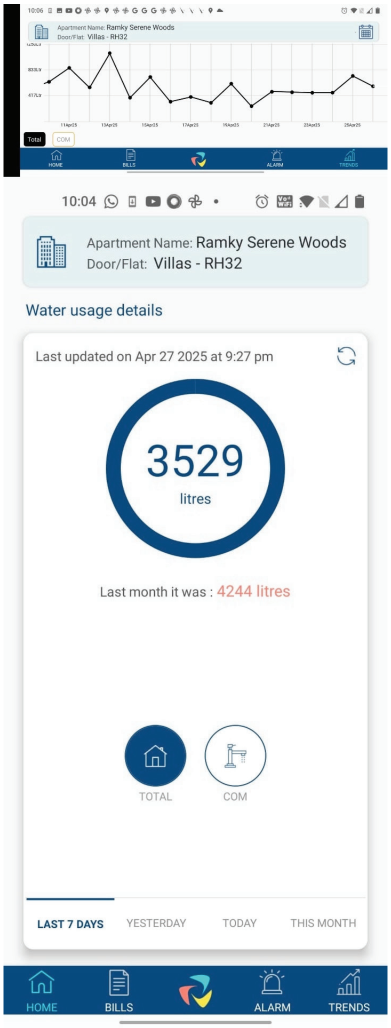
Table 2: Shows the components used in the system.

Component	Details
Microcontroller	Arduino UNO / ESP32 Wroom
Flow Meter	Mechanical turbine
Display	OLED (1.3")
Motors & Valves	MG995 servo motors, 12V solenoid valves
Power & Control	TP4056 BMS, 18650 Li-ion battery, MT3608 voltage booster
Input Devices	Keypad (4×4) / (8×8), buzzer
Connectivity	IoT remote software, chip-enabled microcontroller

Data Collection:

The research focuses on assessing current water conservation practices through need assessment and data collection, revealing critical gaps such as limited data monitoring, low user engagement, and inadequate automation. To address these issues, a comprehensive analysis of household water consumption was conducted at both macro (household) and micro (appliance) levels. An IoT-based flow meter, WeGot™, was installed on the main pipeline to monitor real-time water usage, providing valuable data via the WeGot™ app for daily and weekly analysis. This macro-level monitoring captured the overall water consumption of a typical three-member household, revealing weekly use ranges between 3000L and 5000L, and daily use from 400L to 700L.

Figure 7 shows the images from the WeGot application indicating macro data of daily and weekly water consumption for a household of 3 people. WeGot is the name of the company that makes IoT-based water measurement meters. Images from the WeGot application that illustrate macro statistics of a household of three's daily and weekly water usage are shown in Figure 7. WeGot manufactures IoT-enabled water meters that track and display household water usage trends.



Apartment Name: Ramky Serene Woods
Door/Flat: Villas - RH32

Water usage details

Last updated on Apr 27 2025 at 9:27 pm

3529 litres

Last month it was : 4244 litres

Figure 7: Images from the WeGot application indicating macro data of daily and weekly water consumption for a household of 3 people. WeGot is the name of the company that makes IoT-based water measurement meters.

The data highlighted consumption patterns and areas needing conservation. Micro-level data, collected using stopwatches and graduated containers, focused on key outlets like showers and dishwashers, showing high flow rates and significant wastage, especially from the RO system, which wasted 70.6% of the water used. This resulted in an estimated wastage of 48L daily, emphasizing the urgent need for targeted interventions. Additionally, public perception surveys were planned to understand consumer behavior and awareness regarding water conservation. Building on these findings, the research proposed the RTMA (Real-Time Measurement and Alert) system, designed for micro-level flow measurement, instant alerts, and automation based on user-defined thresholds. Experiments confirmed the system's initial functionality, establishing a baseline for further development, though flow stability limitations were observed. Overall, this research provides a foundational understanding of household water use and highlights opportunities for technological solutions to enhance water conservation efforts.

Table 3 shows the microdata collection on water outflow rates and consumption estimates at key household usage points, indicating maximum water utilization at the points of shower, dishwashing, and RO water reject. The table provides microdata on water flow and utilization at important residential locations, emphasizing RO water waste, showers, and dishwashing. It highlights the significance of effective water management in domestic activities by displaying flow rates, consumption estimates, and notable water waste.

Table 3: Shows the Micro data collection on water outflow rates and consumption estimates at key household usage points, indicating maximum water utilization at the points of shower, dishwashing, and RO water reject.

Point of Outflow of Water	Test Details	Conclusion	Consumption
Shower	5L water container took 38s to fill	Flow rate: 8 L/min	80L for a 10-minute shower per person
Dishwashing	5L water container took 25s to fill	Flow rate: 12 L/min	240L for 20 mins of dishwashing for a family of 3
RO Water (Purified)	1L of purified water resulted in a wastage of 2.4L of water	29.4% (1L) used for drinking, 70.6% wasted	Total daily drinking & cooking: 20L; total wastage: 48L

Data Analysis:

The **Real-Time Measurement and Alert (RTMA)** system is a rule-based framework designed to enhance household water conservation through IoT-enabled technology. The system integrates predefined operational rules, connected hardware components, real-time measurement capabilities, and user awareness mechanisms to enable proactive water management.

The operational rules include:

1. Setting alerts for predefined water usage limits,
2. Regulating flow by reducing supply once a specified threshold is reached,
3. Automatically blocking water flow beyond a maximum consumption limit, and
4. Activating an auto-block mechanism in response to leak detection.

These rules are implemented through appropriate IoT-enabled tools and hardware components, which are systematically tested and refined during experimentation to ensure reliable and accurate performance.

The measurement component provides real-time data on water consumption, allowing users to continuously monitor their usage patterns. User awareness is strengthened by enabling individuals to define customized consumption limits for various activities through the IoT interface, thereby empowering them to actively regulate their water use.

Overall, the RTMA system provides an intelligent and responsive framework that promotes water conservation by informing users, automating control actions, and preventing wastage through timely alerts and automatic interventions. This integrated approach aims to make household water management more efficient, sustainable, and user-friendly.

Table 4 explains the functional specifications of the five operational modes in the Chrono Aqua OSR device. Each mode, Normal, Alert, Regulate, Eco, and Vacation, is designed to enhance water conservation by offering real-time monitoring, usage alerts, automated flow control, and leak detection, tailored to different household scenarios and user needs. Describes the Chrono Aqua OSR device's five operating modes, which are all intended to maximize water use and minimize waste. These modes include normal monitoring, alarms for overuse, automated control, environmental conservation, and leak protection during vacations.

Table 4: Shows the five operational modes in the Chrono Aqua OSR device.

Modes	Functionality	Purpose
Normal Mode	Real-time monitoring and tracking of water usage	Provides continuous feedback on consumption to enhance user awareness
Alert Mode	Triggers an alarm system upon exceeding a preset water usage limit	Notifies users of potential overuse to prevent wastage
Regulate Mode	Automatically reduces water flow once the preset usage limit is surpassed	Implement flow control to moderate consumption and reduce excess usage
Eco Mode	Temporarily cuts off the water supply when usage exceeds a preset alarm threshold.	Conserve water by enforcing temporary supply suspension during overuse events.
Vacation Mode	Activates an automatic block of the water supply in response to a detected leakage alert	Protect against water loss and potential damage during prolonged user absence.

Flow Rate and Calibration Formula:

The flow rate in liters per hour is calculated by multiplying the pulse count by 60 and dividing by the calibration constant. This formula converts pulse signals into an accurate measurement of water flow, allowing precise monitoring and calibration of flow sensors for effective water management.

$$\textit{Flow Rate}\ (L/h) = (\textit{Pulse Count} \times 60)\ /\textit{Calibration Constant} \tag{1}$$

Rearranged to find Calibration Constant:

To determine the calibration constant, divide the pulse count multiplied by 60 by the known flow rate in liters per hour. This helps calibrate the flow sensor, ensuring accurate measurement by relating pulse signals to actual flow, essential for precise flow monitoring and control.

$$\textit{Calibration Constant} = (\textit{Pulse Count} \times 60)\ /\ \textit{Flow Rate}\ (L/h) \tag{2}$$

Results and Discussion

The Chrono Aqua OSR (NIRI) is an innovative mechatronic system designed for smart urban water conservation. It integrates real-time data monitoring and control to optimize water usage efficiently. Utilizing sensors, IoT technology, and customized algorithms, it dynamically adjusts water flow based on demand, reducing wastage. This system enhances sustain-ability by providing precise control and promoting responsible water management in urban environments. Its adaptability allows for integration into existing infrastructure, making it suitable for diverse applications. Chrono Aqua OSR (NIRI) exemplifies advanced technological solutions for addressing water scarcity challenges, contributing to smarter, eco-friendly urban water systems.

The experimental methods evaluate the Device's performance under different variable conditions. The key variables studied are:

- Variable 1: Impurities in water
- Variable 2: Temperature of water
- Variable 3: Calibration of the Device

Experiment 1: Effect of Impurities in Water:

Experiment 1 investigates how impurities like salt and dirt affect water flow rate. The variable is the presence of impurities. The aim is to determine whether impurities impact the flow rate, helping to understand how water purity influences the performance of flow measurement instruments. Two vessels were prepared, each containing 2 liters of water. One vessel held clean water, while the other contained water mixed with impurities, including a tablespoon of salt and some dirt. The prototype device was first tested with clean water, where the time required for 0.1 liters of water to flow through was measured and recorded. This measurement was repeated three times to minimize fluctuations and ensure accuracy. The same procedure was then conducted using the impure water, with the time and speed for 0.1 liters of flow carefully noted. Finally, the results from both setups were compared to analyze the effect of impurities on water flow speed and timing. Table 5 shows the flow measurement values for normal water. Over the course of three tests, the flow measurement data reveal normal water flow with varying speeds between 3.5 and 3.9 liters per hour. The duration varied between 1 minute 30 and 1 minute 40 seconds, suggesting steady flow rates under typical circumstances. Table 6 shows the flow measurement values for impure water. The impure water flow measurement shows somewhat lower flow rates, between 3.38 and 3.4 liters per hour. The timings, which varied from 1 minute 40 to 1 minute 47 seconds, demonstrated a steady but slightly lower flow than typical water, most likely as a result of contaminants influencing flow efficiency.

Table 5: Shows the flow measurement values for normal water.

Test Number	Time Taken	Speed
Test 1	1 min 30 s	3.5 L/h to 3.9 L/h (fluctuating)
Test 2	1 min 40 s	3.5 L/h
Test 3	1 min 40 s	3.5 L/h

Table 6: Shows the flow measurement values for impure water.

Test Number	Time Taken	Speed
Test 1	1 min 40 s	3.4 L/h
Test 2	1 min 45 s	3.4 L/h
Test 3	1 min 47 s	3.38 L/h

Initial fluctuations in the device's performance were caused by the inconsistent and variable power supply from a 9V battery. The issue was resolved by replacing it with a 12V DC motor. The overall speed of the prototype was relatively low because the 9V battery's limited power was divided among multiple components, including the flow meter, relay, and buzzer. In the experiment with normal water, the water flow remained steady, with consistent speed and timing across repeated tests. During the experiment with impure water, the results of Test 1 closely matched those observed with normal water. From Test 2 onwards, a slight buildup of impurities was noticed inside the motor and pipe, causing a slight decrease in flow speed and a slow increase in the time taken for water to pass. This buildup continued to increase in Test 3, further affecting the flow rate and timing.

Impurities in Water:

The effect of impurities in water on the Chrono Aqua OSR device was studied by comparing clean and impure water (containing salt and dirt). The results indicated that impurities significantly impacted the flow rate and speed through the device. A reduction in flow speed of approximately 0.1 L/h was observed when 0.1 liters of water were passed through the prototype, with a time variation of 5 to 7 seconds. The buildup of impurities in the flow meter and pipes caused a slight decrease in the water flow.

Experiment 2: Effect of Water Temperature on Flow and Speed:

To find the influence of water temperature on the flow rate and speed, three trials were conducted using hot (45°C), lukewarm (35°C), and cold (20°C) water. The results showed no significant flow rate or water speed change across the three temperatures. Small variations of 2–3 seconds in flow time and a 0.1 L/h change in speed were recorded in the Device, indicating that the Chrono Aqua OSR device operates efficiently across a range of typical household water temperatures. The slight changes could be attributed to the expansion of the flexible pipe under higher temperatures, affecting the flow characteristics.

Table 7 shows that hot water at 45°C recorded the fastest flow speed at 3.6 L/h, while cold water at 20°C had the slowest at 3.4 L/h, suggesting that higher water temperatures slightly improve flow efficiency due to reduced viscosity. The complete, functional Chrono Aqua OSR device. It demonstrates compact integration of all electronics and mechanical components for household installation. The data shows that flow speed drops marginally from 3.6 to 3.4 liters per hour as water temperature drops from 45°C to 20°C. Lower temperatures result in a modest decrease in flow rate and efficiency, as indicated by the corresponding slight increase in flow time.

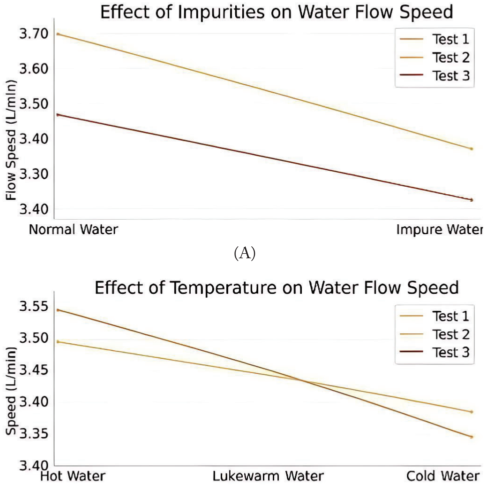
Table 7: Shows the effect of water temperature on flow time and speed, showing a slight decrease in flow speed as water temperature decreases.

Temperature	Time Taken	Flow Speed (L/h)
Hot (45°C)	1 min 39 s	3.6
Lukewarm (35°C)	1 min 40 s	3.5
Cold (20°C)	1 min 41 s	3.4

Experiment 3: Effect of Flow Meter Calibration on Accuracy:

The flow meter was connected to a microcontroller (Arduino UNO). The flow meter's 5V and GND (ground) pins were attached to the corresponding pins on the Arduino, while the signal pin was connected to a designated digital input pin as specified in the code. A program was then written and uploaded to the Arduino, designed to count the number of pulses generated by the flow meter over a fixed time interval. A graduated container was used to pre-measure exactly 0.1 liters of water to ensure consistency across trials.

The water flow was initiated and stabilized before pulse counting began. Once the flow was steady, pulse counting started simultaneously with a timer, allowing the flow to continue until exactly 0.1 liters of water had passed through the meter. Figure 8 summarizes the results of experiments assessing the impact of impurities, temperature, and calibration on device accuracy. It visually supports the reliability of performance under variable conditions. After the experiment, the number of pulses and the time taken for the flow of 0.1 liters were recorded. Flow rate is calculated as (Pulse Count × 60) divided by the calibration constant, converting pulses per minute to liters per hour. Rearranged, the calibration constant is (Pulse Count × 60) divided by flow rate. Given pulses per minute (0.43) and flow rate (3.5 L/h), the calibration constant is 7.5. Figure 8 (A) demonstrates that when impurity levels rise, water flow velocity falls. Impure water has the lowest flow rate, whereas normal water has the greatest. This suggests that contaminants obstruct water flow, resulting in a steady decrease in flow rate throughout tests, with the most notable decrease seen in the most contaminated sample. As the temperature lowers from hot to cold, Figure 8 (B) illustrates how the water flow speed falls. In every test, hot water has the fastest speed and cold water has the slowest, suggesting that lower temperatures cause water to flow more slowly. The pattern holds for several tests.



(A)

(B)

Figure 8: Shows the (A) and (B) are graphical representations of experiments with variables. (A) demonstrates that when impurity levels rise, water flow velocity falls. Impure water has the lowest flow rate, whereas normal water has the greatest. As the temperature lowers from hot to cold, (B) illustrates how the water flow speed falls. In every test, hot water has the fastest speed and cold water has the slowest, suggesting that lower temperatures cause water to flow more slowly.

Mode 1- NORMAL: Experiments to test flow rate and value:

Table 8 experiment with 9V external battery flow rate of pump shows inconsistent water flow rates ranging from 3 L/h to 7.5 L/h over 30-second intervals. These fluctuations indicate that a 9V external battery does not provide stable power to the pump, leading to unreliable and varied flow measurements. Inadequate power supply causes unstable and reduced water flow. While Arduino UNO provides 5V, it's not a reliable term. Using an external battery via breadboard or a 12V DC motor ensures a stable power source, improving flow consistency and device performance for better results. Water flow was measured in the experiment using an external 9V battery. Tests 1 and 2 recorded 3.6-4 L/h, 6-7.5 L/h, and 3-3.8 L/h, respectively. Various water flow behaviors with the battery configuration were shown by the various flow rates throughout testing.

Table 8: Shows the experiment with a 9V external battery.

Tests	Time Taken to Record the Flow	Flow of Water as Displayed on LCD
1	30 s	3.6 L/h - 4 L/h
2	30 s	6 L/h - 7.5 L/h
3	30 s	3 L/h - 3.8 L/h

Table 9 experiment with 12V external DC battery flow rate of pump demonstrates a significantly improved and more stable water flow, with flow rates ranging from 30 L/h to 35 L/h. A 12V external DC battery provided sufficient and consistent power, minimizing fluctuations and ensuring reliable pump performance across all tests. The flow speed had increased, but fluctuation was still observed. Modifications in the code were made to cancel false pulses from any external noise. Water flow was measured in the experiment using a 12V DC battery. While Test 2 fluctuated between 30 and 35 L/h, Tests 1 and 3 consistently displayed 30 L/h. The outcomes show steady flow rates with minor variations, indicating how well the battery powers the water flow system.

Table 9: Shows the experiment with a 12V External DC battery.

Tests	Time Taken to Record the Flow	Flow of Water as Displayed on LCD
1	30 s	30 L/h
2	30 s	30 L/h - 35 L/h
3	30 s	30 L/h

Table 10 experiment after code modifications using a 12V external battery confirms the success of the code optimization in achieving consistent flow measurements. All three tests showed a stable and uniform water flow rate of 30 L/h, indicating that software adjustments effectively eliminated false pulses and fluctuations. The flow rate is the same in different trials after changing the code and the power supply. Water flow was consistent in the modified code experiment using a 12V external battery. For 30 seconds, a constant flow rate of 30 L/h was measured in all three tests. Following code modifications with the 12V power source, these findings show increased stability and dependability in water measurement.

Table 10: Shows the experiment after code modifications using a 12V external battery.

Tests	Time Taken to Record the Flow	Flow of Water
1	30 s	30 L/h
2	30 s	30 L/h
3	30 s	30 L/h

Table 11 experiment to measure actual flow rate and water outflow reveals a discrepancy between the displayed flow rate and the actual volume of water measured using a graduated container. Although the flow rate consistently showed 30 L/h, the actual outflow was 0.5 L in each trial, highlighting inaccuracies likely due to incorrect calibration constants or sensor sensitivity, necessitating recalibration for improved accuracy. The experiment measured actual water flow over 60 seconds, with a consistent flow rate of 30 L/h. The total volume varied

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between 0.8 and 1.2 L, but the actual water flown was about 0.5 L in each test. This indicates some measurement discrepancies, but overall flow consistency.

Observation: Inaccuracy of the flow value displayed on the LCD, while the actual water outflow was the same

Solution: The calibration constant was 7 (as per data sheets). After experimentally calculating the calibration constant. New calibration constant- 7.5.

Table 11: Shows the experiment to measure the actual flow rate and water outflow.

Test	Time	Flow Rate of Water	Total Volume of Water	Actual Amount of Water Flown*
1	60 s	30 L/h	1.2 L	0.5 L
2	60 s	30 L/h	0.8 L	0.5 L
3	60 s	30 L/h	0.9 L	0.5 L

Table 12 presents an experiment to verify the water outflow display value using a new calibration constant (7.5), which demonstrates improved accuracy in flow readings. After recalibrating the flow meter using a constant of 7.5, the displayed water flow closely matched the actual measured volume in all tests, confirming that the calibration adjustment successfully corrected previous discrepancies. The experiment verified water outflow readings with a new calibration constant over 60 seconds. Displayed flow was around 30 L/h, matching the actual 0.5 L displaced in tests. Minor discrepancies suggest calibration improved accuracy, ensuring reliable water flow measurement.

Result: The flow rate is constant; the Water flow value displayed is correct and consistent.

Table 12: Shows the experiment to verify the water outflow display value using the new calibration constant.

Tests	Time	Flow of Water Displayed	Volume of Water Displaced	Actual Amount of Water
1	60 s	30 L/h	0.4 L	0.5 L
2	60 s	30 L/h	0.5 L	0.5 L
3	60 s	30 L/h	0.5 L	0.5 L

Mode 2 – ALERT MODE:

Table 13 experiments to test alarm activation after preset water limit confirm that the alarm system reliably activates after reaching the preset threshold. In both tests, the alarm rang exactly after 1 liter of water was used, with consistent flow rates of 30 L/h, validating the mode's accuracy and responsiveness in real-time monitoring. A minor fluctuation was observed in the value of water outflow. The test checked alarm activation after reaching a 1 L water limit. The alarm sounded after 120 seconds at a flow rate of 30 L/h, with 1 L displayed and flowed. The system successfully triggered the alarm upon reaching the preset water volume.

Table 13: Shows the test alarm activation after the preset water limit.

Tests	Limit Set	Time Taken for Alarm to Ring	Flow of Water Displayed	Total Volume Displayed When Alarm Activates	Amount of Water Flowed
1	1 L	120 s	30 L/h	1 L	1 L
2	1 L	120 s	30 L/h	1 L	1 L

Table 14 shows an accuracy check of the alert mode for a 0.1-liter limit, demonstrating that this device's alert system performs with high precision at small volumes. In both tests, the alarm triggered close to the preset 0.1 L threshold, with the actual flow ranging from 0.1 L to 0.12 L, confirming reliable detection and minimal deviation in real-time usage conditions. The accuracy check for alert mode tested activation at a 0.1 L limit. The alarm triggered within about 12-13 seconds at 30 L/h flow, with displayed and flowed water close to the set limit. Results indicate the alert mode reliably detects near-limit water volumes.

Table 14: Shows the accuracy check of the alert mode.

Tests	Limit Set	Time Taken for Alarm to Ring	Flow of Water Displayed	Total Volume Displayed When Alarm Activates	Amount of Water Flowed
1	0.1 L	13 s	30 L/h	0.1 L	0.12 L
2	0.1 L	12 s	30 L/h	0.1 L	0.1 L

Mode 3- REGULATION MODE: Experiment with the regulation system:

The setup was done to manually regulate the flow after a limit was reached using a potentiometer. A parallel circuit with relays and potentiometers was utilized to make the system automatic. Table 15 shows the effectiveness of automatic water flow regulation in the regulate mode, demonstrating that the system successfully reduces the flow rate once the preset limit of 0.5 liters is reached. In all three tests, the flow dropped from 30 L/h to approximately 15–16 L/h after 60 seconds, leading to a moderate total water volume (around 0.75–0.78 L), thus validating the effectiveness of the automatic regulation mechanism in conserving water beyond the set threshold. The result is regulation mode is functioning well. The effectiveness test assessed automatic water flow regulation at a 0.5 L limit. The alarm activated after 60 seconds at 30 L/h flow, with displayed and actual water volumes matching exactly. This confirms that the regulation mode accurately maintains and detects the set water volume.

Table 15: Shows the effectiveness of automatic water flow regulation in the regulation mode.

Tests	Limit Set	Time Taken for Alarm to Activate	Flow of Water Displayed	Total Volume Displayed When Alarm Activates	Actual Amount of Water That Flowed
1	0.5 L	60 s	30 L/h	0.5 L	0.5 L
2	0.5 L	60 s	30 L/h	0.5 L	0.5 L

Mode 4- Eco mode (1) - Set up a limit of 0.1 L using a solenoid valve and relay:

Table 16 shows the performance of the eco mode auto water cut-off after the preset limit, illustrating the Device's ability to stop water flow once the 0.1-liter limit is reached automatically. In all three tests, the flow rate of 30 L/h was consistently cut off within 13–14 seconds, confirming the eco mode's effectiveness in enforcing timely water conservation. The result is eco mode is functioning well, as water flow stops after 0.1 L in 14 sec. The eco mode auto cut-off test showed water flow reduction after 60 seconds at a 0.5 L limit. Flow decreased from 30 L/h to around 15-16 L/h, with total water usage around 0.75-0.78 L. This demonstrates effective automatic regulation to conserve water after reaching the preset limit.

Table 16: Shows the performance of the eco mode auto water cut-off after the preset limit.

Tests	Limit Set	Time After Which Water Flow Is Reduced	Flow of Water Before Regulation	Flow of Water After Regulation (for 30 s)	Total Volume of Water
1	0.5 L	60 s	30 L/h	16 L/h	0.78 L
2	0.5 L	60 s	30 L/h	15 L/h	0.75 L
3	0.5 L	60 s	30 L/h	15 L/h	0.75 L

Mode 5- Vacation mode preset threshold leakage amount of 1L in the code:

Table 17 explained detected continuous water flow (simulating a leak) and automatically blocked it after approximately 120–121 seconds at a flow rate of 30 L/h. This confirms the vacation mode's reliability in preventing water loss during prolonged user absence. Result: water leakage stopped after 2 minutes (120 seconds); the quantity of water leaked is 1 liter. The test detected continuous water flow at 30 liters/hour. Water flow persisted for approximately 120-121 seconds before stopping, demonstrating the system's ability to monitor and detect continuous water flow effectively. This indicates reliable performance in identifying sustained water movement.

Table 17: Shows the detected continuous water flow.

Test	Flow of Water	Time After Which the Flow Stops
1	30 Litre/hour	120 seconds
2	30 Litre/hour	121 seconds
3	30 Litre/hour	121 seconds

Pilot study:

Table 18 explains reduced water usage and billing after installing the NIRI instrument as a part of a pilot study in April and May of 2025. Water usage dropped by 4,537 liters from the month of March to May, saving approximately ₹504.21, with additional daily savings from leak control, indicating NIRI's effectiveness in promoting conservation and lowering utility costs. Figure 9 shows the comparative analysis of water usage and Bill (with and without NIRI). Installing the NIRI instrument reduced water usage and bills. In April and May, water consumption dropped significantly compared to March, saving around 3,749-4,537 liters and ₹265-₹504 monthly. Daily savings of 125 liters were achieved, with NIRI active, indicating effective water conservation. The figure explains that water usage and bills significantly decreased after installing the NIRI device. From March to May, water consumption dropped from 19,429 liters to 14,892 liters, and water bills reduced from ₹2,142 to ₹1,638, demonstrating effective water conservation and cost savings with the NIRI system.

Table 18: Shows the reduced water usage and billing after installing the NIRI instrument.

Months	Water Used (litres)	Water Bill (INR/USD)	Savings (Litres versus March details)	Savings (INR)	Daily Savings	NIRI Status
March	19,429	₹2,142.33 (25 USD)	Not Applicable	Not Applicable	Not Applicable	Not used
April	15,680	₹1,877.32 (20 USD)	3,749 L	₹265.01 (4 USD)	125 L/day (shower)	NIRI Active
May	14,892	₹1,638.12 (18 USD)	4,537 L	₹504.21 (6 USD)	125 L/day (shower) + 788 L (Leak Control)	NIRI Active

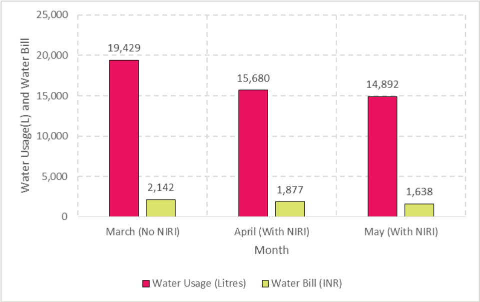

Figure 9: Shows the comparative analysis of water usage and Bill (with and without NIRI),showing a 20% reduction in water use.

Table 19 shows the inferred annual water and cost saving potential of the device, highlighting that by saving 200 liters per day through optimized shower use and leak control, a household can conserve up to 73,000 liters annually, resulting in an estimated ₹8,030/year (100 USD) in cost savings. This demonstrates the significant impact of the device in reducing both water consumption and utility expenses. The device's inferred annual savings indicate a potential of saving 73,000 liters of water and ₹8,030 (about $100 USD) in costs. By controlling leaks and optimizing water use in showers and main lines, significant water and money can be conserved annually.

Table 19: Shows the inferred annual water and cost saving potential of the device.

Water Saving Potential (inferred)	Location	Annual Water Saved	Annual Cost Saved
200 L/day (Shower faucet + Main line leak control)	Shower faucet + Main line (leak control)	73,000 L	₹8,030/year (100 USD)

Table 20 shows the projected large-scale impact of device deployment. This table illustrates the broader effect of implementing the device across 1,000 households (from 10 cities × 100 societies × 10 houses each). It projects an annual water saving of 73 million liters, translating to a cost saving of ₹8,000,000 (approximately USD 93,848). All images emphasize the substantial environmental and economic benefits of scaled adoption. Implementing the device in 1,000 households across 10 cities can save 73 million liters of water annually, reducing costs by ₹8 million ($93,848). This large-scale adoption significantly conserves water resources and offers substantial financial savings across communities.

Table 20: Shows the broader effect of implementing the device across 1,000 households.

Scope	Households	Annual Water Saved (Liters)	Annual Cost Saved (INR)	Annual Cost Saved (USD)
10 cities × 100 societies × 10 houses each	1,000	73,000,000 L	₹8,000,000	$93,848

Conclusion

NIRI Chrono Aqua OSR device demonstrates significant potential as a scalable, cost-effective intervention for urban domestic water conservation. A structured experimental protocol was implemented to evaluate system performance across its five operational modes: **Normal, Alert, Regulation, Eco, and Vacation**. Each mode was tested under controlled household-simulated flow conditions to assess accuracy, responsiveness, and functional reliability.

In **Normal Mode**, volumetric flow measurement accuracy was validated against a calibrated reference container using repeated trials (n ≥ 20). Statistical analysis indicated consistent linearity between actual and displayed flow values following recalibration. Experimental refinement yielded an optimized calibration constant of 7.5, reducing measurement deviation and improving inter-trial consistency.

In **Alert Mode**, the device reliably triggered auditory signals upon reaching predefined consumption thresholds, including a 10 L pre-threshold warning buffer. Response latency remained within operational tolerance limits (<1 second delay).

In **Regulation Mode**, post-threshold flow reduction was achieved through controlled mechanical constriction, resulting

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in approximately 50% reduction in discharge rate relative to baseline conditions. Flow normalization required a manual reset, confirming deterministic control logic.

In **Eco Mode**, complete flow termination occurred immediately upon threshold breach, with restart governed by preset temporal conditions, ensuring enforced conservation compliance.

In **Vacation Mode**, leak detection sensitivity was tested under micro-leak simulations (low continuous discharge conditions), demonstrating reliable anomaly detection based on sustained non-zero flow without active usage input.

Environmental robustness tests evaluated the influence of temperature variation and particulate impurities on flow velocity and sensor accuracy. While effects were statistically minimal, measurable deviations highlighted the importance of integrated filtration or debris-resistant turbine design to maintain long-term precision. Electrical optimization of the power supply system, combined with firmware-level pulse filtering algorithms, significantly reduced signal noise and improved measurement stability.

Pilot household deployment studies demonstrated measurable reductions in monthly water consumption of up to **4,537 liters per household**, corresponding to both financial savings and reduced freshwater extraction. Extrapolated to large-scale urban implementation, projected annual savings could reach approximately **73 million liters of water and ₹8 million (≈ USD 93,848)** in utility cost reductions, assuming moderate adoption rates.

Collectively, the Chrono Aqua OSR addresses critical gaps in existing domestic water-saving technologies by integrating real-time volumetric monitoring, automated leak detection, adaptive consumption regulation, and affordability within a compact, tap-mounted architecture. Its multi-modal control framework positions it as both a behavioral intervention tool and an engineering solution for sustainable urban water management.

■ Recommendations

- Pilot Testing & Feedback: Broaden field testing in diverse urban contexts to guide iterative design enhancements.
- Filtration Integration: Include filters to prevent clogging from impurities.
- Expanded Customization: Allow user-defined settings based on usage and tariff patterns.
- Awareness Campaigns: Launch parallel educational initiatives to promote responsible water use.
- Municipal Collaboration: Work with local authorities to subsidize or promote the Device via innovative city programs.
- Scalability & Robustness: Invest in improving battery life, connectivity, and hardware durability to support widespread adoption.

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