

Smart Water Consumption Monitoring and Billing System

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Abstract— Effective management of water supply networks is essential for smart cities and agricultural systems, where real-time monitoring plays a vital role. Water meters, particularly electromechanical or fully electronic models, are more suitable for these applications than traditional mechanical meters due to their compatibility with Automated Meter Reading (AMR) technologies. This study presents a smart water metering system designed to monitor and record customer water consumption in real time. The data collected is processed by an integrated data processing unit, enabling several key functionalities: (1) fair and accurate water billing, (2) detection of abnormal consumption patterns caused by leaks or flooding, with automatic alert generation, and (3) the ability to shut off water supply in cases of flooding or non-payment. The system is developed as an Internet of Things (IoT) application, with a focus on implementation specifics and design considerations. A wireless transmitter can be embedded within the meter to provide real-time data, and a mobile application may be integrated to give users a convenient tool for monitoring their water usage. To validate the system, a laboratory-scale hardware prototype was constructed, simulating two customers connected to a shared water source. The prototype was successfully tested using custom-developed software executed on a laptop.

Keywords: Smart Water Meter; IoT; Automated Meter Reading (AMR); Water Consumption Monitoring; Leakage Detection; Real-Time Data Acquisition.

I. INTRODUCTION

Water scarcity and inefficient resource utilization have emerged as pressing global challenges in the 21st century, particularly within urban centers and agricultural regions [1, 2]. The growing demand for water, driven by population growth, urbanization, and climate change, has underscored the urgent need for smarter, more equitable, and sustainable water management strategies [1, 3]. One of the primary barriers to efficient water use lies in outdated metering and billing infrastructure. Traditional water billing systems, which rely heavily on manual readings and mechanical meters, are often plagued by measurement inaccuracies, delayed reporting, and inequitable billing practices [4, 5].

A particularly illustrative case can be found in Egypt, where approximately 60% of residential buildings operate with a single, shared water meter [6]. In such settings, water bills are typically divided equally among residents, regardless of individual consumption levels [6, 7]. This uniform billing model not only discourages responsible water usage but also fosters financial inequality among households with varying consumption patterns. The inability to attribute water usage accurately contributes to waste and limits accountability, both of which are critical issues in a water-scarce environment [2, 7].

To address these limitations, this paper introduces the Smart Water Billing System (SWBS)—an IoT-based architecture designed to enable real-time water consumption monitoring, accurate billing, and proactive detection of abnormal usage patterns [8, 9]. SWBS is equipped with functionalities to detect and report irregular water usage—such as that caused by leaks or flooding—and to issue real-time alerts [9, 10]. Furthermore, it includes the capability to remotely suspend water supply in cases of persistent flooding or non-payment, thereby promoting both safety and financial discipline [10].

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Recent studies [11-20] have focused on integrating IoT, edge computing, and artificial intelligence into smart water metering systems to enhance consumption accuracy, leakage detection, and billing transparency. However, most of these solutions remain limited by high implementation costs, lack of multi-user normalization, or insufficient real-time control, which this study aims to address.

The proposed system leverages the convergence of low-cost electromechanical sensors, wireless data transmission, and cloud-based analytics to modernize water distribution management. Unlike conventional mechanical meters that require manual inspection, SWBS integrates Hall Effect flow sensors (YF-B1) with ESP8266 microcontrollers to automatically capture consumption data and transmit it via wired or wireless connections to a centralized platform. This real-time data flow allows utilities to generate dynamic billing based on actual usage, while also empowering end-users with mobile applications to track and manage their personal consumption patterns.

The Smart Water Billing System introduces three core innovations that address current water management shortcomings:

1. **Sensor Accuracy Enhancement:** The system employs dynamic error-correction algorithms to improve the reliability and precision of low-cost Hall Effect flow sensors (YF-B1), ensuring consistent and accurate consumption measurements.
2. **Multi-Tier Normalization Framework:** SWBS incorporates an algorithmic model that normalizes individual sub-meter readings in relation to a shared main meter. This resolves fairness issues prevalent in buildings—particularly in Cairo—where single-meter billing is still common. By allocating costs proportionally based on actual consumption, the system ensures equitable billing and promotes water conservation (Egyptian Water Regulatory Agency, 2023).
3. **Edge Computing Integration:** Data collected by the sensors is preprocessed locally on ESP8266 microcontrollers before being transmitted to the cloud. This edge computing approach reduces both latency and bandwidth consumption, enhancing system responsiveness and scalability.

By combining affordability, transparency, and advanced analytics, the proposed SWBS presents a robust solution for improving water governance in residential and agricultural settings. Its modular and scalable design offers a pathway toward smarter cities, improved resource equity, and enhanced environmental sustainability.

II. TYPES OF WATER METERS

Water meters are essential instruments used to measure the volume of water consumed by residential, commercial, and industrial users. Their classification depends on the measurement principle employed. In modern smart water metering systems, the choice of water meter type significantly affects accuracy, cost, energy consumption, and integration with automated systems. The major categories include displacement meters, velocity-based meters, and multi-jet or turbine meters, as discussed below.

A. Displacement Meters

Displacement meters operate by physically displacing a known volume of water, making them suitable for applications with low to medium flow rates. These meters are known for their precision in residential billing scenarios.

1) Velocity Water Meters

Velocity meters function by measuring the speed of water flowing through a known cross-sectional area. The flow rate is derived from the product of the flow velocity and the cross-sectional area. These meters are commonly used where large flow volumes are involved, such as

in industrial and irrigation systems. Subtypes under velocity meters include several sensor-based designs.

2) Mechanical Flow Meters

Mechanical flow meters use moving mechanical parts—such as impellers, turbines, or paddles—to detect and measure flow rate. As water moves through the meter, it rotates a mechanical element, whose speed is proportional to the flow rate. Mechanical meters are cost-effective but may suffer from wear and tear, making them less suitable for high-precision or long-term IoT applications.

3) Vortex Flow Meters

Vortex meters measure the vortices shed by a bluff body placed in the flow stream. The frequency of vortex shedding is proportional to the velocity of the fluid. These meters have no moving parts and provide reasonable accuracy with a wide range of fluids, including water. They are often used in industrial systems where flow stability is moderate.

4) Ultrasonic Flow Meters

Ultrasonic meters determine water flow by measuring the transit time or frequency shift (Doppler effect) of ultrasonic signals transmitted through the water. These meters are non-intrusive, with no moving components, and offer high accuracy and durability. Their suitability for integration into smart systems makes them ideal for modern IoT-based water metering applications.

5) Magnetic Flow Meters

Also known as electromagnetic meters, these devices operate based on Faraday's Law of Electromagnetic Induction. When water—a conductive fluid—flows through a magnetic field, it generates a voltage that is proportional to the flow rate. Magnetic flow meters are accurate, durable, and require no mechanical parts, but they are generally more expensive and require electrical power.

B. Multi-Jet Meters

Multi-jet meters use multiple ports to direct water onto an impeller. The number of jets provides balanced forces on the impeller, improving durability and reducing wear. These meters are widely used in residential and commercial buildings for medium-range flow measurement due to their cost-effectiveness, mechanical robustness, and moderate accuracy.

C. Turbine Flow Meters

Turbine meters, sometimes considered a subtype of velocity or multi-jet meters, use a rotor positioned axially in the flow path. As water flows through the meter, the rotor spins at a speed proportional to the flow rate. Turbine meters offer a wider flow range and better accuracy than traditional mechanical meters. However, they are sensitive to flow disturbances and debris, and thus require clean water and proper flow conditioning.

III. SCOPE OF THE PROJECT

The proposed system, titled Smart Water Consumption Monitoring and Billing System aims to modernize water utility operations by integrating IoT technologies with web-based customer services. The project addresses the inefficiencies of conventional water billing and management systems by offering a centralized, automated, and user-friendly platform for both consumers and utility providers. The scope of the project encompasses a wide range of functionalities, categorized into administrative operations, customer services, and smart monitoring features, all integrated through a web-based application and IoT-enabled hardware infrastructure.

A. Customer Registration and Information Management

The system provides a secure module for customer registration and data retrieval. Each customer is assigned a unique digital profile, which includes personal information, property details, water meter association, usage history, and billing records. This centralized database ensures that all customer interactions and transactions are properly archived and accessible for administrative or analytical purposes.

B. Maintenance Material Management

To streamline field operations, the system includes a component for registering and tracking maintenance materials used in meter installations, repairs, or replacements. Each item—such as valves, sensors, meters, and pipes—is logged with quantity, usage date, and associated customer service requests. This feature enhances inventory tracking, reduces wastage, and ensures accountability in maintenance operations.

C. Meter Reading Registration

Meter readings are automatically captured through IoT-enabled Hall Effect flow sensors (YF-B1) integrated with ESP8266 microcontrollers. These readings are periodically transmitted to the central database via Wi-Fi, reducing human error and manual labor. In areas lacking full automation, manual reading entries are also supported, with built-in validation checks to minimize input errors. This dual-mode capability ensures the system's applicability in both developed and resource-constrained environments.

D. Payment Processing and Billing Management

The SWBS platform supports multiple payment registration methods, including manual payment entry, online payment integration, and real-time payment status updates. Once meter readings are processed, the system calculates individual bills based on actual consumption using a dynamic pricing model. In multi-residence buildings, the system implements a multi-tier normalization framework that fairly allocates costs among customers based on sub-meter readings. The billing module also handles overdue payment tracking and bill history generation.

E. Report Generation

Administrative and operational reports can be generated on demand or scheduled periodically. These reports include:

- Customer usage summaries
- Billing history and revenue tracking
- Maintenance logs
- Anomaly detection reports
- System performance metrics

These reports assist utility managers in making data-driven decisions regarding infrastructure planning, customer service enhancement, and policy enforcement.

F. Real-Time Monitoring and Anomaly Detection

A critical innovation of this project is its ability to detect abnormal water usage patterns, particularly those caused by leakages or flooding at the consumer's premises. By leveraging real-time flow data and predefined consumption thresholds, the system can trigger immediate alerts to both the consumer and utility provider. Alerts are delivered through SMS, email, or mobile app notifications, enabling swift response to potential damage or wastage.

G. Remote Water Supply Control

To enhance safety and billing compliance, the system includes functionality for remotely locking or unlocking the customer's water supply. This control is executed through an electronically actuated valve connected to the main supply line. The lock function is automatically triggered under two main conditions:

1. Continuous abnormal water flow due to potential flooding or pipe bursts.
2. Non-payment of water bills beyond a pre-defined grace period.

This capability promotes both conservation and financial accountability, particularly in high-density urban housing contexts where centralized oversight is essential. The integrated scope of SWBS positions it as a holistic solution for smart water management, offering not only operational efficiency and consumer transparency but also proactive risk mitigation and equitable resource allocation. The system's modular design ensures scalability for municipal use, while its low-cost hardware requirements make it suitable for deployment in emerging economies.

IV. DATA COLLECTION METHODOLOGY

Efficient data collection is central to the operation of any smart water billing system. The accuracy, reliability, and timeliness of the collected data determine the effectiveness of the system in billing, anomaly detection, consumption analytics, and customer feedback. In the proposed SWBS, data collection is achieved through a multi-stage process involving sensor integration, wireless communication, centralized storage, and intelligent analytics. This section details each phase of the methodology and outlines the billing process compliant with regulatory guidelines set by Egypt's Water Regulatory Authority (WRA) and the Ministry of Housing, Utilities, and Urban Communities.

A. IoT-Based Data Acquisition

The first step in the data collection process is the installation of smart water meters at each consumer's premises. These meters are equipped with Hall Effect flow sensors (e.g., YF-B1) that measure water consumption in real time. The volume of water passing through the pipe is converted into electrical pulses by the sensor, which are counted and processed by an embedded ESP8266 microcontroller.

These readings are captured at defined time intervals and temporarily stored in local memory. Each record includes metadata such as timestamp, meter ID, flow rate, and total accumulated volume. This granular approach enables the system to construct detailed consumption profiles for every consumer.

B. Wireless Data Transmission

Once data is acquired, it is transmitted to a centralized platform using wireless communication technologies. In the proposed system, Wi-Fi (IEEE 802.11) is the primary mode of communication between the smart meters and the cloud gateway. Each ESP8266 module, embedded within the smart meter, is programmed to establish secure periodic connections to transmit the collected readings.

In future enhancements, alternative protocols such as LoRaWAN, NB-IoT, or Zigbee may be considered for extended coverage and energy efficiency in low-power wide-area networks (LPWANs), especially in rural or remote areas.

C. Centralized Data Storage

The transmitted data is received by a centralized data processing unit or cloud server. All incoming records are stored in a relational database system (RDBMS) or cloud-native data lake, depending on the deployment scale. Each customer's data is indexed using unique identifiers, including consumer number, meter serial number, and geographic location.

The storage architecture is optimized for:

- Time-series queries (for tracking usage over time),
- Real-time anomaly detection,
- Bill generation based on dynamic consumption,
- Historical analysis for regulatory reporting.

D. Data Analysis and Anomaly Detection

Once stored, the collected data is analyzed using a range of data analytics and machine learning techniques. Algorithms are employed to:

- Detect anomalies such as sudden spikes in flow (indicative of leakage or flooding),
- Forecast consumption patterns,
- Segment customers based on behavior,
- Flag potential cases of meter tampering or malfunction.

The analysis also supports demand forecasting and infrastructure planning at the utility provider level, contributing to smart city development goals.

V. WATER BILL CALCULATION AND BILLING LOGIC

In Egypt, the calculation of water bills is regulated by the Water Regulatory Authority (WRA) and adheres to tariffs defined by the Ministry of Housing, Utilities, and Urban Communities. The billing algorithm in the SWBS complies with these national standards to ensure regulatory alignment and transparency.

A. Tariff Structure and Categorization

The WRA defines multi-tiered tariff structures based on:

- Consumer type: Residential, Commercial, or Industrial
- Meter size: e.g., 0.5-inch, 1-inch, etc.
- Consumption brackets: Volume-based categories such as 0–10 m³, 11–20 m³, etc.

Each tier is associated with a specific price per cubic meter (m³), which increases progressively with higher consumption.

B. Consumption Measurement

Water consumption is measured in cubic meters by the smart meters. The system calculates the difference between the current and previous readings to determine usage within the billing cycle. Readings are rounded to the nearest cubic meter according to WRA regulations.

C. Base Charges and Additional Fees

The core bill comprises:

- **Base water charges** = Total consumption (m³) × Applicable tariff
- **Additional service charges:**
- **Sewage fees** (if connected to municipal drainage)
- **Service fees** (maintenance and meter reading services)
- **Environmental taxes** or local council surcharges (if applicable)

These components are calculated automatically by the SWBS and compiled into a detailed billing statement, which includes:

- Billing period
- Meter serial number and reading history
- Consumer details
- Itemized charges (base, service, and tax components)
- Total amount due
- Payment due date and previous balance (if any)

D. Billing Automation and Distribution

Once computed, bills are:

- Stored in the database for record-keeping,
- Pushed to the consumer portal or mobile application, and
- Optionally sent via email/SMS for immediate user access.

The platform also provides online payment options and maintains a full ledger of paid and unpaid invoices. In the case of overdue payments beyond a predefined grace period, the system can trigger an automated command to lock the consumer's water supply using a remotely controlled valve mechanism integrated into the meter assembly. The described methodology ensures a robust, scalable, and transparent approach to data collection and billing in smart water utility networks. By aligning with national regulations and integrating intelligent automation, the system enables both operational efficiency and customer satisfaction.

VI. HARDWARE IMPLEMENTATION

A. Block Diagram Overview

The implementation of the proposed SWBS is visualized through the system architecture shown in Figure. 1, which depicts the hierarchical flow of water from the public utility to individual residential flats. The setup consists of a Company Main Meter (CM) connected to the public water grid, followed by a Smart Major Meter (SM0), which measures the aggregate water consumption of a residential building for customer water flow control which normally open water valves (VLVn) are added. Individual smart meters, labeled SM1 to SMn and the valves VLV1 to VLVn, are installed at each flat, and data from all meters is processed and normalized by a central data monitoring and processing unit.

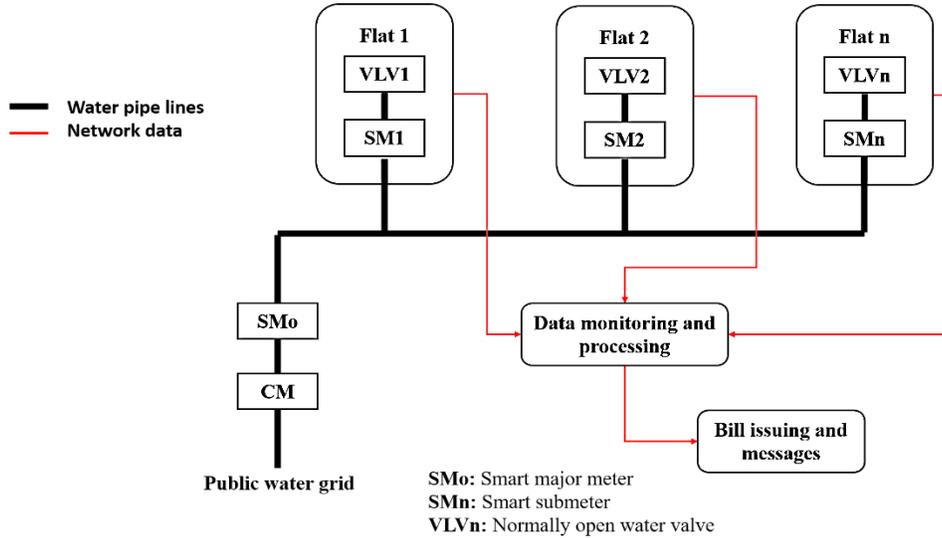


Figure 1. The SWBS

B. System Methodology

The hardware-based methodology implements the following operations:

- **Real-Time Consumption Monitoring:** Each sub-meter (SM1–SMn) records monthly water usage at the apartment level. Simultaneously, SM0 captures the total inflow to the building.
- **Normalization of Consumption:** Sub-meter readings are normalized against SM0 to calculate each unit's consumption weight. This ensures a fair cost distribution among residents.
- **Dynamic Bill Distribution:** Based on the normalized readings, the system allocates billing amounts proportionally.
- **Anomaly Detection:** The system performs continuous diagnostics to:
 - Identify off-grid units that may be bypassing metering.

- Detect leak-induced overconsumption.
- Generate alerts and lock valves automatically in the event of floods or leaks.

C. Model Block Diagram

To validate the proposed design, a scaled-down laboratory prototype was developed, which mimics real-world functionality. This model includes microcontroller-based smart meters, flow sensors, wireless communication modules, and a software interface developed on a laptop for real-time data acquisition, processing, and visualization. Figure. 2 illustrates the proposed model block diagram.

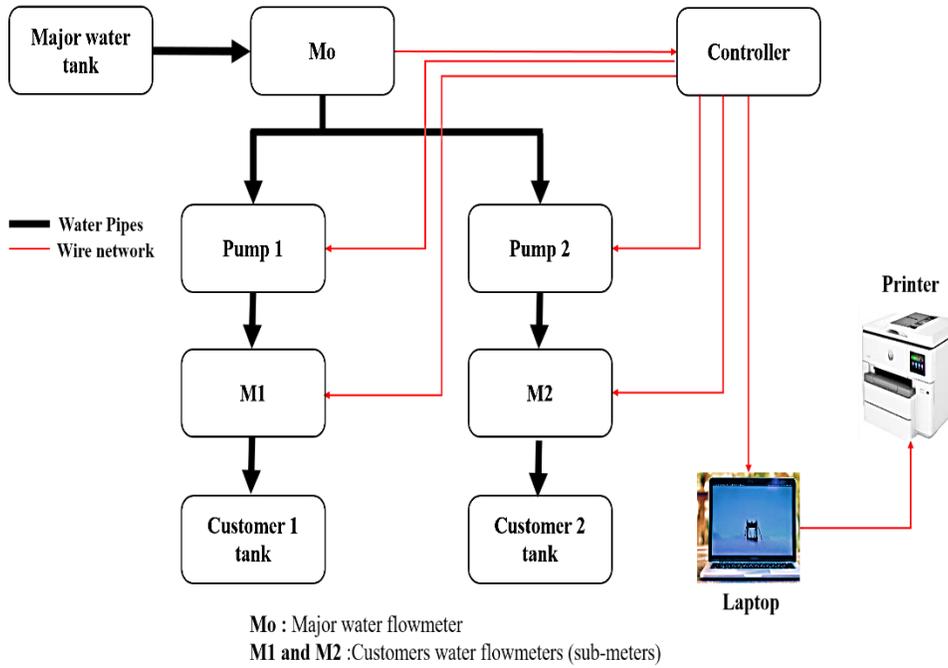


Figure 2. Model Block Diagram

D. General Smart Water Meter Structure

Each smart water meter consists of three primary components:

1. **Flow Sensor (YF-B1)** – for measuring volumetric water flow.
2. **Microcontroller Unit (ESP8266)** – for processing and transmitting data.
3. **Power and Control Circuitry** – for interfacing sensors, executing control logic (e.g., valve lock), and ensuring stable operation.

Figure. 3 illustrates the general structure of the proposed smart water meter, which integrates a Hall Effect flow sensor (YF-B1), a microcontroller unit (ESP8266), and a power and control interface. The flow sensor measures the volumetric rate of water passage, while the microcontroller processes the sensor pulses, computes total consumption, and transmits the data wirelessly to the central server. The control circuitry manages power regulation and enables automated valve actuation for remote water shutoff during leak detection or non-payment scenarios. This modular design ensures accurate measurement, reliable communication, and efficient system scalability for smart water management applications.

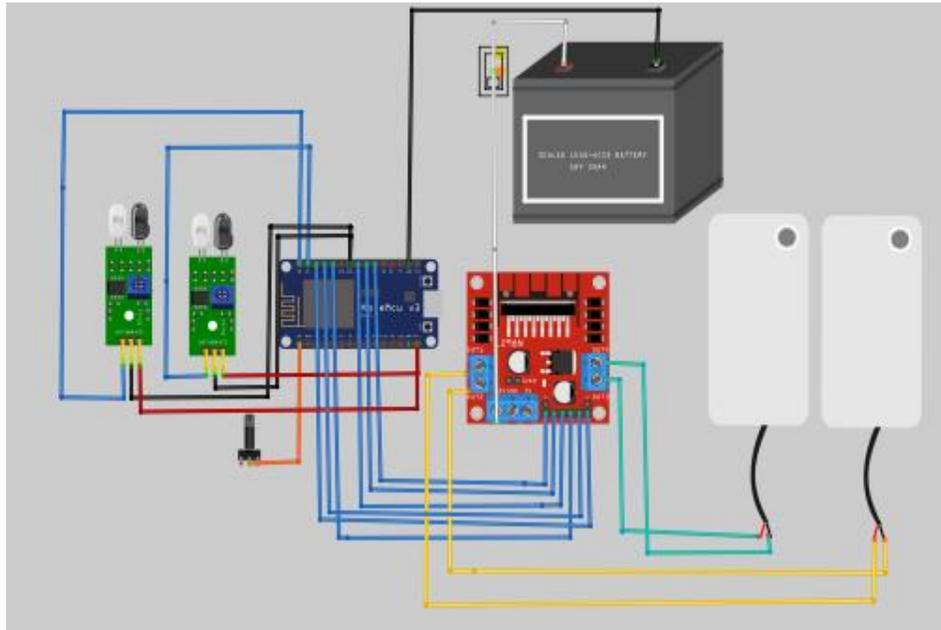


Figure 3. General Smart Water Meter Block Diagram

E. Smart Meter Circuit Design

Figure. 4 presents the circuit diagram of the smart water meter, showing the interconnection between the YF-B1 flow sensor, the ESP8266 NodeMCU microcontroller, and the relay-controlled solenoid valve. The flow sensor outputs pulses proportional to the water flow rate, which are processed by the ESP8266 for real-time consumption monitoring and wireless data transmission. The relay module enables automated valve operation, allowing remote control of water supply based on system commands. The circuit also includes a regulated power supply and USB interface for programming, ensuring stable performance and easy maintenance during deployment and testing.

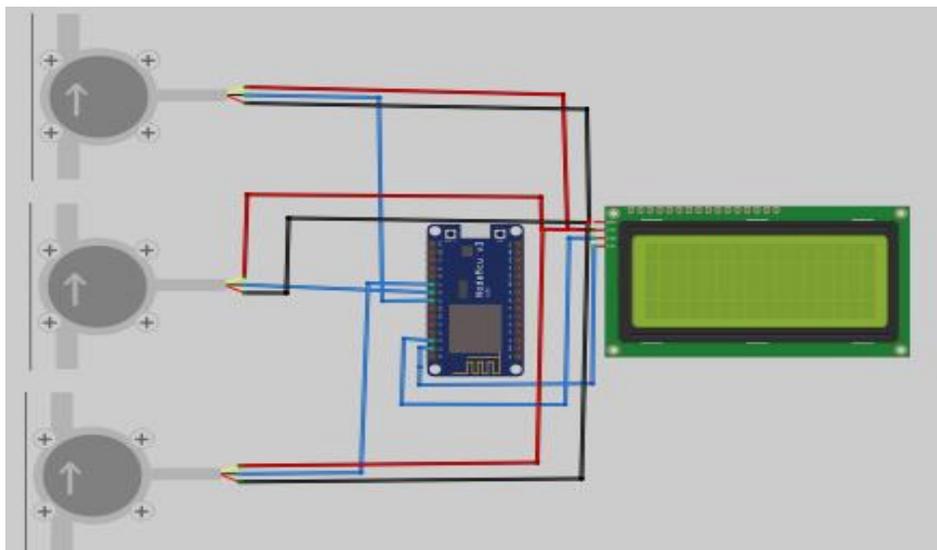


Figure 4. Smart Water Meter Circuit Diagram

The circuit integrates:

- A **YF-B1 flow sensor** connected to the digital GPIO pin of the ESP8266 NodeMCU.
- A **relay module or solenoid valve** for automatic water supply control.
- Power supply unit (regulated 5V–3.3V for MCU).
- USB interface for programming and debugging.

F. Key Hardware Components

1) ESP8266 NodeMCU Wi-Fi Development Board

The **ESP8266** by Espressif Systems is a cost-effective microcontroller with built-in Wi-Fi support and TCP/IP stack. Its small form factor, powerful 32-bit Tensilica L106 core, and easy programmability make it ideal for IoT-based smart meter applications.

Specifications:

- Voltage: 3.3V
- Processor: Tensilica L106 (32-bit, 80–160 MHz)
- RAM: 32K instruction + 80K data
- Flash Memory: Up to 16MB
- GPIO: 17 (Multiplexed)
- ADC: 1 input (10-bit resolution)
- Power: 10 μ A (deep sleep) to 170 mA (active)
- Network: 802.11 b/g/n, Soft-AP, P2P
- TCP Connections: Up to 5

Figure. 5 shows the ESP8266 NodeMCU Wi-Fi development board used as the core processing unit of the smart water meter. It handles data acquisition from the flow sensor, processes consumption readings, and transmits the results to the central server via Wi-Fi. Its compact design, built-in TCP/IP stack, and low power consumption make it ideal for real-time IoT-based water monitoring and billing applications.



Figure 5. ESP8266 NodeMCU Development Board

2) YF-B1 Water Flow Sensor

The **YF-B1** is a compact and highly sensitive Hall Effect-based flow sensor that generates electrical pulses proportional to flow rate. It is widely adopted for domestic and industrial applications.

Working Principle:

Water rotates a built-in rotor; a magnet embedded in the rotor triggers the Hall sensor to emit a pulse for every predefined volume of flow. These pulses are counted by the MCU to compute instantaneous and cumulative flow.

Specifications:

- Flow Range: 1–30 L/min
- Operating Voltage: 5V–24V
- Operating Temperature: –25°C to 80°C
- Output: Pulse frequency (Hz) proportional to flow
- Threaded Inlet/Outlet for easy installation
- High sealing performance
- RoHS compliant

Figure. 6 illustrates the YF-B1 Hall Effect water flow sensor, which converts the flow of water through the pipe into electrical pulses proportional to the flow rate. These pulses are counted by the ESP8266 microcontroller to calculate instantaneous and cumulative water consumption. Its compact size, high sensitivity, and wide operating range make it well-suited for smart water metering applications requiring accurate and reliable flow measurement.



Figure 6. YF-B1 Water Flow Sensor

G. Integration and Testing

The entire hardware system was tested under controlled lab conditions. The ESP8266 was flashed with custom firmware using the Arduino IDE. Data from YF-B1 sensors was successfully transmitted via Wi-Fi to a simulated cloud server running on a laptop. Billing logic and leak detection algorithms were validated through simulated leakage conditions and meter tampering scenarios. The testbed confirmed:

- Accurate pulse-to-volume conversion.
- Reliable data transmission.
- Effective real-time alerting and shutoff mechanisms.

This hardware implementation successfully demonstrates the feasibility of the proposed smart water billing system. Future iterations can scale this design for building-wide deployments, integrate with cloud services (e.g., AWS IoT, Blynk), and include solar-powered versions for sustainability.

VII. CONCLUSIONS

This study presents a robust and scalable smart water billing and monitoring system leveraging IoT technologies to address inefficiencies in traditional water metering and billing processes. By integrating real-time data acquisition, wireless communication, centralized analytics, and automated billing, the proposed system enables accurate consumption tracking, early leakage detection, and proactive customer engagement. The methodology demonstrates how smart meters, combined with cloud-based platforms, can facilitate transparent and fair billing, reduce water losses, and support utility providers in managing resources more efficiently. Furthermore, the inclusion of a tariff calculation model aligned with Egypt's national billing framework enhances the practical relevance and applicability of the system. The ability to remotely monitor usage and control flow not only empowers users with actionable insights but also contributes to national water conservation goals. Although the proposed system demonstrates a functional prototype with high measurement accuracy and real-time control, future research will include benchmarking against state-of-the-art IoT metering frameworks to quantify improvements in accuracy, scalability, and latency. Additionally, cybersecurity considerations such as data encryption, authentication, and protection against unauthorized valve actuation will be incorporated to mitigate risks of data tampering and system manipulation. Comparative evaluations will also be conducted to validate the system's robustness under varying network conditions and larger deployment scales. Additionally, the future work will focus on optimizing data analytics with AI algorithms and expanding the system for broader integration with smart city infrastructure.

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