Smart Water Management Technology: An IoT-Based Solution for Efficient Water Resource Management

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Abstract:* *Efficient management of water resource is critical in addressing growing concerns around water quality and scarcity, particularly in urban and rural settings of most underdeveloped countries or regions. The regions lack an efficient system which optimizes water storage and usage - leading to water scarcity caused by mismanagement. The objective of this work is to control the water demand constraints, while also enabling the water quality, water levels, and temperature monitoring in a just in time fashion. Among the system components are sensors for assessing water level and remote control of water pumps, water sample quality measurements by turbidity as well as measuring environmental conditions like temperature. As the central microcontroller for this setup, an Arduino Uno R3 is able to receive and process various sensors' data and coordinate automated actions to be made, for example turn on the water pump when the water level drops below a certain level or a threshold.

Data transmission is achieved through the Message Queuing Telemetry Transport (MQTT) protocol, with an ESP32 WiFi module to facilitate seamless communication. Through system integration, the "Smart Water Watch" device aims to solve the problems posed by conventional water management systems and presents a rapid and low-cost modern solution suitable for domestic, commercial and industrial settings.

Keywords: Arduino, MQTT, ESP32, Water Management, Internet of Things (IoT)

1. INTRODUCTION

Water is thus regarded as one of the most precious resources on Earth. However, its management still remains to be one of the most nagging problems in urban and rural settings. The growing populations and the impact of climatic change have made the efficient use of water one of the critical aspects for ensuring sustainable development. That said, traditional water management systems have been found inefficient, resulting in waste, poor resource allocation, and insufficient monitoring of water quality and leakages.

Smart Water Management Technology intends to address these dilemmas by embedding IoT technology into existing water management systems. This smart system uses a set of sensors to monitor real-time physical parameters of water quality, leakage, and water temperature. The system is hinged on Arduino Uno R3 microcontroller, which gathers data from the sensors and manages automation of water flow control according to predefined conditions. Turbidity sensor is used to ensure safe water, while the ultrasonic sensor measures water levels effectively. Communication employs MQTT protocol, making it conducive for cable-free handling and implementation with a WiFi module [8] when data is sent wirelessly to a central application for control and monitoring.

Leveraging continuous data acquisition for real-time insights, alongside automating the utilization of water, allows the Smart Water Watch system to achieve many things. The key values include being practical, scalable, and cost-efficient, allowing any households, businesses, and zones in industrial settings to actively participate.

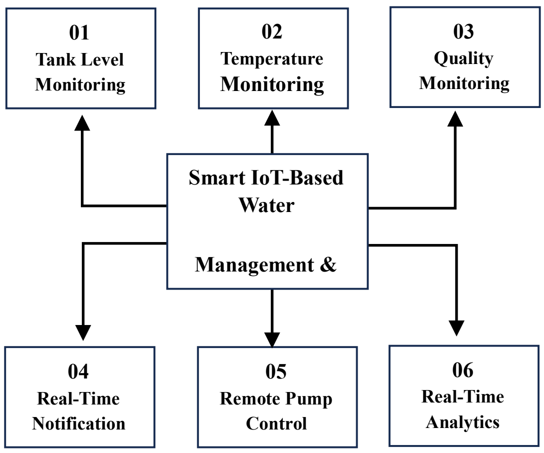

Fig 1: Obtainable System Functionalities of IoT-Based Water Management

2. PROBLEM STATEMENT

The global stock of fresh water is not insufficient, but its distribution poses a number of problems: a global problem in arid areas, a seasonal problem in countries that do not have sufficient storage capacity to cope with the dry season, and a quality problem when water becomes unfit for consumption (as in the case of floods, for example).

Traditional methods of water management are simply not capable of addressing the enormity of these challenges. They are characterized by manual interventions, lack of real-time monitoring, delayed responses to critical issues such as leaks, and decision-making gaps. The absence of integrated data analytics systems severely restricts effective decision-making and long-term planning for sustainable water resource utilization.

Hence, there is a pressing need of technological solutions that deliver accurate and timely information on water resources as well as automation of the management process. The Smart Water Management Technology (SWMT) system, which makes use of cloud computing and Internet of Things sensors represents a potential solution to address these challenges by enabling real-time monitoring, optimizing water usage by identifying needs and combating waste.

3. LITERATURE REVIEW

This review analyzes previous research and innovations in Smart Water Management Systems. It examines existing studies or solutions on water resource management through IoT technologies Internet of Things (IoT).

No	Title	Author (s)	Year	Proposed Method
1	Water quality monitoring system based on Internet of Things [1]	Chengcheng Zhang, Jian Wu, Jiancheng Liu	2020	An online platform for instant water quality monitoring that integrates STM32 microcontroller, sensors, WiFi wireless transmission, and remote management to monitor parameters like turbidity, pH value, and temperature, providing pre-warning for water quality issues.
2	Smart Water Buddy: An Economical and Open-Source Smart Domestic Water Management Solution [2]	Isuru Sachitha Herath	2019	The "Smart Water Buddy" system utilizes a Layered IoT system architecture and employs unsupervised machine learning for detection of water usage irregularities.
3	Automatic Water Refilling System [3]	AYE THANDAR TUN, THET ZIN HTWE, CHAW SU AUNG	2020	The proposed system is an automatic water filling system using a reed switch and magnet sensor to control a pump motor based on water levels in a tank, turning the pump ON when the water level is low and OFF when the tank is full.
4	Design and development of Smart Water Quality Monitoring System Using IoT [4]	Waheed Muhammad Sanya, Mahmoud Abdulwahab Alawi, Issah Eugenio	2022	In this research, a smart water quality monitoring system has been developed in which pH, turbidity and temperature of the water are measured, and cloud data analytics are performed through IoT technology.

5	An Intelligent IoT and ML-Based Water Leakage Detection System [5]	Mohammed Rezwal Islam (Graduate Student Member, IEEE), Sami Azam, Bharanidharan Shanmugam, Deepika Mathur	2023	The study proposes a system that utilizes IoT technology and machine learning for real-time water leakage detection, intended to prevent water losses and mitigate ecological and economic impact of pipeline leakages
6	Monitoring water quality of Coimbatore wetlands, Tamil Nadu, India [6]	Chandra R, Nishadh K.A, Azeez P. A	2010	The study focuses on monitoring water quality using environmental monitoring assessments to ensure the sustainability of wetlands in Coimbatore.
7	Towards an IoT Based Water Management System for A Campus [7]	Prachet Varma, Akshay Kumar, Nihesh Rathod, Pratik Jain, Mallikarjun S., Renu Subramanian, Baradwaj Amrutur, Mohan Kumar, Rajesh Sundaresan	2015	The pipeline output driver with a transmission output driver and matching technique for the transmission network is indicated in this proposed system. It combines the relation values of components from the expanded version of BVD model for receiver circuit. This is the solution to optimise the working of the transmission system.

3. PROPOSED SYSTEM

The objective of the Smart Water Management Technology (SWMT) system is to offer integrated solutions for managing and monitoring water resources. This system is based on a network of IoT sensors for real-time data acquisition of crucial water parameters. It uses a cloud architecture for data processing and analysis, allowing it to scale and perform advanced analytics.

The SWMT system collects data on different types of parameters such as water level, temperature, turbidity with automatic notification to the user. The user interface of the web application serves as a bridge between the technical backend and frontend making it easier for the user to interact and make decision. In addition, the proposed model enables the remote control of water pumps for easy access to water supply.

By addressing the issues of water management, this study seeks to improve environmental sustainability, efficiency, and resource conservation in both urban and rural water systems.

3.1 System architecture

Fig. 2 illustrates the SWMT system architecture. We can observe from Fig. 2 that the design of the system is based on a robust 5-layer IoT architecture that integrates various hardware and software components to facilitate effective water resource management. This comprises the perception, network, middleware, application, and business layers, as illustrated in Fig. 3.

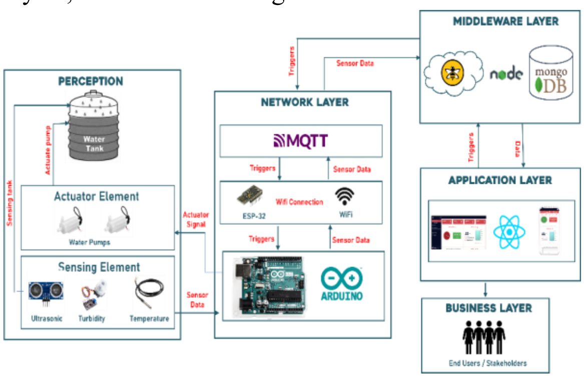

Fig 2: System Architecture

At the perception layer live the data sensing and actuation elements. Data representing water level, temperature, and turbidity are collected at this level by sensors and converted from analog to digital data by the Arduino controllers.

The network layer comprises the ESP32, MQTT protocol, and WIFI network to handle data communication between the perception layer and the middleware layer to facilitate remote monitoring.

Data storage, processing, and computational logic are handled by the middleware layer. This layer houses MongoDB, the database for storage, the NodeJS server, and the HiveMQ cloud service for data communication.

At the application layer lies the user interface for delivering services to the end users. Components at this layer include the web dashboard and pump control logic.

The business layer manages data analysis and decision-making for policy formulation.

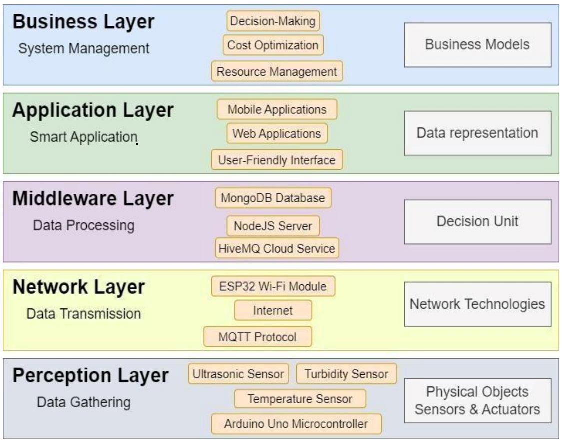

Fig 3: System Diagram

The proposed smart water management technology, integrates various hardware components, sensors, controllers, actuators as well as software requirements to amplify the efficiency of sensing, data transmission, and actuation.

3.2. Hardware

Arduino uno R3 board

It acts as a central controller for the system and handles signal and data communication between various system components i.e. actuators, sensors, and the esp32 board.

Specification: Atmega328p microcontroller, 14 digital I/O (input/output) pins, 6 analog input pins, a 16 MHZ ceramic resonator, and an in-circuit serial programming (ICSP) header and reset button.

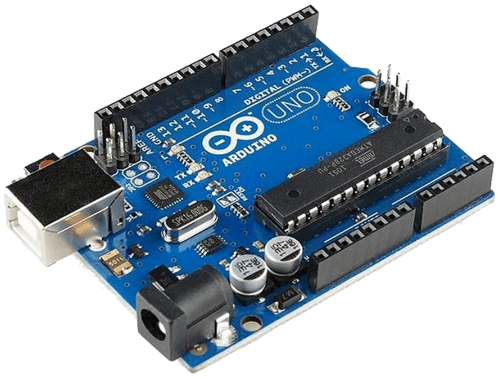

Fig 4: Arduino Uno R3 board

Esp32 WiFi module

It handles wireless communication and data transmission between the Arduino and cloud.

Specification: dual-core processor, 2.4 GHz Dual-Mode WiFi + Bluetooth Development, 38 PIN

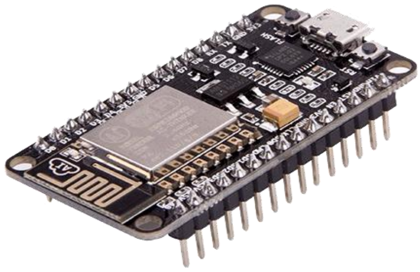

Fig 5: ESP32 WIFI Module

Ultrasonic Sensor (HC-SR04)

It measures the water level by calculating the distance from the surface of the water back to the sensor using ultrasonic sound waves [11]. It consists of a transmitter that uses a piezoelectric crystal to generate sound waves and a receiver that receives the echoes or ultrasonic waves as they bounce off an object or surface.

Specifications:

Supply voltage: +5V

Measurement range: 2 to 400 cm

Accuracy: ±1 – 3% of the measured distance

Fig 6: ultrasonic distance sensor (HC-SR04)

To calculate the water level, we attached an ultrasonic sensor to the downside of the covering of the tank facing the water. The ultrasonic sensor determines the distance between itself and the water's surface.

Distance calculation: The distance from the water surface is calculated from the duration measured by the sensor using the pulseIn function which measures the time it takes for the waves to reflect off the water's surface and return.
Where:

$$distance = \frac{duration}{2} \times \frac{1}{29.1}$$

distance = the distance from the sensor to the surface of the water
duration = the time it takes for soundwaves to travel from the sensor to the surface

29.1 = speed of light

Water level: To derive the corresponding water level or quantity, we use the following formula:

$$waterQty = H - distance$$

Where:
H = 20 cm (the height of the tank)
water Qty represents the calculated water quantity or level.

Fig 7: Ultrasonic sensor attached to the miniature main tank

Turbidity Sensor
It measures or judges the concentration of suspended particles [10] in the water using optical principles to evaluate the light transmittance or scattering. The intensity of transmitted light is converted by the receiving end relative to the corresponding current. Turbidity is measured in Nephelometric Turbidity Unit (NTU).

Specifications:
Working voltage: 5.00V DC
Working current: 40mA (MAX)
Response time: <500ms
Analog output: 0~4.5V

Fig 8: Turbidity Sensor

i. Calibration and Noise reduction:

To ensure an accurate reading, a calibration was done to tone down the noise from the sensor. The output analog voltage from the sensor has huge variations and is too noisy to measure. Hence, we took 800 readings [10] and then took the average value for the readings to reduce the fluctuations.

$$V_{avg} = \frac{\sum_{i=1}^{800} V_i}{800}$$

Where:
V_{avg} is the average voltage read from the sensor,
V_i is the individual voltage readings

ii. Voltage to NTU conversion:

The response from the sensor is categorized into two voltages:

For voltages below 2.5 V, the NTU value is fixed at 3000 NTU. This is demonstrated in Fig. 9, where the voltage is fixed at 3000 for a corresponding NTU value of 2.45.

If V_{avg} is < 2.5 V, Turbidity = 3000 NTU

For voltages above 2.5 V, the turbidity is measured as follows:

$NTU = -1120.4 * (V_{avg}2) + 5742.3 * V_{avg} - 4353.8$

As we can observe in Fig. 9 and Fig. 10, the NTU value for average voltages above 2.5 is calculated using the above formula.

Average Voltage	NTU
2.45	3000
2.52	2678.3
2.70	2104.7
2.85	1612.8
3.00	1225.6

Fig 9: Voltage to NTU conversion table

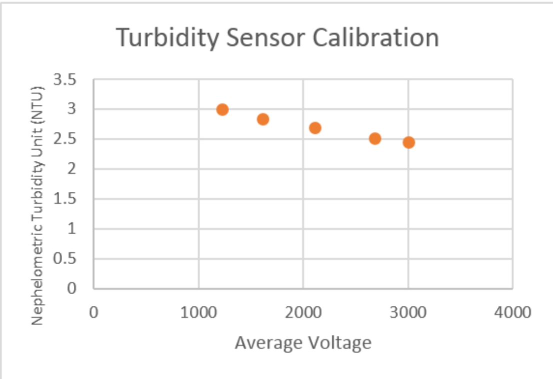

Fig 10: Turbidity Calibration Plot

Temperature sensor (DS18B20):
The DS18B20 temperature sensor is a submersible digital temperature sensor [9] that directly converts water temperature to digital data. Its high precision (up to 0.0625°C resolution) and one-wire interface make it ideal for aquatic monitoring. Used with the DallasTemperature library, it provides crucial data on water temperature, which correlates with microbial activity, enabling real-time assessment of water quality and potential pathogen risks.

Specification:
Temperature Range: -55°C to +125°C
Operating Voltage: 3 ~ 5.5 VDC
Accuracy: ±0.5°C (from -10°C to +85°C)

Fig 11: DS18B20 temperature sensor

Other components used include: two dc water pumps, two 5V relays, two 9V battery, some resistors, some diodes, some jumper wires, and a breadboard.

3.3. Software

Arduino IDE: used to program both the Arduino and esp32 boards.
Libraries used: WiFi, PubSubClient, ArduinoJson, OneWire, DallasTemperature, SoftwareSerial

NodeJs (ExpressJS): backend language used to program the webserver to handle HTTP (hypertext transfer protocol), and API requests between MQTT and the front end.
Libraries used: passportJs, mongoose, HTTP, expressJs, MQTT, socket.io

ReactJs with tailwind: frontend programming for a user-friendly web dashboard.

MQTT protocol: used for real-time data communication between the perception layer and the middleware layer where the web server lives.

MongoDB: NoSQL database for storing historical usage data and logs.

Pump Control Logic:
The system uses two 3-6V DC water pumps powered through a 5V relay and two 9V batteries respectively.

Pump 1: Supplies water from the source tank otherwise used to represent boreholes or other forms of water source. If the water level is below 5 Liters, the pump automatically opens to begin filling the tank as shown in Fig. 12. Likewise, if the water level exceeds 18 Liters, the pump automatically closes.

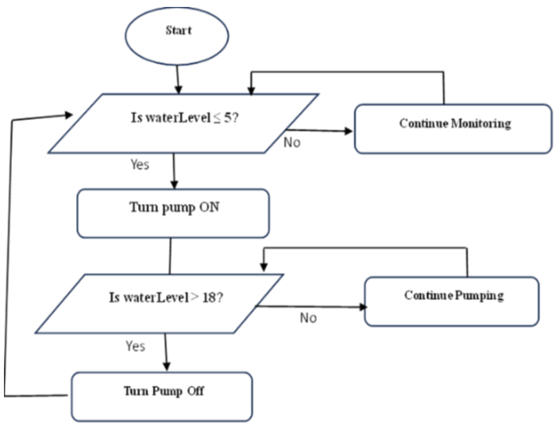

Fig 12: Pump 1 control flow chart

Pump 2: Supplies water from the main tank to be used for the assigned purpose – household usage, school or industrial supply, etc. Pump two is controlled remotely by the user from the web app through a button press as observed in Fig. 13.

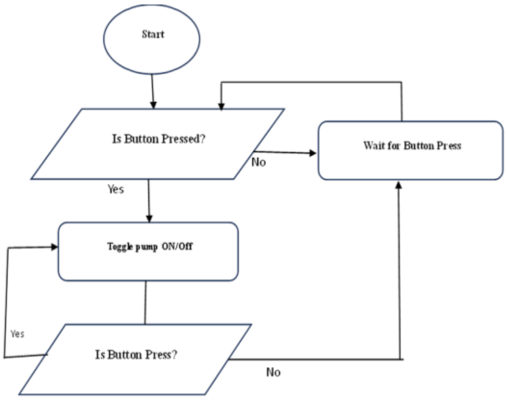

Fig 13: Pump 2 control flow chart

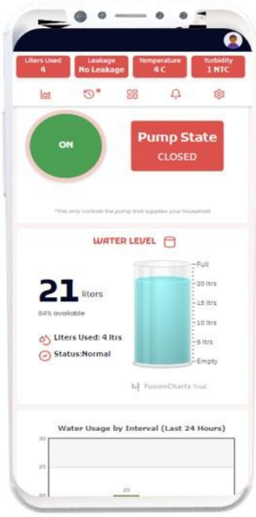

Fig 14: Web dashboard (Mobile) for controlling pump 2

The web application was developed to have a robust user interface and user experience that delivers all the functionalities of the system to the user - ReactJs and tailwind are the main frontend technologies used to achieve this result. Other libraries utilized such FusionCharts for real-time water tank simulation and usage chart as seen in Fig. 15, and redux for state management. Both historical and real-time data are retrieved from the backend and displayed on the dashboard for user convenience.

Features: Real-time tank simulation, remote pump control, historical usage chart, saving tips, history, and notifications including email alerts (see Fig.16 and Fig. 17).

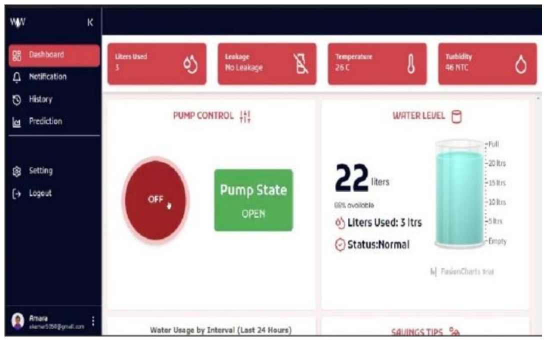

Fig 15: Web application dashboard

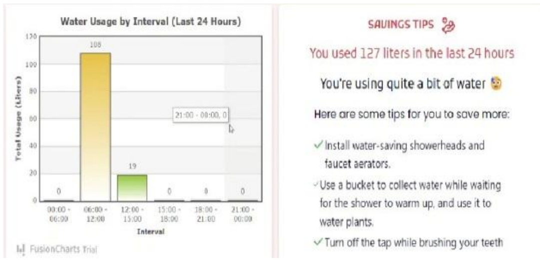

Fig 16: Water usage chart & Historical data

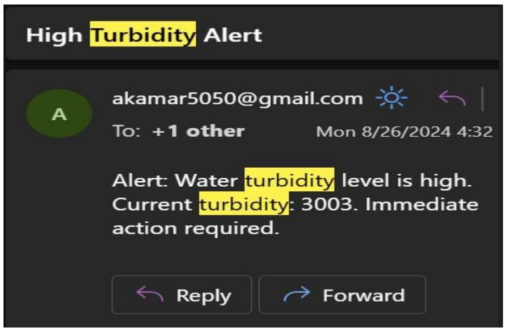

Fig 17: High turbidity email alert

3.4. Data Flow and Interaction

The data flow within the SWMT system can be summarized as follows (see Fig. 18):

Data Acquisition: Sensors continuously collect data on water quantity, water quality, and water temperature, sending it to the microcontroller.

Data Transmission: The microcontroller aggregates the data and transmits it to the cloud platform using secure communication protocols.

Data Processing: The cloud platform processes incoming data, generates forecasts, and detects anomalies.

User Interaction: Users access the application layer to visualize data, receive alerts, and make informed decisions based on the insights provided.

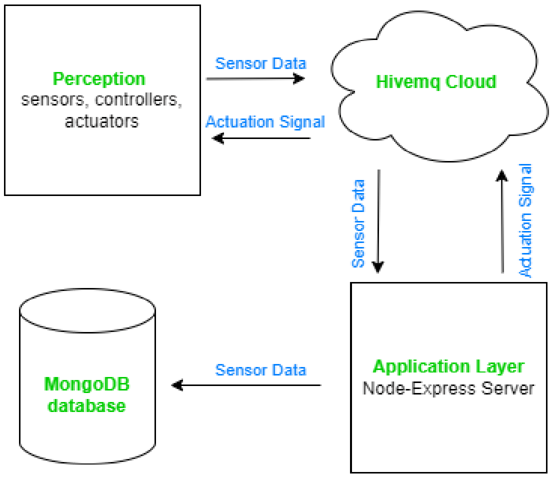

Fig 18: Data flow diagram

4. RESULT

To ensure that every part of the SWMT system functions as intended, it was put through extensive functional testing. By comparing the data which was gathered to the pre-determined reference values of the sensors we determined the accuracy of the sensors. By monitoring the packet loss, transmission latancy and the capacity of the microcontroller, cloud platform, and sensors to communicate we see how reliable it was. The sensors, microcontroller, and cloud integration subsystems were closely tested to make sure that they complied with the projects design requirements. By doing all this process it made sure that the important components of the SMWT system was operating as planned.

4.1 Testing of Framework Integration

To verify that the components of SWMT framework interacts consistently, framework interaction testing was done. A series of real world data testing was performed, including variations in water levels, temperature changes and ph differences. These tests aimed to monitor the changing environmental situations and to validate the components could dependably communicate and function as a whole. Important points noted were the system's responsiveness to sensor input data, the accuracy of the data and the transfer to the cloud storage system.

Successful integration testing confirmed that the SWMT framework appears to function well in an actual setup.

4.2 Optimization

Sensor Performance

Thewas tested against varying water conditions. Observations made show that there was a slight delay in the response time of the turbidity sensor as the water condition changed from clear to cloudy or murky. This was solved by smoothing out the extra noise using filters.

Energy Consumption

The water pumps consumed the most power despite being connected to a 5V relay. To solve this issue, diodes were added where necessary to dampen the noise and interruptions. We also implemented an interval-based operation to minimize power usage.

Communication Efficiency

The system was initially tested with the ThingSpeak platform which had a significant delay. MQTT communication came in handy as a suitable alternative. The MQTT monitored for data loss or delays. It was observed that the MQTT protocol reduced the delays by a significant margin.

4.3 Evaluation of Execution

An extensive execution assessment was done to ensure the SWMT framework accomplished its goals for execution. Important metrics including data accuracy, response time of the framework, energy consumption, and the predictive accuracy of machine learning models were examined. The accuracy of the information was assessed by contrasting real-time sensor results with pre-established benchmarks. Reaction time is the time taken by the sensors to detect and respond to(such as operating a valve). The energy consumption of the components (sensors and microcontrollers) was analyzed to ensure sustainability and reliability. Predictive models were used to monitor, analyze and predict the user data for system improvement for real-world performance optimization.

5. DISCUSSION

5.1 Accuracy of Information and Real-Time Verification

The SWMT architecture successfully provided precise real-time monitoring of important water parameters, resulting in the following outcomes:

1. Monitoring water level

Sensors gave 2% variation and rest being the accurate readings which were taken from the actual and recorded levels. This helped prevent users from water shortages and flooding by providing the users with informed decisions about the water levels.

2. Water Turbidity
The turbidity sensors alerted the users when the water quality dropped below safe levels. This helps users to know the quality of the water.

3. Temperature
Sensors collected the water temperature so that it helps to predict the water use and optimizing preservation during high temperature days.

5.2 Vitality Productivity

The SMWT framework optimized both the water and energy utilization due to its automated control system Automated Tank Refilling: By automating tank refilling in accordance with water level edges, the framework reduced the need for human mediation. This reduced flooding and prevented unnecessary water use, resulting in a 15% reduction in water consumption.

Vitality Effectiveness: The system reduced energy consumption by 12% by computerizing pumps and valves based on real-time data, resulting in a toll reserve fund for users and the advancement of economical practices.

5.3 Preservation

The SWMT framework successfully promoted optimal use and preservation of water:
Reduction in Water Wastage: By preventing floods and identifying spills, the system's real-time monitoring and predictive analytics significantly reduced water waste by 18%.

Optimal Water Use Designs: Using predictive analytics to identify the best times to use water resulted in a 10% reduction in water use during peak demand periods. Users described how these tiny bits of information improved their management of water resources.

Behavioural Alter: As a result of the system's real-time alerts and recommendations, users became more involved in monitoring their water usage, resulting in more sustainable consumption habits.

5.4 User Satisfaction

The intuitive design of the system led to high levels of fulfilment and engagement.
Information visualization tools helped users become more conscious of how they use water, which helped them make better decisions and promote water conservation.

6. CONCLUSION

Due to global environmental changes, the water resource management has become critically important. The traditional process which relied on the manual process have become inefficient and outdated for long-term sustainability and real-time variations.

In this context, SWMT system was introduced, integrating cloud computing, AI and IoT to enhance the reliability and efficiency for water management. The SMWT monitors water levels, quality and consumption with real-time data and future-oriented recommendations.

The system gives deep insights which help reduce the water usage by 8% during peak demands times based on the trends. The mechanized controls with the maximizing tank refills also observing the natural observation tracking such as temperature, pH and turbidity tracking.

The study demonstrates that the SWMT system improves water quality monitoring, user interface and supports water conservation efforts. These results shines light to potential tech-driven solutions in addressing the challenges of water management. The future focus will be on expanding the systems application to commercial, industrial and residential sectors, enhancing the sustainable resource management.

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