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Narrowband-Internet of Things based water metering system: a case-study for Nairobi County.

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Declaration and Approval

Declaration

I declare that this work has not been previously submitted and approved, in whole or partial, for the award of a degree by this or any other University. I believe the thesis contains no material previously published or written by another person except where due reference is made in this thesis.

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Signature ……………………. Date 29/05/2023…………………………

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Abstract

The adoption of smart water metering systems is gaining interest in commercial and domestic sectors. This technology can monitor water usage and solve challenges like leakages and water theft. Water companies in Kenya have started looking for solutions to monitor water usage, especially in urban centers. The broad implementation of these meters is facing limitations such as poor infrastructure for network connectivity and short battery life, leading to downtimes in data transmission. This study designs and implements a smart water metering system that utilizes Narrowband-Internet of Things (NB-IoT) communication technology. NB-IoT communication technology is a classification of Low Power Wide Area Networks (LPWANs) connectivity designed for IoT devices. The study included integrative reviews to determine the current water meters and how current data is collected and processed. The implemented system ensured transparency in collecting water metering, continuity of water supply to homesteads, and reduced labor for the water vending companies in Kenya. The system has a combination of hardware and software that demonstrates how NB-IoT technology is suitable to facilitate solving the existing issues faced by Nairobi City Water and Sewerage Company (NCWSC). The collected metering data was sent to a central server in real-time. It was then processed and analyzed to determine usage patterns. In addition, a web interface was developed to assist in the visualization of information by clients. The system demonstrated exceptional reliability over the deployment period by providing water consumption data. The communication reliability was exponential as the NB-IoT connection was maintained even inside buildings in Strathmore University indicating penetrations through the walls hence easy to deploy in other areas beyond Nairobi.

Keywords – *Narrowband-Internet of things (NB-IoT), Internet of Things (IoT), Low Power Wide Area Networks (LPWAN)*

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Abbreviations

3G	–	Third Generation of Connectivity/ Network Technology
AMQP	-	Advanced Message Queuing Protocol
API	–	Application Programming Interface
BLE	–	Bluetooth Low Energy
CoAP	-	Constrained Application Protocol
GPRS	-	General Packet Radio Services
GPS	-	Global Positioning System (GPS)
IoT	-	Internet of Things
LoRaWAN	-	Long Range Wide Area Network
LPWANs	-	Low Power Wide Area Networks
LTE-M	–	Long-Term Evaluation Machine
M2M	–	Machine-to-Machine Communication
MCU	–	Micro Controlling Unit
MQTT	-	Message Queuing Telemetry Transport
NB-IoT	-	Narrowband-Internet of Things
NCWSC	-	Nairobi City Water and Sewerage Company
NFC	–	Near Field Communication
RFID	–	Radio Frequency Identification
SMWS	–	Smart Meter Water Systems

Definition of Terms

LoRa	IoT communication technique that uses long-range, low-power, license-free sub-gigahertz radio frequency bands such as 169 MHz, 433 MHz (Asia), 868 MHz (Europe), and 915 MHz (North America).
Machine-to-Machine Communication	This describes communication between two or more fully automated computer systems where data is transferred without the involvement of any humans.
Sigfox	This technology uses a narrowband (or ultra-narrowband) spectrum. Binary phase-shift keying (BPSK), a popular radio transmission technology that adjusts the phase of the carrier radio wave while employing relatively few spectrum fragments, is used to encrypt data.
Narrow Band-IoT	This is cellular telephony channel-based Low Power Wide Area Network (LPWAN) radio technology standard that facilitates the interconnection of a wide range of devices and services.
LoRaWAN	A standardized Media Access Control (MAC) layer is designed to extend the LoRa physical communication layer to Internet networks.
Low Power Wide Area Network	A low-power wide-area network (LPWAN, LPWA, or LPN) is a sort of wireless wide-area network designed to provide long-distance communications at a low bit rate between devices (connected objects) powered by batteries, such as sensors.

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Dedication

I dedicate this accomplishment to my parents, who have always been my pillars of strength and support and whose everlasting love has been my life's compass. This accomplishment was made possible by your sacrifices, support, and unfailing confidence in me. I will be eternally grateful for your constant support, tolerance, and love. I dedicate this thesis to you as a symbol of my gratitude for everything you've done for me. Your love and support have been the driving force behind my achievement, and I aim to continue to make you proud in my future undertakings.

Chapter One: Introduction

1.1. Background to the Study

Kenya has over 70 water and sewerage companies, most of which are found in urban areas (Kipkoech, 2021). The need for water and sanitation services is anticipated to rise due to the urban population, which currently stands at about 12 million and is forecasted to reach 14 million by 2050 ("Providing Sustainable Sanitation," 2020). Rehabilitating water catchment areas has boosted the water supply in Nairobi County because of increased water use ("Nairobi Drinking Water," 2022). However, not every neighborhood in Nairobi has access to reliable piped water. According to Ledant (2013), while lower-income areas have limited access, middle- or higher-income districts typically have a coverage of 85-95%.

Kisiangani et al. (2018) indicated that water meters are essential for monitoring and quantifying water usage in metropolitan areas. When metering becomes inefficient and precise data is unavailable, water corporations face financial instability (Mutikanga et al., 2011). This issue has necessitated the creation of a smart water metering system to aid in the reduction of water losses caused by neglect or inaccurate reading of water meters. It will also give end users a real-time study of their water consumption and knowledge of monthly water bill fluctuations.

Globally, Internet of Things (IoT) usage has increased significantly in last years, with major companies such as Cisco, Dexcom, and Intel investing heavily in the technology (Green, 2022). These efforts have yielded an increasing return on investment for businesses and people.

According to Patel et al. (2016), IoT is an interconnection of info-sensing devices that transmit data and communications to achieve smart recognition, location, tracking, monitoring, and management. The IoT stack consists of intelligent endpoint devices, gateways for connectivity, and cloud data centers for global data analysis and storage (Sethi & Sarangi, 2017).

About 12 innovation hubs and startups in Kenya are creating IoT for smart homes and agriculture technologies, resulting in an increase in IoT adoption (Hersman, 2019). This expanding IoT landscape in Kenya enables collaboration between various sectors, such as telecommunications companies and research labs. This is meant to provide services within their traditional business blocks and achieve low power wide area networks (LPWANs) connectivity to sustain reliable IoT device communication (Maombo, 2022).

IoT innovation has contributed to the development of smart water meter systems, such as the one developed by Kenya Airport Packing Service (KAPS). KAPS aims to provide utility managers with a real-time water supply and consumption data and improve customer communication. However, typical data transmission technologies such as GPRS are inefficient for outdoor applications due to their high-power consumption ("KAPS Innovative Water Management System," n.d.).

Sensor nodes such as water meters rely on battery power. The lifespan of these batteries is affected by factors such as data collation, data communication frequency, and the technology employed. Kalyan et al., (2020) indicated that LPWAN technologies, such as Long-Range Wide Area Network (LoRaWAN), Long Term Evaluation for Machines (LTE-M), Sigfox, and NB-IoT, provide broad area connection with minimal transmission power and are appropriate for such applications.

1.2. Problem Statement

Most piped water resource providers in Kenya rely on manual water meters whose readings are made and processed at the end of a monthly consumption period for consumers (Kingdom et al., 2006). This makes the process of gathering data expensive due to its labor-intensive nature. The adoption of smart water metering systems in urban locations such as Nairobi is emerging. However, the problem of reliable power supply for the metering devices hinders the wider deployment of the infrastructure (Ramakrishnan et al., 2020).

Metering devices are mainly powered by batteries that need to be recharged or replaced periodically. Frequent transmission of meter reading data to cloud infrastructure is a process that consumes significant battery power. Conventional data communication technologies such as Wi-Fi, 3G GPRS, and 4G LTE were designed for computers and mobile phones that users carry, so their batteries are easily recharged when depleted.

Consequently, this indicates that frequent depletion of their batteries will result in unreliable meter readings, and manually recharging them will increase the cost of operation. LPWAN technologies have been designed to support sensor applications, such as smart water metering, that transmit small volumes of data at a high frequency (Mekki et al., 2019). There is a need for the development of NB-IoT smart water meters to address power challenges faced by IoT devices and ensure that the cost of operation incurred by frequently battery replacement is lowered.

1.3. Objectives of the Study

1.3.1. General Objectives

The general objective of the study was to implement an NB-IoT-based smart watering system that collects water usage and developed a visualization platform for water companies and their customers.

1.3.2. Specific Objectives

i. To study existing problems associated with existing water meters.
ii. To review work done on smart water meters and technologies used.
iii. To implement a smart metering system that transmits data using NB-IoT.
iv. To test the smart water metering system in Nairobi County.

1.4. Research Questions

i. What are the existing problems associated with existing water meters?
ii. What is the work done on smart water meters and technologies used?
iii. How can we implement a smart water metering system that transmits data using NB-IoT?
iv. What are the test results for the smart water metering system in Nairobi County?

1.5. Significance of Study

This study offered a solution that improved data collection techniques of water consumption for the water and sewerage companies in Kenya. This helped water companies to be more efficient in the collection of usage data for the preparation of water bills for their customers while aiming to improve customer experience due to transparency manner since they were able to see their consumption levels facilitated NB-IoT-based smart water metering systems.

1.6. Scope and Limitations

The research focused on smart water metering systems that used NB-IoT technology to solve data collection and transmission challenges for water companies in Kenya. The research adopted IoT technology to develop a battery-powered water meter prototype. This device sends data to cloud database in real-time and displays values on a web application to demonstrate a more reliable approach to collecting water consumption data remotely.

The prototype developed was NB-IoT enabled, demonstrating how reliable LPWAN connectivity protocols are reliable for long distances and can save power if implemented in rural or urban centers. The test was conducted in Nairobi, Madaraka area, where Safaricom has an NB-IoT network deployed already.

Chapter Two: Literature Review

2.1. Introduction

The smart city paradigm has influenced the management of sustainable urban water resources. Water utilities are increasingly using smart metering programs for end users to understand how much water is used in cities (Novotny, 2008). Such a thorough and continuous flow of information is supposed to increase network efficiency and improve water planning by having more precise demand patterns and projections and lowering some labor expenses, such as those associated with the manual meter reading.

2.2. Empirical Literature

Sithole et al. (2016) studied and designed a solar powered smart meter to detect water leakage in customer premises and report this in real-time using Arduino Uno as the microcontroller and a flow rate sensor to detect the quantity of water flowing through the sensor. Data that was collected was saved in Electrically Erasable Programmable Read-only Memory (EEPROM) was employed to save data temporarily before transmission. The quantity of water was then displayed to customers through a Liquid-crystal display (LCD) while data was transmitted to a database using GSM/GPRS for visualization through a web page. The outcome of this device was that the flow meter data was accurate by 99.4%, and the error encountered was due to human error during the process of Closing and opening the valve and losses by the flow meter itself. This study concluded that a smart meter is ideal for domestic or residential homes to monitor real-time usage.

Horsburgh et al. (2017) developed an inexpensive intelligent water metering technique to measure the amount of water used and the behavior of people using water in restrooms. Highly efficient automatic faucets and flush valves for toilets were used in this study. The inexpensive smart water meters demonstration showed that institutions could remotely measure the amount of water used, identify leakages in the pipeline, and malfunction with meters, a feature that can help meet the goal of sustainable water usage. The study used a Raspberry Pi computer and a hall sensor for the meter. The Raspberry Pi worked as the microcontroller by storing data collected by sensors. The data was stored in an SD card in CSV file format and then retrieved daily over a Wi-Fi network. This test showed that smart meters could assist in managing water and remote monitoring of water quantity usage in various residential areas or institutions.

Li et al. (2019) developed a smart water meter reading system that used a lightweight convolution network to recognize meter numbers. A cloud platform was used to test if the system could handle images converted into text format using a convolutional neural network (CNN). Wi-Fi or 4G modules were then used to send data to a real-time database. The result indicated that the CNN model reduced the computational time of water data by 10 times, the model space was reduced by up to 7 times and saved up to 3 times in running time compared to standard convolution kernels. This model fits well for industrial use.

Saidi et al. (2020) devised a smart water meter system consisting of software, hardware, and power line communication (PLC) to investigate accurate water utilization and billing processes. At the end of the study, Saidi et al. (2020) validated the result using flow sensors, an LCD, power grid lines, and short message service (SMS). Flow sensors collected the cumulative water consumption in a household, LCD displayed the water reading to clients, PLC coded and decoded data, and then transmitted data over power lines. SMS was used to notify customers of their bills and consumption rates.

Hsia et al. (2021) designed an automatic water meter reading system using co-designed hardware, software, and GSM/4G to transmit data. Data collected is transmitted to the database using the TCP/IP protocol. Hsia et al. (2021) utilized hardware and software to develop this system. This study concluded that an accuracy of up to 97% could be achieved if errors related to software and communication could be sorted out. Communication errors due to wrong data parameters transmitted and errors from meter sensing were some of the issues highlighted. Since GSM uses a lot of power during data transmission, the device must be supplied with power to run all the time. Hsia et al. (2021) study proposed a system that uses Radio Frequency (RF) sensing techniques that will fit into the existing pipes that supply water. To save energy, the power supply should be geared toward data transmission.

Ye et al. (2021) proposed a Smart Water metering system (SWATS) that used LoRa. The adopted technology used sensors and microcontrollers to access the source of water utilization in real time and then calculate the amount of water utilization in real time. This study further indicated that mechanical water meters are widely used, but smart water meters would be appropriate for managing resources such as water wells. Smart water meters such as SWATS can assist in water management while consuming low power, making them low-cost and friendly to battery-powered approaches.

Nadipalli et al. (2021), design a prototype for a intelligent water metering system. The system applied a flow sensor and an ESP8266 module to relay collected data to a cloud-based server. The study collected data measurements about water utilization by family or individual, and the consumption data was observed by the end consumer using a server. The billing process differs from the consumer plan they have subscribed to. To reduce power waste by device, if the consumer is out of the house, the water supply is cut off by controlling a relay from the dashboard. This study indicated that such a system could save thousands of litres, conserving water.

Lalle et al. (2020) studied the total of smart water meters that one LoRaWAN gateway can support. End devices were transmitting data to a single channel gateway that was deployed in the centre of well-distributed nodes within a 7500m radius. Nodes were allowed to send data within 300 seconds. The default channels for the European Union were utilized, with payload size set to 32 bytes. This study showed that a network of 100 small water metering nodes obtained 80% packet delivery. A fixed spreading factor of 12 (SF12) worked well for all 100 nodes and had to be left constant. Therefore, a single LoRaWAN gateway can support up to a thousand smart water meters with a 92% packet delivery ratio.

2.3. Theoretical Literature

Al-Naser & El-Medany (2018) proposed a serverless cloud-based infrastructure for smart water metering for the kingdom of Bahrain. This proposed system used API gateways, Amazon lambda functions, DynamoDB, or Amazon S3 storage that contains information that the customer relates to, such as bills. Data from the water meters is submitted to web servers to make sure that water usage has been monitored. Therefore, the serverless solution is implemented to ensure that customers can access the requested information. The API gateway triggers the Amazon lambda, therefore running the user request. The processed information is stored in a Dynamo cloud or Amazon S3 storage. When a client requests this information, it is then displayed to them on request since it has been preprocessed. This proposal was to provide a more secure, reliable, low-cost system.

Mankad and Arolkar (2020) indicated a need for a framework that best works for smart water metering systems. The study discussed how an open-source framework free from online could support smart metering applications. This framework includes Grid eXchande Fabric or the Open Smart Grid Platform (OSGP). This framework, therefore, allows users to monitor and control devices using web applications. Communicating interfaces that usually work for OSGP is CDMA and GPRS. From the investigation done by Mankad and Arolkar (2020) of all the open framework applications, they concluded that OSGP suites smart water metering systems.

Horspool (n.d.) indicates that water meters measure characteristics of liquid water, such as speed of flow and quantity used. Many water meters are used for monthly billing purposes or to measure the right amount of water to use or add to predictions or processes. The water meter reading process differs depending on the meter type as indicated below.

2.3.1. Mechanical Water Meter Reading

This type of water meter has a lining figure that shows the volume of water flowing through it. The volume is cubic meters, and the dial should be read in two faces. The upper part, with several rollers of a numeric dial, is ready to get water capacity passing through the meter. The first five rollers from the left are the complete units in cubic meters, and the last two are decimals (SeoClick, 2022).

Figure 2. 1: Mechanical Water Meter (SeoClick, 2022)

2.3.2. Digital Water Meter Reading

This type of meter has a digital display, which makes it easier to read the amount of water streaming through it. The display shows the totalized amount of water that has been consumed. The amount displayed is in cubic meters (SeoClick, 2022).

Figure 2. 2: Digital Water Meter ("Innov8 Digital Register", n.d.)

2.3.3. IoT Smart Water Meters

The visualization of data from water meters is done through applications. The apps display the water through the meters instantly, and users can make a comparison over time. These meters have a communication module that sends data to cloud databases (SeoClick, 2022). These types of water meters are composed of components that include microcontrollers, Sensors, communications modules, and algorithms that assist in collecting the data needed.

2.4. IoT Communication Technologies

The advancement of IoT communication technology has assisted the devices developed to communicate with each other and therefore become part of the global Internet (Bahashwan et al., 2020). According to Al-Sarawi et al. (2017) IoT Communication technologies can be LPWAN or short-range networks. Figure 2.3 illustrates the categorization of these communication technologies.

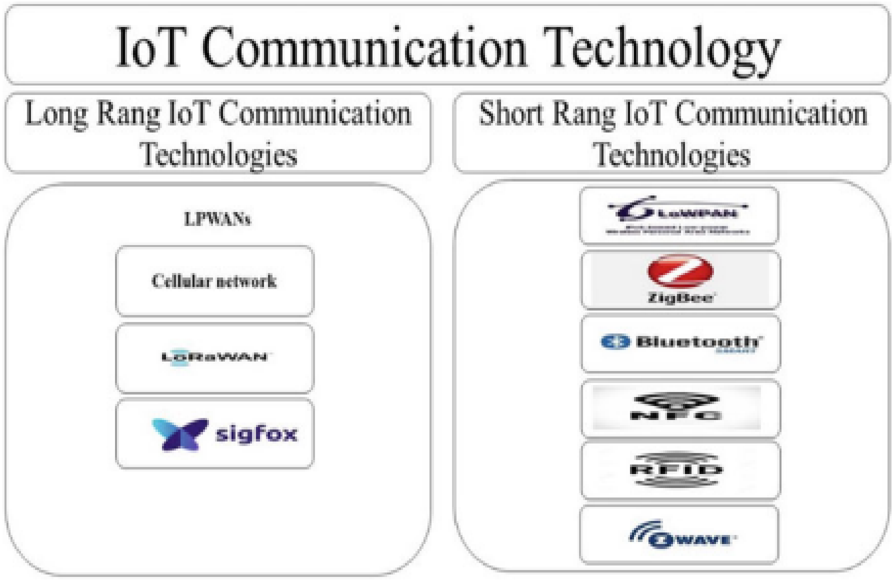

Figure 2. 3: IoT communication Technologies (Bahashwan et al., 2020)

2.4.1. LPWANs Cellular Networks

Wireless technologies play an important role in linking mobile devices and smart items to the cloud. Furthermore, radio frequency (RF) could be utilized to remove wires due to their transmission style, speed, cost, security, bandwidth consistency, and range. LTE-M and NB-IoT are examples of common long-distance IoT communication methods that leverage LPWANs for long-distance broadcast.

Revolutions have happened in cellular networks, allowing devices enabled with cellular networks to be faster and support data and voice communication with enhanced media and sleepless roaming capabilities. Cellular devices are growing in number and functionality, with this network being utilized for entertainment and phone calls (Liu et al., 2014). According to Okoro (2014), a cellular network can be built in various ways, and various continents or countries utilize different standards, such as Code-Division Multiple Access (CDMA) and GSM. Through this technology, users with mobile stations (MS) connect to the network, and this makes MS, also called user equipment (UE), to be the most important cell network equipment.

A mobile station refers to a wireless or a portable gadget that comprises of software for transmitting voice or data, broadband adapter, a transceiver, a control unit (CU) and an antenna. These gadgets are utilized by users for communication over a network. This type of network that IoT employs is called cellular IoT, which works in through various generations of mobile network technologies such as 2G, 3G, 4G and 5G.

2G is a cellular technology that is best suited for machine-to-machine (M2M) environments. M2M is a type of communication where machines exchange data with each other. 2G falls under the licensed spectrum, which means that it is regulated by the government. Other types of cellular technologies that fall under the licensed spectrum include NB-IoT and LTE-M. All these technologies can be embedded into devices that are low-power consumers ("A Guide to Cellular IoT," n.d.). Most cellular technologies use a lot of power, but NB-IoT and LTE-M are designed for low-power consumption and low data usage during data collection and transmission to databases. This makes them a good choice for M2M applications, where devices must operate for long periods using a battery.

2.4.1.1. LTE-M

According to 3GPP release 13, LTE-M is a cellular technology that is designed to support IoT devices. It uses narrowband channels with a bandwidth of 1.08 MHz and operates on the LTE spectrum. LTE-M enables extended coverage and deep indoor penetration through a variety of techniques, including power-saving mode, discontinuous reception (DRX), and extended discontinuous reception (eDRX), which allow devices to operate for extended periods on a single battery charge and save power when not actively transmitting or receiving data. This communication technology also supports mobility management and paging, allowing devices to switch between base stations without losing connectivity. It includes several power-saving features, such as power headroom reporting, which allows devices to adjust their transmit power based on the strength of the signal received by the base station. LTE-M also includes enhanced security features, such as encryption and authentication, to safeguard data transmitted across the network (ETSI, 2016).

According to Borkar (2020), LTE-M is a versatile technology that supports numerous applications and devices, with the capacity to accommodate up to 100,000 devices per access station. It offers superior indoor coverage compared to LTE, as it can overcome path loss and attenuation caused by walls and floors. LTE-M has the advantage of operating at low power and can last up to ten years on a single battery charge. This is especially useful in remote areas where there is no access to electricity. It also supports both immediate and critical applications that require minimal delays, as well as applications that can tolerate delays of a few seconds. Moreover, LTE-M is cost-effective, and its functionality is comparable to that of LTE. It can also support voice as a standard LTE feature, and it is compatible with both LTE networks and MTC traffic, eliminating the need for a gateway. To ensure compatibility, LTE-M is deployed in-band within an LTE carrier and is upgradeable from LTE software, offering a seamless transition toward 5G MTC solutions. This information is based on Borkar's research in 2020.

2.4.1.2. NB-IoT

NB-IoT is a modern LPWAN standard that allows for long-distance and low-data-rate IoT applications. It has cutting-edge capabilities such as extensive coverage, exceptional energy efficiency, and widespread connectivity. Furthermore, NB-IoT offers a variety of innovative features for deploying LPWAN that effectively address issues such as low reliability, inadequate security, and high operational and maintenance costs. Top mobile equipment and module manufacturers can incorporate NB-IoT into their products, and it can work seamlessly with 2G, 3G, 4G, and 5G cellular networks (Ismail et al., 2018).

NB-IoT operators consider devices, measurements of data rate and latency to be crucial. The two factors that affect the performance of NB-IoT is typically modulation and spectrum bandwidth. These factors are dependent on the frame structure of the uplink and downlink transmission modes. The key technical aspects of NB-IoT include modulation and spectrum bandwidth, transmission mode, operation mode, and NB-IoT frame structure. The NB-IoT radio network technology is equipped with software that enables access to three types of spectrum bands, which are 1800 MHz for 2G and 4G, 2100 MHz for 3G and 4G, and 900 MHz for 3G and 4G. These spectrum bands are supported by modules from various manufacturers. The implementation of NB-IoT can be carried out in three different operating scenarios, which are in-band, guard-band, and standalone (Hassan et al., 2020).

To repurpose unused cellular service spectrum for standalone services, one or more GSMs on both sides of the spectrum with a bandwidth of 200 kHz and a guard interval of 10 kHz can be formatted to transport NB-IoT traffic, enabling a seamless transition to LTE massive machine communications (Wang et al., 2017). Two scenarios are possible: the guard-band scenario, in which NB-IoT traffic is placed in the guard-band of LTE carriers without using LTE resources, and the in-band scenario, in which NB-IoT can share LTE resources based on mobile user or device demand. The latter option is more cost-effective but requires an eNodeB software upgrade (Sharma & Wang, 2020). Figure 2.4 depicts the process of assigning NB-IoT to a selected carrier from the LTE spectrum based on the three operation options. The standalone option requires new hardware for antenna and RF systems, resulting in higher initial costs. In contrast, the initial cost for both in-band and guard-band options is similar, but the spectrum cost varies because in-band uses coexisting LTE signals while guard-band uses free physical spectrum. Regardless of the operation option chosen, the deployment of NB-IoT should be transparent to UEs, which only need to search for a 100 kHz carrier as an anchor carrier for initial synchronization.

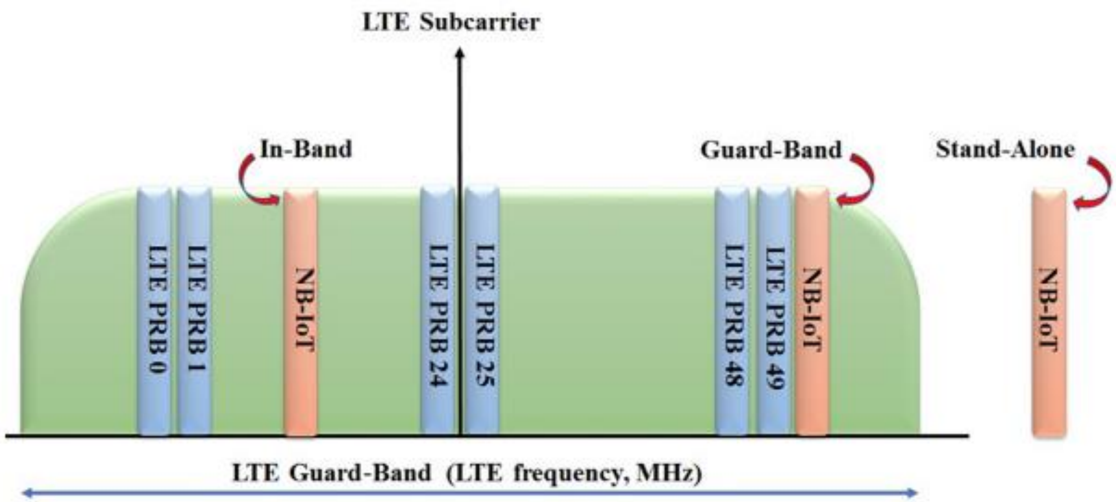

Figure 2. 4: LTE spectrum carrier selection for NB-IoT (Hassan et al., 2020)

2.4.2. LoRaWAN and Sigfox

2.4.2.1. LoRaWAN

LoRaWAN is a low power, with long-range communication capabilities to transmit a few bytes of data over 20 km in open areas and 5 km in urban areas while consuming little power (Basford et al., 2020). The LoRa Alliance oversees the development and supporting the technology, which features middle access control and permits communication between devices or via gateways. A client device, a gateway, and a server comprise the LoRaWAN architecture. LoRa's physical layer enables long-distance connectivity, low data transfer rates, and low-power wireless connections. The network is designed in the form of a star and runs in the unlicensed Industrial, Scientific, and

Medical (ISM) spectrum (Foubert & Mitton, 2020). The LoRa Alliance oversees developing and specifying LoRaWAN specifications.

The LoRaWAN technology is separated into three types of end devices that may send and receive data (A, B, and C). The gateway connects end devices to network servers, whereas the server maintains the entire network (Vangelista et al., 2015). Class A devices interact bidirectionally and use battery sensors, Class B devices segregate up-link and down-link communication to reduce latency, and Class C end devices are suitable for real-time applications but have lower power efficiency (Navarro-Ortiz et al., 2018). Figure 2.5 depicts the LoRaWAN network architecture, which contains a client device, a gateway, and a server.

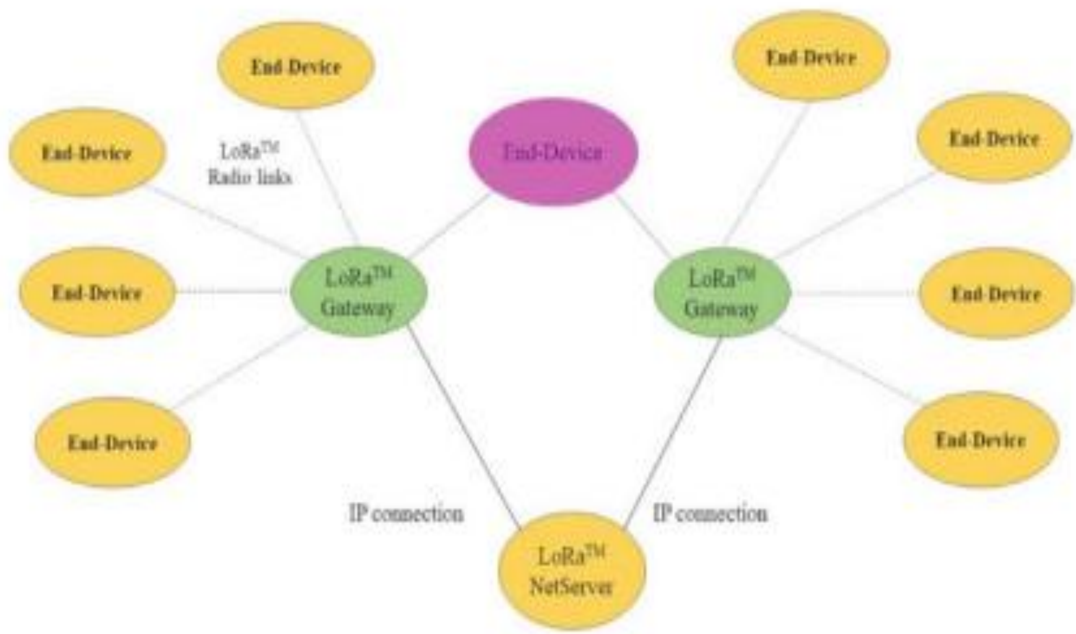

Figure 2. 5: LoRaWAN Architecture (Bahashwan et al., 2020)

2.4.2.2. SigFox

Sigfox is capable of bi-directional transmission and can manage millions of smart items, with a range of 30-50 km in rural areas and up to 3-10 km in urban areas (Sigfox, 2018). This technology belongs to the low-power wide-area wireless technologies family, capable of supporting a diverse range of applications including M2M. It operates at a transmission rate ranging from 10 to 1000 bits per second and is powered by batteries, utilizing a star network architecture (Al-Sarawi et al., 2017

2.4.3. Short-Range Communication Technologies

Near-field communication (NFC), IPv6 over low-power wireless personal area network (6LoWPAN), Bluetooth, Zigbee, Z-wave, and radio frequency identification (RFID) are all examples of short-range communication technologies. These communication systems employ low-power networks in order to send data (Bahashwan et al., 2020).

2.4.3.1. 6LoWPAN

The 6LoWPAN protocol is the primary and most employed IoT communication standard due to its basis on an Internet Protocol (IP) internetworking standard. This protocol enables direct connectivity with another IP network without requiring intermediary devices like translation gateways or proxies. The Internet Engineering Task Force (IETF) developed this standard for low-power wireless IEEE802.15.4 networks utilizing IPv6 for IP communication. With its capacity to handle up to 2128 IP addresses, 6LoWPAN provides ample addresses for IoT devices (Al-Sarawi et al., 2017).

The goal is to handle addresses of various lengths at a low cost and with little power consumption. 6loWPAN is compatible with a wide range of topologies, including mesh and star topologies. 6loWPAN offers an adoption layer between the MAC layer and the network layer (IPv6) to handle compatibility between IEEE 802.15.4 and IPv6 (Salman & Jain, 2016).

2.4.3.2. Zigbee Technology

ZigBee is a communication protocol established by the ZigBee Alliance, which is grounded on the IEEE802.15.4 low-power wireless network standard. The primary purpose of ZigBee is to allow cost-effective and advanced communication protocols for personal area networks utilizing small digital radios that are low-power to transmit data over extended distances. ZigBee is used in applications that require secure networking devices, extended battery life, and low data rates. Additionally, ZigBee supports multiple network topologies, such as mesh, star, and tree network topologies (Bahashwan et al., 2020).

This type of communication technology is faced with challenges such as a short range of communication, hence not suitable for outdoor wireless communication systems; low data transmission speeds, low network stability; and is expensive to use compared to other technologies (Prasanna, 2022).

2.4.3.3. Bluetooth

Bluetooth is a sophisticated technology that is embedded into many smart gadgets and is used for data transmission and reception over short distances or in personal area networks. The Bluetooth ISM band operates between 2.400 and 2.485 GHz. Furthermore, the Bluetooth network style is star topology (Celosia & Cunche, 2019).

Bluetooth low energy (BLE) is a type of Bluetooth technology that is frequently used in smart devices and the Internet of Things (IoT) model to achieve low power consumption, low latency, and low bandwidth (Ghori et al., 2019). While universal Bluetooth is commonly used in mobile phones due to its sufficient throughput, it is also applied in data stream applications like audio, with a standard limit of seven simultaneous users.

The most recent Bluetooth technology is highlighted to be Bluetooth 5 and is offering improved speed, range, and broadcasting capacity, with new features aimed especially at IoT devices and smartphones (Collotta et al., 2018).

2.4.3.4. NFC

Near Field Communication (NFC) is a communication technology that wirelessly allows data to be sent between devices by just touching or bringing them close together. This technology is adopted in mobile phones, contactless payment systems, and industrial applications. It can operate in a variety of modes, including reader/writer, card emulation, and peer-to-peer. It also facilitates the connecting, commissioning, and control of IoT devices in several scenarios (Coskun et al., 2013).

2.4.3.5. RFID

RFID is made up of a reader and a Radio Frequency tag, with a tiny chip that transmits data wirelessly. The RFID tag wirelessly transfers small amounts of data to respond to the reader. RFID technology is used for short-distance communication to automatically recognize items and people. RFID tags are famous since they have long been utilized in health care, national security, poll payment, libraries, agriculture, and proximity cards. There are two types of active reader tags: passive reader tags and active tags. Those tags that are active use high radio frequencies and are powered by batteries. Whilst passive tags are powerless and do not use many frequencies (Atlam et al., 2020).

2.4.3.6. Z-Wave

The Z-wave Technique is a low-power wireless technology utilized for communication that serves as an excellent protocol for IoT devices since it can link to 30-50 devices. It is especially advantageous for home automation and light commercial settings. This wireless transmission protocol is reliable and suitable for transmitting brief messages between network nodes or a control unit. It is divided into five layers: application, routing, transfer, medium access control (MAC), and physical (PHY). Additionally, it operates on the 900 MHz ISM band and broadcasts at 9.6 and 40 kbps.

The Z-wave 400 series can function at 2.4 GHz and sustain data rates of up to 200 kbps. This technology comprises two main components: the controller and the slaves. The controller directs the slaves, while the slaves execute the orders given by the controller. The controller maintains a routing table to select the most efficient route to reach the destination. The slave nodes simultaneously act as routers and relay messages to other nodes within the network (Gomez & Paradells, 2010).

2.4.3.7. Wi-Fi/802.11

Wi-Fi is a wireless technology that permits the transmission of Internet protocol data from a network connection to a host computer using radio waves. It is based on the WLAN wireless Ethernet 802.11b standard. Compared to dial-up, most internet connections, such as satellite, digital subscriber line (DSL), or cable, are faster. Wi-Fi is a wireless connection between a computer and an internet connection at home or in public spaces, such as hotel rooms or business conference rooms. It involves a wireless client and a base station that connects two wireless clients. With Wi-Fi, users can access the internet without the need for cables. It is a wireless technology like cell phones, and it enables computers to send and receive data within and beyond the range of a base station (Al-alawi, 2006).

2.5. IoT Data Protocols

IoT protocols are set guidelines that are utilized to exchange data between electrical devices (Eshghi, 2021). Numerous IoT protocols have been developed expressly to suit the needs of rapid and reliable corporate transactions. Others, on the other hand, are tuned to satisfy data-gathering needs, such as sensor updates in limited networks. Each of these protocols has advantages and downsides when dealing with diverse IoT scenarios (Vahidnia & Dian, 2021). As a result, understanding the characteristics of various IoT protocols is crucial to selecting the best-fit protocol for your use case.

2.5.1. Constrained Application Protocol (CoAP)

CoAP is a web transfer protocol that is specifically created for use with small nodes and networks. These nodes usually have limited read-only memory (ROM) and random-access memory (RAM) and are equipped with 8-bit microcontrollers. Moreover, the networks that use this protocol, such as IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs), often experience high packet error rates and have a typical throughput of tens of kbit/s. The primary purpose of the CoAP protocol is to enable machine-to-machine (M2M) applications like smart meters and building automation.

CoAP enables built-in service and resource discovery, as well as essential Web principles like Internet media formats and URIs. CoAP is meant to connect simply with HTTP for Web integration while satisfying requirements (Shelby et al., 2014).

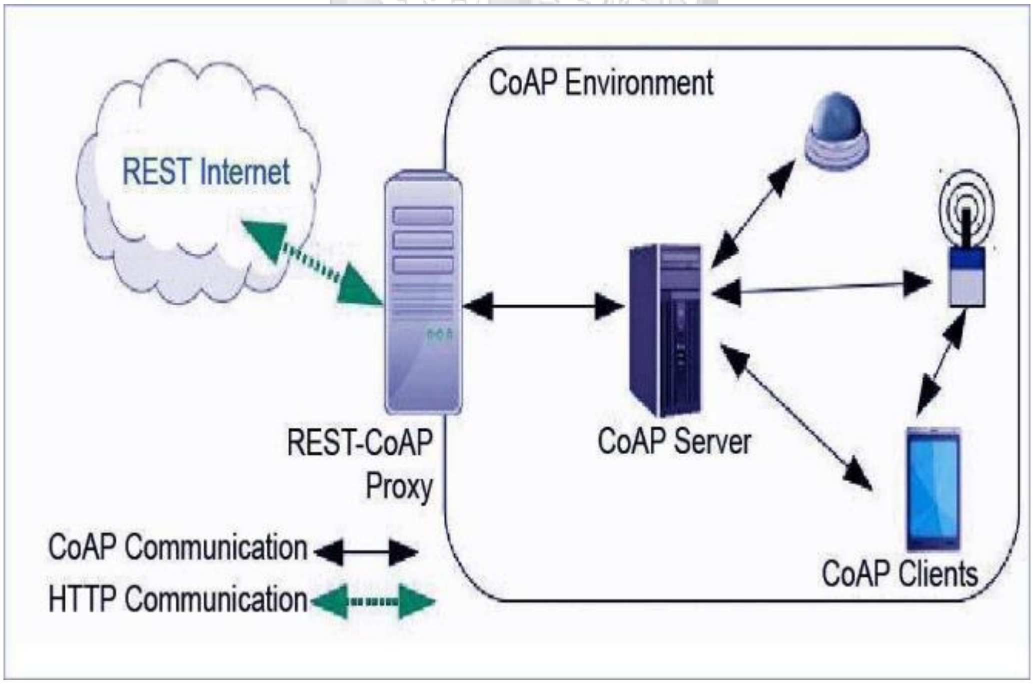

Figure 2. 6: CoAP Architecture ("4 Key IoT Protocols," 2018)

2.5.2. Advanced Message Queuing Protocol (AMQP)

The design of AMQP IoT protocols is made up of soft and hard components that route and preserve messages inside a broker carrier, as well as a set of policies that connect the components. This protocol enables patron programs to interface with the AMQP model and broker communication (Vahidnia & Dian, 2021). It includes the following components for seamless operation: -

Exchange: Routing messages that it has received from the publishers and queues them.

Message Queue: Temporarily stores messages until they may be completely processed by the requesting client software.

Binding: This term expresses the connection between the message queue and the change.

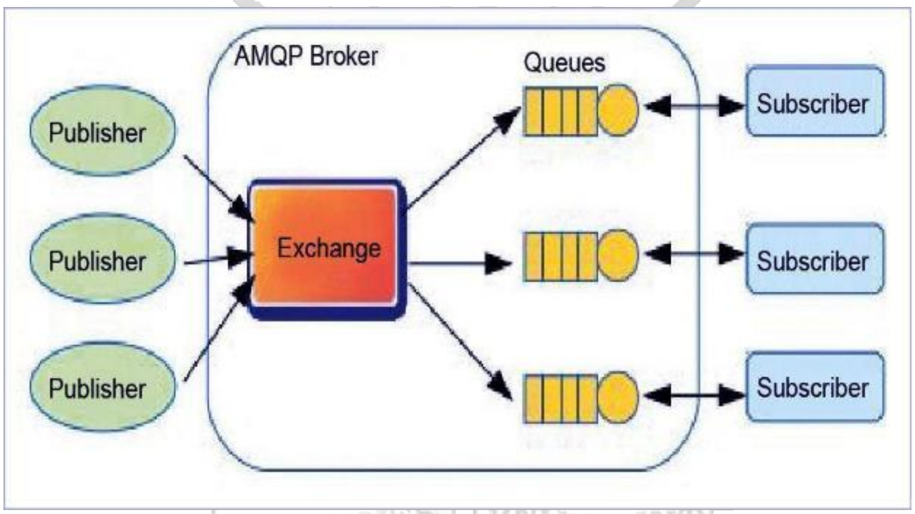

Figure 2. 7: AMQP Architecture ("4 Key IoT protocol", 2018)

2.5.3. Message Queue Telemetry Transport Protocol (MQTT)

MQTT is a machine-to-machine communications protocol. MQTT is a protocol that connects devices and networks to applications and middleware. There is a subscriber, publisher, and broker for these Internet of Things protocols. The material is created by the publisher and distributed to subscribers through the broker. The broker guarantees security by double-checking publisher and subscriber authorization (Vahidnia & Dian, 2021).

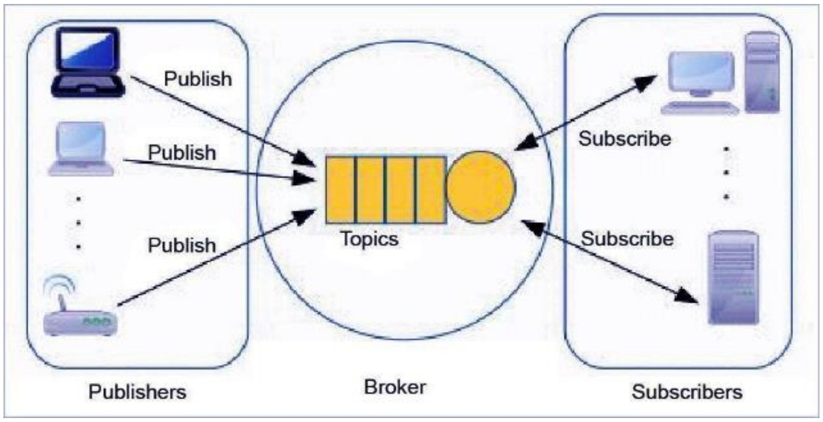

Figure 2. 8: MQTT Architecture ("4 Key IoT Protocols," 2018)

2.6. Smart City Architecture

2.6.1. IoT Architecture

The IoT architecture is the flow of data from sensors to cloud servers. (Team, 2021) The sensors are affixed to the "things," and they collect data from their environment. Large cloud servers recognize, store, and process the incoming data to produce the necessary outputs. To start a chain reaction, data is delivered back over the clouds to the "objects." When dealing with huge amounts of data, a proper architecture must be implemented to control the flow of data, signal processing, computations, and storage for future reference. The IoT architecture involves sensors and actuators, an internet gateway for data delivery, edge information technology, and clouds for data analysis and storage (“IoT Architecture,” 2019).

The physical layer has sensors and actuators that collect data from the environment and help control the environment based on the data gathered by sensors. Data is then converted from analogue to digital by internet gateways using Data Acquisition Systems. Preprocessing and analytics of data before it is sent to existing systems happen at the edge of information technology. The edge is located on the node side, not the data center side. Only data that is important from the node side is sent to servers. Cloud analytics and data centers are where data is sent for final analytics and storage (“IoT Architecture,” 2019). Figure 2.9 shows the IoT architecture layers and various components.

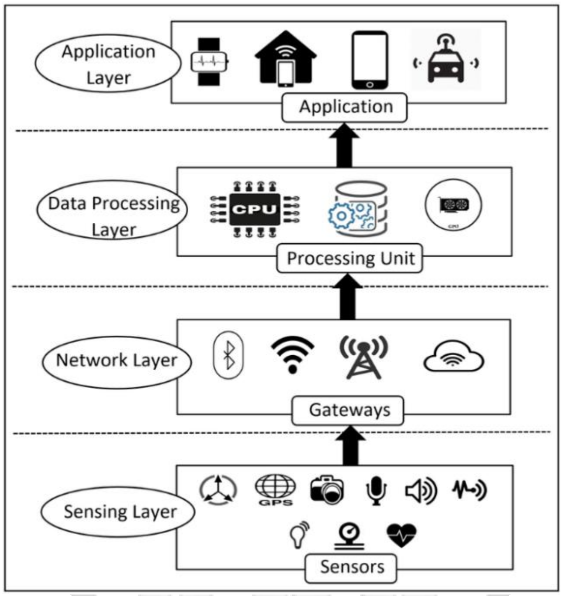

Figure 2. 9: IoT Architecture Layers and Components (Sikder et al., 2018)

2.6.2. NB-IoT system Architecture

The third-generation partnership project (3GPP) has a specific IoT solution called NB-IoT or LTE-NB that utilizes a bandwidth of 200 kHz ("NB-IoT Architecture", n.d.) NB-IoT is categorized under LPWAN technology to improve the battery life of devices, be more affordable, improve indoor coverage, and accommodate as many devices as possible in the IoT ecosystem (Samarth, 2020). Khan et al. (2019) studied the NB-IoT system architecture. This architecture consisted of sensing, communication, information management, analysis, and data storage functionalities.

NB-IoT systems can be categorized into three layers: perception, network, and cloud platforms (Khan et al., 2019). The perception layer consists of nodes that collect environmental data through specific sensors depending on the parameters to be collected. Devices then pack data into a format that the network layer can receive. The network layer consists of Base-stations (BS) that support the NB-IoT network. This network assists in sending data to cloud platform servers. The Cloud platform server consists of interfaces for secure communication between user applications, data analysis, storage, and the NB-IoT network. Figure 2.10 shows the architecture of the NB-IoT system.

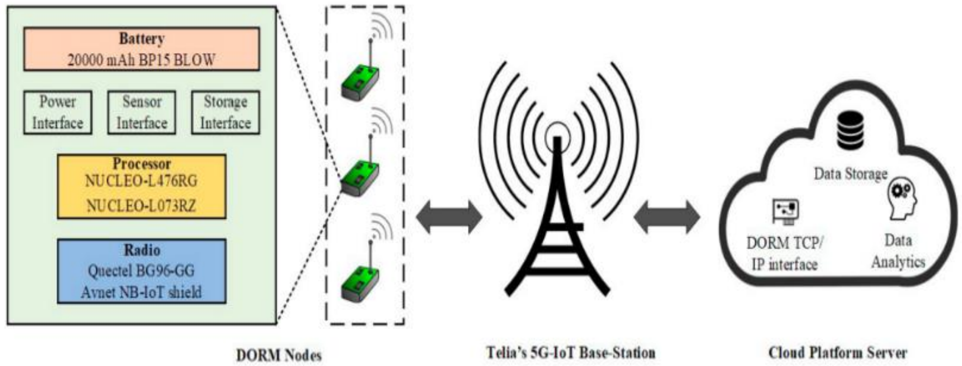

Figure 2. 10: NB-IoT System Architecture (Khan et al., 2020)

2.7. Algorithms

2.7.1. Smart Metering Algorithm

Li and Chong (2019) proposed a self-power smart water meter that used the micro-hydro water turbine generator (WTG) as the main component of this device. It was designed to store the power generated in the batteries to power the microcontroller. The flow rate was transmitted to a sink node through a wireless transceiver. Figure 2.11 shows the water metering process that was adopted. The design consisted of input and output components, and Bluetooth was chosen as the communication protocol. Values were read as an analog signal are concerted by analog to digital conversion (ADC) to a voltage value and then used two sets of moving averages to filter out the high-frequency components. The outcome was then utilized to compute the flow rate. In the end, the total volume of water was calculated by integrating the flow rate across time.

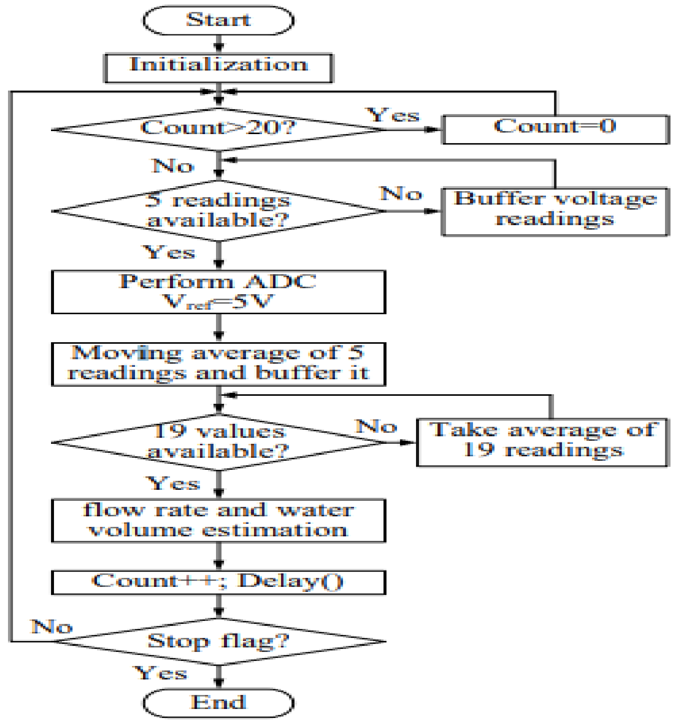

Figure 2. 11: Smart Meter Algorithm (Li & Chong, 2019)

2.7.2. Flow Meter Algorithm

Flow rate is the volume of liquid that passes through a given area in a given amount of time and can be determined in a variety of ways, including by measuring the velocity of the liquid. The velocity of the liquid is influenced by the pressure of the liquid, and the cross-sectional area of the pipe is also a factor in determining the flow rate. The flow rate is equal to the average velocity of the liquid multiplied by the cross-sectional area of the pipe. According to Sani (2021), the fundamental relationship for finding the flow rate of a liquid in this scenario is given by equation (1), (2), and (3).

$$Q = V * A \tag{1}$$

Where Q = flow rate/total flow rate of water through the pipe.

V = Average velocity of the flow

A = Cross-sectional area of the pipe (Viscosity, density, and friction of the liquid in contact with the pipe also influence the flow rate of water)

$$\text{Pulse frequency } (Hz) = 7.5 \times Q, where\ Q\ is\ flow\ rate\ in\ Liters/Minute \tag{2}$$

$$Flow\ Rate\ \left(\frac{Liters \times Litrs}{Hour \times Hours}\right) = \left(\frac{Pulse\ Frequency\ \times 60\ Minutes}{7.5Q}\right) \times \left(\frac{Pulse\ Frequency\ \times 60\ Minutes}{7.5Q}\right) \quad (3)$$

This also can be understood as indicated by equation (4), (5), and (6).

$$Frequency\ of\ a\ Sensor\ (Hz) = 7.5Q\ \times \frac{Litres \times Litres}{Minutes \times Minutes} \quad (4)$$

$$Litres = \frac{Q \times Time\ Lapsed\ (seconds) \times Q \times Time\ Lapsed\ (seconds)}{60\left(\frac{seconds}{minutes}\right) \times 60\left(\frac{seconds}{minutes}\right)} \quad (5)$$

$$Litres\ = \frac{Pulse \times Pulse}{7.5 \times 60 \times 7.5 \times 60} \quad (6)$$

2.8. Embedded Systems Technologies

2.8.1. Microcontrollers

According to Wu et al. (2020), a microcontroller unit (MCU) is a tiny computer on a single integrated circuit or microchip that is utilized in IoT applications for data collection, transport, and analysis. Memory, power consumption, communication protocols, architecture, the number of connection pads, price, and security features all play a role in the choice of an MCU (Koon, 2019). For programming and futureproofing, the MCU should have enough ROM and RAM. Wearable devices should be able to operate on the MCU with little battery consumption, and the required application should have the right communication module.

It's important to consider the MCU's architecture as most applications run on AVR or ARM, and the decision should be made according to the complexity of the system. For the type and quantity of sensors or actuators that will be connected, the MCU should have adequate GPIOs. Scalability needs to be considered to make expansion simple after the prototype is finished and evaluated.

2.8.2. Sensors Modules

2.8.2.1. Water Flow Sensor

YF-S201 water flow sensor takes control of fluid volume through it. It has a hall effect sensor and a turbine wheel with a magnet placed inside the plastic enclosure. Any fluid through the sensor rotates the turbine wheel, making the magnet flux interface with the hall sensor. The fluid speed through the sensor makes the hall effect sensor create a pulse signal as the output used to calculate volume (“Water flow Sensor,” 2017).

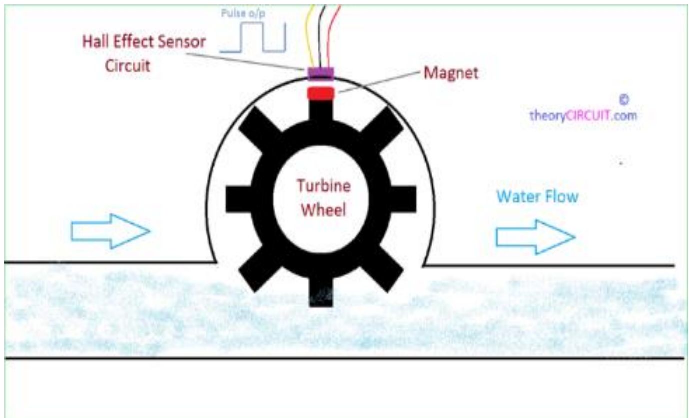

Figure 2. 12: Water Flow Sensor (" Water flow Sensor," 2017)

2.8.2.2. GPS Module

GPS module is used for navigation purposes. The module checks the earth's location and gives data output in the longitude and latitude of where it is (“NEO6MV2 GPS Module,” n.d.). The output from the GPS is usually in National Marine Electronics Association (NMEA) standards string format.

Figure 2. 13: GPS Module ("GPS Receiver Module," n.d.)

GPS satellite transmission happens at a frequency of between 1.1 - 1.5 GHz to the receiver. The GPS module, receiving data, computes time and its position, and this is achieved by calculating the time required for the signal to travel from the satellite to the module as shown by equation (7) and (8).

$$Distance = Speed \times Time \tag{7}$$

$$Speed: Radio\ Signal\ Speed = Speed\ of\ Light\ (3 \times 10^8) \tag{8}$$

Where time is taken by the signal to travel from the satellite to the receiver

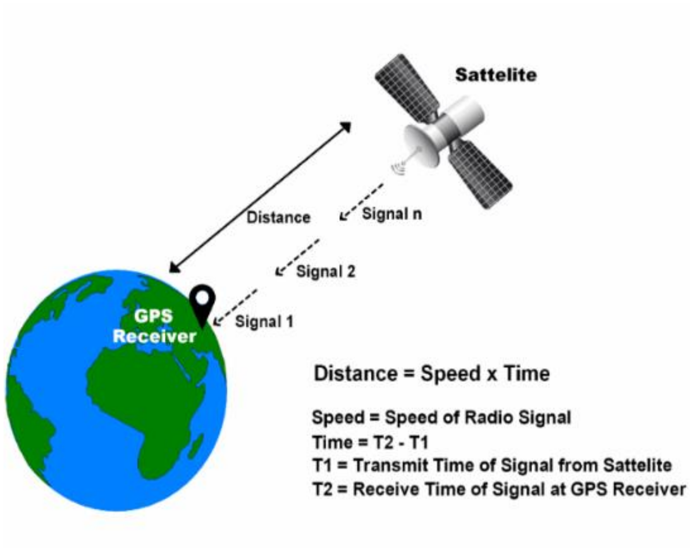

Figure 2. 14: GPS Distance Calculation ("GPS Receiver Module," n.d.)

Time travel can be attained by subtracting the time when the signal was sent and the time the receiver got the signal. This is achieved by both the sender and receiver simultaneously generating a pseudocode signal. These signals are compared, and the travel time is the difference (“GPS Receiver Module,” n.d.).

2.8.2.3. Wireless Communication Modules

Communication systems can be wireless or cabled, using regulated or not regulated communication mediums. Because wireless communication does not require a physical channel to transmit messages, signals are sent through space. Because space only allows signals that are not regulated for transmission, the medium utilized in wireless communication is known as an Unguided Medium (Teja, 2021).

a) RFID and Bluetooth Modules

RFID systems have two major parts: a tag connected to the thing that needs to be detected and a reader that identifies the tag. A reader has a module with radio frequency and an antenna that generates a high-frequency electromagnetic field. It includes a microchip that saves and processes data, and the antenna usually receives and transmits signals. When the tag is placed close to the reader, an electromagnetic field is created by the reader. This sends electrons through the tag's antenna, which powers the chip. The chip then sends back the information it has stored in the form of another radio signal to the reader. The NXP MFRC522 IC-based RC522 RFID module has both RFID cards that are writeable with an option to store any message (Agnihotri, n.d.).

The HC-05 Bluetooth Module is a simple Bluetooth SPP (Serial Port Protocol) module for creating a wireless serial connection. It can talk to controllers or PCs through serial communication, making it easy to connect. The HC-05 Bluetooth module has a switch that lets you switch between master mode and slave mode. It can either receive or send data (Benne, 2022). Figure 2.15 and 2.16 below shows RFID and Bluetooth modules, respectively.

Figure 2. 15: RFID Tag Module (Agnihotri, n.d.)

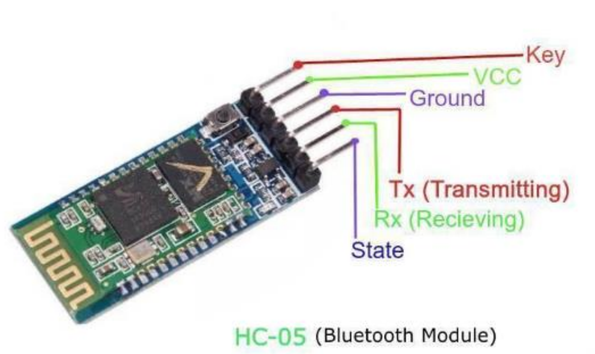

Figure 2. 16: Bluetooth Module (“All about HC-05,” 2020)

b) Wi-Fi Module

The ESP8266 fully supports the Transmission Control Protocol stack. A simple serial interface is used to accept commands from the module. The ESP8266 module is significantly less expensive than the Wi-Fi Shield ("Using the ESP8266," n.d.). Figure 2.17 depicts the ESP8266 Wi-Fi Module.

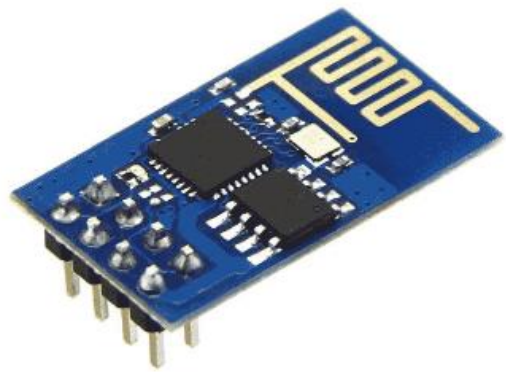

Figure 2. 17: ESP8266 Wi-Fi Module (techZeero, 2018)

c) LoRa Modules

A LoRa module is a piece of hardware that lets you connect to the Internet wirelessly using the LoRaWAN protocol. LoRa is a wireless technology that lets M2M and IoT applications send data over long distances with low power and safety. Most LoRa modules have a LoRa transceiver, an MCU, and other parts like RF switches, LNAs, and TXCOs. LoRa modules use very little power and can reach up to 15 km in urban areas and 2–5 km in rural areas (suburban). They are used in Internet of Things devices that run on batteries and are connected to a large network with hundreds of nodes spread out over a large area ("LoRa Modules," n.d.).

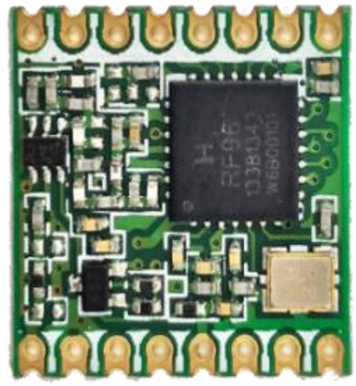

Figure 2. 18: RFM96 LoRa Module (“RFM95W Feature,” n.d.)

d) GSM/GPRS

A Global System for Mobile Communications (GSM) and GPRS modules are chips or circuits that allow a mobile device or computer to connect with a GSM or GPRS system. GSM was created to describe the protocols used by cell phones on second-generation (2G) digital cellular networks. It is now the global standard for mobile communications, accounting for more than 90% of the market and being used in over 219 nations and territories (Rathore, 2021).

Figure 2. 19: Sim900 GSM/GPRS Module (“SIM900 Power Supply,” 2017)

2.9. Conceptual Model

Figure 2.20 shows the conceptual framework for the proposed system. The system uses IoT devices to collect water and location-based data. The flow meter sensor and GPS module will collect water and location data, respectively, and the data will be transmitted to a database using the SIM7080G NB-IoT module. Water data transmitted to a database was processed for billing purposes after every session of water usage in real time and bill updated. The GPS data was used to map the location of every device allocated to a client.

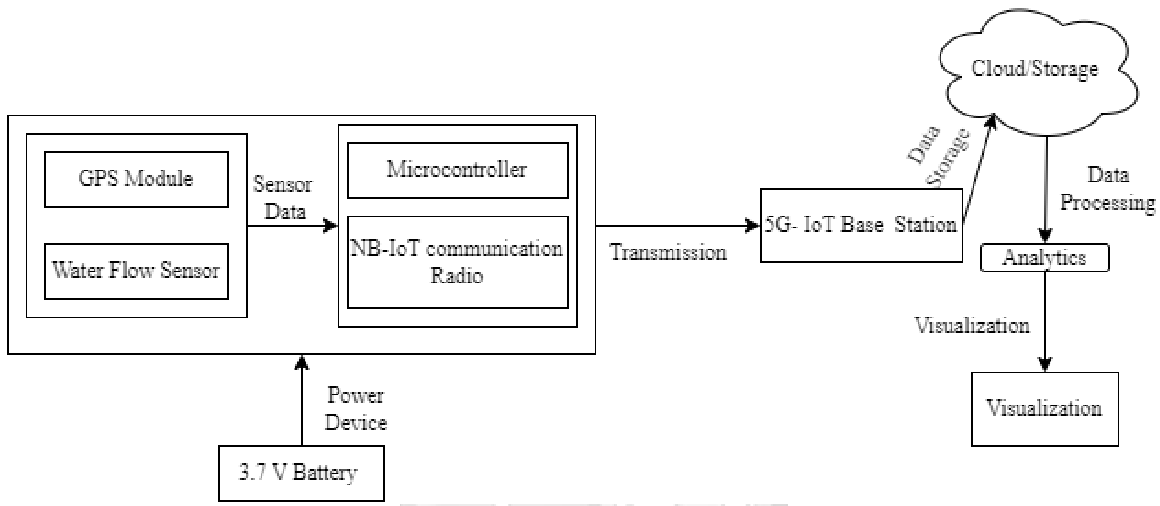

Figure 2. 20: Proposed Conceptual Model for NB-IoT Smart Water Meter

Chapter Three: Methodology

3.1. Introduction

The validity of the research is anchored by the methodology used (Imed, 2022). This uniform procedure is used to carry out all stages required to evaluate, create, implement, and manage a system (Saravanan et al., 2017). A good methodology helps conduct better research and gives the researcher legitimacy and control not to go beyond the scope. When developing a system, methodology gives the researcher a reference point if questions and critiques arise.

3.2. Research Design

The purpose of this project was to develop a smart water meter and produce, test, and design a prototype adopted addressing the problem associated with manual water meter readings. A research design is a strategy for determining the sort of study, data gathering, and analysis. It is an orderly collection of facts or data that has been explored by developing a hypothesis and then coming up with factual findings ("Research Design," 2021).

An applied research design was embraced in this study. Identifying a market need for the product, designing a product that had the potential to meet the need (s), building a prototype, and testing whether the prototype met the desired functions in terms of cost, environmental consequences, and profitability when it is introduced to the market are all part of the research design (Marder, 2011).

This study also developed a smart water metering prototype capable of collecting data and transmitting it to a cloud server for storage and analysis. A cross-sectional study was conducted, incorporating a sample of elements from an interest population at one moment. The research concentrated on a portion of the population's data, which was examined, and conclusions were drawn.

3.3. Population and Location of the Study

A sample is a subset or component of a larger group known as the population, and a target population is a sample chosen to reflect a specific group (Gall, 2010). According to Gall (2010), identifying the target group is partly dependent on what the researcher wants to know. This study targeted Strathmore university as the development and validation of the device were conducted in-house. Development of the device was done in the IoT lab at @iLabAfrica at Strathmore university. IoT lab is one of the research labs in @iLabAfrica that does research that cuts across various domains that contribute to the development of the country’s economy. This unit has resources that include microcontrollers, sensors, and technical expertise, and they will help in the development of the device that will be key in this study.

The device developed was deployed at Strathmore university for testing and validation purposes. During the analysis of water meters, it was appropriate to gather information that explained the gaps that exist in data collection mechanisms with existing water meters. Furthermore, the outcome was presented to the affected stakeholders. The study identified people who have water meters on their premises to share their experiences with water meters installed in their apartments and how water bills were shared with them after consumption data was collected. Participants are adults who have water meters from Nairobi city water and sewerage company (NCWSC).

3.4. Sample Size

This study employed a purposive sampling technique. According to Campbell et al. (2020), when doing a study, there is a need to ensure that a strategy to onboard participants is integrated into the whole process of the study. The goal of the study is attained when a sample is chosen in a way that fits with the axiological, ontological, and epistemological points of view. Purposive sampling is utilized to pick participants that will most likely yield appropriate and important information, and this procedure was a better way of identifying and selecting cases that will use fewer resources. In this study, the purposive method was suitable because it targeted individuals who have water meters installed in their apartments and are adults living in Nairobi. This method allowed the researcher to get the needed information from selected individuals who have water meters installed in their apartments and those who work for a water company located within Nairobi, saving time and resources. The researcher targeted a maximum of 15 persons within Nairobi County who use water meters. Among these were two representatives from NCWSC and a questionnaire was shared with them to understand data collection method from water meters, challenges associated with the process, and the billing process. A smart water meter prototype was deployed at Strathmore University after approval from the management.

3.5. Data Collection Methods

The main objective of research tools is to gather data from research participants regarding a particular topic of interest. In contrast, an effective tool produces impartial, precise, responsive, effective, and applicable outcomes. The study employed the following tools.

3.5.1. Questionnaire

The questionnaire was shared as a research instrument to collect data from Nairobi County residents and water utility employees. The procedure involved individuals responding to questions based on their prior experiences with the service, users had higher expectations regarding the benefits they would receive from the proposed system.

3.5.2. Prototyping

In the prototyping phase, the developed application was provided to the maintenance department of Strathmore University to deploy and provide constructive feedback on its functionality and satisfaction.

3.5.3. Documents Reviews

Documents were reviewed as part of the research, including looking at related studies in the smart water metering system that have been developed to provide critical feedback on current implementations and expand our understanding of how to effectively implement the proposed solution.

3.6. Data Analysis Methods and Presentation

Data that was gathered from participants was presented numerically using statistical data from quantitative research methods. This study aimed to collect accurate data to produce accurate results. This study used pie charts to represent the findings after data collection and analysis.

3.6.1. User Responses

3.6.1.1. Mobile Phone

The study assessed whether respondents had smart mobile phones to determine how easily users could access web application services. Figure 3.1 below shows that all participants owned a smartphone. This result confirmed that most clients could access web-based applications via their phones because these devices come with web browsers pre-installed.

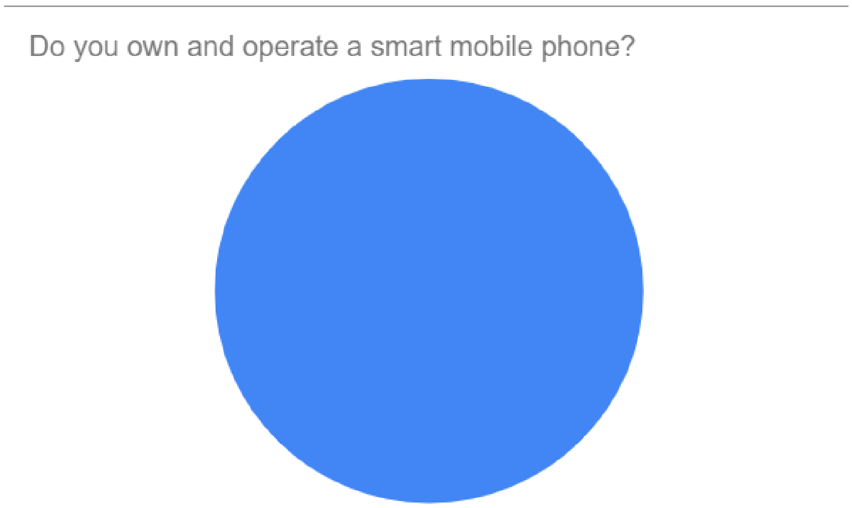

Figure 3. 1: Smart Phone Operators within Nairobi County

3.6.1.2. Water Data Collection

The success of this study was determined by investigating the experience users have when data is collected from water meters installed on their premises. From the study, as shown in Figure 3.2, it was identified that 70.6% of the respondents have employees from NCWSC access the water meter to collect usage data, while the remaining 29.4% do not see them. This was important to understand the level of transparency in data collection. Figure 3.3, on the other hand, shows data from the NCWSC regarding the frequency of data collection. It was noted that the company sends out agents to the field monthly.

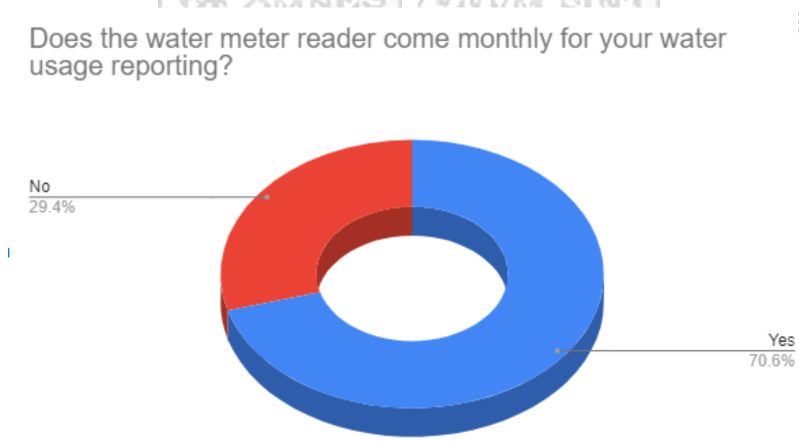

Figure 3. 2: Water Meter data Collection statistics

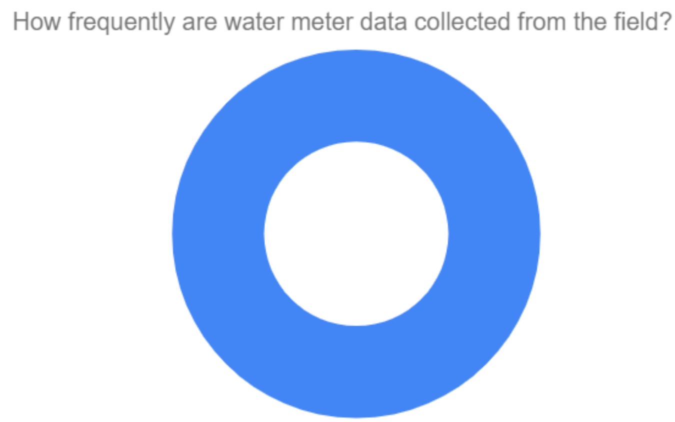

Figure 3. 3:Statistics of NCWSC agents being sent to the field.

As shown in figure 3.3, the two NCWSC representatives interviewed strongly agreed that the current method of data collection presents challenges, specifically agents not reading data from their customers.

3.6.1.3. Length of Experience with Meters

The researcher was curious about the period during which water users had water meters as a basis for understanding the issues that the study needed to address. According to figure 3.4, 5.9% of respondents have had water meters for more than six years, 35.3% for more than 15 years, and 58.8% have used water meters between 1 year and five years.

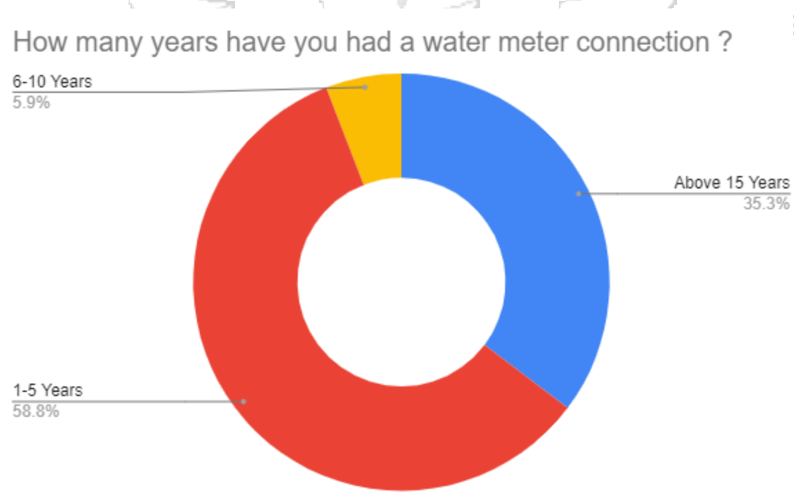

Figure 3. 4: Statistics of years users have been using a water meter.

3.6.1.4. Water Billing Platform

It was important to understand how the users do receive their water bills. According to figure 3.5, 58.8% of respondents receive water bills in the form of a manual printout, 29.4% via SMS, and 5.9% via email and an app.

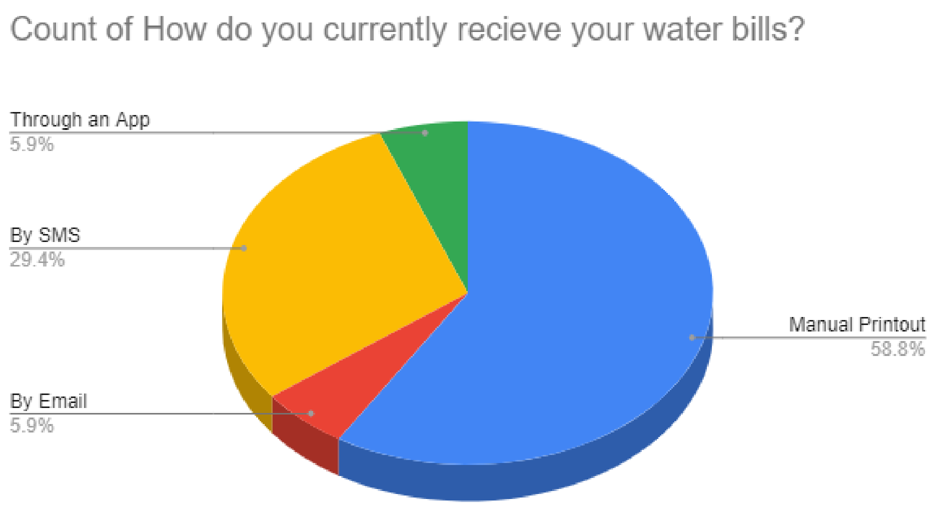

Figure 3. 5: Statistics on medium users receiving their bills.

3.7. Research Quality

Both the reliability and validity of the study contributed to the study's overall quality. The term validity is used to describe the accuracy of the conclusions drawn from an evaluation. "Inferences are drawn from data that is relevant to the interpretation of scores" (Bruin, 2010). On the other side, reliability proves repeatability and stability across time. When it comes to tests, the less reliable they are, the more measurement errors there are; hence another definition of reliability is "the degree to which a test is devoid of measurement errors" (Bruin, 2010). The application of the methodology correctly ensured reliability. The researcher planned the methods so that each phase of the study proceeds with little or no difficulty. Second, reliability was achieved by standardizing the research conditions (Middleton, 2019). For example, when collecting data, the researcher kept the number and rate of outside influences as low as possible since these things can change the results.

In contrast, validity was ensured by selecting appropriate measurement methods. The researchers ensured that the methods and measurement techniques used were of high quality and measured what was required for the study. In addition, the researcher conducted extensive research based on research objectives to help them build on existing knowledge. Second, validity was achieved by employing appropriate sampling methods based on the needs of the study (Paul et al., 2019). The stratified sampling technique, as proposed above, was employed to help the study achieve all its research objectives. The researchers ensured that the population was clearly defined in terms of range, geographical location, and profession.

The dependability of information sources obtained from the sample size, study location, research tools, and other areas of research was ensured. This was achieved after approval by the ethics supervisor and data from prior successful research studies that may have employed the same methodology.

3.8. System Development Methodology

The research made use of agile software development approaches, which is an iterative strategy that divides work into smaller iterations and focuses on short-term planning. The project scope and requirements were stated at the outset with several iterations. Each iteration spanned a period of one to four weeks and consisted of requirement analysis, design, programming, testing, and validation. Agile was chosen because it provides a practical methodology, encourages teamwork and cross-training, enables functional demonstration, and decreases resource requirements.

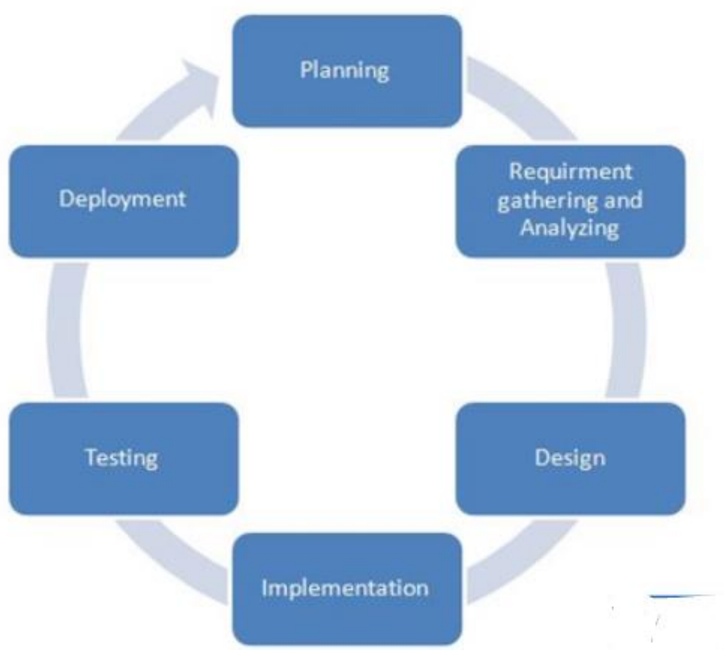

Figure 3. 6: Agile Development System Methodology (Lithmee, 2018)

3.8.1. Planning

During this phase, all the requirements for the project and the objectives were established. Planning aided in outlining the study's phases and the responsibilities of each person or organization designated as a participant. During planning, the costs and resources needed to implement the solution were put into place. Tools, which are discussed under the implementation stage, are comprised of hardware and software.

3.8.2. Requirement Gathering and Analysis

This stage focused on determining technologies that supported the development of smart water meters. A literature review was done to determine these technologies. Device manuals and datasheets were reviewed to understand their architectures, pin configuration, and how they operate. The best software and libraries used during development were also identified at this stage. Through this, the study identified the best method to use in the development of hardware and software, integrating the two to have a final product.

3.8.3. Design

The system design incorporated both visual and architectural elements. The architecture was built on sensors, controllers, and other physical devices, whilst the visual design utilized computer programs to generate structure charts, data flow diagrams and Hierarchical Input Process Output (HIPO) diagrams. The data flow diagrams depict the movement of data into and out of the system, the structure charts provide greater detail by decomposing the system into smaller functional modules, and the HIPO diagrams provide an overarching perspective of the system and its modules.

3.8.4. Implementation

During this phase, a prototype was built. The system was built in pieces that were integrated, and their interoperability was tested indoors to test if the objectives and requirements were met. The tools involved comprised hardware and software parts. Hardware fabricated sensors and microcontrollers. An integrated development environment (IDE) such as Visual Studio was used for firmware and web app development. The programming language used at the hardware level is C++ and JavaScript. Firebase was configured to store data and host the web app.

3.8.5. Testing

Testing was done by deploying the device to a household of a selected site. The test parameters would be whether the device sends data collected using the NB-IoT network, compatibility, and reliability. Data were recorded in a database as proof that data was transmitted over the NB-IoT network. The system evolved to be plug-and-play with the existing water pipelines, and the data collected was real-time and accurate.

3.8.6. Deploying

This stage included installing the data collection device and teaching users how to use the web application for data visualization. Strathmore University in Nairobi County was the first to use the system.

3.9. Utilization and Dissemination of Research Results

The results of this study are to help water companies and their stakeholders in dealing with water data collection and billing issues. This study introduces a better mechanism of water data collection and proper billing in an open and timely manner using LPWAN networks such as NB-IoT that are suitable for IoT devices.

The result assists future researchers interested in solving problems that can be addressed through NB-IoT. These findings were disseminated through publications on publication sites.

3.10. Ethical Considerations

It is a requirement to certify the study and its findings, and institutional permission is required. Strathmore University is already certified and can give a certificate of ethical clearance for the project. During the studies, confidentiality, validity, voluntary participation and consent, risk of damage, and research methodologies are significant ethical problems. To guarantee that all ethical concerns are addressed during the study, the researchers did the following:

Make a trust contract. It was used in the researcher's and participants' conversations. The two parties gave informed and unequivocal permission for the requirements of the study.

Applied the third principle of ethics. According to the Economic and Social Research Council (ESRC), the confidentiality of the information provided by research participants and the identity of respondents must be maintained" (Smill, 2003). In situations when secrecy is restricted, anonymity should be encouraged.

The study assured the safety and security of all participants by providing them with the required safety equipment, training, or consulting services. Follow the guidelines for informed consent. These guidelines were developed by the National Commission for Science, Technology, and Innovation (NACOSTI) and are protected by Kenyan law.

Chapter Four: System Design and Architecture

4.1. Introduction

Sarma et al. (2007) indicated that 50-60 % of project success is associated with focus on their requirements, and most of those that fail are due to the improper gathering of requirements, analysis, and how the resources are managed. To overcome this drawback, there is a need to embrace computer-aided software engineering (CASE) tools (Sarma et al., 2007). Unified Modeling Language (UML) is one of the tools that assist in system design and Architecture.

4.2. Requirement analysis

Chung and do Prado Leite (2009) highlighted that the functional and non-functional aspects define a system's utility. They pointed out that, like anything else, system quality is essential and ought to be considered when creating high-quality software. The user's requirements were recorded in this study along with the key study goals, and they have been broken down into non-functional and functional requirements, as shown below.

4.2.1. Functional Requirements

The developed functional requirements were based on the desired behaviors that would be accomplished in a system. These, therefore, encompassed the numerous system functions and capacities that were discovered to be compatible with the study's goals. They are highlighted below:

Sign in and out: Both online application users and mobile users must be logged in to utilize the applications and then sign out to finish using the application.

Water meter-monitor: This feature will allow the managers of the water companies to examine the water meter's behavior.

Message send: This feature will allow users to send messages to water companies and for water companies to send messages to their customers.

Edit Profile: Customers should have the ability to edit their own profile and verify the details regarding their invoices and the amount of water consumed.

Sending notifications: This feature enables water companies to inform their customers of important information.

View Water Bills: Customer will view their water bills, and water companies to view their customers' bills from the admin web app.

Reports: The system should produce reports when needed.

4.2.2. Non-functional Requirements

These specifications list a system's fundamental characteristics. The system must possess these characteristics. When these non-functional requirements are not met, negative outcomes occur. These are the non-functional requirements:

Availability: Indicates how dependable the system is always. The system must be accessible constantly.

Reliability: Indicates how well a system continually carries out its intended functions without fail.

Accuracy: The recommended water metering system should meet a predetermined accuracy standard with a low mistake rate. Accuracy enables accurate billing to customers.

Usability: Describes how simple it is to understand and use a system's features.

Maintainability: Describes how simple it is to identify flaws and problems in a system and correct them so that it satisfies user needs.

Reaction time: There should be a maximum amount of time between when a request is made and when the user receives feedback from the system.

4.2.3. Domain Requirements

The following are the requirements for this study:

A smartphone capable of using applications such as Firefox or Google Chrome.

Windows 8 operating system.

Central Processing Unit (CPU) with Core i3 2.4 GHz.

4 GB of Random Access Memory (RAM).

1 GB of free hard disk space.

4.3. System Architecture

The system architecture discusses the relationships between the various system parts that enable the system's functionality. The system architecture describes how the structure, design, and user needs of the system must be addressed. Figure 4.1 illustrates the subsystems and how they are connected to each other to achieve the smart water metering system. The components used in the proposed system are users, IoT modules (Water flow meter sensor, GPS module, NB-IoT module, ATmega328P), integration API, and online server space or database and visualization dashboard for both customers and water companies' management.

The IoT node is placed on a water pipeline to take water flow rates. The flow rates are converted to liters at the node level. Locational data is also collected and stored together with the water volumes in the ATMEGA328P EEPROM and later transmitted to a database which is later consumed by API to the dashboard for visualization.

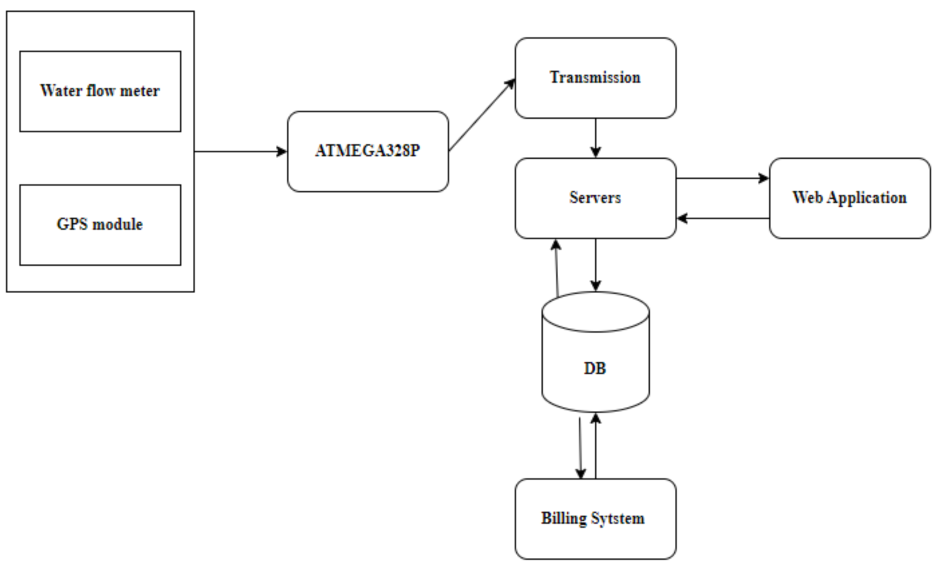

Figure 4. 1: System Architecture

4.4. System Design

System design entails the use of the UML diagram, which is a structural diagram describing how the system looks statically by showing classes of the systems, attributes, methods or operations, and relationships among various objects (Jin, 2022). This includes the use of system sequence diagrams, use case diagrams, partial domain models, context and data flow diagrams, entity diagrams, and class diagrams. All of these were utilized at different phases of the design process to describe, illustrate, and record the system's functionality.

4.4.1. Use Case Model

A use case diagram is a text-based method of explaining complex data models. A system is divided into use cases and actors using use case diagrams. To properly arrange the various players for the new system, use case diagrams depicting system behavior were created, as illustrated in Figure 4.2.

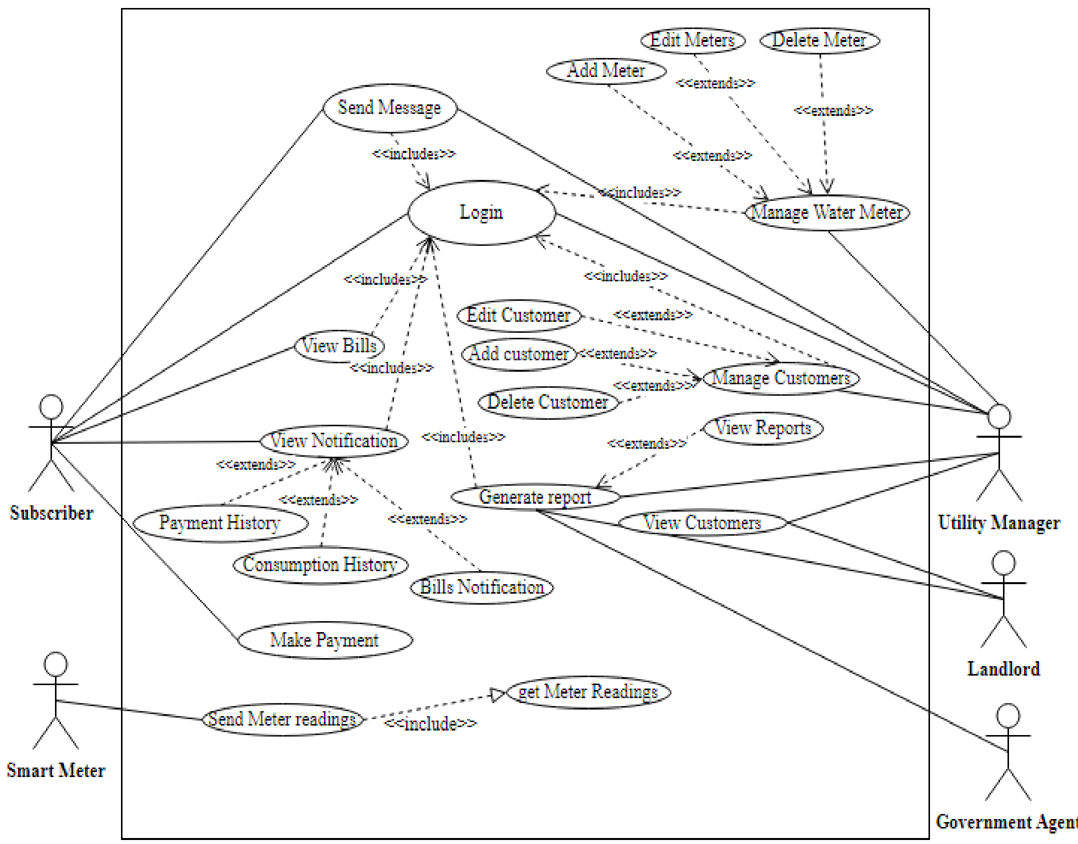

Figure 4. 2: Smart Water Meter Use Case diagram

4.4.2. Use Case Descriptions

4.4.2.1. Adding Customers

This is a detailed process of how a new customer is registered into the system by the water company manager. Table 4.1 shows the scenario.

Table 4. 1: Use case description of adding a new customer.

Use Case	Add New Customer
Description	A new customer registration into the system by Manager
Source	Manager
Inputs needed	Customer Details
Preconditions	The manager is logged into the system. The customer is 18 years and above. The customer is new to the system
Post Condition	The system records a new customer
Flow of Events	The system displays to manager options to select form. The manager chooses the "Add a New Customer" option. The customer provides personal details. The manager enters information into the system. The manager clicks the submit button. A new customer is added to the system. The manager receives a success message

4.4.2.2. Generating Reports

This use case contains information about the process of the water company manager retrieving regular reports from the system. This report includes customer bills, water meters, and water consumption patterns by each customer. Table 4.2 shows the scenario of generating reports from the system.

Table 4. 2: Use case description of report generation

Use Case	Generate report
Description	Generation of reports by the manager
Source	Manager
Inputs	Customer details and duration
Preconditions	The manager is logged into the system. The manager selects the type of report
Postcondition	Report is generated

Event flow	A list of options is presented to the manager. The manager chooses the "Generate report" option; the Manager clicks submit button on the system. Managers received reports with the option to view or save the report

4.4.2.3. View Billing Information

This use case indicates the entire procedure followed up to viewing bill information from the system. Table 4.3 exhibits a detailed approach followed.

Table 4. 3: Use case description for the billing process

Use Case	View Billing Information
Description	Customer-generated water bills from the system
Source	Customer
Inputs	Customer account details
Pre-condition	The customer is signed into the system. The customer selects the type of reports he desires
Post Condition	A customer report is generated.
Events flow	The customer is shown an option to choose from by the system. The customer clicks the "Generate report" option. The customer clicks the submit button on the system. The customer gets a report with the option to view or save it.

4.4.3. Data Flow Diagrams

The data flow diagram (DFD) tool was utilized in this study to identify how data between various components of the system flow.

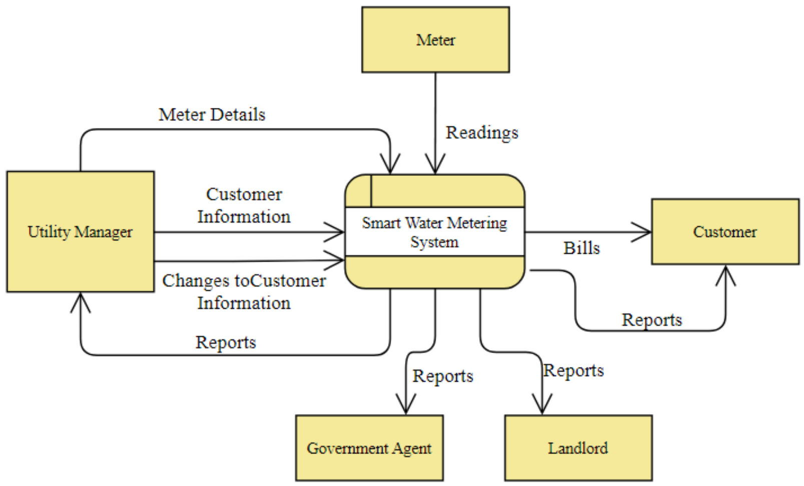

Figure 4. 3: Data flow diagram for the proposed system

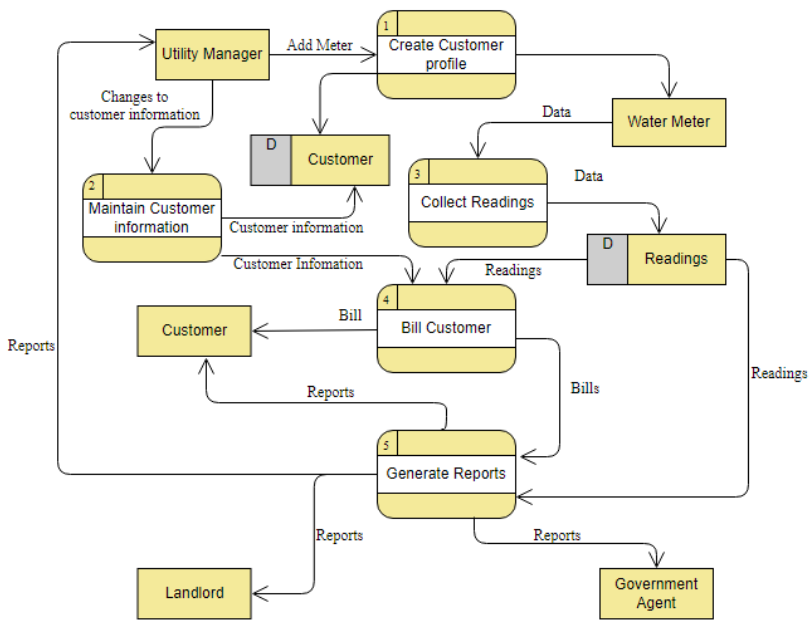

Figure 4. 4: DFD level 0

4.4.4. System Sequence Diagram

In this study, a sequence diagram was employed to visualize the flow of data between various actors and the system. Figure 4.5 presented below illustrates an actor obtaining their water usage level and making payments.

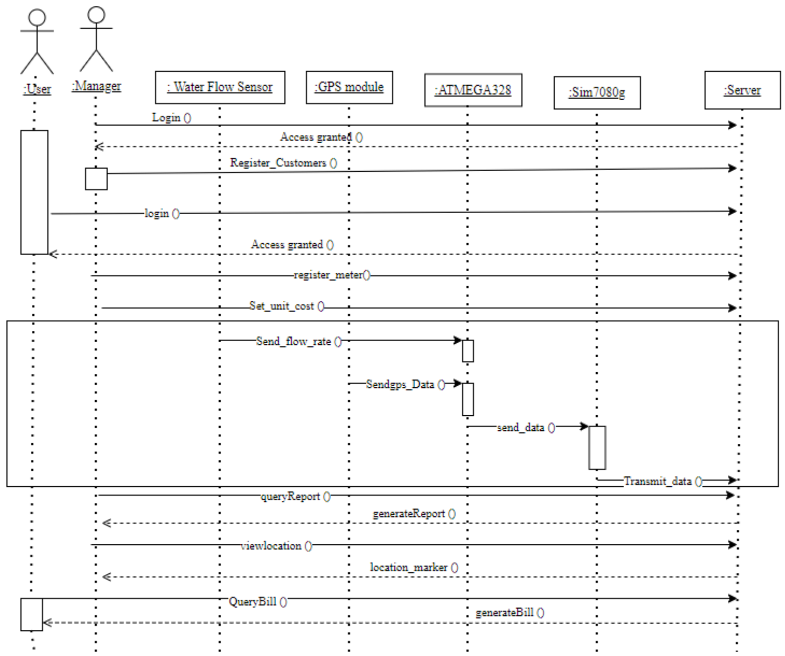

Figure 4. 5: Sequence diagram

4.4.5. Entity Relation Diagram

The study involved creating a system that would store data for various components and entities, such as customer information, meter inflow and outflow data, consumption, and billing information. To illustrate how these entities are related within the database, an entity relationship diagram was employed.

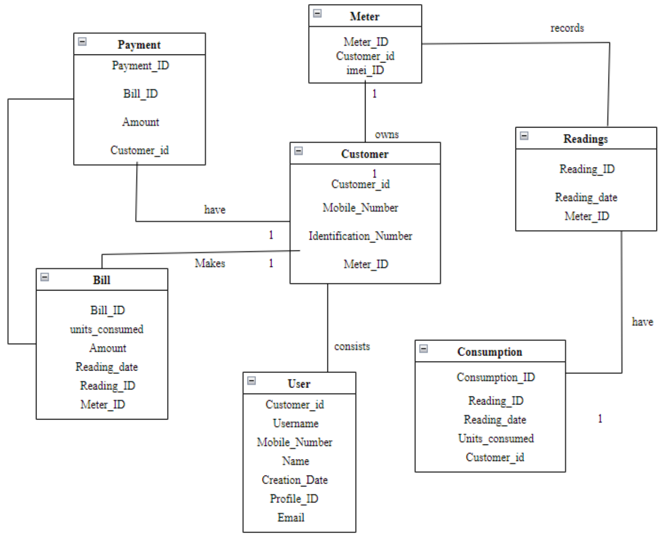

Figure 4. 6: Entity relationship diagram

4.4.6. Partial Domain Model

Figure 4.6 shows the partial domain model of the proposed system. The model has classes of the system while indicating attributes, names, multiplicity, and entity relationships.

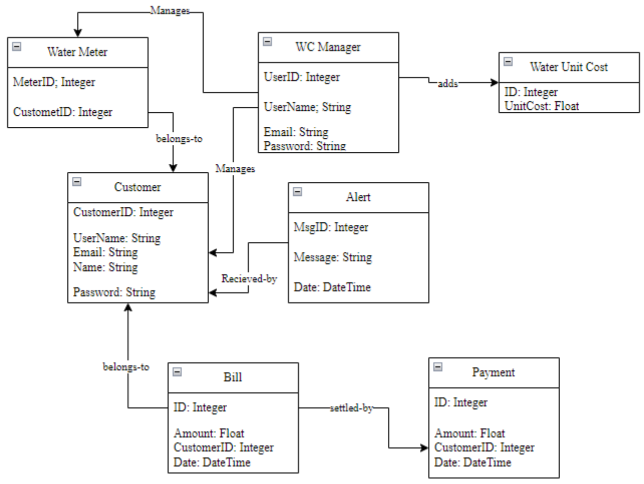

Figure 4. 7: Partial domain model

4.5. Wireframes

Wireframe diagrams are visual representations for an application interface that take into account users' and developers' needs and what is required to come up with an application that has goals and objectives in mind. Wireframes are suitable because they represent how the features in the application will look and work, although they are subject to change over the development period.

4.5.1. Login

Figure 4.8 shows a login wireframe that has a form that requires the user to enter a valid username and password. The sign-in button allows the user to access their respective dashboard if the correct credentials are entered.

Figure 4. 8: User login page wireframe

4.5.2. Admin Landing page

Figure 4.9 shows the admin landing page after successfully logging in. This page allows the admin to see all the possible navigations they can make. This includes a map showing the location of all customers' water meters, and upon clicking the icon on the map, basic information about the devices is displayed. The admin can also navigate to customer, device, and message pages from the landing page.

Figure 4. 9: Admin landing page wireframe

4.5.3. Customer Management page

Figure 4.10 shows the customer management page from the admin's access level. From this page, admins can add, edit, or delete customers from residential, business, or property manager account types.

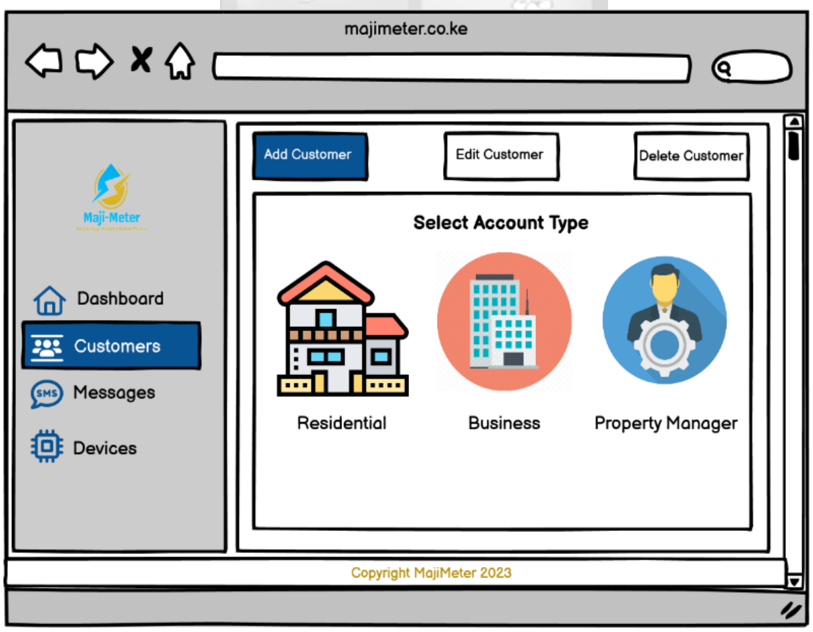

Figure 4. 10: Wireframe for admin to manage users.

4.5.4. Add User

Figure 4.11 shows a wireframe from the admin's side on the process of registering a new customer into the system and allocating them a water meter ID alongside their information.

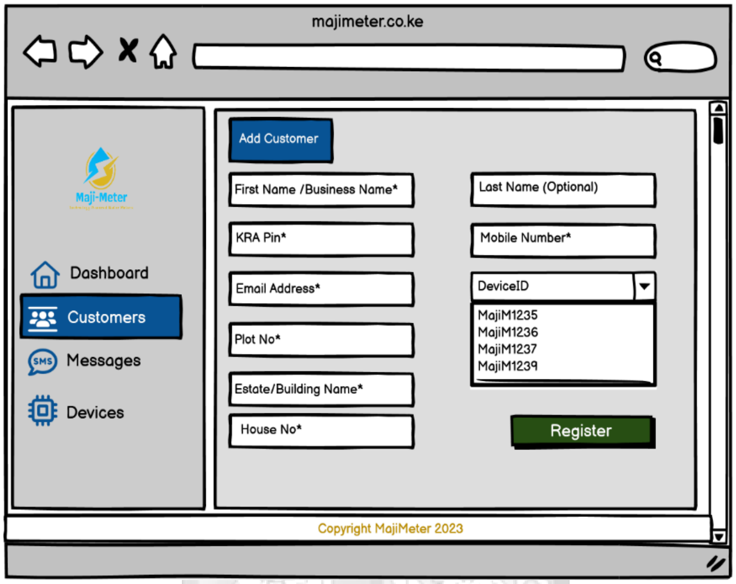

Figure 4. 11: Add user wireframe.

4.5.5. Update User

Figure 4.12 shows a wireframe of the process followed by admins to update an existing user in the system.

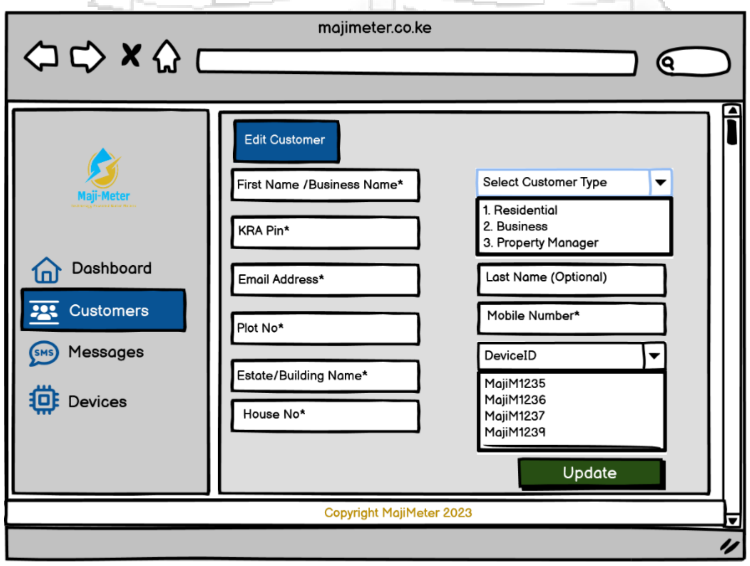

Figure 4. 12: Update user wireframe

4.5.6. Delete User

Figure 4.13 shows the process of removing a customer from the system. The system usually asks the administrator if they are sure about deleting a user from the system.

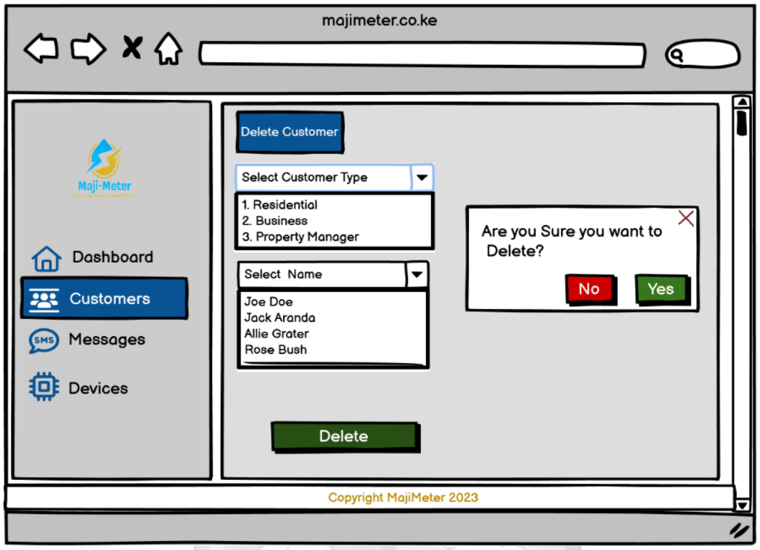

Figure 4. 13: Delete user wireframe.

4.5.7. Device Monitoring Page

Figure 4.14 shows the wireframe of device monitoring, where admins can see a list of all the devices in the system and their metadata. From this page, admins can select a device they would like to monitor.

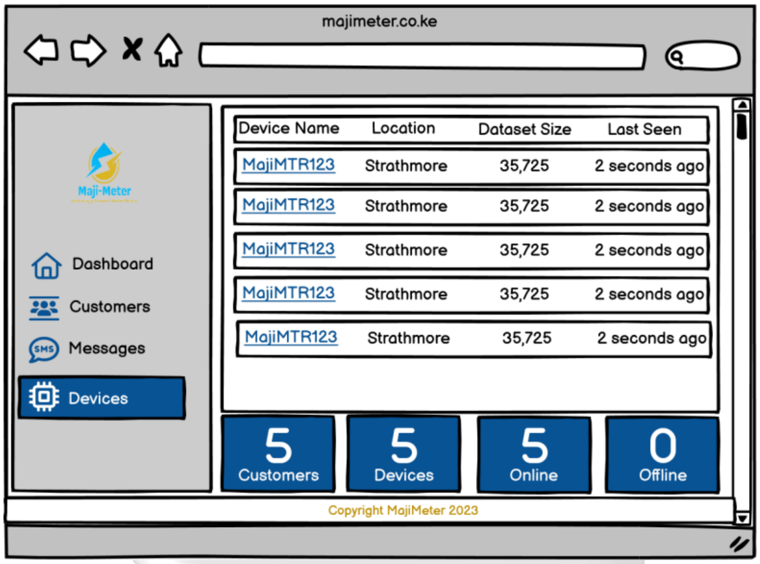

Figure 4. 14: Device monitoring wireframe

4.5.8. Customer Landing page

Figure 4.15 shows a wireframe of the customer landing page after login. From this page, customers can see a summary of the most important information, such as their name, device ID, daily water usage, the amount of the usage, and the total amount they are supposed to pay to settle their bills. There will also be a graph showing the overview usage insights. From this page, customers can navigate to other pages such as history, messages, devices, and downloads.

Figure 4. 15: Customer landing page wireframe

4.5.9. Customer Device Monitoring Page

Figure 4.16 shows a wireframe for monitoring a device that a customer is allocated by water company.

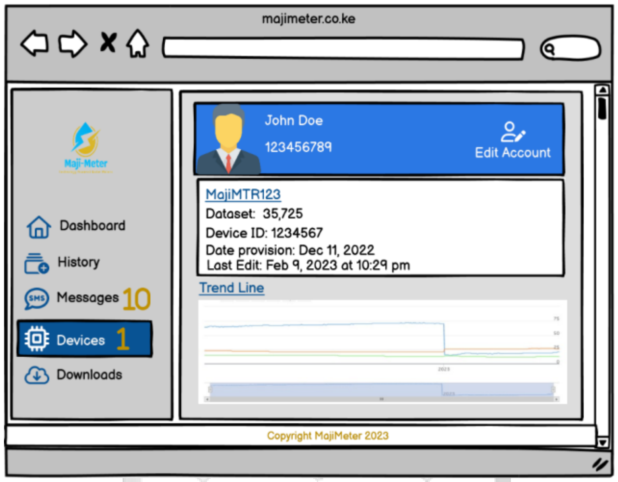

Figure 4. 16: Customer device monitoring page

4.5.10. Messaging Page

Figure 4.17 shows a wireframe for sending a message to a customer. They can select which admin they want to address and upload files.

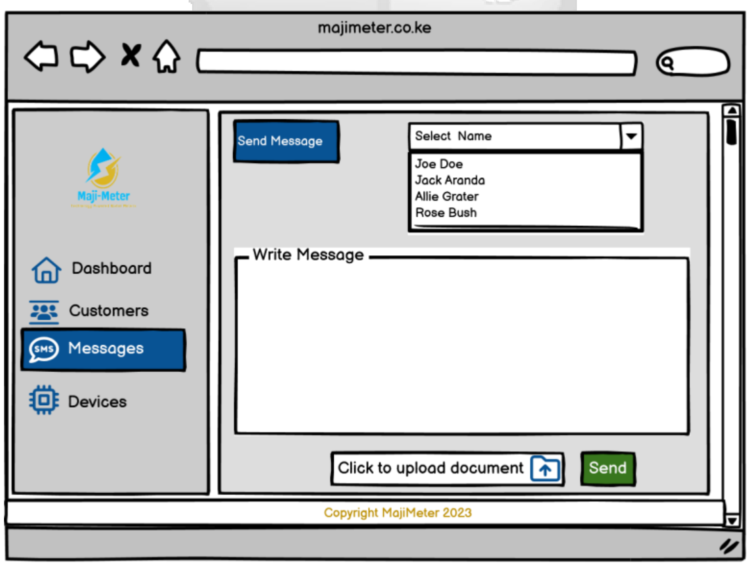

Figure 4. 17: Wireframe to send a message.

4.5.11. Receive Message Page

Figure 4.18 shows the wireframes where customers can see received messages. Upon clicking, they can read the communicated information.

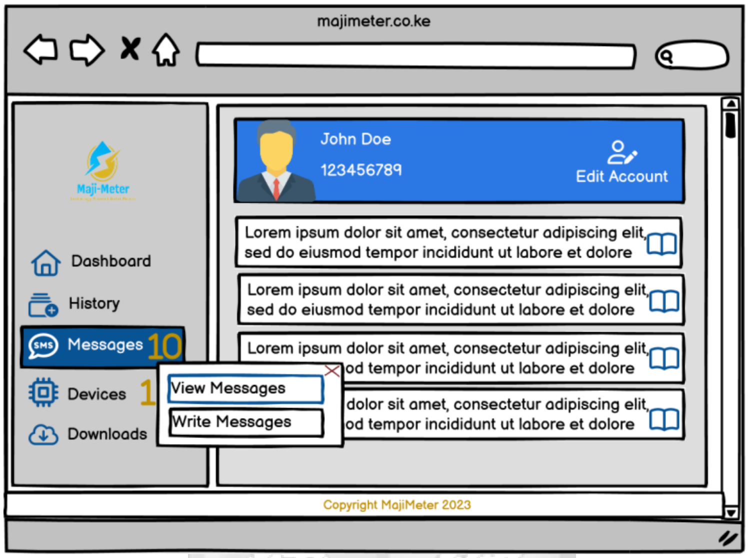

Figure 4. 18: Wireframe on reading and receiving messages.

Chapter Five: Implementation and Testing

5.1. Introduction

System implementation is the process of developing a design for a computer system. In contrast, system testing ensures that the system meets the satisfactory level and the intended use (Kurbel, 2008). These two are closely related to ensure the system functionality is met; hence, both should go hand in hand.

5.2. Development Environment

The implementation process was ensured to go smoothly by selecting an appropriate development environment. The essential components required for the development procedure include hardware, software, and cloud services, which are listed as follows:

5.2.1. Hardware Requirements

Table 5.1 shows the hardware requirements for Nb-IoT-based Smart Water Meter

Table 5. 1: Hardware requirements

Hardware	Description
ATMEAGA328P-PU	ATmega328p-pu is an Atmel AVR family microcontroller used across a wide range of applications. It has a high-performance ability with low-power capability. This microcontroller has 23 programmable I/O lines with a 2-wire serial interface. It has a flash memory of 32kb, 2kb SRAM, and 1kb EEPROM. The operating voltage ranges between 1.8v and 5.5v.
SIM7080G NB-IoT module	SIM7080G module is a cellular module used to access global connectivity for IoT and M2M applications with the support of various cellular communication technologies, including 2G,3G,4G, NB-IoT, and CAT-M1. This module also supports GPS location services allowing tracking of IoT devices
YF-S201 Water Flow Meter	YF-S201 water flow meter is a compact device deployed in a water pipeline. The device has a turbine inside that revolves around when water is flowing. The rotation of the turbine is then

	converted to an electrical signal and converted to the water flow rate that is used to calculate the volume of water that has passed through it.
DS3232 RTC	DS3232 is a real-time clock chip that provides accurate time in IoT and embedded applications. This chip uses a serial interface to communicate with the microcontrollers and is controlled by software commands.
22pf Capacitors	The two 22pf Capacitors are connected to the crystal oscillator of a microcontroller to assist in stabilizing the load capacitance needed by the crystal. This help in improving the performance and reliability of the circuit, reduces noise and stabilizes voltage.
2200uf capacitor	This type of capacitor stabilizes the power supply on the electrical circuit by doing power filtering, decoupling, and buffering.
10k Ohm Resistor	The 10k Ohm resistor is connected to the reset pin of the microcontroller to act as a pull-up resistor to ensure that the reset pin of the MCU is at a known state when the circuit is powered on and to prevent accidental reset of the MCU because of electrical issues or noise from the current.
Jumper Cables	They connect components to provide an electrical connection on a breadboard.
Breadboard	This is a prototyping tool where components are placed and connected during the prototyping stage for experimental purposes before moving them to a PCB design.
NB-IoT Sim card	NB-IoT sim card is designed for IoT communication over the NB-IoT network. It's connected to the NB-IoT module for communication purposes

5.2.2. Software Requirements

Table 5.2 illustrates the software requirements of an NB-IoT-based Smart water meter.

Table 5. 2: Software Requirements

Software	Description
Operating system	Windows 7 and above
Internet browser	Any browser. Google Chrome is the preferred one.
Arduino IDE	Arduino IDE version 1.8* or higher
Vscode	Vscode IDE version 1.7* or higher

5.2.3. Cloud Services Requirements

Table 5.3 describes the cloud services requirements for implementing an NB-IoT-based smart water meter.

Table 5. 3: Cloud services requirements

Cloud Services	Description
Microsoft Azure	Azure student account is the preferred service for implementation and testing purposes.
Firebase	Firebase real-time database was used as a NoSQL database. Google provides this service as a free service for running tests.

5.3. Server Configuration

In this study, a Linux virtual machine was created in Microsoft Azure and hosted the following applications.

Table 5. 4: Application to install on the server.

Application	Description
Eclipse Mosquitto	This is the MQTT Broker
Node-Red	Application to integrate MQTT into a database platform

5.3.1. Setting up a Virtual Machine

Azure virtual machine is utilized by creating the server's name and selecting Ubuntu 18.04 LTS-Gen2 chosen as the server operating system, as shown by image 5.1.

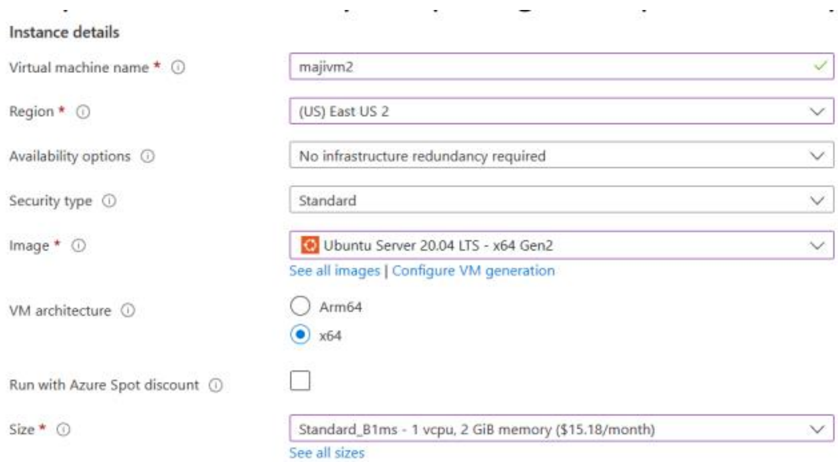

Figure 5. 1: Setting Azure server with Ubuntu OS.

The next step was to set security features to use while accessing the server by the administrator. The password was picked as shown in image 5.2.

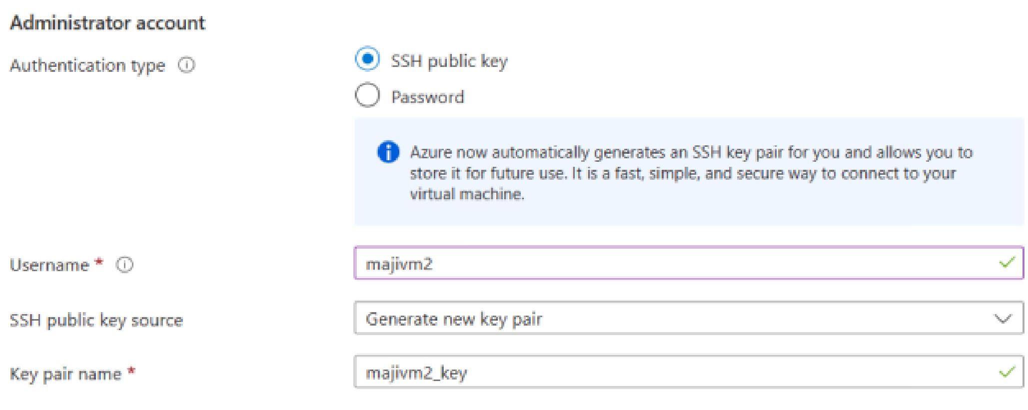

Figure 5. 2: Setting Security for SSH

Communication to and from the server needs the following ports to be open.

Table 5. 5: Port Numbers to allow on the server.

Port Number	Service offered
80	HTTP
433	HTTPS
22	SSH
1883	MQTT

After setting up the server, a public IP address was provided, and set up for a domain name system mapped to the IP address was done and shown in image 5.3.

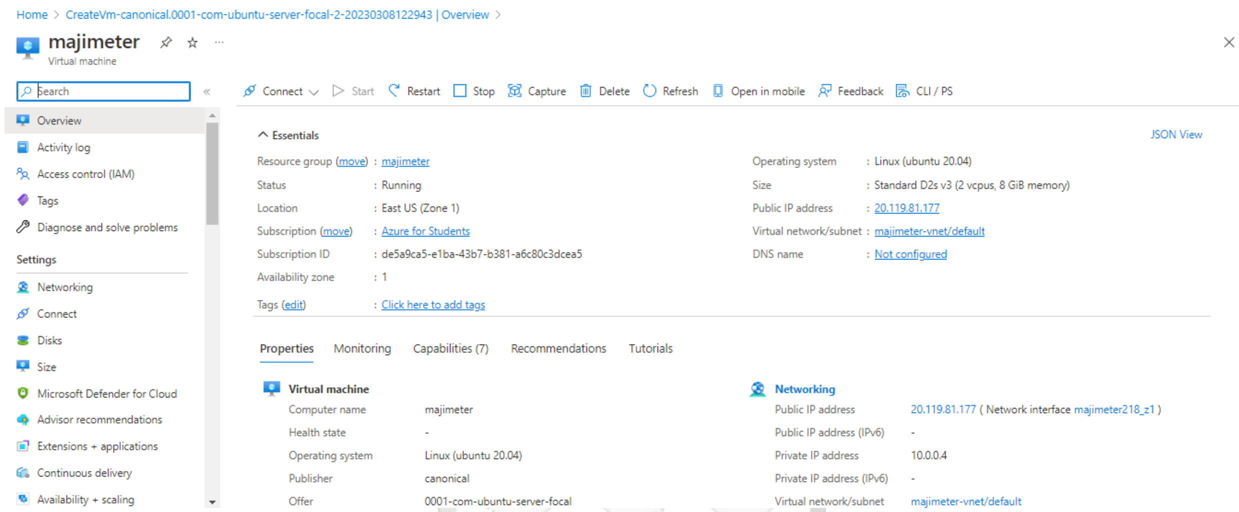

Figure 5. 3: Image of an operational server

Adding inbounding port rules in the server on the networking page was essential, as indicated in table 5.6.

Table 5. 6: Inbounding Ports Rules to Set in the Server

Priority	Name	Port	Protocol	Source	Destination	Action
1010	Node-RED	1880	TCP	Any	Any	Allow
400	MQTT	1883	TCP	Any	Any	Allow

Image 5.4 below shows a snapshot after adding the above ports to the server.

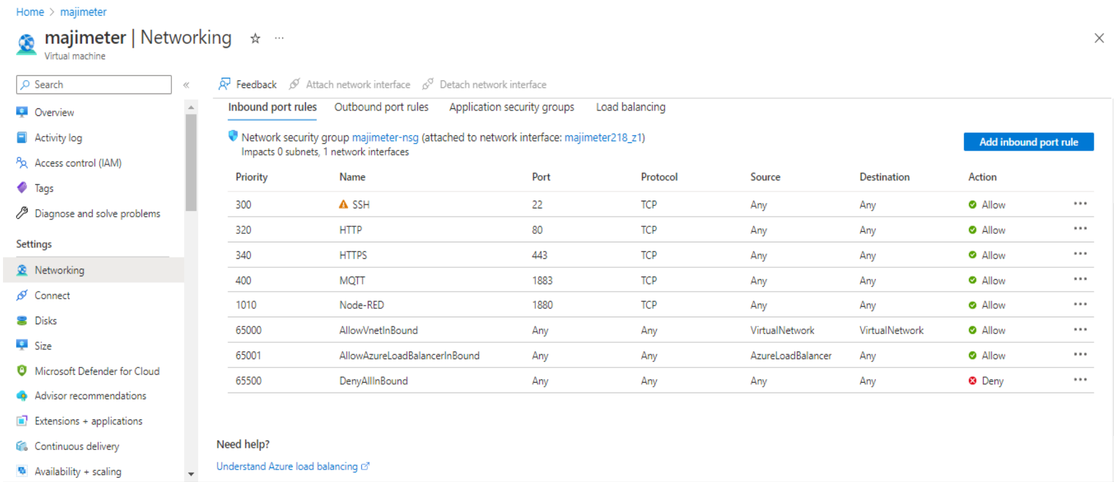

Figure 5. 4: Inbounding ports added on the server.

5.3.2. Setting up MQTT Broker

The broker of choice was Eclipse Mosquitto. Table 5.7 shows commands that were used to prepare the broker.

Table 5. 7: Commands to Set MQTT Broker

Command	Description
$ sudo apt update	Updating the package information index
$ sudo apt install -y mosquito	Install Mosquitto package
$ sudo systemctl status mosquito	Checking if the package is loaded and running

Image 5.5 shows the mosquitto service running on the server.

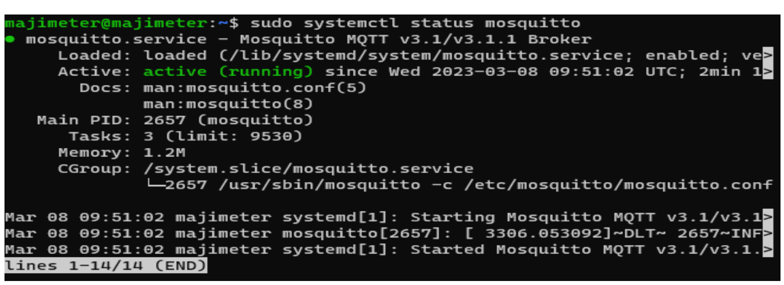

Figure 5. 5: Running the Mosquitto server

The MQTT file is edited to enhance security in the default file by editing it. The config directory was accessed, and anonymous connections were disabled. Credentials for users were then created to improve safety. Table 5.8 below shows commands used to set up this.

Table 5. 8: Setting MQTT Broker encrypted password.

Command	Description
$ sudo nano /etc/mosquitto/conf.d/default.conf	Creating a default configuration directory under nano and disabling anonymous connections by adding the following information. allow_anonymous false password_file /etc/mosquitto/passwd
$ sudo nano /etc/mosquitto/passwd	Adding users' credentials to allow them to connect to the broker. In this file, the username and password were added in the following format. Username: password
$ sudo mosquitto_passwd -U /etc/mosquitto/passwd $ sudo cat /etc/mosquitto/passwd	Encrypting passwords using the mosquitto_passwd utility to enhance security

Image 5.6 below shows a snapshot of the encrypted mosqutto service password.

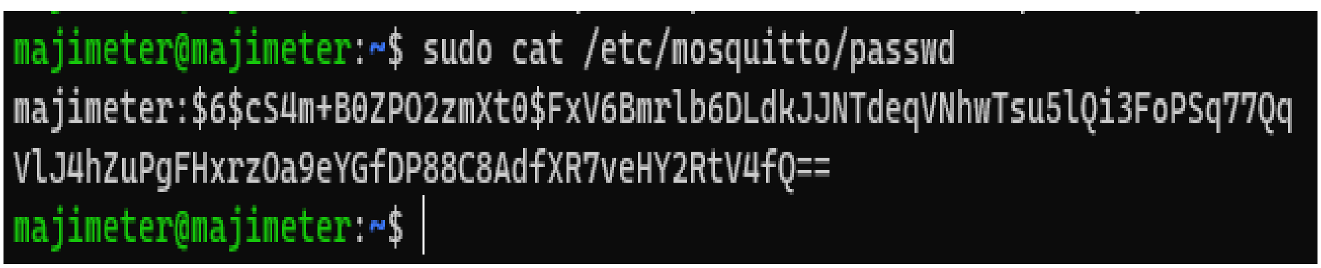

Figure 5. 6: Encrypted password for MQTT Broker

5.3.3. Setting up Node-Red

Some dependencies were pre-installed, which aided in setting up Node-Red in the server. Table 5.9 below shows commands that were used in installing dependencies.

Table 5. 9: Command to set up Node-Red dependencies.

Command	Description
$ sudo apt install curl	Enable installation of software repositories of various packages by ubuntu-users
$ curl -fsSL https://deb.nodesource.com/setup_18.x | sudo -E bash -	Add Node.js
$ sudo apt-get install -y Node.js	Install Node.js
Node-v	Check installed Node.js Version
$ sudo apt install aptitude	Installing Node package manager to manage Node.js
$ sudo aptitude install npm	Install npm with aptitude
npm -v	Check npm version

After the dependencies were installed, Node-Red was configured. Table 5.10 shows the command that was used.

Table 5. 10: Configuring Node-Red in the server.

Command	Description
$ sudo npm install -g --unsafe-perm node-red node-red-admin	Install node-red using a node-red-admin utility
$ sudo npm install -g --unsafe-perm pm2	Stating node-red automatically whenever an instance is restarted.
$ npm install uuid@latest	Updating uuid
$ pm2 start `which node-red` -- -v	To run node-red through npm
$ pm2 save $ pm2 startup	Setting up startup script for npm

It's important to enhance security in Node-Red. The commands in table 5.11 were used to enhance this.

Table 5. 11: Setting Node-Red security.

Command	Description
$ node-red-admin hash-pw	Making a one-way cryptographic hash password
$ nano ~/.node-red/settings.js	Opening Node-Red settings files to update the file and add a password
$ node-red	Start running node-red
$pm2 restart all	Restarting all

Image 5.7 shows a snapshot of Node-Red running on the server.

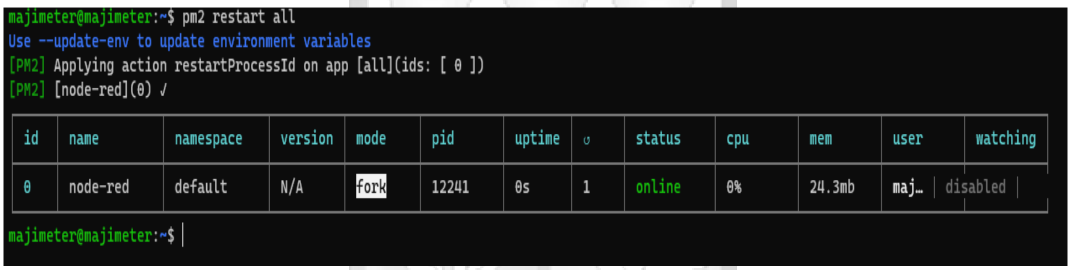

Figure 5. 7: PM2 service showing Node-Red running.

5.4. Hardware Setup

The hardware components were assembled, and ATmega328p-pu MCU was used. Figure 5.8 shows a PCB with a description of the components in table 5.12.

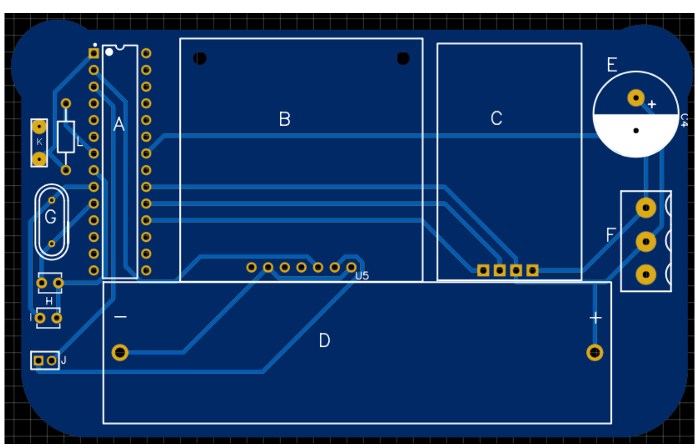

Figure 5. 8: PCB design for NB-IoT Smart Water Meter

Table 5. 12: Modules to be placed on the PCB.

Lebel	Description
A	ATmega328p-pu
B	SIM7080G Module
C	DS3232 RTC
D	18650 LiPo Battery 3.7V
E	35v 2200uf Capacitor
F	YF-S201 Water meter connector
G	16 MHz Crystal Oscillator
H & I	22pf capacitor
J	TX Jumper
K	0.01uf capacitor
L	10k Ohm Resistor

The actual prototype device is illustrated in figure 5.9.

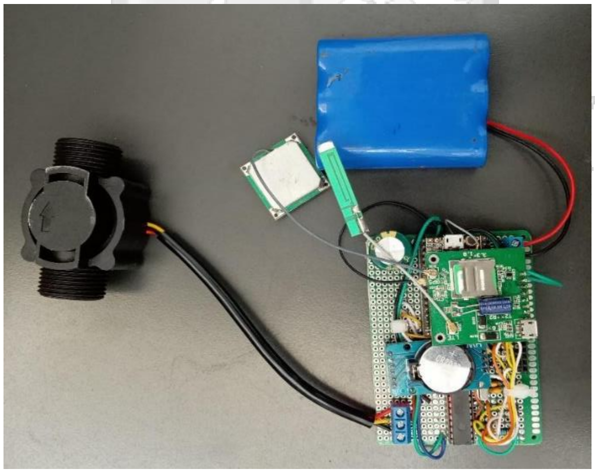

Figure 5. 9: NB-IoT Smart Water Meter prototype

Figure 5.10 shows a code snippet based on C++ that runs on the ATmega328p-pu an AVR-based MCU.

Figure 5. 10: C++ Code for Smart Meter

Figure 5.11 shows snapshot of putty showing encoded data that is being sent to an MQTT broker. Data that was collected by the device was transmitted to a NoSQL database in an encrypted format. To have this data being visualized in a human readable format, a decoder was employed by the subscriber.

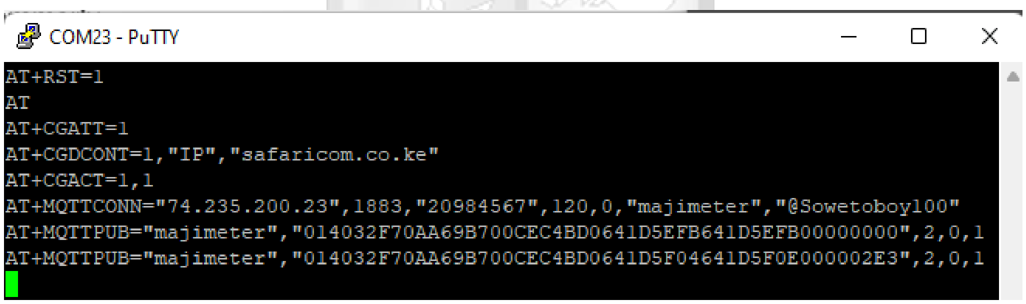

Figure 5. 11: Encoded payload from device

5.5. Prototype Packaging

The casing design for the prototype was done using fusion 360, a free version of the software for students, and the sliced using Ultimaker Cura 4.12.0. Figure 5.12 below shows the package for the prototype deployed at Strathmore University during the testing phase.

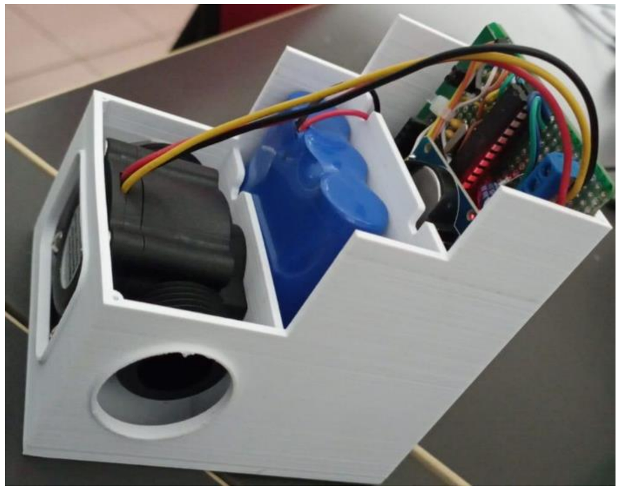

Figure 5. 12: Packaged NB-IoT Smart Water meter with a 3D printed casing.

5.6. NoSQL Database Setup

This kind of database was chosen due to its ability to scale and being a real-time database that is always available and free for testing purposes. Firebase real-time database allows storage of data bounded to real-time data in a NoSQL format. A decoder was prepared to format data appropriately to store it after being collected and processed by the device. The database view is as shown in image 5.13.

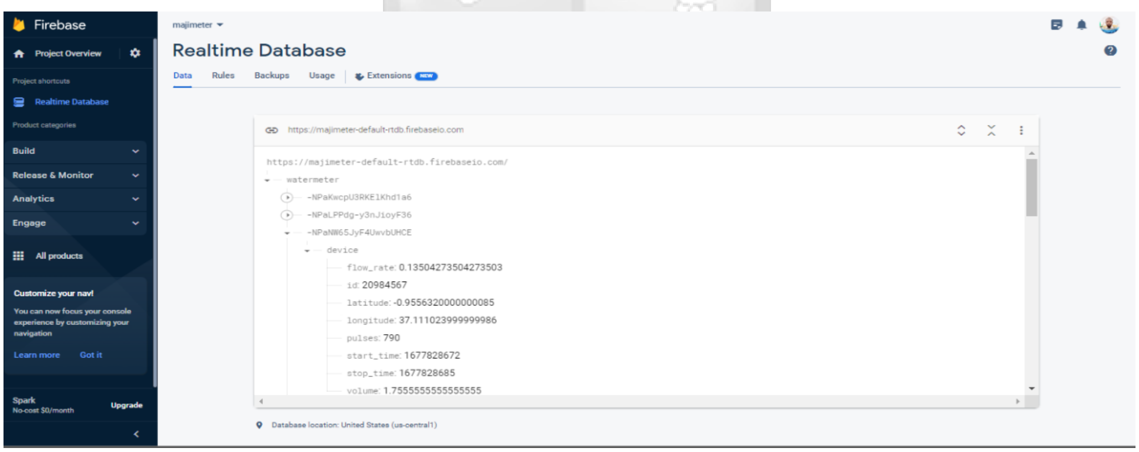

Figure 5. 13: Data Stored in Firebase

5.7. User Interface Implementation

The user interface in this study is accessible using a web application and responsive to any screen size, including mobile devices. The water company customer has an interface different from that of water management.

5.7.1. Water Utility Customers

5.7.1.1. User Login Page

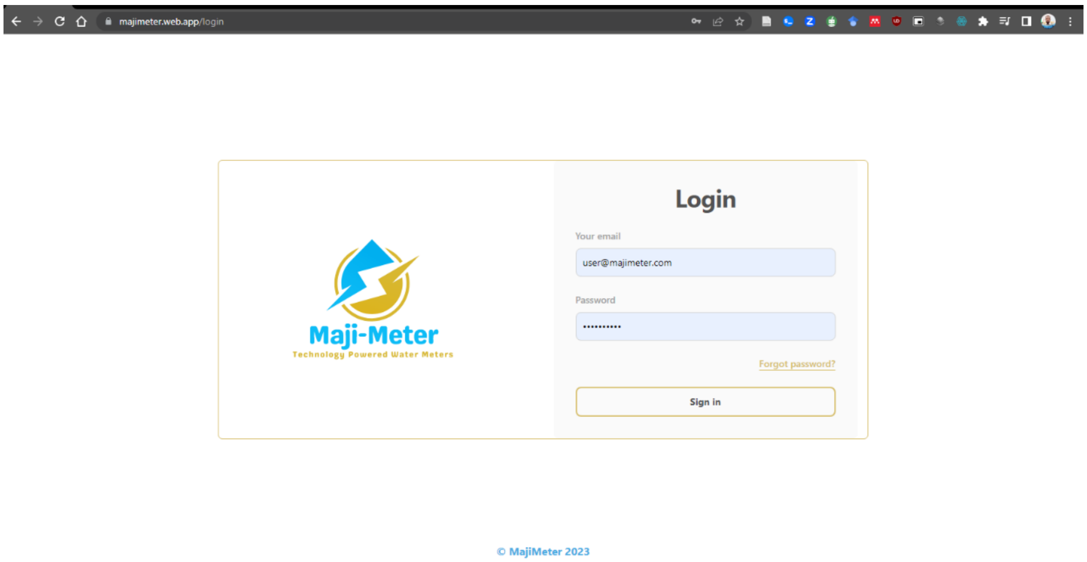

Figure 5. 14: User login page

5.7.1.2. Dashboard

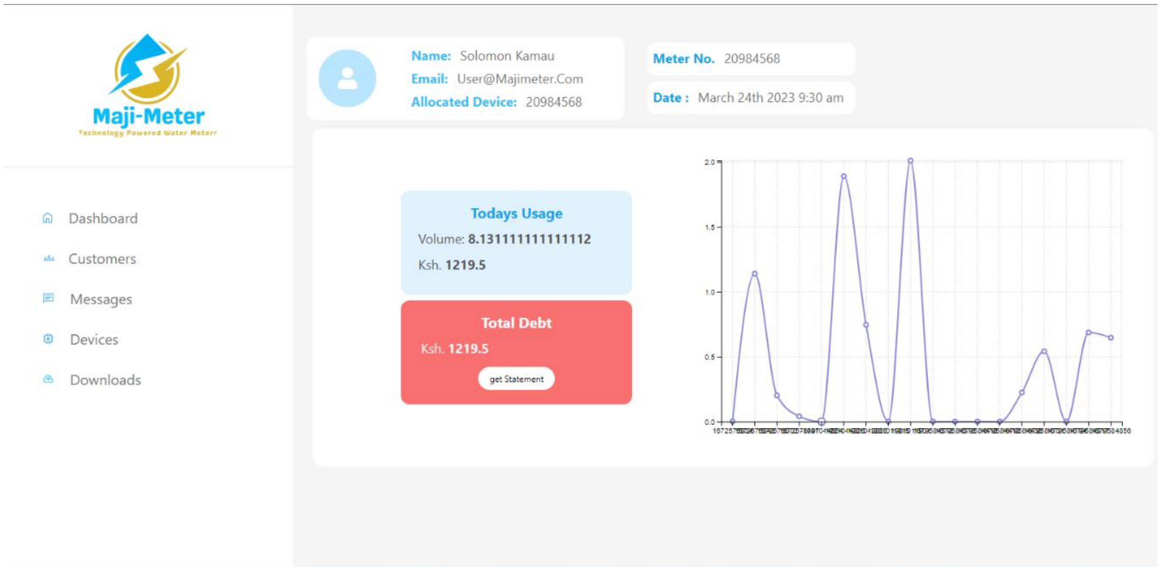

Figure 5. 15: User landing page

5.7.2. Water Company Manager

5.7.2.1. Admin Login Page

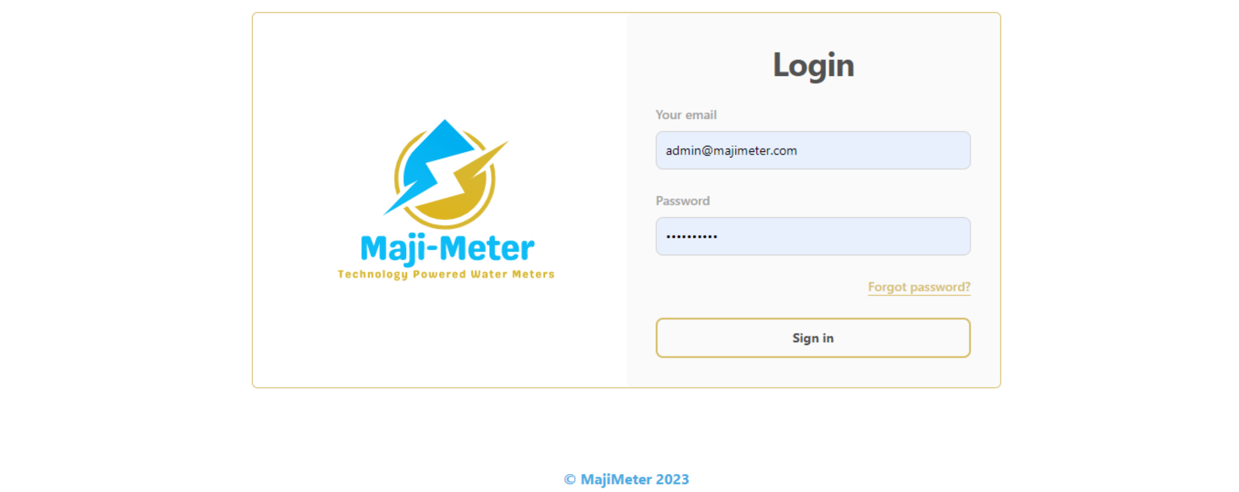

Figure 5. 16: Admin login page

5.7.2.2. Admin Landing Page

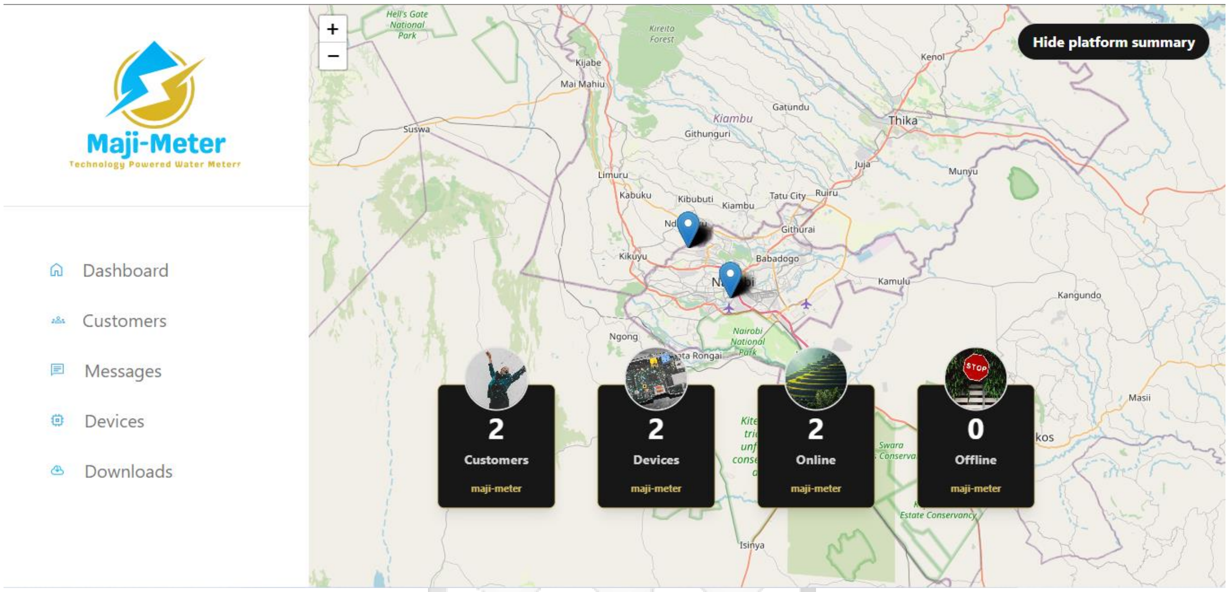

Figure 5. 17: Admin landing page

5.7.2.3. Device Monitoring

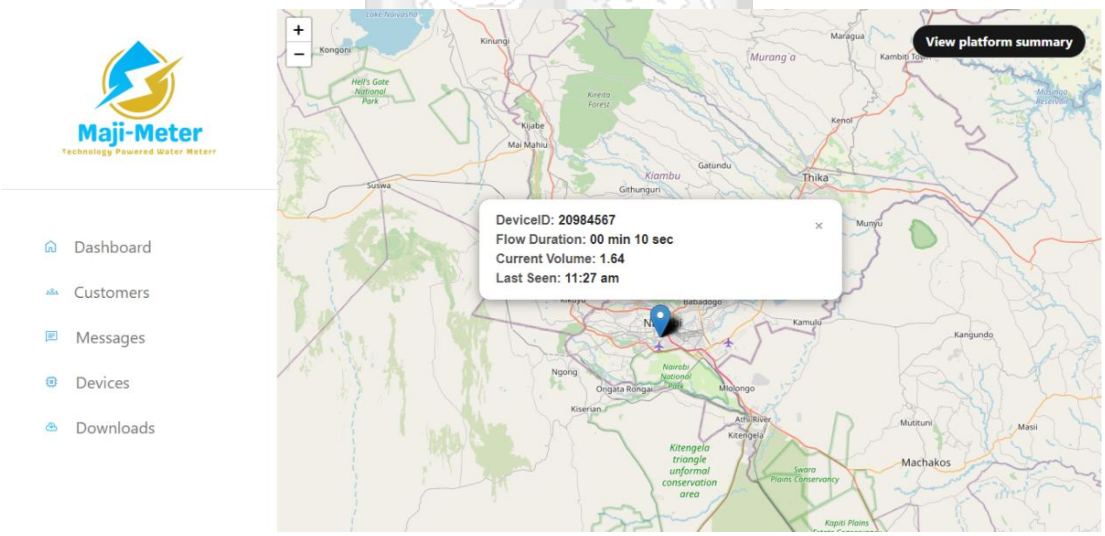

Figure 5. 18: Device location-based monitoring.

5.8. Testing

After integrating all system components, the system was evaluated to ensure it was functioning properly. During the development process, functional testing was done repeatedly. This was done to ensure all requirements were fulfilled and the system ran flawlessly. Additionally, the testing procedure confirmed that all bugs were fixed. Table 5.13 shows the test cases that were run for testing.

5.8.1. Functional Requirements

Table 5. 13: Testing Functional Requirements

Test Case	Pre-Condition	Test Data	Expected Result	Pass/Fail
Sensors Collecting data	Sensors must be connected to the right input pins on the MCU	Water flow rate Time	Flow rate data and time displayed on the Arduino IDE serial monitor	Pass
Conform SIM7080G is connecting to the NB-IoT network	Connect SIM7080G to FTDI module	Simple AT Commands AT+COPS=0	Safaricom APN displayed	Pass
Confirm Data transmission to a Database	Sensors and SIM7080G must be connected to the MCU, and the code uploaded	Volume GPS Start time. Stop time	Data sent to the Firebase database	Pass
Account Sign In	Email and password are provided, and the device has internet access	Email: admin@maji-meter.com Password: 123456	Login Successful	Pass
Water Meter Monitoring	Device data is saved in the database	Volume	Displays data collected by the device	Pass

View Water Bills	Water consumption level, water unit price	Water bills	Calculated water bill consumption wise is displayed	Pass
View Water Consumption Reports	Water consumption over time	Consumption levels	Graph summary of water consumption level	Pass

5.8.2. Compatibility Testing

This test was done to verify that the web app can be accessed using different web browsers in user's phones and computers. The tested browsers included Mozilla Firefox and Google chrome. Table 5.14 illustrates this.

Table 5. 14: Operating System Version Tested

Browser	Compatibility
Google Chrome browser (V110 and above)	YES
Mozilla Firefox browser (V64 and above)	YES

5.8.3. Validation

The NB-IoT smart water meter was validated through rigorous testing and analysis to guarantee that it satisfied the requirements. The validation was conducted to ensure that there was accuracy and dependability of data collected by the system. This validation was to gain assurance that the NB-IoT water meter data is accurate and will contribute to more sustainable smart cities by facilitating the efficient management of water supplies.

Chapter Six: Discussion of Results

6.1. Overview

The result of the developed solution in comparison with the objectives and research question that guided this study are discussed in this chapter. The main goal was to design and develop an NB-IoT-based smart water meter to collect water-related data and send it to databases, integrating it with a visualization platform for water companies and their customers.

As highlighted in the problem statement, this study seeks to address challenges faced when collecting data from water meters, such as power, connectivity, and labor-intensive processes, through adopting LPWAN communication technologies. The developed system addresses this issue by collecting water-related data and transmitting it through the NB-IoT network, an LPWAN communication technology addressing the power issue as the device can last with power for more than five years before recharge and replacements. This also helps improve transparency processes between water suppliers and customers by providing the correct water bills. Water companies also have a chance to lower losses incurred when their field agents miss manual water reading to some of their clients.

The study established that the NB-IoT network infrastructure exists in Nairobi, and IoT devices can utilize this infrastructure to transmit data for longer distances while using low power. Furthermore, this communication technology is strong, and sensors can be deployed anywhere, even inside the building, as they can penetrate through walls. With this network, devices can last longer with battery power, and it's ideal for automating the data collection process, lowering the cost incurred, and improving accuracy.

6.2. Results of the Study

The achievement of the study was a smart water meter prototype communicating through NB-IoT Communication network to send data to a cloud infrastructure using the MQTT protocol. Node-RED subscribed to the data and then saved it to a firebase database.

This system enabled the collection and analysis of water usage data, which could be used for billing purposes by water utility companies and watch trends in water consumption by both users and their water suppliers. By using this system, water companies can reduce losses incurred by unbilled resources while there is transparency between users and water companies.

NB-IoT technology provided reliable and secure communication, while MQTT ensured efficient and lightweight messaging. Node-RED simplified the integration of different components, while Firebase offered a scalable and flexible database solution.

Overall, the smart water meter system developed in this study offered an innovative and practical water management and conservation solution using NB-IoT frequency bands which could contribute to a more sustainable future while accommodating more IoT devices.

6.3. Validation of the System

This task's main aim was to determine if the system met its proposed performance and how effective it was in collecting data and sending it over narrow-band frequencies dedicated to IoT devices. The study involved installing a node in Strathmore University premises and monitoring water consumption over a period. The result of the study showed that smart water meters with NB-IoT capabilities could be effective and appropriate in solving financial losses by water companies and ensuring transparency between the customer and their water providers. Furthermore, the stable narrow-band frequencies can support more IoT devices both indoors and outdoors over a long distance while using less power. The reliable system seemed a go-to solution for better water management in Nairobi.

6.4. Performance Evaluation and Reliability

Several critical parameters were analyzed in the performance evaluation of the NB-IoT water metering device deployed at Strathmore University to establish its effectiveness and reliability. The gadget displayed exceptional communication dependability, consistently maintaining a stable NB-IoT connection across the university campus, even in regions with varied signal levels. The device's data accuracy was a major strength, as it constantly recorded water consumption readings that were nearly identical to those acquired from traditional water meters. The device's battery life was efficient, with the device working for extended durations without the need for regular battery replacements or recharging. Data transmission efficiency was remarkable, with data transmission from the device to the central server being quick and successful.

The device's metering performance was extremely accurate, demonstrating its capacity to properly monitor water use and record results after every use session. Furthermore, the NB-IoT water metering device exhibited resilience in a variety of environmental situations, and its security features maintained the privacy and integrity of the transmitted data. These encouraging findings demonstrate the device's ability to provide precise water consumption statistics as well as its potential for further application outside Strathmore University.

6.5. Assessment of the Developed System in Relation to Research objectives

In this study, an NB-IoT smart water metering device was developed with a web application for the end users. This section highlights the objective of the study in relation to the results and finding acquired. The first objective was to investigate problems associated with reading existing water meters. The study clarified that water utility companies encounter various issues while collecting water data, and there is no transparency in the billing process for customers. Most water meters that have been installed are manual and rely on human experts to read and collect data, which is then done manually.

6.6. Research Limitations

Due to the high cost of components, the number prototypes designed during the research were limited. This affected the number of devices that would have been distributed to end users for more insight. To guarantee continuous data upload, the device relied on data. This implies that the system incurs data expenses, which telecommunications companies would bill customers for.

Chapter Seven: Conclusion, Recommendations, and Future Works

7.1. Conclusions

After this study, several conclusions were drawn as follows:

i. NB-IoT communication technology has proven to be dependent on and is a cost-effective approach for smart metering systems because it can transmit data over long distances while using less power. It is appropriate for urban and remote areas where this infrastructure already exists.

ii. Smart metering devices that are NB-IoT enabled can avail accurate and real-time data on water usage patterns. This information can be used to manage water usage at homes and industries to reduce cost and wastage.

iii. Adopting Smart Water Meters as a tool to collect consumption data can lead to significant cost savings for consumers and water companies.

iv. The upfront cost for developing and setting up smart water meters that transmit data using NB-IoT infrastructure is expensive. Still, it's worth investing in it as the long-term benefits and returns are good.

v. The deployment of NB-IoT-based smart water meters necessitates establishing a strong and dependable network infrastructure, which may need to be expanded or upgraded to accommodate the new technology.

Overall, smart water metering systems that utilize NB-IoT are promising for improving water management and reducing waste. This technology will likely become more widely adopted in the futur**e.**

7.2. Recommendations

After this study, the subsequent recommendations were drawn:

i. Water Companies should embrace smart water metering technology, especially NB-IoT-based ones, because the infrastructure already exists. This will automate the data collection, optimize operations, and cut losses incurred through inconsistent water consumption data.

ii. Telecommunication companies that are locally available such as Safaricom, Airtel, and Telkom, should ensure that NB-IoT infrastructure is reliable and that the network is strong in every part of the country. This will support the deployment of NB-IoT-based smart meters.

iii. The government should put policies that push consumers and water management companies to adopt Smart Water meters to reduce revenue loss incurred when manual water meters are in place.

iv. Customers should be involved in the NB-IoT water meter deployment process and should be trained on the benefits of this technology, its efficiency, and its transparency.

v. Further research should be conducted on NB-IoT technology and how this can be adopted in developing smart cities and Villages to improve the overall sustainability of urban and rural areas.

7.3. Future Works

Smart water meters with NB-IoT connectivity promise technology that can help improve water management and conservation. Work under NB-IoT smart water meters is expected to evolve in several directions in the future:

i. Incorporate data analysis since more data will be collected by NB-IoT water meters. Hence, there will be an opportunity to use data analytics techniques to have more insights into water usage patterns and areas of improvement.

ii. Integration of this kind of device with existing building management systems to improve efficiency and reduce wastage caused by manual systems.

iii. Improving this system to incorporate real-time water usage monitoring to detect anomalies such as leakages and other unpredicted occurrences.

iv. Remote control and management, if incorporated, allow water cuts where leakages have been detected and water payment has not been made.

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APPENDICES

Appendix A: Questionnaires

Appendix A.1: Questionnaire to Water Consumers'

Questionnaire to water consumers with water meters

The purpose of this survey is to gather data on the usage of the NB-IoT-based smart water meter in Nairobi County, with the goal of analyzing an approach for it. All information collected from the survey will be used only for academic research purposes, and your identity will remain anonymous.

Please do your best to answer the questions in this survey. There are no right or wrong answers, and we appreciate your response. Your name is not required anywhere on the form, and the information gathered is solely for academic research purposes.

(Please make an effort to answer all questions to the best of your ability)

Does a water meter reader visit your premises on a monthly basis to record water meter readings?

Yes []   No [ ]

How many years have you had a water meter connection ?

Less an year [ ]   1-5 years [ ]   6-10 years [ ]   11-15 years [ ]   Above 15 years[ ]

How are your water bills sent to you?

By Email [ ]   By SMS [ ]   Manual Printout [ ]

How satisfied are you with the methods of bill receipt mentioned above? (1 is lowest, 5 is highest)

Satisfaction Query	1	2	3	4	5
Are you satisfied with the current bill-receiving mode?					

Do you have a smart phone and use it?   Yes [ ]   No [ ]

Do you have and use an email account?   Yes [ ]   No [ ]

THANK YOU FOR YOUR TIME AND PARTICIPATION

Appendix A.2: Questionnaire to Water Companies

Questionnaire to Nairobi City Water and Sewerage Company (NCWSC)

The purpose of this survey is to gather data on the usage of the NB-IoT-based smart water meter in Nairobi County, with the goal of analyzing an approach for it. All information collected from the survey will be used only for academic research purposes, and your identity will remain anonymous.

Please do your best to answer the questions in this survey. There are no right or wrong answers, and we appreciate your response. Your name is not required anywhere on the form, and the information gathered is solely for academic research purposes.

(Please make an effort to answer all questions to the best of your ability)

How frequently is field data from water meters collected?

Weekly [ ]   Monthly [ ]   Quarterly [ ]

Do you usually perform spot checks to ensure the accuracy of the readings?

Yes [ ]   No [ ]

What is the billing cycle for your company?

Monthly [ ]   Quarterly[ ]   Yearly[ ]

Do you frequently have unrecorded customer data?

Yes [ ]   No []

Do your customers fail to pay their bills?

Yes [ ]   No []

What method do you currently use to send bills to your customers?

Through a Portal Account [ ]   By Email [ ]   By SMS [ ]   Manual Printout [ ]

THANK YOU FOR YOUR TIME AND PARTICIPATION

Appendix B: Codes Snippet

Appendix B: I: C++ Code to Send Data to MQTT Broker

```
{
    Serial.println(F("AT+CGACT=1,1"));
    Serial.flush();//Wait for string to  be sent
    delay(100);
    _buffer = Serial.readString();
    if (_buffer.indexOf("OK") >= 0)
    {
      break;
    }
    else
    {
      delay(1000);
    }
  }
 }
 while (1);

 last_millis = millis();
 do
 {
  if (millis() - last_millis > 120000)
  {
    resetFunc(); //call reset
  }
  else
  {
    sprintf(CONNECT,
            "AT+MQTTCONN=\"%s\",%s,\"%08lu\",%s,%s,\"%s\",\"%s\"",
            HOST, PORT, CLIENT_ID, ALIVE_SECONDS, CLEAN_SESSION, USERNAME, PASSWORD);
    Serial.println(CONNECT);
    Serial.flush();//Wait for string to  be sent
    delay(100);
    _buffer = Serial.readString();
```

```
    if (_buffer.indexOf("OK") >= 0)
    {
      break;
    }
    else
    {
      delay(1000);
    }
  }
}
while (1);

last_millis = millis();
do
{ if (millis() - last_millis > 120000)
  {
    resetFunc(); //call reset
  }
  else
  {
    uint32_t _latitude = (LATITUDE + 180) * 1000000;
    uint32_t _longitude = (LONGITUDE + 180) * 1000000;

    DateTime now = rtc.now();

    start_time = now.unixtime();
    stop_time = start_time;

    sprintf(PAYLOAD,
            "%08lX%08lX%08lX%08lX%08lX%08lX",
            CLIENT_ID, _latitude, _longitude, start_time, stop_time, pulses);
    sprintf(PUBLISH,
            "AT+MQTTPUB=\"%s\",\"%s\",%s,%s,%s",
            PUB_TOPIC, PAYLOAD, QOS, DUP_FLAG, REMAIN_FLAG);
    Serial.println(PUBLISH);
    Serial.flush();//Wait for string to  be sent
```

```
      delay(100);
      _buffer = Serial.readString();
      if (_buffer.indexOf("OK") >= 0)
      {
        break;
      }
      else
      {
        delay(1000);
      }
    }
  }
  while (1);
}

void loop()
{
  if ((pulseIn(2, HIGH, 2000000)) && pulseIn(2, LOW, 2000000))
  {
    if (pulses)
    {
      pulses++;
    }
    else
    {
      DateTime now = rtc.now();
      start_time = now.unixtime();
      pulses++;
    }
  }
  else
  {
    if (pulses)
    {
      if (pulses > 5)
      {
```

```
//Send
last_millis = millis();
do
{ if (millis() - last_millis > 120000)
  {
    resetFunc(); //call reset
  }
  else
  {
    uint32_t _latitude = (LATITUDE + 180) * 1000000;
    uint32_t _longitude = (LONGITUDE + 180) * 1000000;

    DateTime now = rtc.now();

    stop_time = now.unixtime();

    sprintf(PAYLOAD,
            "%08lX%08lX%08lX%08lX%08lX%08lX",
            CLIENT_ID, _latitude, _longitude, start_time, stop_time, pulses);
    sprintf(PUBLISH,
            "AT+MQTTPUB=\"%s\",\"%s\",%s,%s,%s",
            PUB_TOPIC, PAYLOAD, QOS, DUP_FLAG, REMAIN_FLAG);
    Serial.println(PUBLISH);
    Serial.flush();//Wait for string to  be sent
    delay(100);
    _buffer = Serial.readString();
    if (_buffer.indexOf("OK") >= 0)
    {
      break;
    }
    else
    {
      delay(1000);
    }
  }
}
```

```
        while (1);
        //Reset Parameters
        start_time = 0;
        stop_time = 0;
        pulses = 0;
        //Attach Interrupt and Power Down
        attachInterrupt_sleep();
      }
      else
      {
        //Reset Parameters
        start_time = 0;
        stop_time = 0;
        pulses = 0;
        //Attach Interrupt and Power Down
        attachInterrupt_sleep();
      }
    }
    else
    {
      //Reset Parameters
      start_time = 0;
      stop_time = 0;
      pulses = 0;
      //Attach Interrupt and Power Down
      attachInterrupt_sleep();
    }
  }
}
```

Appendix B: II: Vue.Js Code

```
methods: {
  getAllDevices() {
    const db = getDatabase();
    const customerRef = ref(db, "watermeter");
    onValue(customerRef, (snapshot) => {
      const data = snapshot.val();
      let keys = Object.keys(data);
      for (let i = 0; i < keys.length; i++) {
        let k = keys[i];
        let values = data[k].device;
        // console.log("values === > ", values);
        if (!this.devices.includes(values) && !this.keys.includes(k)) {
          this.devices.push(values);
          this.keys.push(k);
        }
      }
    });
    this.devices = JSON.parse(JSON.stringify(this.devices));

    if (JSON.parse(JSON.stringify(this.devices)).length > 0) {
      this.isLoaded = true;
      // location
      let mostResentUpdate =
        this.devices[JSON.parse(JSON.stringify(this.devices)).length -
1];

      this.filteredDevices = new Set(
        JSON.parse(JSON.stringify(this.devices)).map((item) => item.id)
      );
      console.log(this.filteredDevices);

      const groupedById = groupBy(
        JSON.parse(JSON.stringify(this.devices)),
```

```
          (item) => item.id
        );
        // const result = Object.values(groupedById);
        console.log(groupedById);
        // get size of groups
        let groupSize = Object.entries(groupedById);
        this.groups = groupSize;
        console.log(">> ", groupSize);
        //split group
        let devices = [];
        for (let x = 0; x < groupSize.length; x++) {
          devices.push(this.getGroupItems(groupSize[x]));
        }
        this.filteredDevices = devices;

        console.log(JSON.parse(JSON.stringify(this.groups)));
        let totalVlm = 0;
        if (this.userAssignedDevice.toString() === this.groups[0]) {
          this.data = JSON.parse(JSON.stringify(this.groups[0][1]));

          for (
            let x = 0;
            x < JSON.parse(JSON.stringify(this.groups[0][1])).length;
            x++
          ) {
            totalVlm +=
JSON.parse(JSON.stringify(this.groups[0][1]))[x].volume;
          }
        } else {
          this.data = JSON.parse(JSON.stringify(this.groups[1][1]));
          for (
            let x = 0;
            x < JSON.parse(JSON.stringify(this.groups[1][1])).length;
            x++
          ) {
```

```
            totalVlm +=
JSON.parse(JSON.stringify(this.groups[1][1]))[x].volume;
          }
        }
        this.totalVolume = totalVlm / 1000;
        this.bill =
          (this.pricePerUnit * Math.round((totalVlm / 1000) * 100)) / 100;
        console.log("== > > ", JSON.parse(JSON.stringify(this.data)));
      }
    },

    getGroupItems(group) {
      console.log(" = > ", group);
      // get latest value
      let size = group.length;
      console.log(" == > ", size);
      // add to filtered list
      console.log(" === > ", group[1][group[1].length - 1]);
      return group[1][group[1].length - 1];
      // this.filteredDevices.push();
    },
  },
  mounted() {
    this.getAllDevices();
  },
};
</script>

<style></style>
```

Appendix C: Ethics Review Certificate

Strathmore
UNIVERSITY

27th February 2023

Mr Kamau Solomon Itotia,
solomon.kamau@strathmore.edu

Dear Mr Kamau,

RE: Narrowband-Internet of Things Based Water Metering System: A Case for Nairobi

This is to inform you that SU-ISERC has reviewed and **approved** your above **SU- master's** research proposal. Your application reference number is **SU-ISERC1581/23.** The approval period is from **27th February 2023 to 26th February 2024.**

This approval is subject to compliance with the following requirements:

i. Only approved documents including (informed consents, study instruments, and MTA) will be used
ii. All changes including (amendments, deviations, and violations) are submitted for review and approval by SU-ISERC.
iii. Death and life-threatening problems and serious adverse events or unexpected adverse events whether related or unrelated to the study must be reported to SU-ISERC within 48 hours of notification
iv. Any changes, anticipated or otherwise, that may increase the risks or affect the safety or welfare of study participants and others or affect the integrity of the research must be reported to SU-ISERC within 48 hours
v. Clearance for the export of biological specimens must be obtained from relevant institutions.
vi. Submission of a request for renewal of approval at least 60 days prior to the expiry of the approval period. Attach a comprehensive progress report to support the renewal.
vii. Submission of an executive summary report within 90 days of completion of the study to SU-ISERC.

Before commencing your study, you will be expected to obtain a research license from National Commission for Science, Technology, and Innovation (NACOSTI) https://research-portal.nacosti.go.ke/ and obtain other clearances needed.

Yours sincerely,

for: **Dr Ben Ngoye,**
Secretary; SU-ISERC

Cc: Mr Ambrose Rachier,
Chairperson; SU-ISERC

STRATHMORE UNIVERSITY INSTITUTIONAL SCIENTIFIC AND ETHICAL REVIEW COMMITTEE
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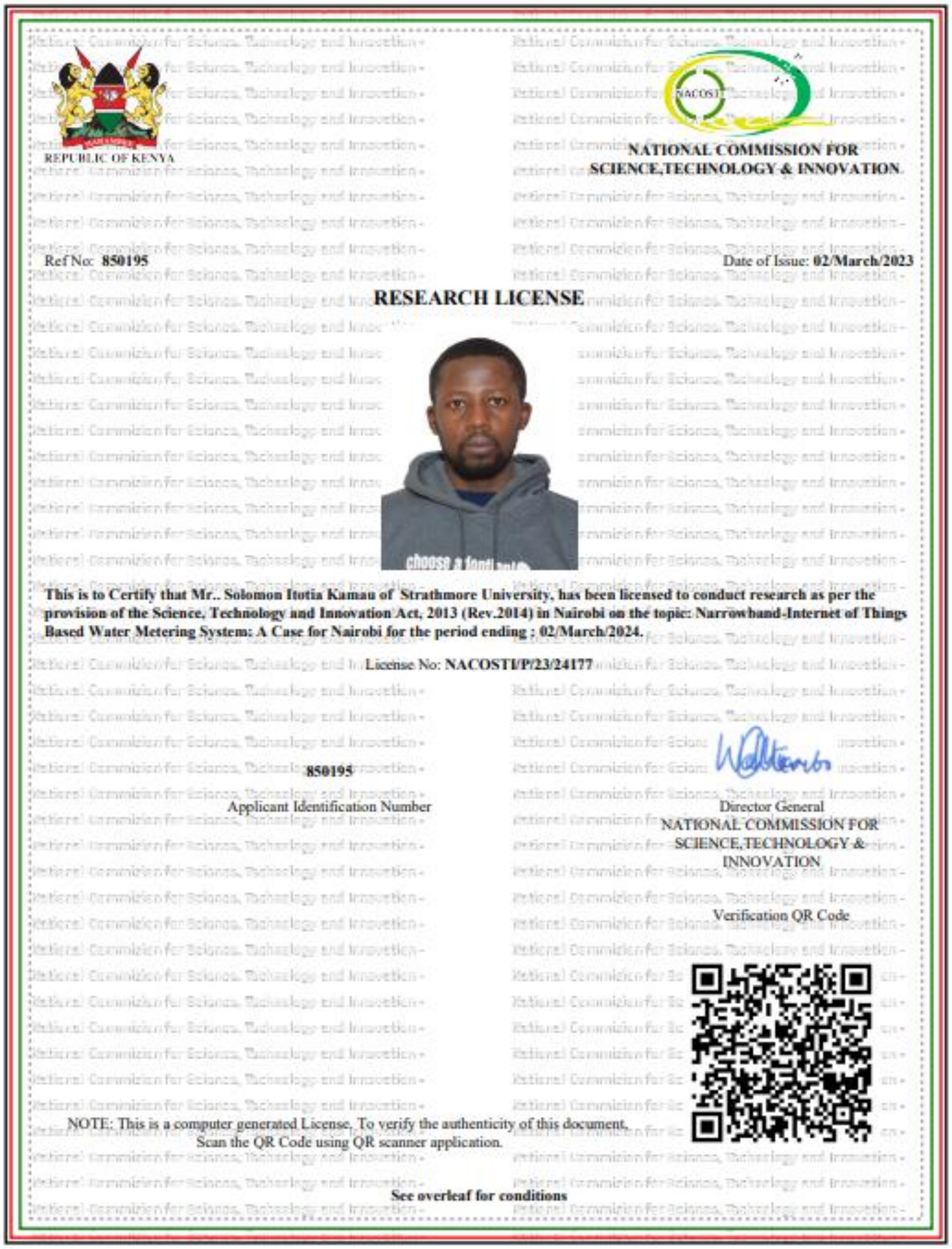
Appendix D: NACOSTI Certificate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Date of Issue: **02/March/2023**

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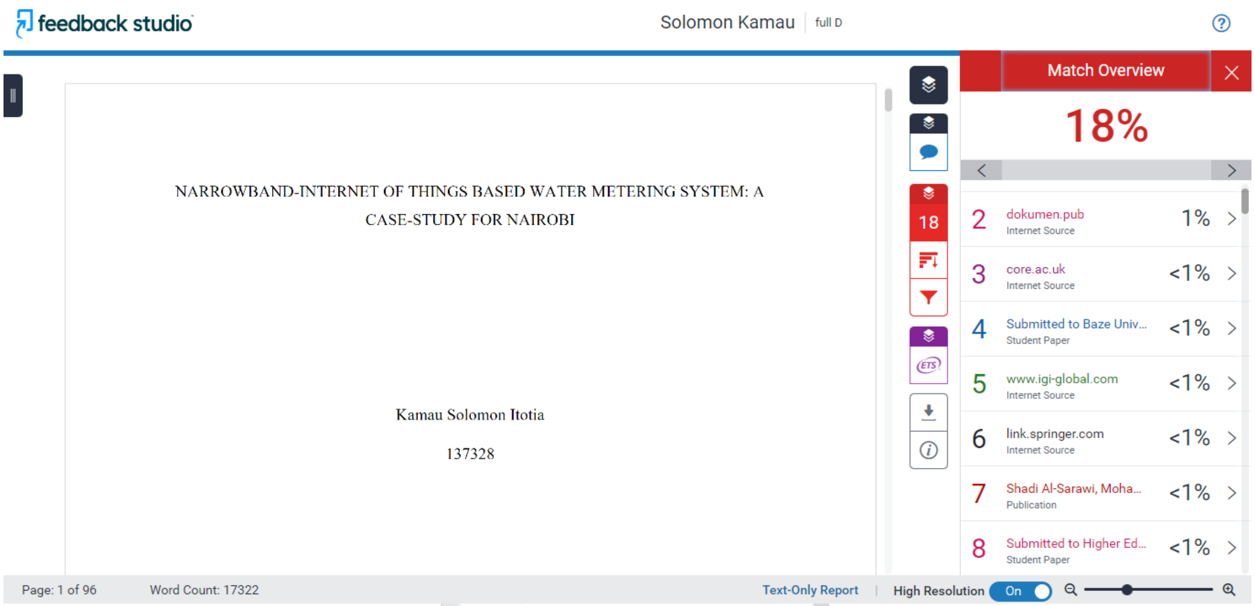
See overleaf for conditions

Appendix E: Study Budget

Item	Quantity	Cost per Quantity (KSh)	Total Cost (KSh)
Printing	150pages	5	750
SIM7080G module	1	3000	3000
SIM Card	1	100	100
Flow Meter	1	1400	1400
Amega328 PU	1	350	350
LiPo Battery (4400mAh)	1	1000	1000
GPS Module	1	800	800
3D printing filament	1	6500	6500
1 PC (Core i7 processor with a 2.4GHz Speed, 12GB RAM, and 500 GB Hard Drive)	1	50000	50000
Miscellaneous			5000
TOTAL COST			68900

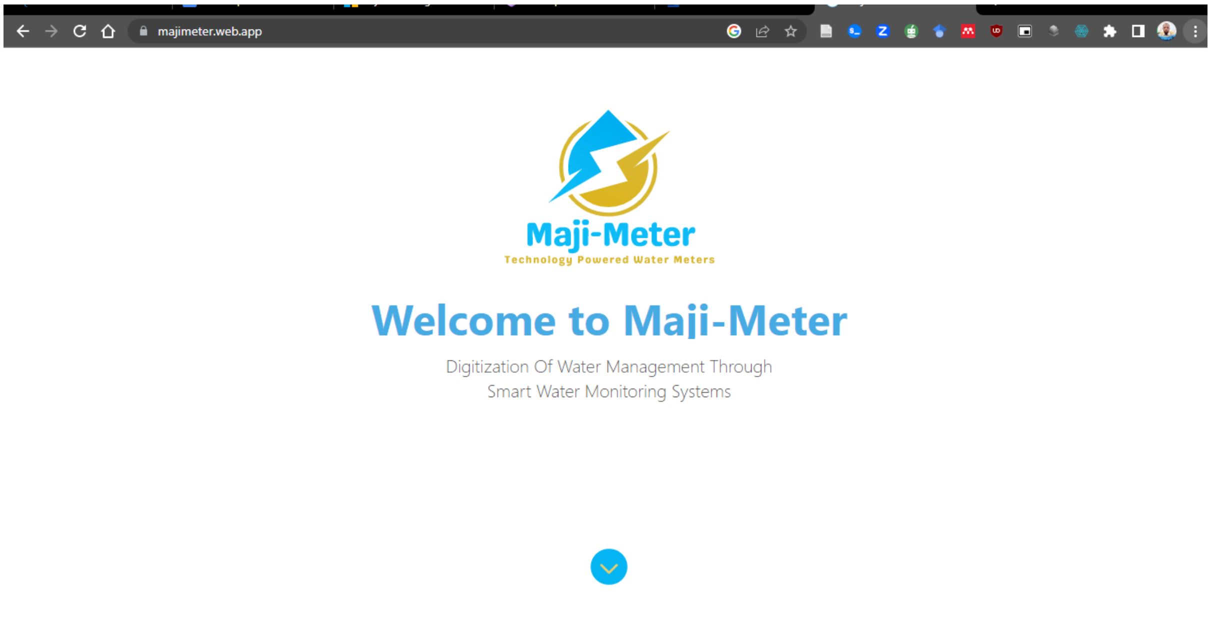
Appendix E: Similarity Index Report



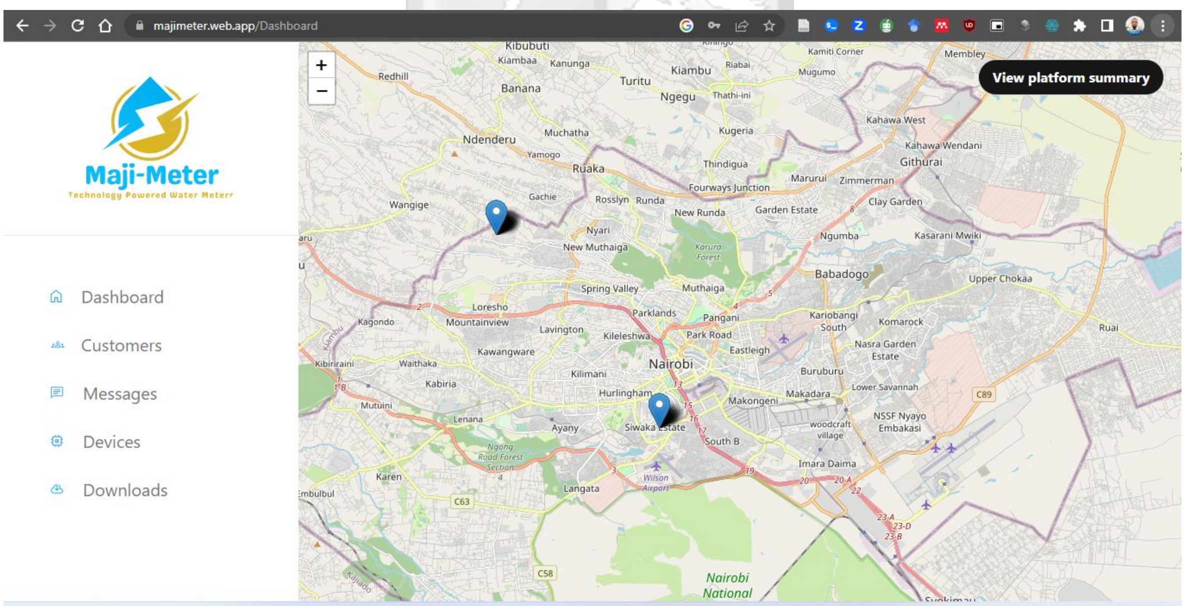
Appendix F: System implementation Screenshots

This section shows screen shots of the implemented system.

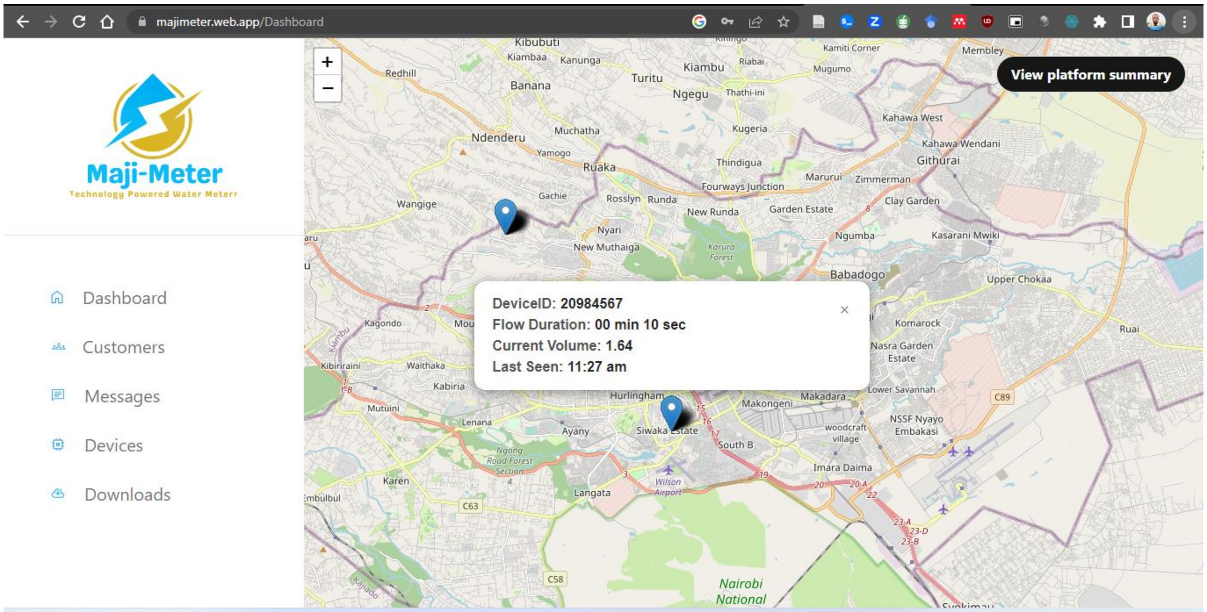
Appendix F.1: Welcome Home Page



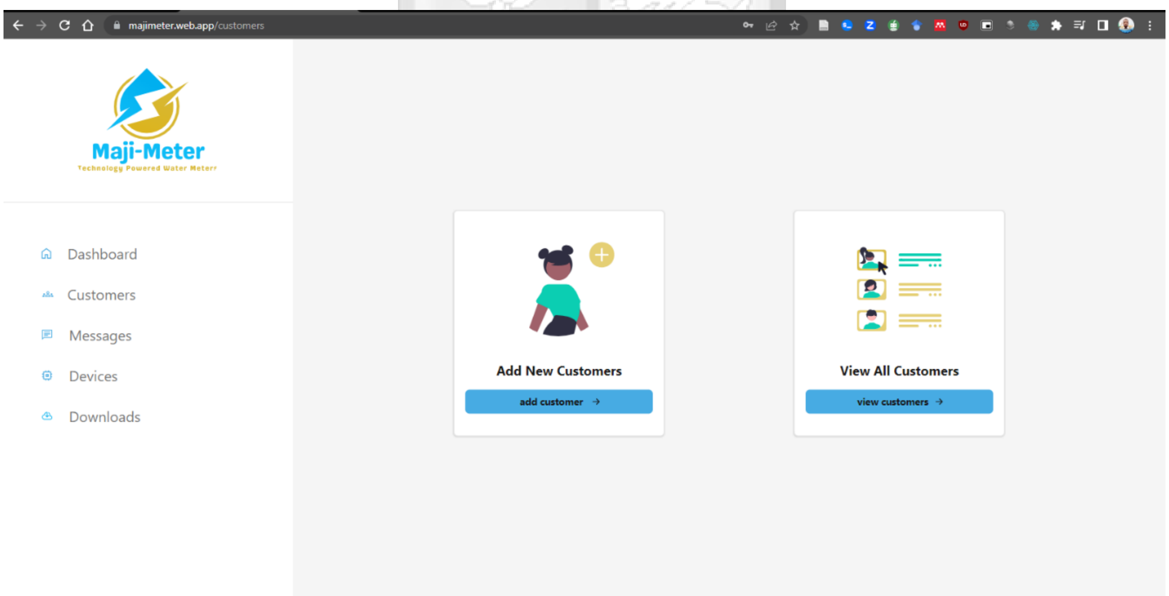
Appendix F.2: Admin Landing and Device Monitoring Page



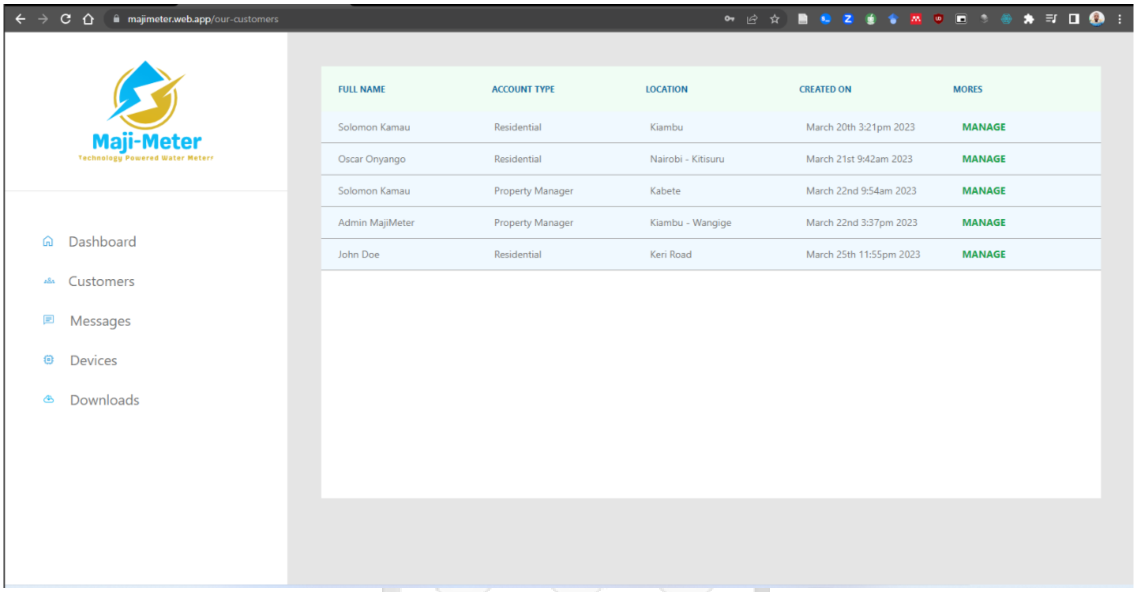
Appendix F.3: Device Parameters Visualization Page



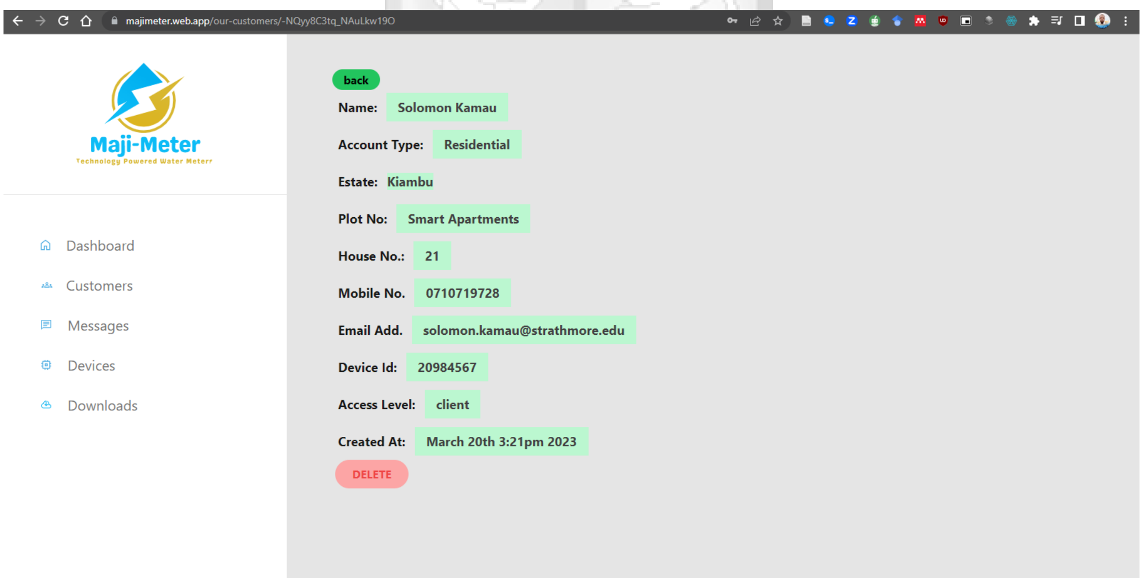
Appendix F.4: Customer Management Interface



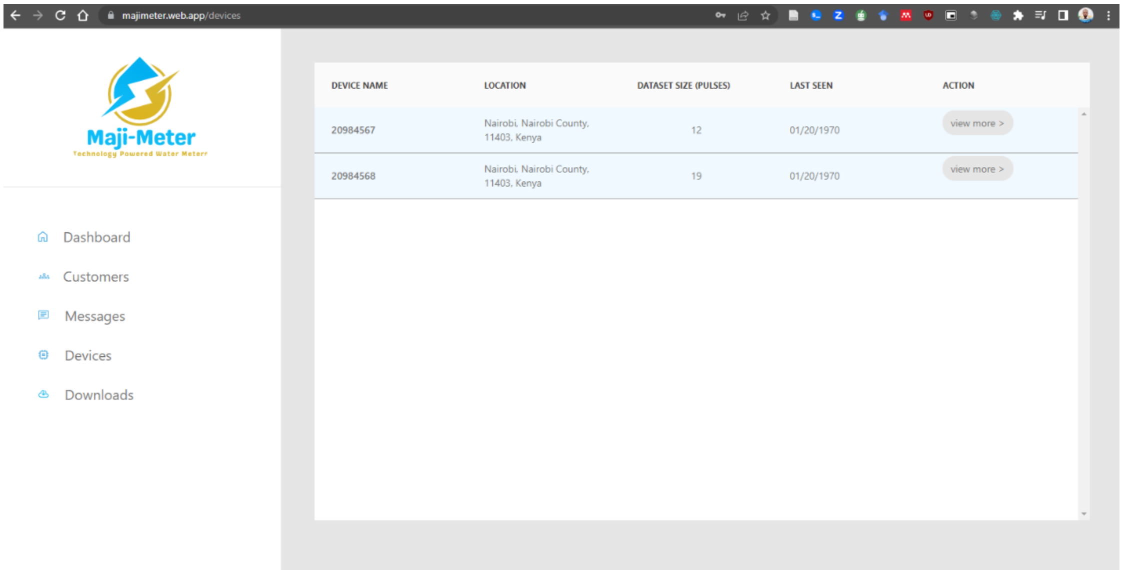
Appendix F.5: Customers List



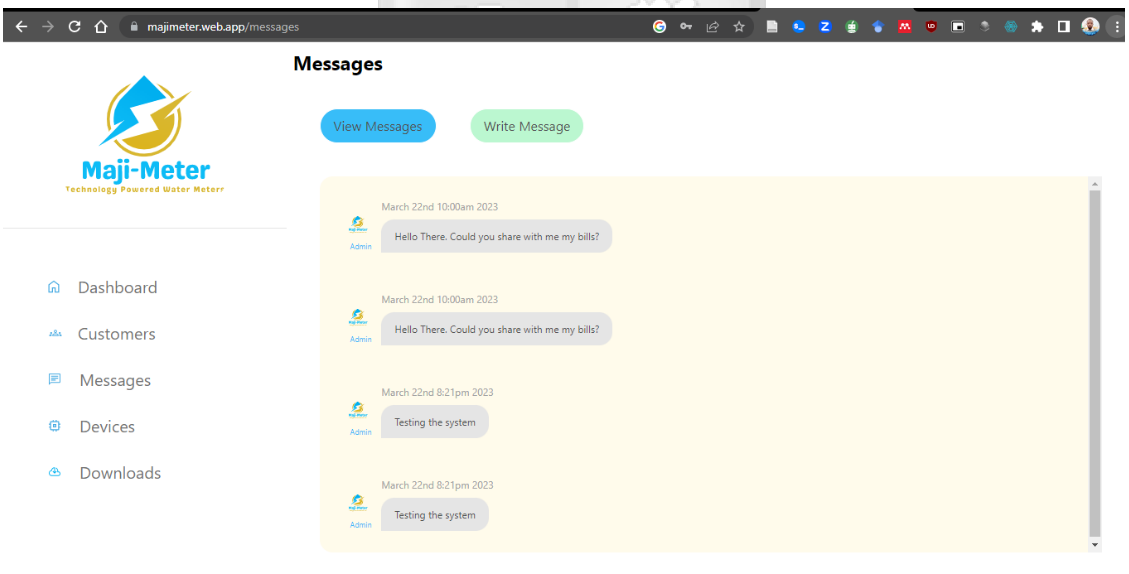
Appendix F.6: Delete Customer



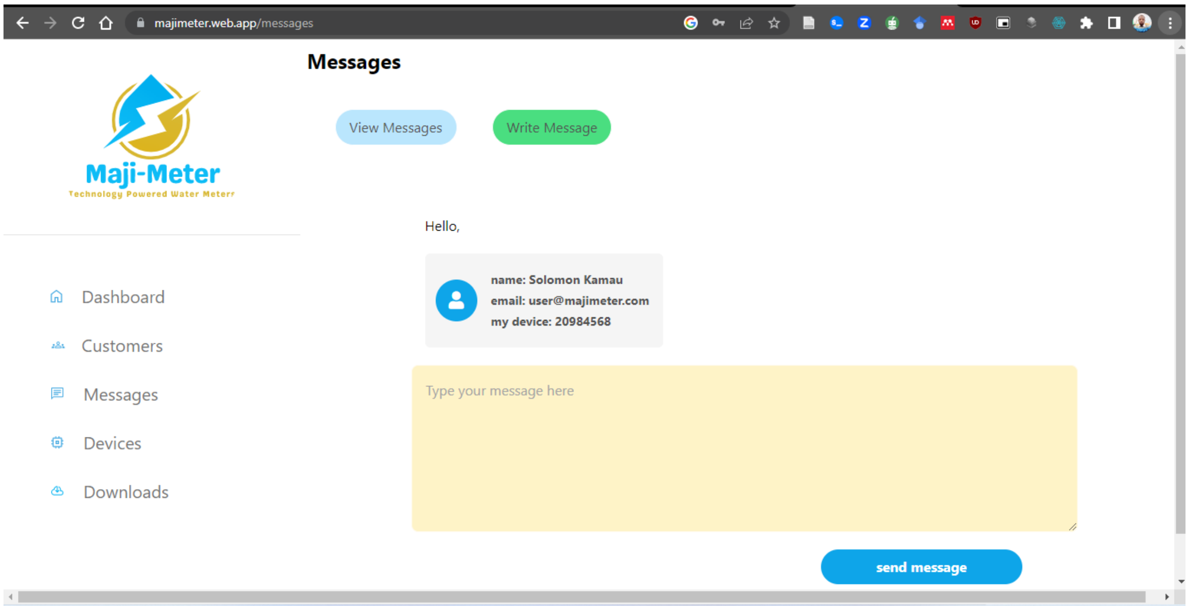
Appendix F.7: Devices List



Appendix F.8: User View Message Page



Appendix F.9: User Write Message Page



Appendix F.10: Forgot Password Page