PROTOTYPE DEVELOPMENT OF A REAL-TIME MONITORING SYSTEM FOR GROUNDWATER LEVEL AND QUALITY USING THE GEOGRAPHY OF THINGS

Report

to the Water Research Commission

by

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DISCLAIMER

EXECUTIVE SUMMARY

Groundwater level and quality monitoring are essential for the sustenance of water resources, especially in an arid and/or semi-arid country like South Africa. Groundwater level and quality data collections from remote areas are currently undertaken once or twice a year using hand-held tape to measure the depth. Samples are taken for laboratory analysis. Although this data is valuable to understanding the resource usage, they are not available in a timely fashion or at the frequency (days to weeks) that water resource managers need them to make relevant decisions such as planning and adaptability.

The objective of this project was to develop a system for acquiring, transferring, analysing and displaying real-time information to manage groundwater level and quality resources from a geographically distributed network of wells. This project entailed the development of a portable, low-cost, real-time, Geography of Things (GoT) sensor prototype system for monitoring groundwater level and quality. The use of an Internet of Things (IoT) analytical platform to remotely monitor the stated groundwater parameters, coupled with a battery monitoring system, as well as location parameters, brought about convenience to the water managers and ultimately aided proactive decision-making.

HIGHLIGHTS OF ACHIEVEMENTS

In this first phase of the project, the design, construction and testing of the sensor prototype were undertaken in a laboratory environment. The developed system prototype monitored the following level and quality parameters of the groundwater, simulating a remote geo-located well:

- Groundwater level
- Percentage humidity
- Environmental temperature
- Speed of sound
- Electrical conductivity
- The pH level
- *Escherichia coli (E. coli)* concentration
- Manganese concentration
- Nitrate concentration
- Groundwater temperature

Furthermore, this prototype was equipped with its own solar system, rechargeable battery, battery monitoring system and location parameters (longitude and latitude). In addition, the system was able to meet the following end-user specification requirements:

- Low cost: The sensing or data acquisition prototype was evaluated to be cost-effective.
- Reliability and flexibility: The sensing prototype was found to be robust, adaptable and accurate.
- Energy-efficiency: The sensing prototype was equipped with a compact solar energy source for self-powering when in remote operations.
- Modular design: The subsystems and components were able to accommodate new technologies without affecting the design of others.
- Real-time: The information available to end-users from a geographically distributed network of wells was collected in a near real-time/on-demand real-time.
- Scalable: The data acquisition unit was able to adapt to the increasing size of the wells.

Two doctoral and two master's students are being trained in the project. The projects and progress of the research students involved in the project are as follows:

- **Chauke Matthews** is a master's student enrolled in a Master of Engineering (MEng) in Electrical Engineering degree since 2020. The title of his research study is "A Geography of Things (GoT)-based scheme for real-time monitoring of groundwater quality".
- **Singh Nirisha** is a master' s student enrolled in a Master of Health Sciences in Environmental Health (MHealthSci – Environmental Health) degree since 2020. Her study is titled "Detection of underground water quality through real-time remote monitoring within two boreholes in rural communities in the Steve Tshwete Local Municipality, Nkangala District jurisdiction".
- **Aderemi Banjo** enrolled for a Doctorate in Engineering (DEng) in Electrical Engineering in October 2019. The title of his study is "Computational efficient and scalable groundwater level management using Edge computing Internet of Things".
- **Tladi Tsholofelo** is enrolled for a Doctorate in Engineering (DEng) in Civil Engineering. Her study is titled "Real-time groundwater level management using integrated GIS and wireless sensor technology."

PROPOSED WAY FORWARD

Bearing in mind that this work was undertaken within a year that had challenges related to the COVID-19 pandemic, the results achieved are satisfactory and strongly point to the possibility of further laboratory investigation before deploying the developed system in the field. In particular, the research team would like to pursue the following within a laboratory environment:

- Carry out further groundwater monitoring using exact borehole diameters that are found in real life.
- Carry out further laboratory investigation on groundwater monitoring using the diffent borehole casing materials that are used in real life.
- Investigate the impact of groundwater level measurement within a pumping well. This is important because if found to be accurate. The current practice of installing monitong wells will be done away with, hence saving a lot of financial outlays.
- Carry out further investigation on how to isolate *E. coli* from other possible pathogens to make sure that when a contaminant is identified, it is specifically *E. coli* and not any other pathogen.
- Carry out further investigation to detect other chemicals in groundwater, especially those from mining activities.
- Investigate non-corrosive casing for our system to ensure that, once deployed, the sensors and accessories are not affected by the conditions in the well.

TABLE OF CONTENTS

EXECUTIVE SUMMARY iii

LIST OF FIGURES vii

LIST OF TABLES ix

CHAPTER 1: BACKGROUND INFORMATION AND RATIONALE OF THE PROJECT 1

CHAPTER 2: PROJECT OBJECTIVE 2

CHAPTER 3: SUMMARY OF PROJECT DELIVERABLES 3

CHAPTER 4: SECTION I: GROUNDWATER LEVEL MONITORING SUBSYSTEM 4

4.1 INTRODUCTION 4

4.2 GROUNDWATER LEVEL MONITORING SUBSYSTEM DESIGN AND DEVELOPMENT 4

4.2.1 Designing of groundwater level monitoring subsystem 4

4.2.2 Data acquisition unit 7

4.2.3 Data capturing and processing unit 8

4.2.4 Data communication unit 9

4.2.5 Data analytics and display unit 9

4.3 CONSTRUCTION OF THE SUBSYSTEM AND DELIVERABLE 9

4.3.1 Construction and required hardware 9

4.6 PERFORMANCE EVALUATION 10

4.6.1 Subsystem testing set-up 10

4.6.2 Subsystem testing results 13

4.7 USER REQUIREMENT SPECIFICATIONS VERSUS SUBSYSTEM PERFORMANCE 16

4.8 SUMMARY OF THE INNOVATION AND CONCLUSION 21

CHAPTER 5: SECTION II: GROUNDWATER QUALITY MONITORING SUBSYSTEM 22

5.1 INTRODUCTION 22

5.2 DATA ACQUISITION UNIT 22

5.3 IOT ARCHITECTURE FOR GROUNDWATER QUALITY SUBSYSTEM 24

5.4 DATA-CAPTURING AND PROCESSING LAYER 25

5.5 CONSTRUCTION OF THE SUBSYSTEM 25

5.5.1 Required hardware 25

5.6 PERFORMANCE EVALUATION 26
5.6.1 Subsystem testing set-up 26
5.6.2 Preparation and testing of water quality parameters: *E. coli*, nitrate and manganese 28
5.6.3 Battery level testing 28
5.7 USER REQUIREMENT SPECIFICATIONS VERSUS SUBSYSTEM PERFORMANCE 28
5.8 SUMMARY OF THE INNOVATION AND CONCLUSION 30
CHAPTER 6: SECTION III: INTEGRATED GROUNDWATER LEVEL AND QUALITY MONITORING SYSTEM 31
6.1 INTRODUCTION 31
6.2 DATA ACQUISITION UNIT 32
6.3 DATA CAPTURING AND PROCESSING UNIT 32
6.4 DATA COMMUNICATION UNIT 33
6.5 DATA ANALYTICS AND DISPLAY UNIT 33
6.6 CONSTRUCTION OF THE PROTOTYPE SYSTEM 34
6.6.1 The overall deliverable (integrated monitoring system) 34
6.7 PERFORMANCE EVALUATION 35
6.7.1 System testing results 36
6.8 USER REQUIREMENT SPECIFICATIONS VERSUS PROTOTYPE SYSTEM PERFORMANCE 36
6.9 SUMMARY OF INNOVATION 37
6.10 CONCLUSION 38
6.11 FUTURE DEVELOPMENTS AND RECOMMENDATIONS 38
REFERENCES 39
APPENDIX 1: DETAIL DIAGRAMS AND TABLES 40
APPENDIX 2: PROPOSALS FOR ARCHIVING DATA GENERATED DURING THE PROJECT 51
APPENDIX 3: LIST OF PUBLICATIONS AND OTHER TECHNOLOGY TRANSFER ACTIONS 52
APPENDIX 4: CAPACITY BUILDING 53

LIST OF FIGURES

Figure 4.1: Block diagram of groundwater level monitoring system 5

Figure 4.2: The simulated model of the groundwater level monitoring system 5

Figure 4.3: Groundwater level monitoring system flowchart diagram 6

Figure 4.4: SIMULINK scope display 7

Figure 4.5: SIMULINK scope display 2 7

Figure 4.6: Schematic diagram of data capturing layer 8

Figure 4.7: Schematic diagram of data capturing layer 8

Figure 4.8: Overall integrated groundwater monitoring subsystem laboratory set-up 9

Figure 4.9: Graphical display unit/storage unit on the ThingSpeak IoT platform 10

Figure 4.10: A 50 mm and 90 mm diameter well 11

Figure 4.11: Set-up 2 12

Figure 4.12: Set-up 3 12

Figure 4.13: Set-up 1 results 13

Figure 4.14: Five-day water levels for experimental set-up 2 14

Figure 4.15: Nine-day water levels for set-up 3 15

Figure 4.16: Temperature fluctuations for set-up 3 15

Figure 4.17: Humidity for set-up 3 16

Figure 5.1: Block diagram of groundwater quality monitoring system 22

Figure 5.2: Groundwater quality monitoring flow chart 23

Figure 5.3: The IoT architecture layer for the groundwater quality system 24

Figure 5.4: Schematic diagram of data-capturing layer 25

Figure 5.5: Overall integrated mini groundwater monitoring system laboratory set-up 26

Figure 6.1: Block diagram of the integrated groundwater monitoring system 31

Figure 6.2: Integrated data acquisition layer 32

Figure 6.3: Integrated data acquisition layer 32

Figure 6.4: Data communication unit 33

Figure 6.5: ThingSpeak IoT analytics and display platform 33

Figure 6.6: The integrated prototype 34

Figure 6.7: The rear side of the integrated prototype 35

Figure 6.8: The integrated groundwater monitoring system during testing 36

Figure 6.9: The displayed resulst on ThingSpeak 36

Figure 7.1: Components used for groundwater-level monitoring subsystem development 40

Figure 7.2: Data acquisition unit for groundwater-level monitoring subsystem 40

Figure 7.3: Data communication unit for groundwater-level monitoring subsystem 41

Figure 7.4: Data capturing and processing unit for groundwater-level monitoring subsystem 41

Figure 7.5: Data processing unit for groundwater-level monitoring subsystem 42

Figure 7.6: The complete groundwater-level monitoring subsystem 42

Figure 7.7: Components used for groundwater quality subsystem development 43

Figure 7.8: Data acquisition unit for groundwater quality subsystem development 43

Figure 7.9: Water quality sensors' calibration set-up 44

Figure 7.10: The result of the water quality sensors' calibration set-up 44

Figure 7.11: Water quality sensors' calibration (pH = 4.00 and electrical conductivity = 1413uS/cm) 45

Figure 7.12: Buffer solutions; (pH = 7.00 and electrical conductivity = 12.88 mS/cm) 45

Figure 7.13: Battery-level monitoring testing 45

Figure 7.14: GPS module testing 46

Figure 7.15: Nitrate concentration samples and HACH DR/890 colourimeter showing colour change, i.e. presence of nitrates 46

Figure 7.16: Email notification testing 47

Figure 7.17: E. coli testing set-up and testing 47

Figure 7.18: Battery level results 49

LIST OF TABLES

Table 4.1: User requirement specifications for the groundwater level monitoring subsystem 4

Table 4.2: User requirement specifications 16

Table 4.3: Performance analysis 17

Table 4.4: Deliverables 21

Table 5.1: User requirement specifications 29

Table 5.2: Performance evaluation 29

Table 5.3: Deliverables 30

Table 6.1: Total costs of the prototype 37

Table 6.2: User requirement specifications 37

Table 7.1: Overall costs of components used for groundwater-level monitoring subsystem 42

Table 7.2: Manganese detection from Pienaars Dam leisure resort boreholes 47

Table 7.3 Nitrate's results for pH level and electrical conductivity 48

Table 7.4: Manganese concentration electrical conductivity and pH results 48

Table 7.5: Manganese standard for AAS reading 49

Table 7.6: Overall costs of components used for groundwater quality monitoring subsystem 50

CHAPTER 1: BACKGROUND INFORMATION AND RATIONALE OF THE PROJECT

One of the United Nations (UN)'s Sustainable Development Goals (SDG), SDG 6, is focused on ensuring access to clean water and sanitation for all (Shah et al., 2018). This report argues that the planet possesses sufficient fresh water. However, bad economics or poor infrastructure result in millions of people, most of whom are children, dying annually from diseases caused by inadequate water supply, sanitation and hygiene. Water scarcity, poor water quality and inadequate sanitation negatively impact on food security, livelihood choices and educational opportunities for poor families across the world. Drought afflicts some of the world's poorest countries, worsening hunger and malnutrition.

By 2050, at least one in four people will be likely to live in a country affected by chronic or recurring shortages of freshwater (Shah et al., 2018). The UN's report highlights a number of facts on figures:

- Water scarcity affects more than 40% of the global population and is projected to rise. Over 1.7 billion people are currently living in river basins where water use exceeds recharge.
- Some 2.4 billion people lack access to basic sanitation services, such as toilets or latrines.
- More than 80% of wastewater, resulting from human activities, is discharged into rivers or the sea without any pollution removal.
- Every day, nearly 1,000 children die due to preventable water and sanitation-related diarrhoeal diseases.
- Hydropower is the most important and most widely used renewable source of energy and, as of 2011, represented 16% of total electricity production worldwide.
- Approximately 70% of all water abstracted from rivers, lakes and aquifers is used for irrigation.
- Floods and other water-related disasters account for 70% of all deaths related to natural disasters.

According to the international World Water Forum (WWF)'s report (Shah et al., 2018), only about 15% of South Africa's total water consumption is obtained from groundwater sources. Very often, the communities that depend on groundwater have no other viable sources. In 2008, the African Ministers Council on Water highlighted that groundwater resources will have to play an increasingly strategic role in Africa, particularly for the most vulnerable and neglected rural communities. Thus, understanding and unlocking South Africa's groundwater potential is crucial to addressing national water security challenges. Groundwater is increasingly being relied upon as a vital water source at different levels – from small-scale supply from an individual borehole to large-scale, sophisticated supply schemes. Groundwater also serves as a potential buffer during droughts, because the volume of water stored in underground aquifers can be significant. Consider that the storage volume of surface water dams is generally equivalent to a few times greater than the volume of the mean annual runoff in the catchment, whereas an aquifer can have a storage volume several thousand times greater than the annual recharge. This stored volume is also not subject to the water evaporation losses that happen in dams.

The growing scarcity and challenges concerning surface water have exacerbated the need to better understand and manage groundwater. The primary step in achieving an efficient groundwater management system would be to implement groundwater monitoring (Singh & Katpatal, 2020). Currently, at most locations, groundwater levels are commonly collected once or twice a year using hand-held tape to measure the depth. At several hundred locations, groundwater level data is obtained by pressure transducers and recorded on an hourly to daily basis (Anumalla, 2004). Although this data is valuable to understanding the resource usage, it is not available in a timely fashion or at the frequency (days to weeks) that water resource managers need them to make relevant decisions (Anumalla et al., 2006). Consequently, this catches both the community and water managers off guard, as they will not be aware of the sustainability of groundwater available for proper intervention in terms of planning and adaptability.

Due to the identified challenges pertaining to groundwater monitoring, it is imperative for water managers to access more timely, accurate groundwater level and quality data to assess conditions and manage adverse situations such as drought and loss of pumpage in agriculture and domestic water supply.

CHAPTER 2: PROJECT OBJECTIVE

The overall objective of this project is to develop a system for acquiring, transferring, analysing and displaying real-time information to manage groundwater level and quality resources from a geographically distributed network of wells. Thus, the following are the user's specifications of this project:

- Low cost: Subsystems and components integration, deployment and operation must be cost-effective.
- Reliable and flexible: The collected data must be dependable for accurate decision-making and the system must be adaptive to different information types.
- Elongated battery lifetime: The battery must be recharged by a portable solar panel to elongate the operation lifetime in remote applications.
- Modular design: The subsystems and components must be able to accommodate incremental new technologies without affecting the design of others.
- Real-time: The data must be available promptly and/or when required by the users without delay.
- Scalable: The system must be duplicable in many data acquisition wells without affecting the performance.

Hence, the following are the specific objectives of the project

Objective 1: Develop a portable low-cost real-time Geography of Things sensor prototype subsystem for monitoring groundwater levels in a laboratory environment.

Objective 2: Develop a portable low-cost, real-time Geography of Things sensor prototype subsystem for monitoring groundwater quality in a laboratory environment.

Objective 3: Integrate the subsystems that are the outcomes of the first two objectives into a groundwater level and quality real monitoring system.

CHAPTER 3: SUMMARY OF PROJECT DELIVERABLES

Deliverable 1: Groundwater level monitoring using a Geography of Things sensor prototype subsystem.

Deliverable 2: Groundwater quality monitoring using a Geography of Things sensor prototype subsystem.

Deliverable 3: Final report: Integrated groundwater level and quality real-time monitoring prototype subsystem.

CHAPTER 4: SECTION I: GROUNDWATER LEVEL MONITORING SUBSYSTEM

4.1 INTRODUCTION

In this section, a real-time groundwater level monitoring subsystem was developed. This involved the integration of different components into sub-units to form the real-time groundwater level monitoring subsystem. Thus, the overall objective of this section was to develop a subsystem with the different integrated units for acquiring, transferring, analysing and displaying real-time information to manage groundwater levels within a laboratory environment using GoT. Hence, the developed subsystem should demonstrate acceptable levels of users' requirement specifications as shown in Table 4.1

Table 4.1: *User requirement specifications for the groundwater level monitoring subsystem*

Design criteria	Users' requirement specifications
Low cost	This subsystem should not cost more than R6,000.
Reliable and flexible	The collected data must be dependable for accurate decision-making and the system must be adaptive to different information types.
Elongated battery lifetime	The subsystem should be able to operate on an elongated battery lifetime.
Modular design	This subsystem must be flexible and should be able to accommodate new components without affecting others.
Real-time	This subsystem must be able to measure data in real-time as required by the user.
Scalable	This subsystem must be duplicable to a larger scale without sacrificing performance.

4.2 GROUNDWATER LEVEL MONITORING SUBSYSTEM DESIGN AND DEVELOPMENT

The aim of this section is to present the design and development of this groundwater level monitoring subsystem. This section will provide hindsight from design to development, and the final implementation of each sub-unit.

4.2.1 Designing of groundwater level monitoring subsystem

The design and modelling of the groundwater level monitoring method will be presented in this subsection. Figure 4.1 shows the block diagram of the groundwater level monitoring subsystem designed to achieve the stated project objective.

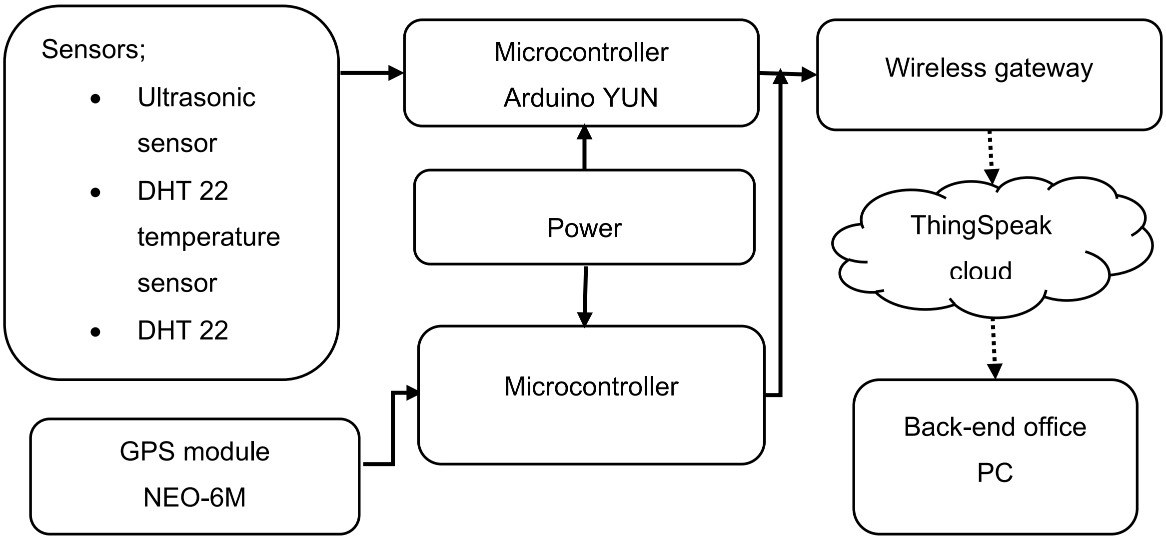

Figure 4.1: *Block diagram of groundwater level monitoring system*

Figure 4.1 represents the block diagram of the proposed groundwater level monitoring system. Figure 4.1 was designed and modelled using SIMULINK/MATLAB 2020 version platform. This is to calibrate the correct values of the components that will be required by each of the sub-units. To achieve this, the process involved the design of the circuit intending to achieve the groundwater level monitoring within the SIMULINK environment. Components used included the following:

- An Arduino board
- A level measurement sensor
- Resistors

The SIMULINK-designed model using these components is depicted in Figure 4.2.

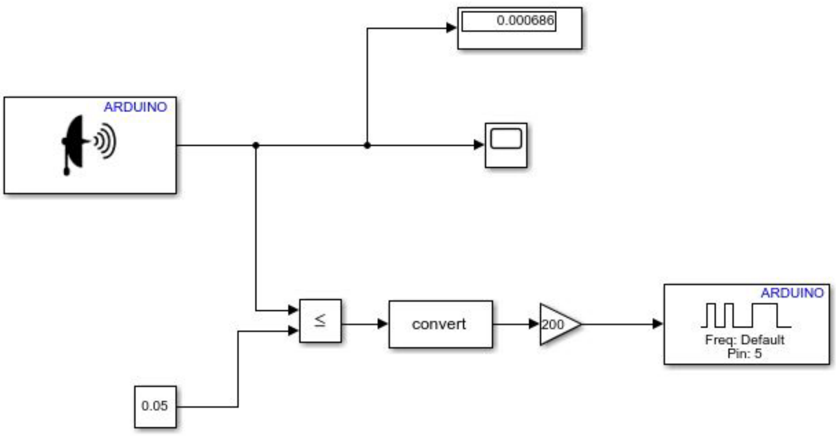

Figure 4.2: *The simulated model of the groundwater level monitoring system*

In Figure 4.2, the corresponding groundwater level variable experimented with changes in time variables. The groundwater level measurement flowchart diagram is shown in Figure 4.3.

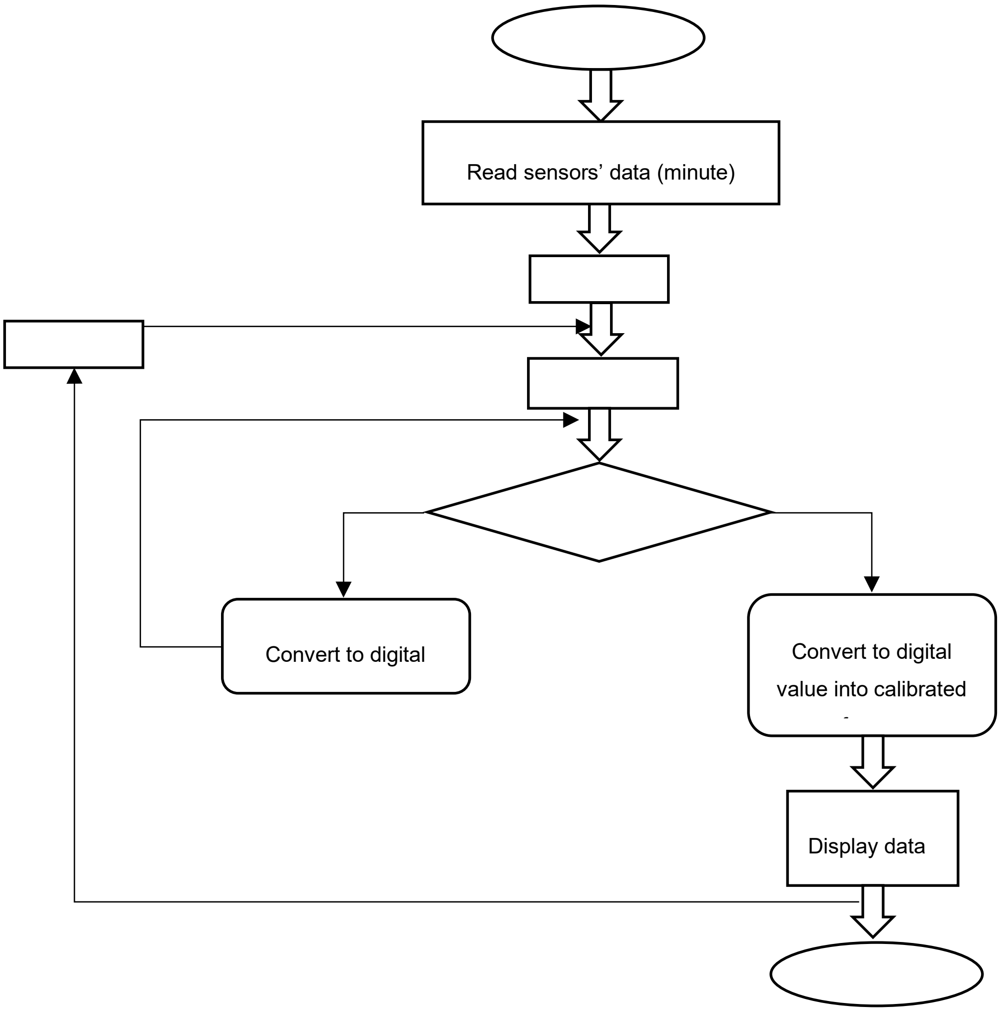

Figure 4.3: *Groundwater level monitoring system flowchart diagram*

The model simulation results were displayed on the scope in Figure 4.2. The corresponding scope results are presented in Figure 4.4 and Figure 4.5, respectively. These figures show the change in distance per second. In this case, the simulation was run for 100 seconds. However, the simulation run time could be extended to more than 100 seconds.

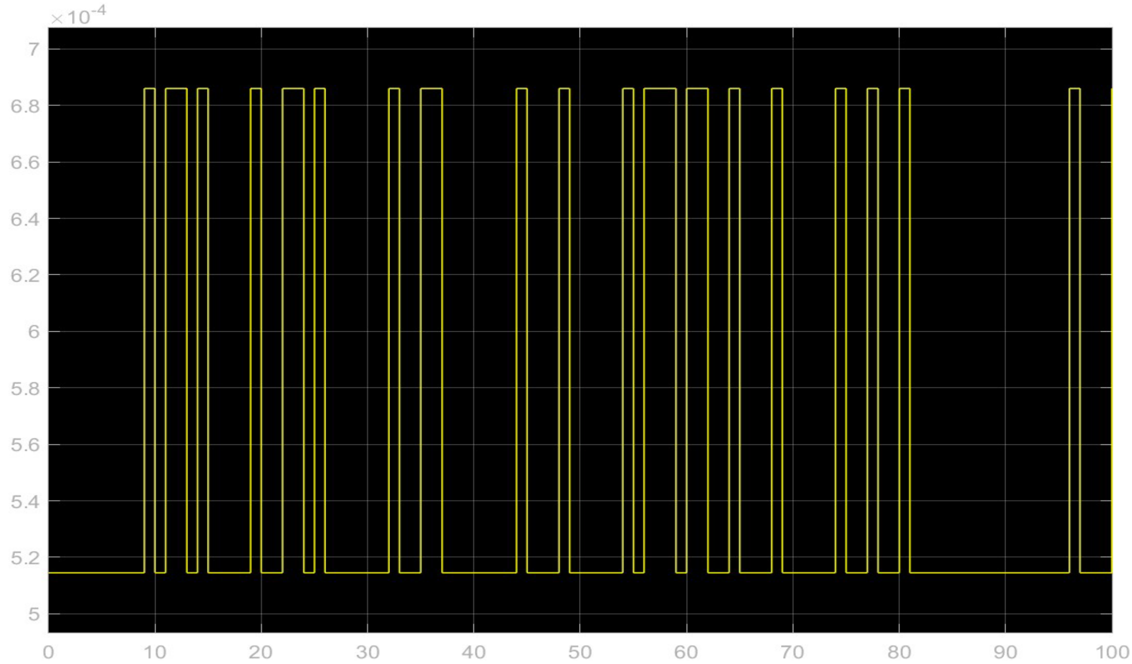

Figure 4.4: *SIMULINK scope display*

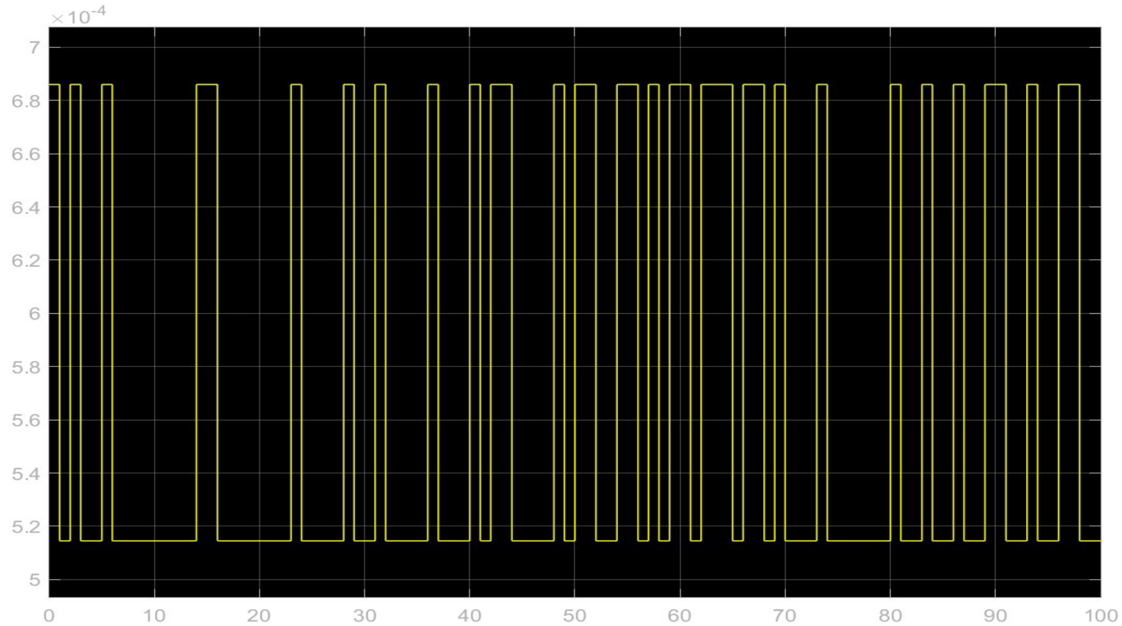

Figure 4.5: *SIMULINK scope display 2*

At the end of this designing and modelling exercise, the designed model and simulated results clearly show the possibility of deploying this model for groundwater level measurements.

This groundwater level monitoring subsystem consists of four units: the data acquisition unit, the data processing unit, the data communication unit, and the data analytics and display unit. These units will be explained in the next subsections

4.2.2 Data acquisition unit

The data capturing unit consists primarily of sensors. The sensors that were used in this system are an HC-SR04 ultrasonic low-cost sensor and a DHT 22 sensor. Although there are many water sensors, they are prone to rust. The HC-SR04 sensor was chosen for this project as it is a non-contact sensor, and has an accuracy of $\pm$ 0.5 and a power consumption of 5V.

Figure 4.6 shows the schematic block diagram of the data capturing unit of the prototype. The sensors were connected to the breadboard and ATmega328P microcontroller-based Arduino Yun. The Arduino-based processing module contains a set of written codes. This is used to perform the processing of raw data, store the codes and transfer the processed captured data into the cloud via internet access.

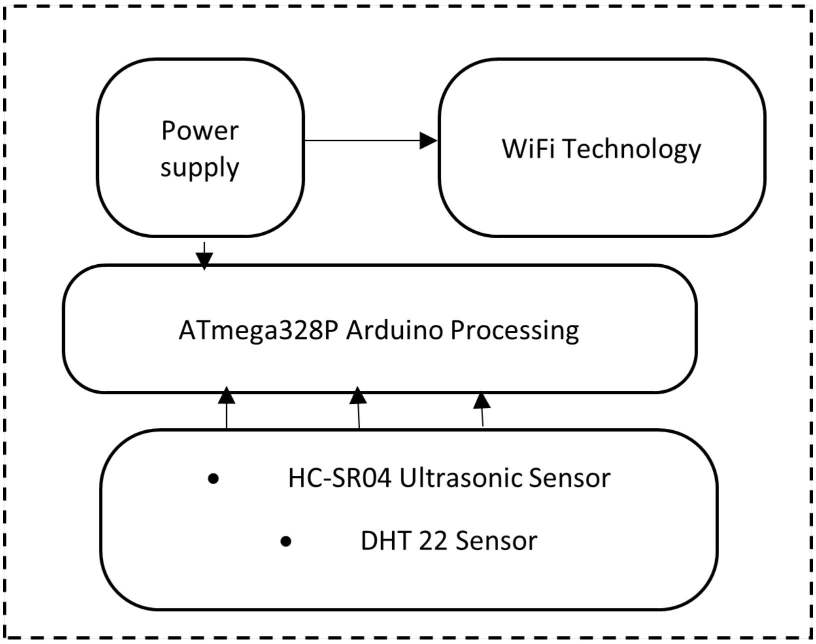

Figure 4.6: *Schematic diagram of data capturing layer*

4.2.3 Data capturing and processing unit

Figure 4.7 shows the block schematic diagram of the data capturing and processing unit. This unit consists of sensors and a microcontroller. These sensors were connected with a cable to a microcontroller-based Arduino module. The microcontroller performs a dual function, while it is powered with a 5V source. It contains a set of mathematical codes that tell the sensors what to do. Secondly, it acts as an interface between the sensors and the network/communication unit. This controller is network enabled, thus, through a network connection using WiFi (for this test within the laboratory), it is able to transfer the measured groundwater parameters into the server or cloud service for processing and storage.

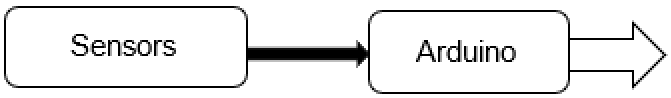

Figure 4.7: *Schematic diagram of data capturing layer*

Furthermore, the processing unit of this subsystem's construction contains a written set codes in c++ on the Arduino IDE platform. These are sets of mathematical equations that are deployed or programmed into the microprocessor of the Arduino to carry out the set-up processing and transferring of the processed data into the cloud. Therefore, the corresponding result will be displayed on the ThingSpeak IoT platform. The following processed parameters were captured with the aid of the deployed sensors:

- Groundwater quantity level
- Calculated speed of sound (ultrasonic sensor uses echo, which is sound's speed for its operation)
- The temperature within the well
- The percentage of humidity
- The location of the device

4.2.4 Data communication unit

The data received from the transmitted end nodes are forwarded to the network server via cellular/WiFi. Via the communication unit, there is centralised and continuous monitoring of the resources, which are transmitted into the cloud in a real-life operation. Therefore, the data communication unit consists of WiFi network connectivity, software and a microcontroller. The unit also serves as a channel of communication between the data acquisition unit, the data capturing and processing units, and the data analytics and display unit.

4.2.5 Data analytics and display unit

The data analytic and display unit is the last unit in this groundwater level monitoring subsystem. The resulting measured parameters are displayed in real-time on the IoT platform in the form of graphs. For this project, a free IoT platform by MATLAB, known as ThingSpeak, is used.

4.3 CONSTRUCTION OF THE SUBSYSTEM AND DELIVERABLE

The final deliverable of this groundwater level monitoring subsystem will be presented in this subsection. This will include the required hardware, the integration of the units and the overall integrated monitoring system.

4.3.1 Construction and required hardware

All the units described were integrated to form the overall groundwater level subsystem. The overall integrated subsystem is shown in Figure 4.8

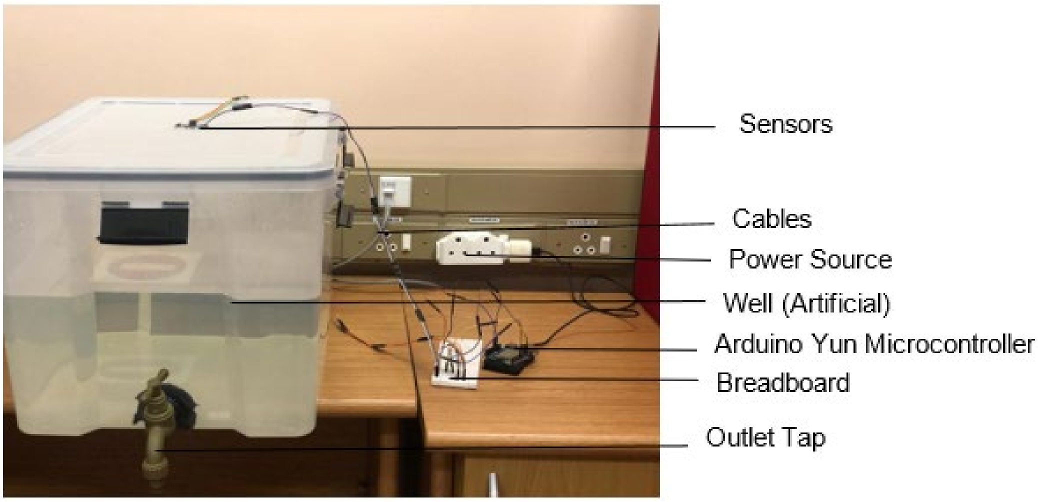

Figure 4.8: *Overall integrated groundwater monitoring subsystem laboratory set-up*

The following components are used for the construction of a mini well within the laboratory environments:

- Breadboard
- Cable
- Arduino ethernet/Wi-Fi shield, internet and IoT Arduino board
- Ultrasonic sensors
- Temperature and humidity sensors
- Internet access

For this construction, holes were bored into the bucket's lid to accommodate these sensors. The bucket was also fixed with a tap to allow the discharge of water, which symbolises the recharging and discharging process within an aquifer of groundwater.

The data acquisition unit's sensors were connected with a cable to a microcontroller-based Arduino. The data acquisition unit's output directly serves as the input of the data capturing and processing unit. Furthermore, the processed data is transferred into the analytics and display unit via the communication unit.

This data is available for anyone with access to the platform. Figure 4.9 gives a picture of the graphical user interface.

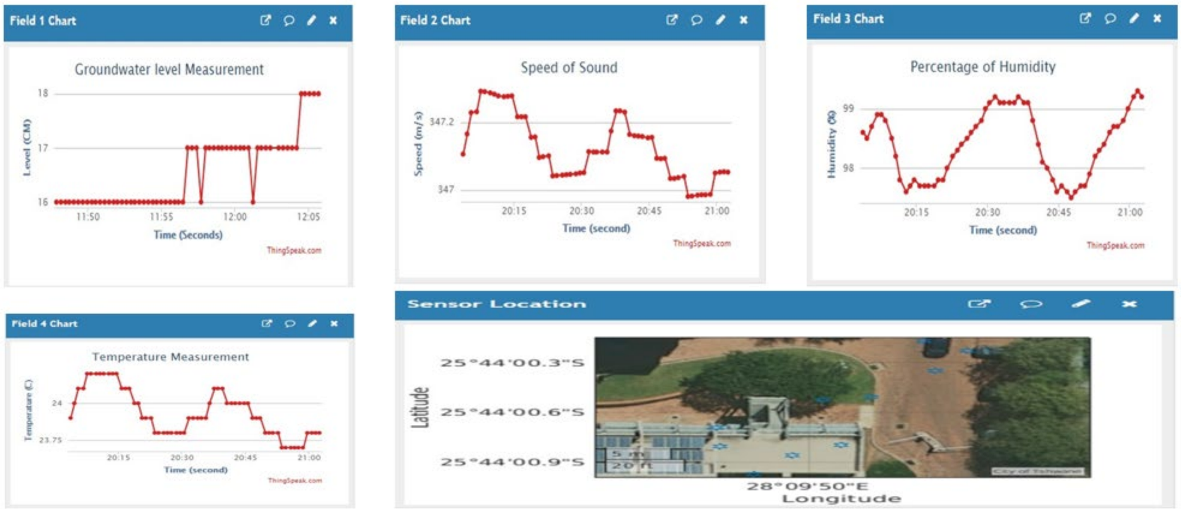

__Figure 4.9:__ Graphical display unit/storage unit on the ThingSpeak IoT platform

4.6 PERFORMANCE EVALUATION

The purpose of testing this groundwater level monitoring subsystem is to ascertain the performance of the prototype. This means the data acquisition's measured reading is compared to the remote reading transferred to the cloud unit via the network unit to the remote data displaying unit to determine the accuracy. Therefore, the measurement readings were taken at different intervals and levels of water within an artificial well constructed in the laboratory at Building 6 of the Tshwane University of Technology to test the prototype. The following were the measured results from the sensors and the artificial mini well. Therefore, this section focuses on evaluating the performance of the groundwater level monitoring subsystem.

4.6.1 Subsystem testing set-up

To test this subsystem, a model well was constructed in a laboratory setting as shown in Figure 4.8.

The following materials were used in the construction of this mini well:

- Ultrasonic sensor
- DHT 22 sensor
- Transparent bucket
- Standard centimetre measuring ruler
- Tap

Furthermore, a total of three set-ups were created with varying geometry and surrounding conditions to determine the limitations of the sensor and its optimal operating conditions within the laboratory environment.

a) Experimental set-up 1

This was the first set-up comprising of the widest well compared to the other wells, i.e. 600 mm x 400 mm x 400 mm rectangular container. The main purpose of choosing a wider well was to limit the obstructions in the well as the accuracy of ultrasonic sensors is highly susceptible to obstacles, and to calibrate the sensor. Figure 4.8 shows set-up 1. In this set-up, the sensor was placed on top of the lid of the container. The lid in this set-up represented the ground surface. The container was equipped with a tap to mimic withdrawals from the well. The well was recharged by pouring the water into the container. Withdrawals from the well were carried out by opening the tap. The only form of fluctuation that was created in this system was through the opening and closing of the tap. Measurements of the sensor were compared with the measurements obtained from the measuring ruler.

b) Experimental set-up 2

This second and third set-up comprised cylindrical wells. Firstly, different diameter wells were tested, i.e. the 50 mm and 90 mm well as shown in Figure 4.10 to determine the minimum diameter from which the sensor can operate. Generally, the smallest borehole diameters range between 50 mm and 100 mm, with the size of the standard borehole being 165 mm in South Africa. The most widely used material for borehole well casings is polyvinyl chloride (PVC). Hence, plastic measuring cylinders were used in this exercise. The readings obtained from the 50 mm-diameter well depicted a high-level inaccuracy due to the obstructions and difficulties associated with keeping the well at a stable position. As a result, the 90 mm well was selected.

Figure 4.10: *A 50 mm and 90 mm diameter well*

A testing bed, approximately 300 mm long, 240 mm wide and 240 mm deep, was created in the laboratory. Its set-up comprised three layers of soil with the sandy soil at the bottom, followed by a silty material and then a loamy material. Figure 4.11 shows set-up 2.

Figure 4.11: *Set-up 2*

The first two bottom layers comprised river sand that was sieved using a sieve of approximately 2 mm in diameter. The material that was retained in the sieve served as the bottom layer of the testing bed, while the material that passed through the sieve served as the second layer. The last layer, i.e. the top layer, was loamy. The thickness of each layer was approximately 50 mm. Water was poured onto the sand bed and moved into the well. The well was 90 mm in diameter, approximately 440 mm high and was perforated at the bottom, up to a height of 50 mm to allow for the movement of water into the well. Water levels were taken for a period of five days.

c) Experimental set-up 3

The third set-up was similar to the second set-up except that gravel was used in the bottom layer of the sand bed instead of river sand. Figure 4.12 shows the third set-up.

Figure 4.12: *Set-up 3*

The second layer of the sand bed was river sand. Unlike the second set-up, the sand was not sieved to separate the coarse material from the finer material. The top layer was loam soil, as in the second set-up. The sensor was set to take readings at a minute time interval as in the previous set-ups. The observations were stopped after a period of nine days when the water levels reached a position of stagnancy.

4.6.2 Subsystem testing results

This section presents and discusses the results obtained from the three set-ups that were created in the laboratory environment.

a) Experimental set-up 1

Figure 4.13 shows the measurement when the artificial well water was measured. The results show a corresponding reading from the artificial well and the sensor reading from the server (cloud). This was performed repeatedly. Therefore, the prototype displays consistent accuracy and efficient operational performance during the test.

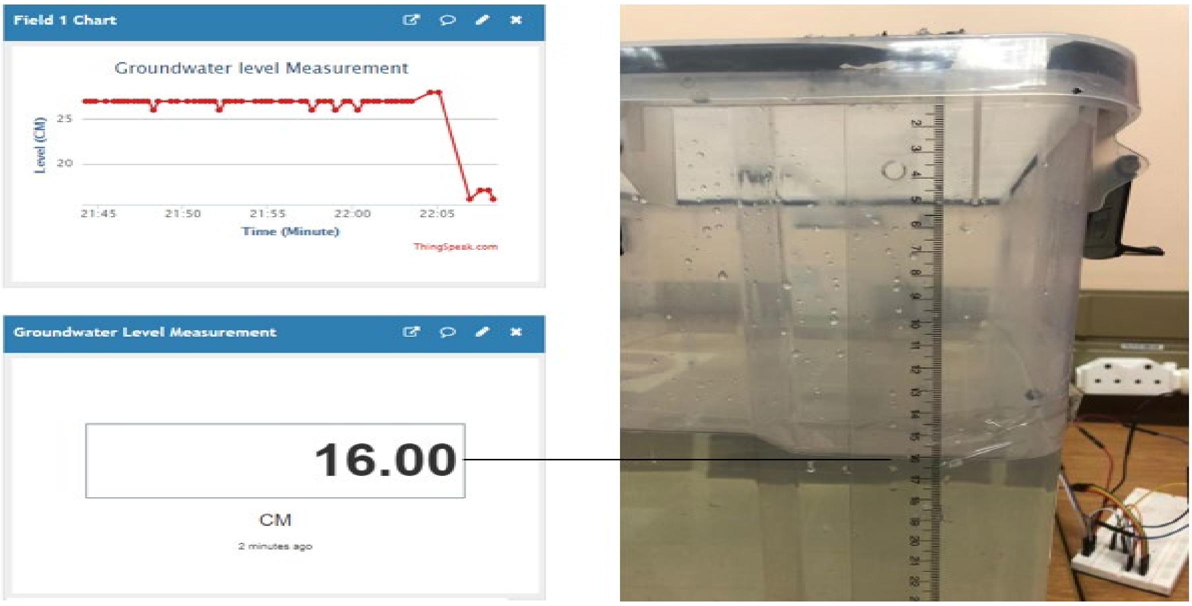

Figure 4.13: *Set-up 1 results*

b) Experimental Set-up 2

The sensor was programmed to send readings at a minute time step, but for the purpose of reporting, data is presented at an hourly time step as shown in Figure 4.14. The data in Figure 4.14 refers to the level at which the sensor was placed (i.e. 44 cm from the bottom of the well). In real life, this would be the ground surface. There was an overall decline of 6 cm in the water level over the five days. The water levels were changing at a rate of approximately 1 cm daily. At the end of the observation period, the well was empty.

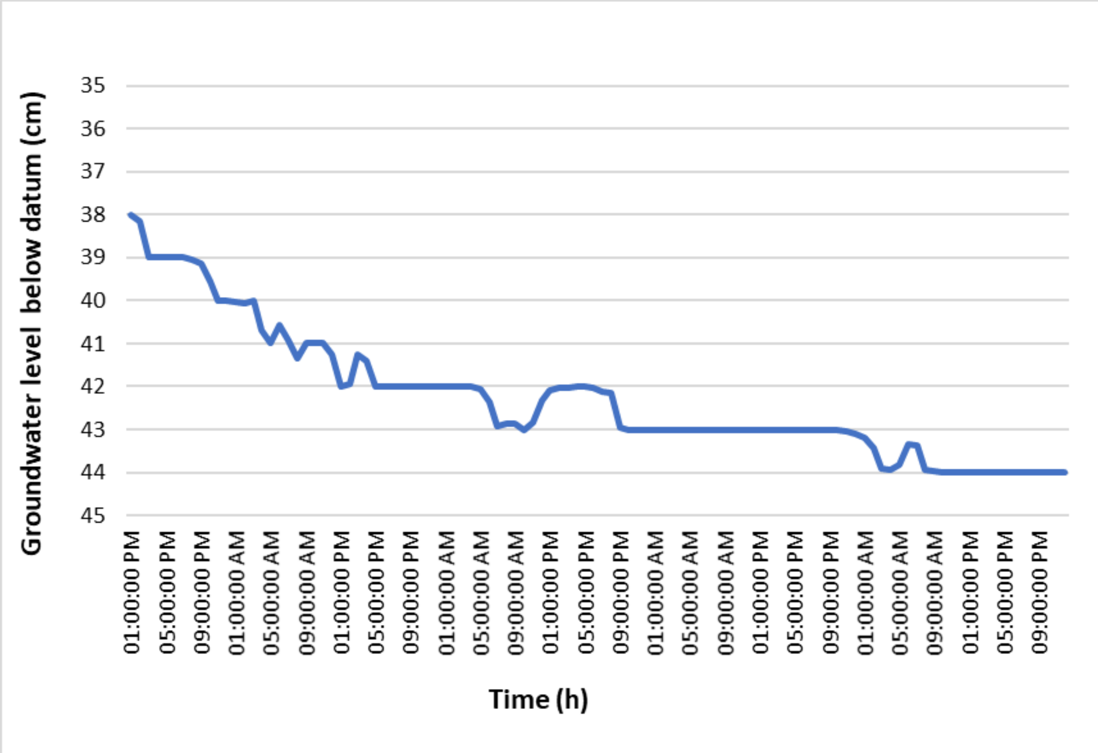

Figure 4.14: *Five-day water levels for experimental set-up 2*

There were, however, several cases within the observation period whereby the water levels were rising and falling at an abrupt rate. The fluctuations could be explained by any of the following reasons: Firstly, the soil types in the sand bed, particularly the sand at the bottom of the sand bed, which is highly porous, allowing for the rapid movement of the water from the sand bed into the well and vice versa. The second reason could be due to climatic conditions. The climate parameters that were measured were temperature and humidity. These parameters were chosen as they affect the accuracy of ultrasonic sensors and were incorporated in calculating the speed of sound when setting up the sensor. The average humidity and temperature observed over the five-day period was 75.1% and 21 ˚C, respectively. High temperature and low humidity are known to be the major stimulants of evaporation. In the case of this exercise, the temperatures were relatively low and humidity was high. Considering that the experiment took place in a closed room setting, there was minimal evaporation. Instead, water dammed up along the surface of the sand bed. Thirdly, the testbed was too small (300 mm x 24 mm x 24 mm). Shallow aquifers are known to have high surface-groundwater interaction, especially in highly permeable soils. As a result, water ended up being trapped in one place.

c) Experimental set-up 3

Figure 4.15 shows the water levels obtained from the sensor over the nine days. As in the previous set-up, an overall decline was observed over the nine days. There was, however, a sharp rise of approximately 1.5 cm in the first to the second hour of the observation period. Then, a steady decline occurred with a few cases observed where the water levels declined and increased at an abrupt rate. Reasons for the abrupt changes were similar to those provided in the second set-up described above. Gravel-like sand is a highly porous material, with gravel being more porous than sand. Thus, the material will behave more or less the same. The overall decline in water levels for the second set-up was approximately 8.5 cm. The rate of decline, as in the second set-up, was approximately 1 cm daily. Towards the end of the nine-days' observation period, there was still some water in the well, unlike in the case of the previous set-up, which was empty. This may be associated with the pore arrangements in the gravel, which have the capacity to retain water within the pores, unlike sand, which easily loses water.

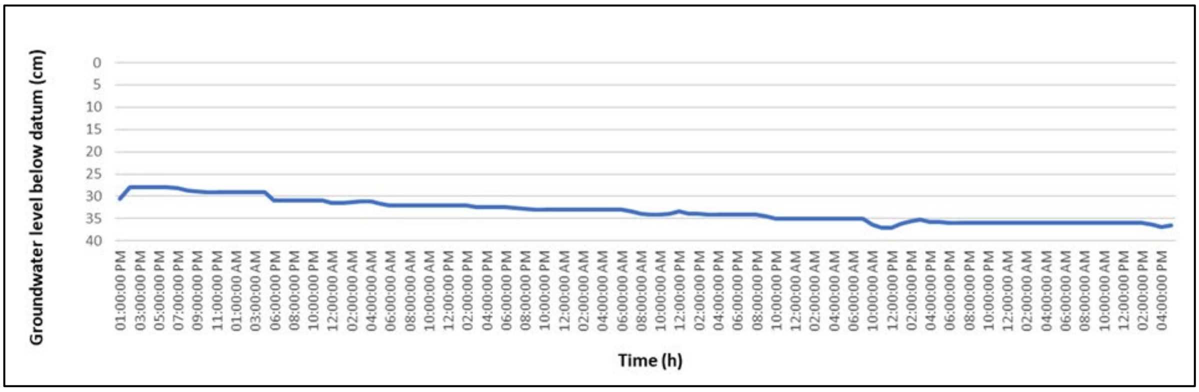

Figure 4.15: *Nine-day water levels for set-up 3*

There were cases while monitoring this set-up whereby data was missing for a period of 19 hours on Day 2, 17 hours on Day 3, 16 hours on Day 4, 24 hours on Day 5 and 10 hours on Day 6. The cause of data loss was due to loss of the Wi-Fi signal. Figure 4.16 and Figure 4.17 depict the temperature and the humidity, and readings observed over the nine-day period.

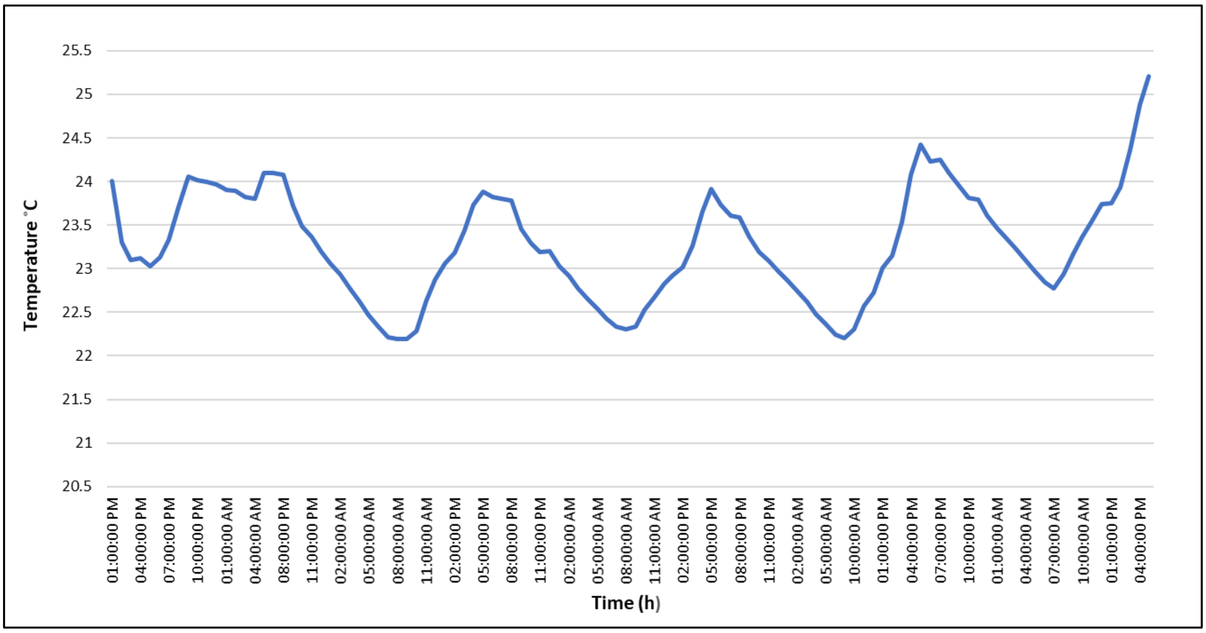

Figure 4.16: *Temperature fluctuations for set-up 3*

Temperature values in the well ranged between 22 ˚C and 25 ˚C over the observation period, with the average temperature being 23.2 ˚C.

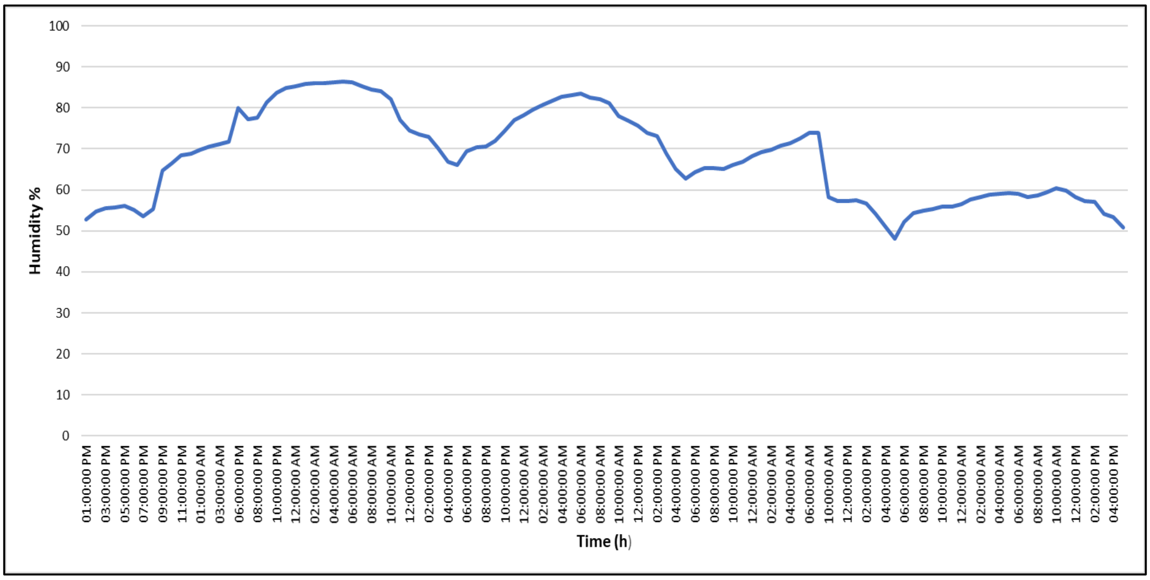

Figure 4.17: *Humidity for set-up 3*

Humidity was in the range of 48% to 86%, with an average of 68.2%. Generally, the data obtained in these three set-ups support the laws governing groundwater flow, which are centred around topography and permeability, i.e. the ability of materials to transmit fluids. Topography could not be illustrated due to the size of the sand bed, however. Climatic parameters, i.e. temperature and humidity in these set-ups, also supported the validity of these results. Based on the data adhering to groundwater movement laws and verifications that were made with a measuring ruler, it can be concluded that this newly developed sensor can adequately measure groundwater levels provided that the limitations of the sensor are not violated, e.g. measurements beyond 5 m groundwater levels.

The results in the three set-ups show consistency and accuracy in the reading and corresponding display on the ThingSpeak platform. This shows that the prototype passed the performance evaluation. The recommended further testing will include using a bigger sand bed, whereby the topographical aspect governing groundwater movement can be illustrated, and introducing a pumping well into the subsystem. Lastly, the sensor would need to be taken to the field. These recommendations are envisaged to be illustrated through a study that will be conducted by one of the doctoral students involved in this project.

4.7 USER REQUIREMENT SPECIFICATIONS VERSUS SUBSYSTEM PERFORMANCE

This subsection aims to provide a detailed report on performance findings versus the objective and deliverable of this subsystem. The cost of the purchased components per unit and the total cost is R1,765.95. The user requirement specifications with comments are displayed in Table 4.2

Table 4.2: *User requirement specifications*

Users' requirements	Users' specifications	Actual achievement
Low cost	R6,000	The total cost of this prototype per unit well is R1,765.95. Hence, this user's required specification was met.
Reliable and flexible	Robust, adaptable	The collected data is reliable and consistent over the period of time. This makes the data dependable for accurate decision-making and the system is adaptive to different information types

Users' requirements	Users' specifications	Actual achievement
Elongated battery lifetime	Prolonged power supply	The system is equipped with a solar PV cell and battery management system
Modular design	Subsystems and components must accommodate new technologies without affecting the design of others.	The Arduino IoT board can accommodate more sensors through multi ports.
Real-time	The information available to water managers from a large geographical area in a near real-time/real-time on-demand	Measured data is available in the negligible time delay between the period of measurement and display.
Scalable	The data acquisition system must be adaptable to a larger scale without sacrificing performance	This prototype can be duplicated on a larger scale without affecting its performance.

Based on the above system design criteria, we investigated the performance of the system, which is defined as the degree to which a prototype or system accomplishes its designated functions within given constraints such as functionality, reliability and usability. Table 4.3 analyses the performance of the developed system in an operating condition.

Table 4.3: *Performance analysis*

	Functionality	
Functionality criteria	**Definition**	**Test description**
1. Suitability	Suitability is the quality of being appropriate for a particular purpose	The purpose of this subsystem is to be able to measure and monitor groundwater parameters. Thus, during the test within the laboratory environment, this subsystem was able to measure the water level, percentage humidity, speed of song and temperature. Thus, this subsystem is suitable for measuring and monitoring groundwater resources.
2. Accuracy	Accuracy is the closeness of the measurements to a specific value.	In this case, a standard centimetre rule is used to compare the sensor's reading. The reading was designed to take place 10 times. The sensor's readings were found to be close to the standard centimetre ruler.
3. Repeatability	Successive measurements are taken under the same measurement condition	During the testing conducted, successive measurements taken by the sensor under the same condition gave the same results.

Functionality		
Functionality criteria	**Definition**	**Test description**
4. Compliance	This is how the prototype conforms to its standard specification	The prototype performs its function as designed to the degree of acceptable tolerance.
5. Security	Security in this context refers to how secure the prototype against external threats	The main microprocessor used has password security. This makes it secure against unauthorised personnel.

Reliability		
Reliability criteria	**Definition**	**Test description**
1. Fault tolerance	This is the ability of the prototype to continue to operate without interruption in the event of failure of some of its components	The major fault noticed during testing of this subsystem is an irregular sensor reading. Despite this, all other parameters are still being measured. This was as a result of different cables being joined together. To rectify this, the cable was changed. While troubleshooting, the ultrasonic sensor was changed. The subsystem continued its operation after the faulty cable or sensor was replaced. This showed that the subsystem is fault-tolerant.
2. Recoverability	This is the ability of the prototype to recover after a fault or being shut down	This prototype can easily recover from any fault detected, This was demonstrated during testing. During this test, sensors were changed. This did not alter the stability or the operation of this subsystem.
3. Reliability	This tests how consistently the prototype measures the groundwater level parameters over for a specific period	Consistent groundwater level measurements were recorded during the testing period of more than a week. During this time, the prototype shows a dependable and acceptable measurement

Usability		
Usability criteria	**definition**	**Test description**
1. Understandability	This is how a user understands the operation of this system	The working principle of this subsystem can be explained to end-users in such a way to make them have a proper understanding.
2. Learnability	This is how an end-user can learn the working of this prototype	After finishing this subsystem, the usage will be explained to the users. This will enable them to learn its usage and operation.
3. Operability	This is how easy it is to deploy and learn the working operation of the prototype	The working principle, deployment, and operation of this subsystem will be explained to the end-users.

Efficiency		
Efficiency criteria	**Definition**	**Test description**
1. Time behaviour	This is the ability of the prototype to perform its function at any given time under the same condition	The prototype is scalable, i.e. the readings can be taken at a different time interval. This shows minimal and acceptable tolerance during the testing. During testing, this subsystem was used continuously for more than seven days. The testing revealed the expected result of the continuous measurement of the water level and other parameters over time.
2. Resource behaviour	This is defined as the ability of the device to function at any given resource	For the prototype, the main resource to measure is the groundwater level. However, for result accuracy, other groundwater parameters, such as temperature and humidity, were also measured. Thus, the prototype was able to measure the level given the availability of these resources
3. Efficiency	This is the ability of the prototype to perform its operation at a required time and resource	At any given resource and time, the prototype efficiently performs its objective, i.e. it measured the groundwater level, logged the data, and performed visualisation.

Maintainability		
Maintainability criteria	**Definition**	**Test description**
1. Analysability	This is defined as the capacity of the prototype to be diagnosed for deficiencies or causes of failures.	The level-measured data is logged as per real-time scenario into the cloud. This makes the causes of failure to be identified if there is no data.
2. Changeability	This is the ability of the prototype to sustain or accommodate changes	Any faulty sensor can easily be replaced in the fastest time in this prototype, as well as upgrading.
3. Stability	This is the ability of the prototype to accommodate unintended consequences as a result of modification	The groundwater-measured parameters are stable during the experiment and will be able to accommodate future modifications.
4. Testability	This is defined as the degree to which the prototype or system facilitates the establishment of test criteria	The prototype has been able to adapt, as well as undergo the subject tests.
5. Maintainability	This is defined as the ease with which components can be modified to correct faults, improve performance or adapt to a changing environment	To evaluate the maintainability of this prototype, two different laboratory locations and different sensors were used to read the level measurement. This evaluation shows stability and conformity in readings.

Portability		
Portability criteria	**Definition**	**Test description**
1. Adaptability	This is defined as ascertaining how the prototype can easily be deployed in the field to perform its intended operation	Sensors used in this prototype have easily been adapted into the system of groundwater level measurement.
2. Installability	This is the ability of the software to be effectively deployed in a targeted environment	The prototype is easy to install.
3. Conformance	This is the ability of the prototype to comply with the requirements and specifications	The prototype meets the required specifications to perform its operations.
4. Portability	This is the process of determining the degree of ease with which this prototype can be transferred to its usage environment	The size of this subsystem could not be measured because it is just parts used without its intended case. However, the overall dimension of the prototype within its case is 27 cm x 27 cm. This makes it handy and easy to carry.

4.8 SUMMARY OF THE INNOVATION AND CONCLUSION

In this specific report, the objective of developing a portable low-cost real-time GoT sensor prototype subsystem for monitoring groundwater level in a laboratory environment was achieved to a greater degree. We report that the groundwater level monitoring using the GoT sensor prototype subsystem was developed, tested in a laboratory condition and the results showed that the system was functioning as expected. The novelty of this subsystem is based on its ability to present the groundwater level information in a real-time scenario, as well as the geographical information of the location. This is very useful for local scale and regional understanding.

From Table 4.3, it can be concluded that the overall objective of this subsystem was achieved. This is highlighted in Table 4.4:

Table 4.4: *Deliverables*

Deliverables	Comment
Objective: To develop a portable, low-cost, real-time Geography of Things sensor prototype subsystem for monitoring groundwater levels in a laboratory environment	This objective was successfully achieved.
Deliverable: Groundwater level monitoring using a Geography of Things sensor prototype subsystem.	The proposed deliverable was developed.

CHAPTER 5: SECTION II: GROUNDWATER QUALITY MONITORING SUBSYSTEM

5.1 INTRODUCTION

In this section of the project, the real-time monitoring subsystem for groundwater quality was developed in a laboratory environment. The proposed groundwater quality monitoring subsystem was based on the use of GoT. The GoT consisted of sensors, microprocessors and other IoT- enabled units. The design specifications of the prototype were expected to be low-cost, portable, flexible, with an elongated battery life, modular and making use reliable, secured communication schemes.

This section will briefly discuss the steps taken from the development stages to the results produced by the prototype during testing in a laboratory environment. We report that the groundwater quality monitoring using the GoT sensor prototype subsystem was developed and tested. The results showed that the system was functioning as expected.

5.2 DATA ACQUISITION UNIT

In this section, the development of a proposed groundwater quality monitoring system will be discussed with the aid of a block diagram and flow chart, as shown in Figure 5.1 and Figure 5.2.

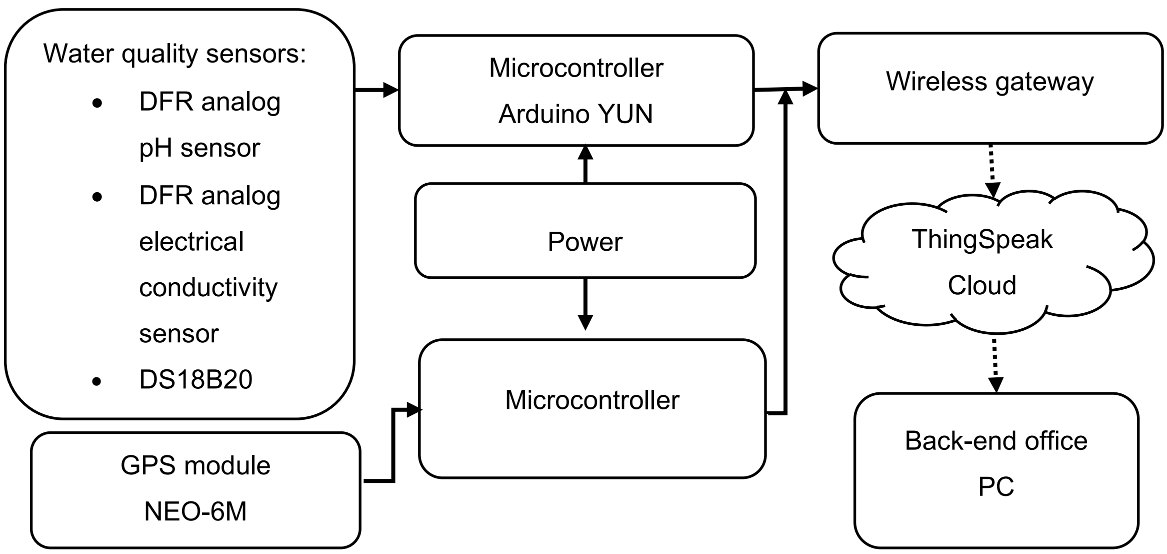

Figure 5.1: *Block diagram of groundwater quality monitoring system*

Figure 5.1 represents the operational block diagram of the proposed groundwater quality monitoring system, where the following apply:

- The pH level, electrical conductivity, temperature sensors and global positioning system (GPS) module will be connected to the microcontroller as the input peripherals.
- These devices will be sending raw or analogue information to the microcontroller for processing. The microcontroller will convert the analogue data to digital data.
- The processed data will be sent to the cloud server via a wireless communication gateway, and the data will be retrieved from an IoT analytical platform called ThingSpeak by a computer located at the back-end office.

- The power supply is monitored by another microcontroller and the power level data is sent to ThingSpeak and displayed on the PC.

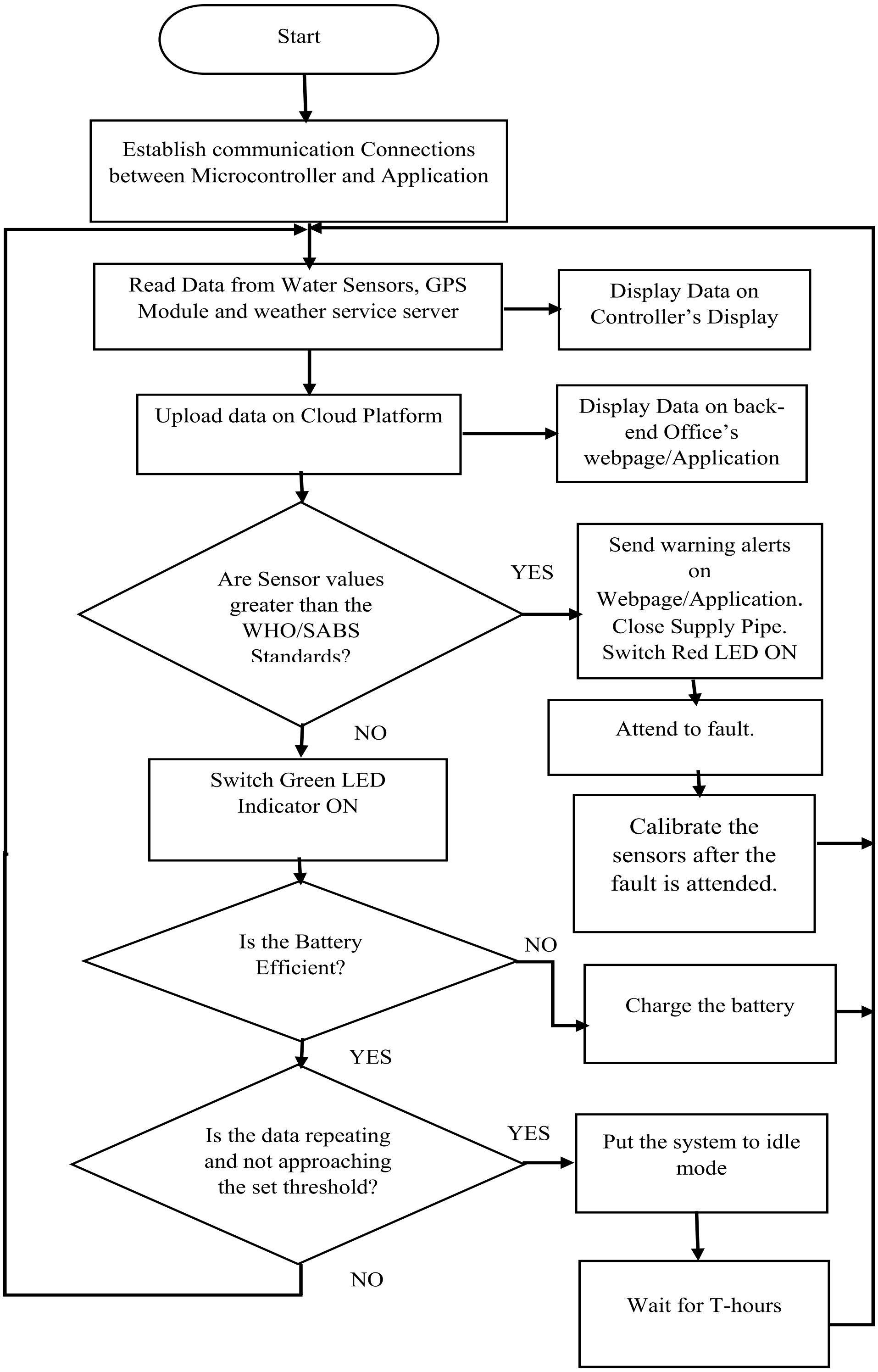

Figure 5.2: *Groundwater quality monitoring flow chart*

Figure 5.2, shows the steps taken to execute the required tasks. These events will take place inside the microcontroller communicating with the connected I/O peripherals.

- The first step taken by the system is to establish communication between the microcontroller and the cloud server's application.
- The system will start reading from water sensors and GPS modules and upload data to the IoT analytical platform.
- Processed data will be visualised on the platform in real time.
- The data will be analysed to see if it is still within the WHO-required standards and will continue sending warnings if the data shows the bad quality of water, upon which the supply pipe will be closed.
- If the water quality is good, the green indicator will always be on, whereas if the quality is bad, the red indicator will turn on.
- After every case of bad water quality has been attended to, the sensors will be calibrated and continue monitoring.
- The battery life will be monitored. If the battery is drained, the charging system will be switched on and the battery will be charged while monitoring.
- If the battery is efficient, the system will continue to check if there is a need to continuously monitor the water quality.
- If the recorded data is constantly repeating and shows no sign of threats to the borehole, the system will go into idle mode for T hours to save the battery life.
- After T hours, the system will continue monitoring and repeat the abovementioned steps.
- If the data is showing any signs of reaching or passing the set threshold, the system will keep monitoring the water quality, while repeating the cycle.

5.3 IOT ARCHITECTURE FOR GROUNDWATER QUALITY SUBSYSTEM

The groundwater monitoring system using GoT is developed from some of the five layers of the IoT architecture. In this project, the focus was mainly on the perception, network, middleware or processing, and application layers. The perception layer was composed of sensors and microcontrollers, which are the physical objects of the system. The network layer focused on how the sensor data was transmitted from one place to another. The middleware layer was the processing unit, in which there was an algorithm to make decisions, and analyse and store data. The data was transmitted to the application layer, where the conclusion was drawn. The four IoT architecture layers used to develop the groundwater quality subsystem are shown in Figure 5.3.

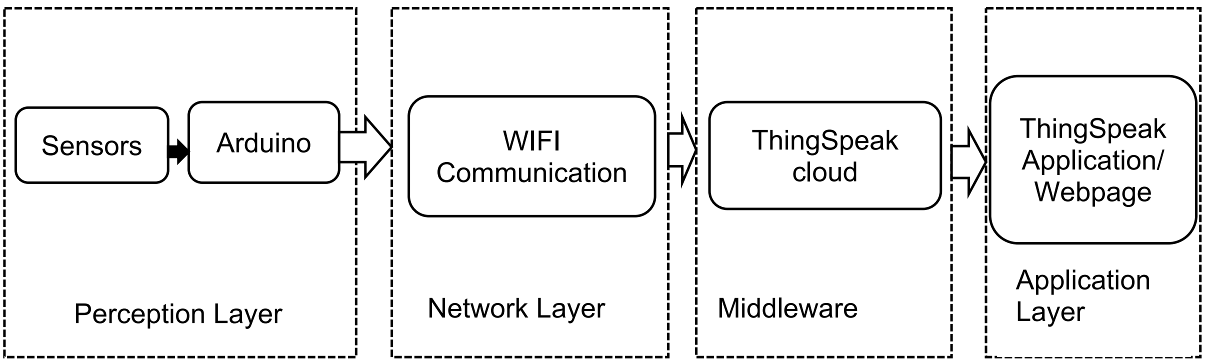

Figure 5.3: *The IoT architecture layer for the groundwater quality system*

5.4 DATA-CAPTURING AND PROCESSING LAYER

Figure 5.4 shows the schematic diagram for the data-capturing layer for the groundwater quality monitoring system. The microcontroller uses an ATmega32P microchip for processing data from different sensors connected to it. A firmware code with specific functions is uploaded on this microchip. Analogue to digital conversions of data are done inside this chip, which is powered by a 5V power supply. The power level of the microcontroller is also monitored by another subsystem microcontroller.

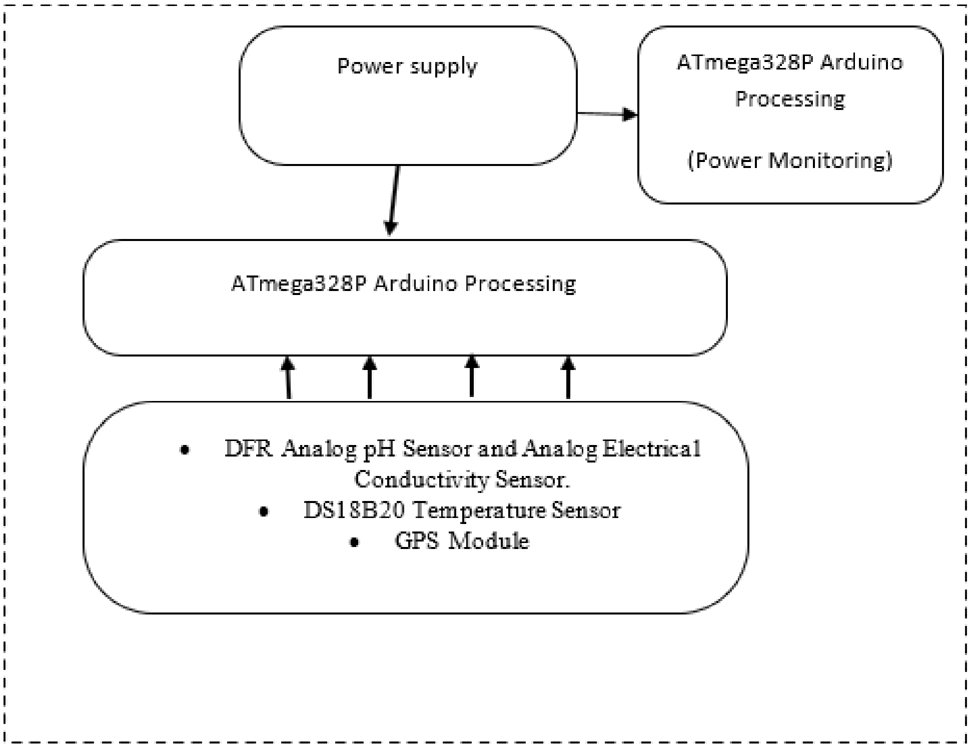

Figure 5.4: *Schematic diagram of data-capturing layer*

5.5 CONSTRUCTION OF THE SUBSYSTEM

The implementation of a designed model for the prototype will be discussed in this section. Specification details of components purchased and construction pictures of the working prototype itself will be covered.

5.5.1 Required hardware

The project used the following hardware components:

- Breadboard
- Jumper cables
- Arduino YUN
- Water quality sensors (pH level and electrical conductivity sensors)
- Temperature sensor
- GPS module
- Solar panel
- 12 V battery
- Liquid crystal display (LCD)
- Eight-channel relay module
- Voltmeter

This required hardware can be divided into the data acquisition unit, the data transferring unit and the data processing unit. The overall integrated groundwater quality monitoring system is shown in Figure 5.5.

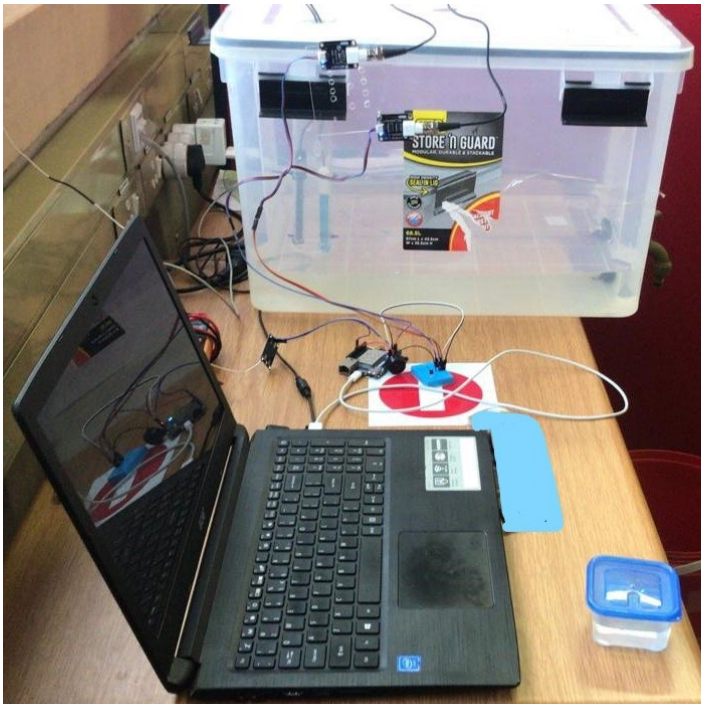

Figure 5.5: *Overall integrated mini groundwater monitoring system laboratory set-up*

5.6 PERFORMANCE EVALUATION

Performance evaluation tests of the prototype will be discussed, as well as the steps taken to reach the final construction of the prototype.

5.6.1 Subsystem testing set-up

The first step of testing is to perform sensor calibration. This is for water quality sensors to be able to read the correct pH level and electrical conductivity values from different water samples. The following apparatus was used to calibrate the sensors:

- DFR analogue pH level and electrical conductivity sensors
- DS18b20 waterproof temperature sensor
- Glass beaker
- Distilled water and buffer solutions
- Computer

Three water quality sensors (pH, electrical conductivity and temperature sensors) were immersed in distilled water for calibration, while their input pins were connected to the microcontroller. Electrical conductivity and pH sensors were connected to the analogue ports of the microcontroller while the temperature sensor was connected to the microcontroller's digital port. The results were displayed on the IoT analytical platform ThingSpeak and the results captured during calibration were shown:

pH level = 7.432

Electrical conductivity = 0.00 mS/cm

The ideal pH and electrical conductivity values for distilled water are expected to be as follows:

pH level = 7.00

The error percentage between the expected and the measured pH level was found to be:

$$Error\ (\%) \ = \frac{7.432-7}{7.00} = 6.171\ \%$$

The calculated error percentage is less than 10%, which is acceptable.

Electrical conductivity = 0.00 mS/cm

This value was equal to the expected value.

The next step was to test the buffer solutions that came along with the sensors. These solutions are also used to calibrate the water quality sensors. The calibrated results are stored in each water quality sensor's electrically erasable programmable read-only memory (EEPROM).T

The results displayed are:

Measured: pH = 3.928

Expected = 4.00 (as shown by the buffer solution in Figure 5.11).

$$\text{Error }(\%) = \frac{4{,}00 - 3.928}{4{,}00} \times 100 = 1.8\% \text{ at the temperature of } 22.6℃$$

Electrical conductivity: measured = 1.42 ms/cm ≈ $1420\mu S/cm$

$$\text{Expected} = \ 1413\mu\text{S/cm}$$

$$\text{Error}(\%) = \frac{(1420-1413)\mu\text{s/cm}}{1413} \times 100 = 0.495\ \%$$

Therefore, the error percentage is still less than 10%.

The following results are for pH = 7.00 and electrical conductivity = 12.88 mS/cm (the error percentage is:

Measured: pH = 7.028

$$\text{Error} = \frac{7{,}028 - 7.00}{7.00} \times 100 = 0{,}4\%$$

Electrical conductivity: Measure = 13.07 mS/cm

$$\text{Error} = \frac{(13{,}07 - 12{,}88)mS/cm}{12{,}88} \times 100 = 1{,}48\ \%$$

Error <10%

For power or battery level monitoring, a microcontroller was used to measure the voltage level of the battery. The measurements were displayed on ThingSpeak, LCD and validated using a multimeter or voltmeter.

The GPS module was also tested in a laboratory environment to receive location coordinates of where the groundwater quality subsystem was placed. Therefore, the results obtained from this water level subsystem indicate that it is able to measure the pH, electrical conductivity and water temperature parameters from any water sample. Further tests will be carried out on water samples containing *E. coli*, manganese, and nitrate. The aim is to test the samples' pH value, electrical conductivity and temperature.

5.6.2 Preparation and testing of water quality parameters: *E. coli*, nitrate and manganese

The prototype was tested in a laboratory environment using different types of water samples. The testing was carried out to determine the pH value and electrical conductivity parameters of each water sample polluted with *E. coli*, nitrate and manganese. To do this, *E. coli* was cultured in a laboratory environment. These samples were prepared using the Colilert 18 test kit method and incubated at 35 °C for 18 to 24 hours. The 51 Well Idexx Quanti trays were used and samples were checked the following day to detect if any *E. coli* was present under the UV light. A volume of 100 ml distilled water was spiked with 10 ml of the positive *E. coli* that was grown from the borehole sample. For nitrate preparations, a colourimeter (HACH DR/890) was used. Samples were placed in two vials. In one vial, the nitrate reagent was added and dissolved for one minute. The colourimeter is set to the nitrate's high-range programme and calibrated or zeroed using the vial without the reagent. The sample is left to react for five minutes and is then placed in the colourimeter. The readings were taken in milligrams per litre (mg/ℓ).

For manganese preparations initially, Sigma-Aldrich Manganese powder (≥99.9% trace metal basis) was used in distilled water to make up different concentrations. Unfortunately, this method was yielding very high manganese concentrations, even at small quantities of manganese powder, and was still not yielding the anticipated ranges for SANS 241:2015 (chronic health ≤0.4 mg/l and aesthetic 0.1mg/l). The HACH DR/890 colourimeter programme 43 (low range), as well as programme 41 (high range), was used to detect the manganese concentrations. Samples from two boreholes from the Pienaars Dam leisure resort in Middelburg were also tested for the presence of manganese and then spiked with manganese.

An email alert notification was used to send warnings when there was a change in the water quality that threatened the lives of groundwater consumers.

For *E. coli* testing, the three sensors were immersed in the solution that contained *E. coli*. The two concentrations gave different readings for pH and electrical conductivity. The first sample recorded a pH level of 11.229. The corresponding electrical conductivity was 8.56 mS/cm. In the second solution, the measured pH level was 10.743, while the electrical conductivity was 8.99. According to the South African National Standards (SANS), there should be zero detection of *E. coli* in potable water.

Further tests were carried out on water samples containing different concentrations of nitrate. The trend shows that an increased nitrate concentration causes a decreased pH level. Higher nitrate concentrations can lower the pH, making the water more acidic. The acceptable nitrate concentration in potable water according to SANS 241: 2015 is less than or equal to 11 mg/ℓ.

Manganese concentrations and their corresponding measured pH level and electrical conductivity were measured. The concentration was first measured using a colourimeter. Some of the concentrations did not have readings, so they were labelled using their weighted values of manganese. Different concentrations of manganese in borehole water were measured in low and high ranges. One concentration of distilled water and manganese was used as a control sample. Their results are presented in Appendix 1.

5.6.3 Battery level testing

The battery level testing results are shown on a voltmeter, ThingSpeak and LCD. The voltmeter was used to confirm the measured results performed by the microcontroller. The results seem to correspond to all the displays.

5.7 USER REQUIREMENT SPECIFICATIONS VERSUS SUBSYSTEM PERFORMANCE

This section aims to provide detailed performance findings of the objective and deliverable of this subsystem. The cost of the purchased components per unit and the total cost show that this quality subsystem costs R3,579.01.

The users' requirement specifications and the actual achievements are displayed in Table 5.1.

Table 5.1: *User requirement specifications*

Users' requirements	Users' specifications	Actual achievement
Low cost	R6,000	The cost for all the purchased components is R3,579.01. this is less than R6,000. This gives room for other additional sensors to be purchased.
Reliable and flexible	Robust, adaptable	The collected data is reliable and consistent over the period of time. This makes the data dependable for accurate decision making and the system is adaptive to different information types.
Elongated battery lifetime	Prolonged power supply	The system is equipped with a solar PV cell and battery management system.
Modular design	Subsystems and components must accommodate new technologies without affecting the design of others	The system is made of subsystem devices that can be easily integrated.
Real-time	The information must be available to water managers from a large geographical area in a near real-time/real-time on-demand	The measured data is available in the negligible time delay between the period of measurement and display.
Scalable	The data acquisition system must be adaptable to a larger scale without sacrificing performance	This prototype can be duplicated on a larger scale without affecting its performance. The system is able to capture changes in the measured water parameters such as pH level, electrical conductivity and temperature.

Table 5.2 shows the performance evaluation of the constructed prototype based on its functionality throughout the testing stages.

Table 5.2*: Performance evaluation*

	Functionality of prototype
Criteria	**Design specification**
Suitability	The system is good for groundwater quality monitoring as it gives important water quality parameters (temperature, pH level, electrical conductivity, *E. coli*, nitrates and manganese)
Accuracy	The results for electrical conductivity were fluctuating due to negatively charged electrons moving to the positive probe. The GPS module was able to locate the model well.
Adaptability	If the GPS module is deployed to the site, it will easily receive the coordinates and it will be easy to track the wells. If the system is to be deployed at a different well, calibration of the pH sensor and electrical conductivity will need to be performed.
Compliance	The prototype performs its function as designed and meets the basic operations for similar products.

	Functionality of prototype
Security	The Arduino YUN has connected to a password-encrypted wireless access point and the cloud server was private.
User friendliness	The cloud server displays already processed information that is easy to understand
Reliability	Calibrations were done using buffer solutions and the sensors were able to measure the buffer solutions. Google Maps was used to verify the location, which makes the system reliable.
Efficiency	The error percentage between the expected values and measured values was less than 10%.
Operations	The prototype was able to switch from measuring one sample to another and could display the results.

5.8 SUMMARY OF THE INNOVATION AND CONCLUSION

The incorporation of GoT items such as the location indicator that was used in the groundwater quality monitoring system brings change and uniqueness from the existing systems. While the location of the boreholes is known by the water managers, this can even help newly hired water engineers to drive to the borehole sources by themselves using their smart devices and smartphones as navigators. The use of an IoT analytical platform to remotely monitor the quality is also bringing convenient ways of monitoring groundwater quality. The introduction of a battery-level monitoring subsystem also brings change to the monitoring systems deployed in far-flung wells as the quality of the groundwater can be continuously monitored with fewer concerns about power issues. The knowledge of system power usage makes the system more user friendly and easy to troubleshoot in case of breakdowns.

The main objective of developing a portable low-cost real-time GoT sensor prototype subsystem for monitoring groundwater quality in a laboratory environment was achieved. The developed groundwater quality monitoring using the GoT sensor prototype subsystem was tested in a laboratory environment. The results showed that the system was able to operate in different temperatures.

From Table 5.1, it can be concluded that the overall objective of this subsystem was achieved. This is highlighted in Table 5.3:

Table 5.3: *Deliverables*

Deliverables	Comments
Objective: To develop a portable, low-cost, real-time GoT sensor prototype subsystem for monitoring groundwater quality in a laboratory environment.	This objective was successfully achieved.
Deliverable: Groundwater quality monitoring using a GoT sensor prototype subsystem.	The deliverable of the project was accomplished.

CHAPTER 6: SECTION III: INTEGRATED GROUNDWATER LEVEL AND QUALITY MONITORING SYSTEM

6.1 INTRODUCTION

This project aimed to develop an innovative GoT sensor prototype that is capable of monitoring groundwater level and quality in real time. The expected impact of this developed prototype is to address the sustainability and quality of groundwater resources. The real-time monitoring of groundwater resources not only curbs problems of food insecurity, livelihood choices and educational opportunities for poor families across the world, but also fosters climate change adaptations. Drought that leade to dry aquifers afflicts some of the world's poorest countries, worsening hunger and malnutrition. Thus, the study set out to achieve the following objectives:

- Develop a portable, low-cost, real-time GoT sensor prototype subsystem for monitoring groundwater levels in a laboratory environment.
- Develop a portable, low-cost real-time GoT sensor prototype subsystem for monitoring groundwater quality.
- Integrate the first two objectives with the communication protocols, servers and display unit into a functional sensor prototype system that can be evaluated as being fit for purpose.

Having achieved the first two objectives, the third objective, the integration of both the quality and the level subsections, will be discussed in this section. Figure 6.1 represents the simplified block diagram of the integrated groundwater monitoring system.

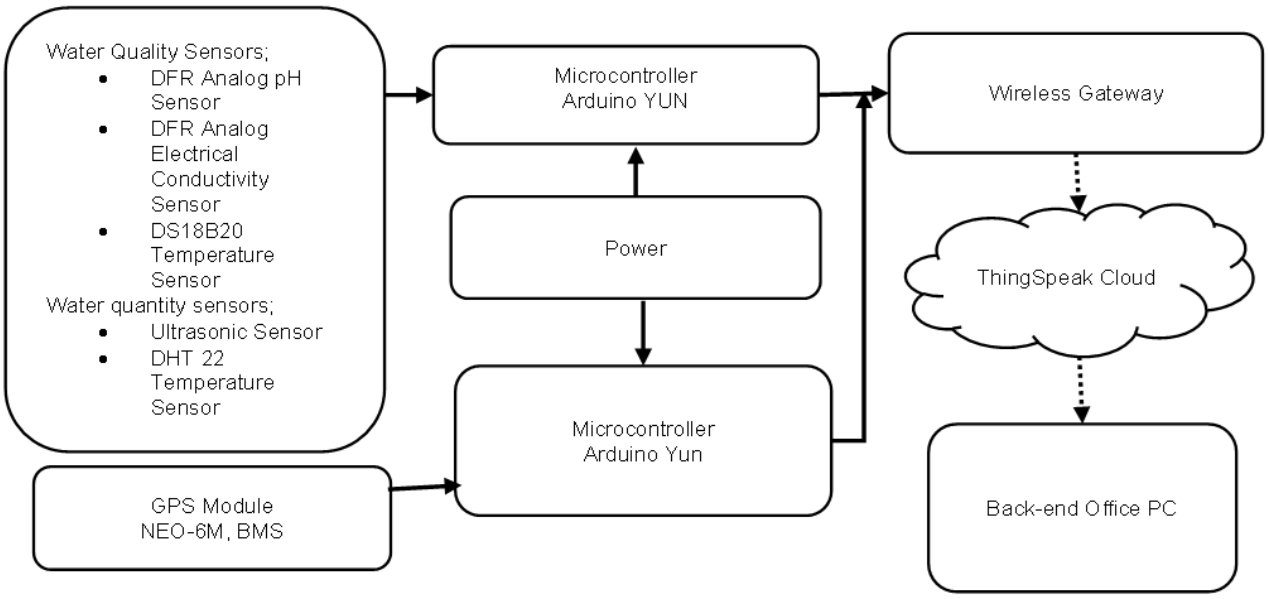

Figure 6.1: *Block diagram of the integrated groundwater monitoring system*

Figure 6.1 comprises four different units: the data acquisition unit, the data transfer and processing layer unit, the communication unit, and the analytic and display unit. Both section 4 and section 5 were combined into this integrated system. This was done to be able to measure both the level (groundwater level) parameters and the quality parameters (as explained in section 4 and section 5, respectively). Furthermore, the operations of each subsystem remain as explained in section 4 and section 5, respectively.

6.2 DATA ACQUISITION UNIT

The data acquisition unit of this integrated monitoring system comprised both the data acquisition layers for level and quality subsystems in section 4 and section 5, respectively. These integrated units are represented in Figure 6.2. This layer comprises mainly the data acquisition sensors.

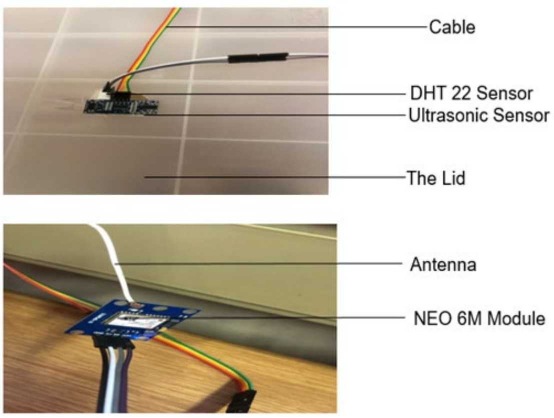

Figure 6.2a: Level data acquisition unit

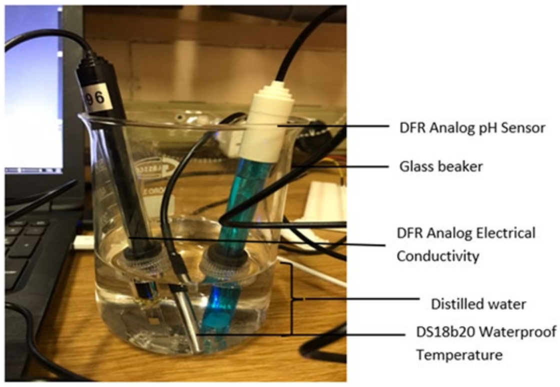

Figure 6.2b: Quality data acquisition unit

Figure 6.2: *Integrated data acquisition layer*

6.3 DATA CAPTURING AND PROCESSING UNIT

The integrated diagram of the data capturing and processing unit is shown in Figure 6.3. As explained in sections 4 and section 5, the main brain behind this layer is the Arduino YUN REV 2 ATmega32P-based microchip. This unit captures the data acquired by the data acquisition unit as well as the processing of the data from the connected sensors. Its operations in this prototype are already discussed extensively in the previous sections 4 and 5.

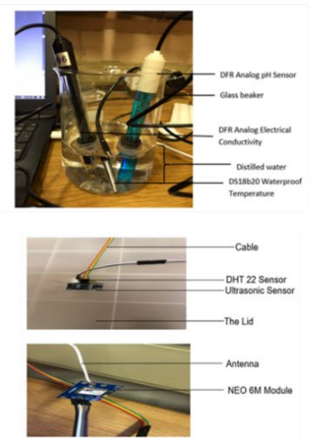

Figure 6.3a: *Data capturing unit*

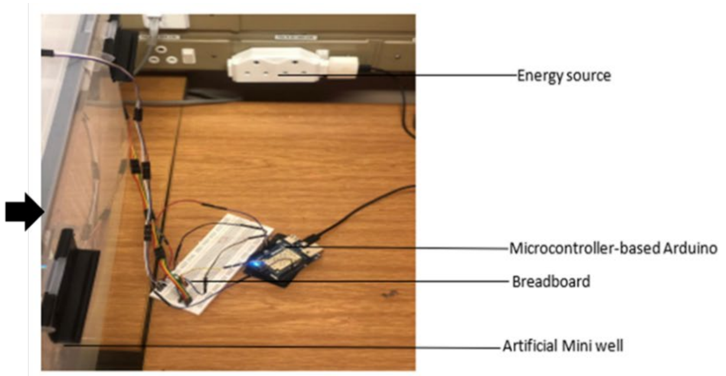

Figure 6.3b: *Data processing unit*

Figure 6.3: *Integrated data acquisition layer*

6.4 DATA COMMUNICATION UNIT

The data communication unit performs the operation as described in sections 4 and 5, respectively. Figure 6.4 shows the data communication unit. The unit is made up of the Wi-Fi-enabled Arduino board and the wireless network node. Processed data is transmitted between the physical layer and the analytics and display unit.

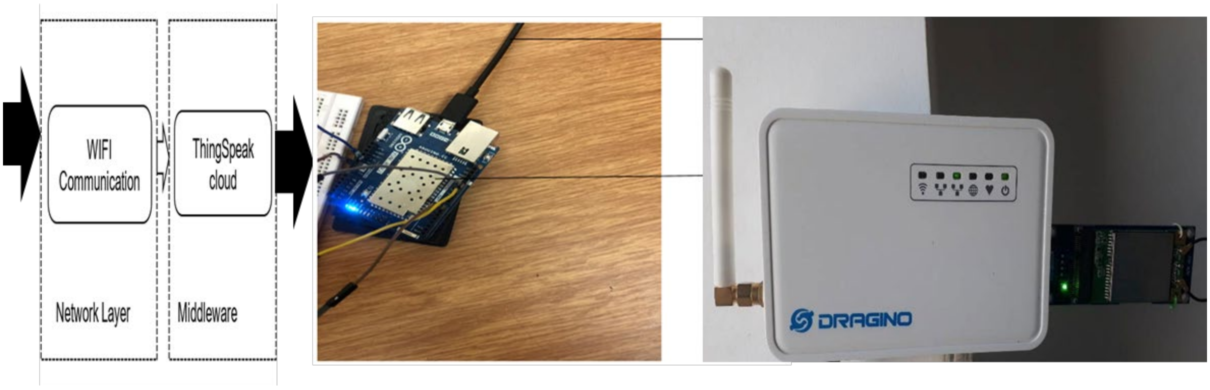

Figure 6.4: *Data communication unit*

6.5 DATA ANALYTICS AND DISPLAY UNIT

This unit performs the function of displaying all the measured parameters in a graphical and digital format. Furthermore, the processed data from the other units is transferred into the storage cloud. For this project, open-source ThingSpeak from MATHWORK is used. The graphical display from the ThingSpeak platform is shown in Figure 6.5.

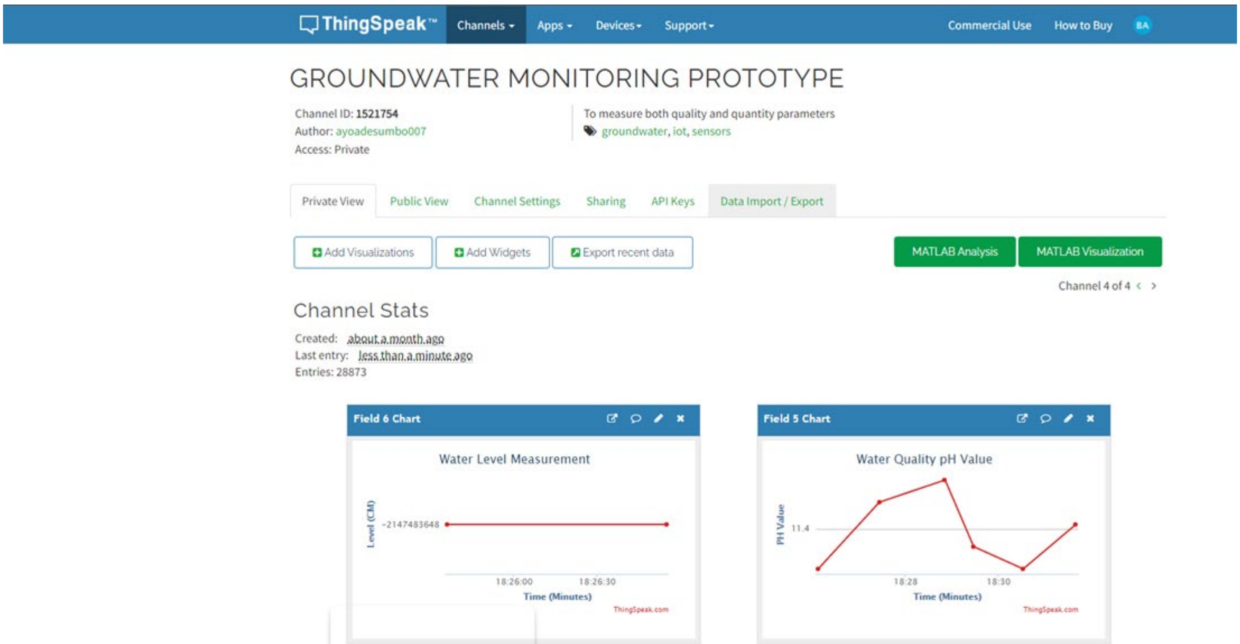

Figure 6.5: *ThingSpeak IoT analytics and display platform*

6.6 CONSTRUCTION OF THE PROTOTYPE SYSTEM

The construction of this integrated prototype will be described in this section. This is a continuation of Section 4 and section 5. Thus, assembling the subsystems into a single unit will be carried out here. The cloud service for the easy display of all the measured parameters was also harmonised. Thus both the level and quality parameters measured are displayed via the ThingSpeak platform.

6.6.1 The overall deliverable (integrated monitoring system)

For the overall integration of this prototype, all the units of each subsystem mentioned in section 4 and section 5 were assembled into a single unit. Figure 6.6 is a diagram of the final casing for this prototype.

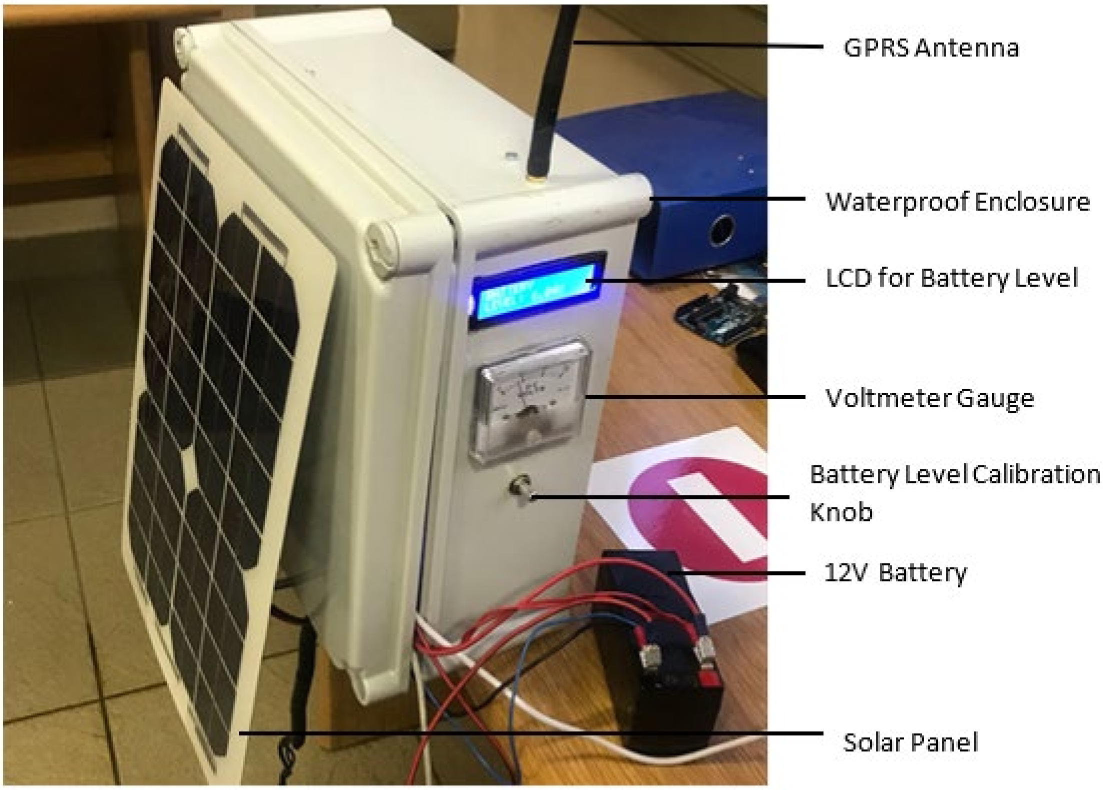

Figure 6.6: *The integrated prototype*

Figure 6.6 also contains an output connector port for sensors' connection. The rear side is shown in Figure 6.7.

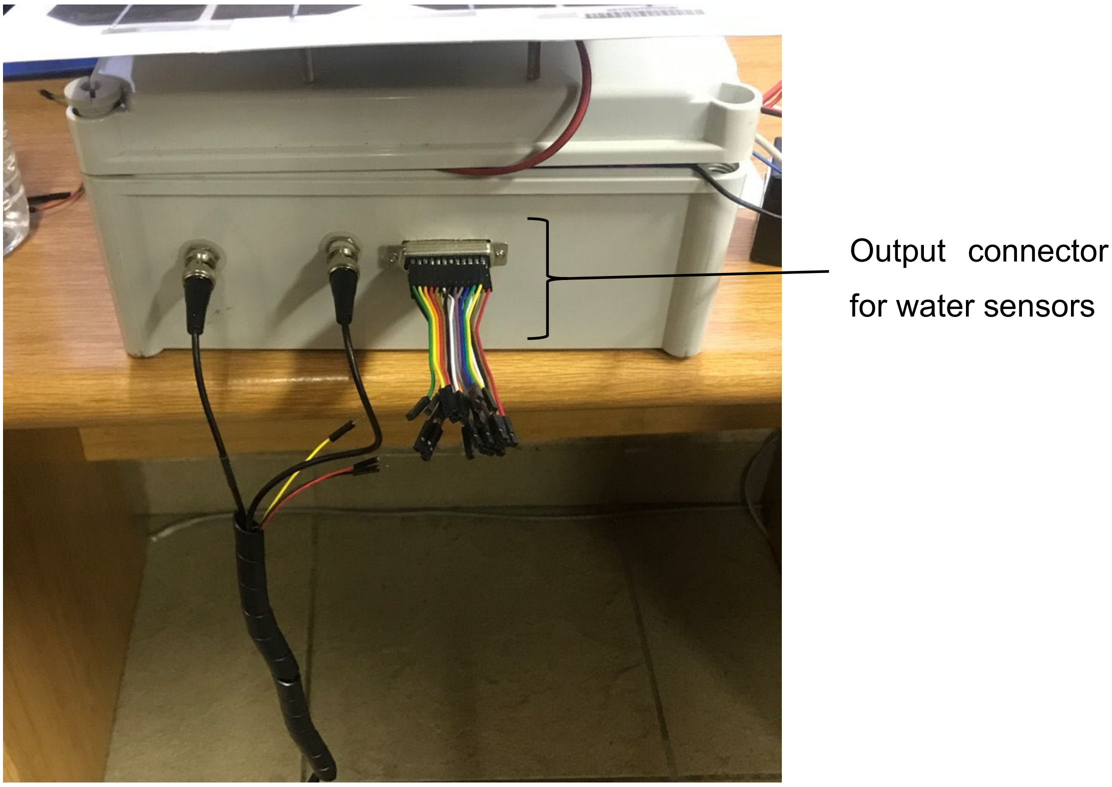

Figure 6.7: The rear side of the integrated prototype

6.7 PERFORMANCE EVALUATION

The same performance evaluation that was carried out on each of the subsystems was carried out on the integrated prototype. During the period of testing, the system showed an acceptable level of performance that was previously obtained before the subsystems were coupled. Therefore, the level subsystem's parameters, such as water level, water space temperature, water percentage of humidity and the speed of sound were measured.

The water quality subsystem was able to measure the pH level, electrical conductivity and water temperature. The pH is the potential of hydrogen in water, with the potential measured on a logarithmic scale of 0 to 14. If the pH sensor reads a value below 7, this indicates that the water is acidic, while a reading above 7 indicates that the water is alkaline or basic. A value equal to 7 indicates the neutrality of the water. According to SANS 241: 2015, the acceptable pH level for drinking water must be greater than or equal to 5 and less than or equal to 9.7 at 25 °C.

Electrical conductivity is the ability of water to conduct electricity. The presence and concentration of ions, mobility, valence and the temperature at which conductivity is measured affect this ability. Hence, the temperature sensor is included in the prototype. The acceptable measurement for electrical conductivity is equal to or less than 170 mS/m. Figure 6.8 shows the integrated groundwater monitoring system during testing.

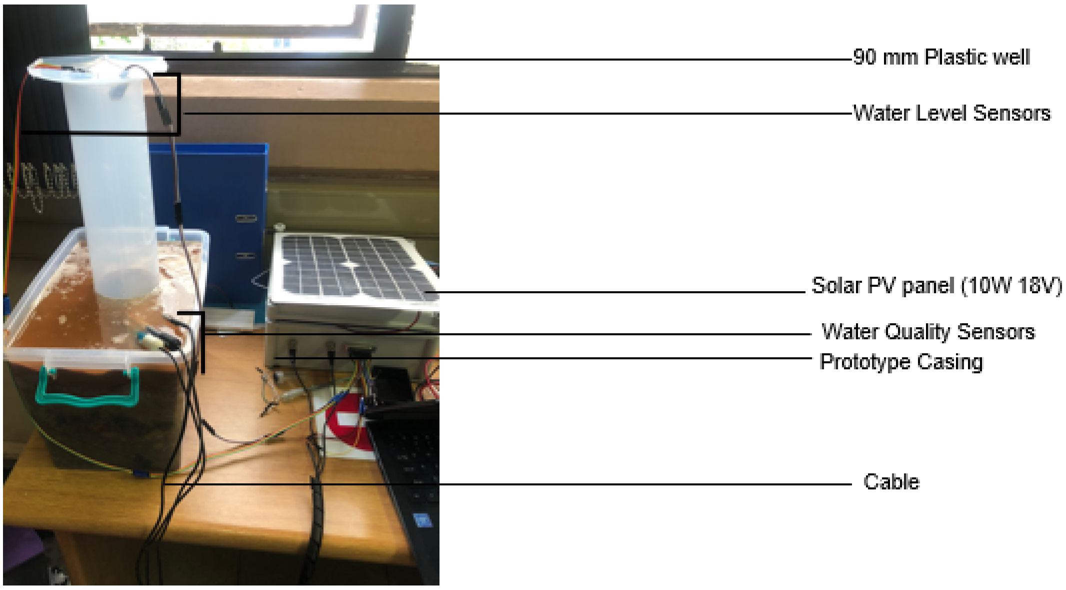

Figure 6.8: *The integrated groundwater monitoring system during testing*

6.7.1 System testing results

Performance testing was carried out on this final prototype. The results of this test were displayed on the harmonised ThingSpeak cloud service platform. This is displayed in Figure 6.9. These results correspond with the results obtained during the test of the individual subsystem carried out in section 4 and section 5, respectively.

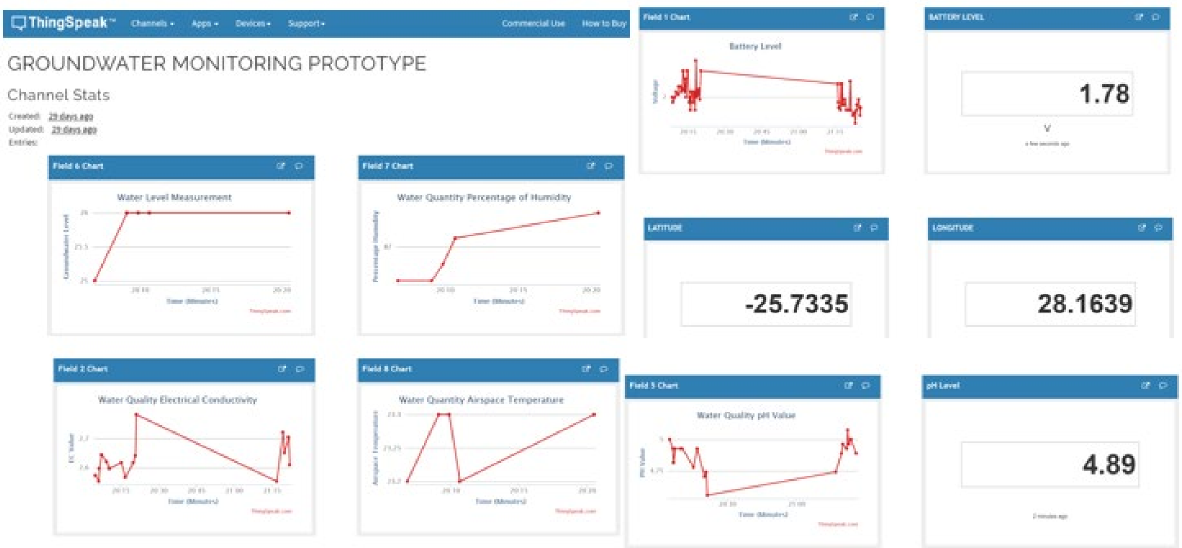

Figure 6.9: *The displayed resulst on ThingSpeak*

6.8 USER REQUIREMENT SPECIFICATIONS VERSUS PROTOTYPE SYSTEM PERFORMANCE

This section aims to provide detailed performance findings of the objective and deliverable of this prototype as a whole. The total cost for both subsystems is calculated in Table 6.1.

Table 6.1: *Total costs of the prototype*

Tools	Prices (per unit)
The total cost of the level monitoring subsystem	R1,765.95
The total cost of the quality monitoring subsystem	R3,579,01
The total amount of the prototype per unit	**R5,344.96**

The users' requirement specifications with comments are displayed in Table 6.2

Table 6.2: *User requirement specifications*

Users' requirements	Users' specifications	Actual achievement
Low cost	R6,000	The total cost of this prototype per unit well is R5,344.96. Hence, this users' requirement specification was met.
Reliable and flexible	Robust, adaptable	• Quantity sensor: contactless sensor, accurate up to 4 m depth • Water quality sensors were able to measure different physical parameters (pH level, electrical conductivity and temperature) in different concentrations of contaminated water samples
Elongated battery lifetime	Prolonged power supply	The system is equipped with a solar PV cell and battery management system.
Modular design	Subsystems and components must accommodate new technologies without affecting the design of others	The Arduino IoT board can accommodate more sensors through multi ports.
Real-time	The information must be available to water managers from a large geographical area in near real-time/real-time on-demand	Measured data is available in the negligible time delay between the period of measurement and display.
Scalable	The data acquisition system must be adaptable to a larger scale without sacrificing performance	This prototype can be duplicated on a larger scale without affecting its performance.

6.9 SUMMARY OF INNOVATION

When compared with the existing monitoring systems in the market, the developed system prototype has the following unique attributes:

- The system can monitor both level and quality parameters of groundwater in real time.
- This system is equipped with a GoT-based sensor, which provides the geo-location of the groundwater wells that are being monitored, alongside the level and quality of the groundwater.
- This system is equipped with a battery monitoring system to manage the power consumption of the remotely deployed system.

6.10 CONCLUSION

This project has been able to bridge the design gaps of recent proposals by achieving the joint monitoring of the groundwater level and quality data using radio resource-efficient GoT suited to emerging economies. The prototype developed is a novel integrated groundwater level and quality data acquisition sensor, which includes other technologies that have been proposed for low-power long-range communications and the GoT. The main idea of the project was to develop a real-time and sustainable groundwater level and quality monitoring system for remote data collection sites that meet a set of design requirements: low cost, miniaturisation, flexibility, battery lifetime, modularity and reliable untethered communication.

The developed system prototype was able to monitor the following level and quality parameters of the groundwater from a remote geo-located network of wells:

- Groundwater level
- Percentage humidity
- Environmental temperature
- Speed of sound
- Electrical conductivity
- The pH level
- *E. coli* concentration
- Manganese concentration
- Nitrate concentration
- Water temperature

Furthermore, this prototype is equipped with its own solar system, rechargeable battery, battery monitoring system and location parameters (longitude and latitude).

6.11 FUTURE DEVELOPMENTS AND RECOMMENDATIONS

The developed monitoring system is a work in progress, thus future development will include the following:

- Long-range, non-contact sensors need to be explored to measure deep wells (i.e. contactless range more than 4 m).
- The short cable length of the water quality sensor needs to be investigated and improved to allow measurements in deep wells.
- Biological and chemical parameters can be detected with the aid of trained sensors using artificial intelligence.
- An energy harvesting technique may be introduced for elongated battery life.
- The laboratory prototype will be implemented and deployed in real-world field testing.

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SHAH E, LIEBRAND J, VOS J, VELDWISCH GJ and BOELENS R (2018) The UN-Water and Development Report 2016 – Water and jobs: A critical review. Development and Change **49** 678–691.

SINGH CK and KATPATAL YB (2020) A review of the historical background, needs, design approaches and future challenges in groundwater level monitoring networks. Journal of Engineering Science and Technology Review **13 (2)** 135–153. https://doi.org/10.25103/jestr.132.18.

APPENDIX 1: DETAIL DIAGRAMS AND TABLES

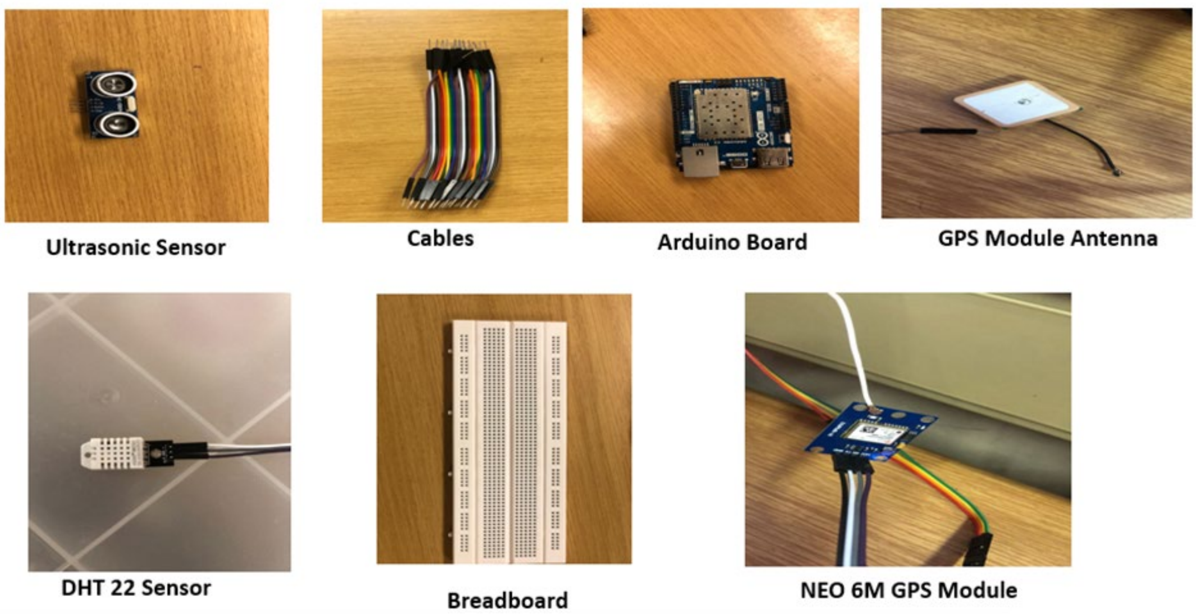

Figure 7.1: *Components used for groundwater-level monitoring subsystem development*

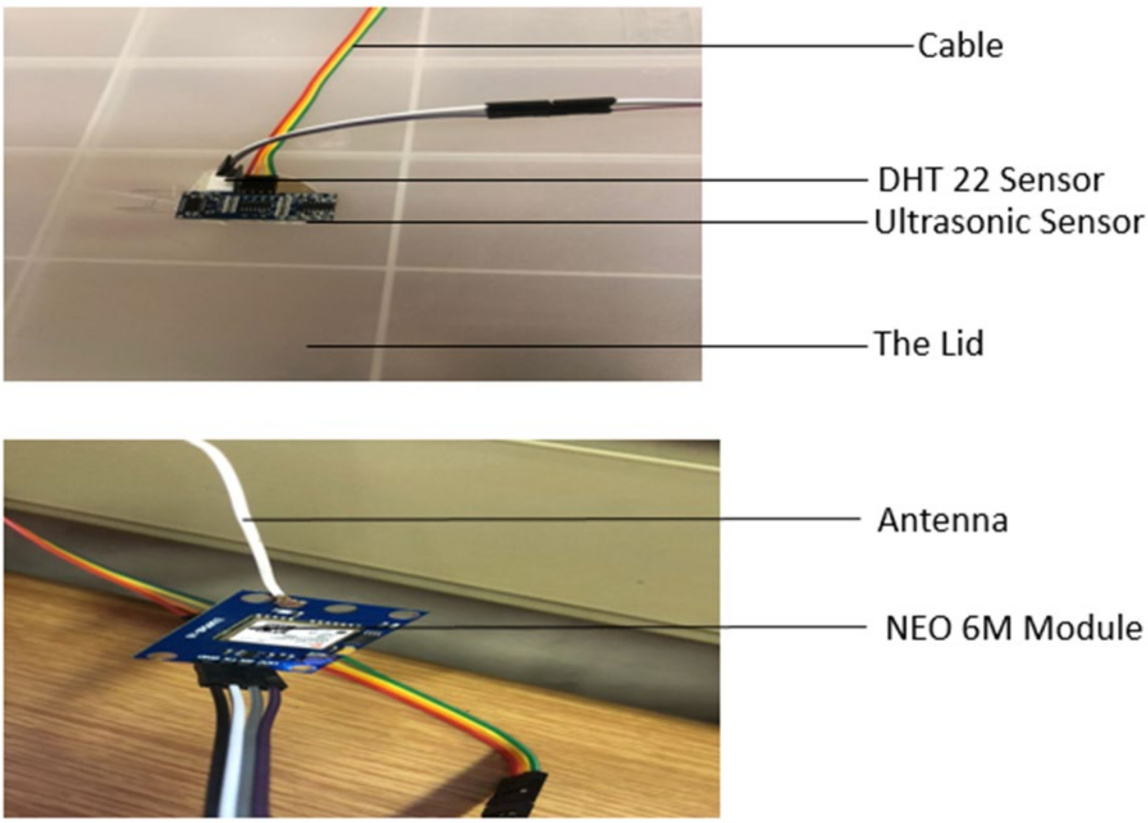

Figure 7.2: *Data acquisition unit for groundwater-level monitoring subsystem*

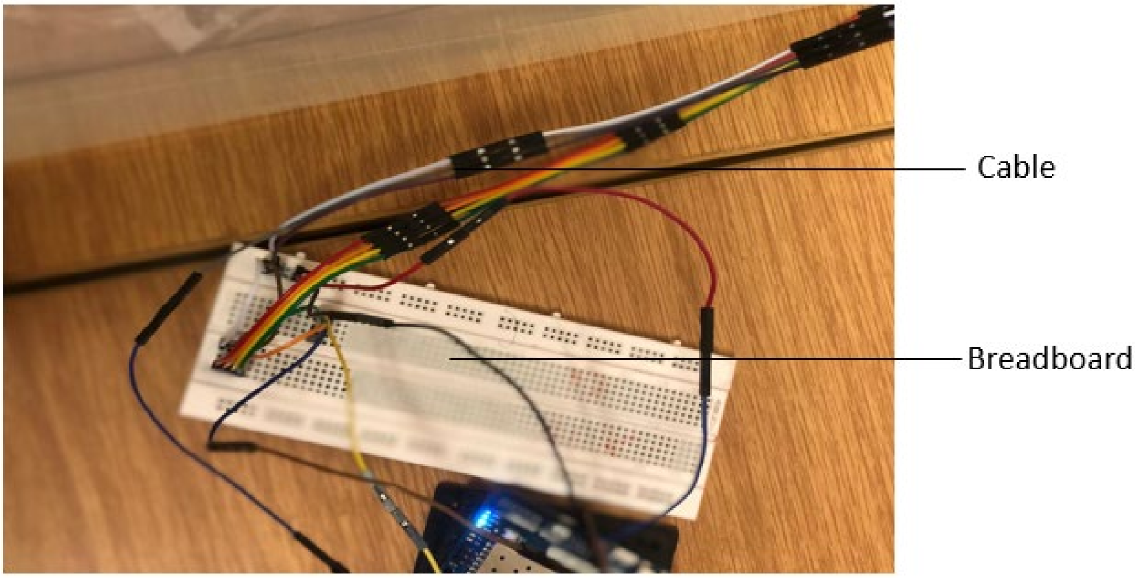

Figure 7.3: *Data communication unit for groundwater-level monitoring subsystem*

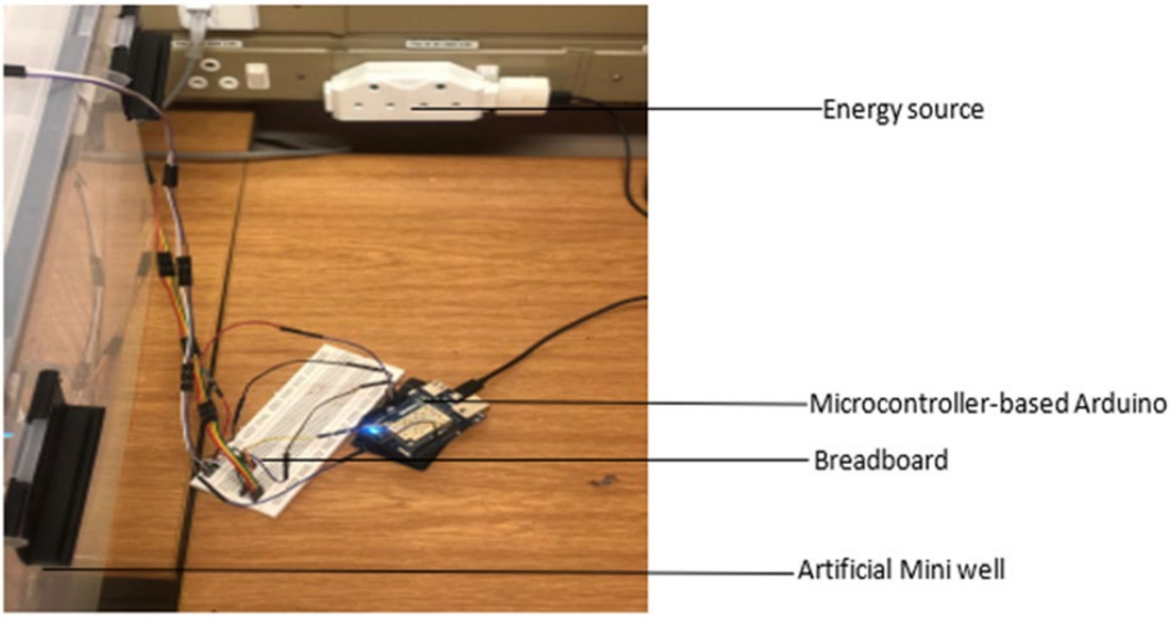

Figure 7.4: *Data capturing and processing unit for groundwater-level monitoring subsystem*

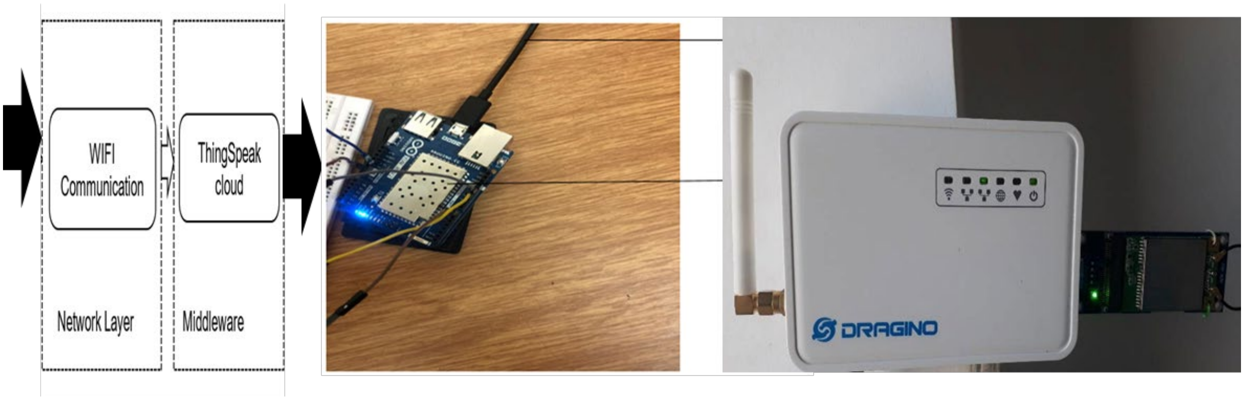

Figure 7.5: *Data processing unit for groundwater-level monitoring subsystem*

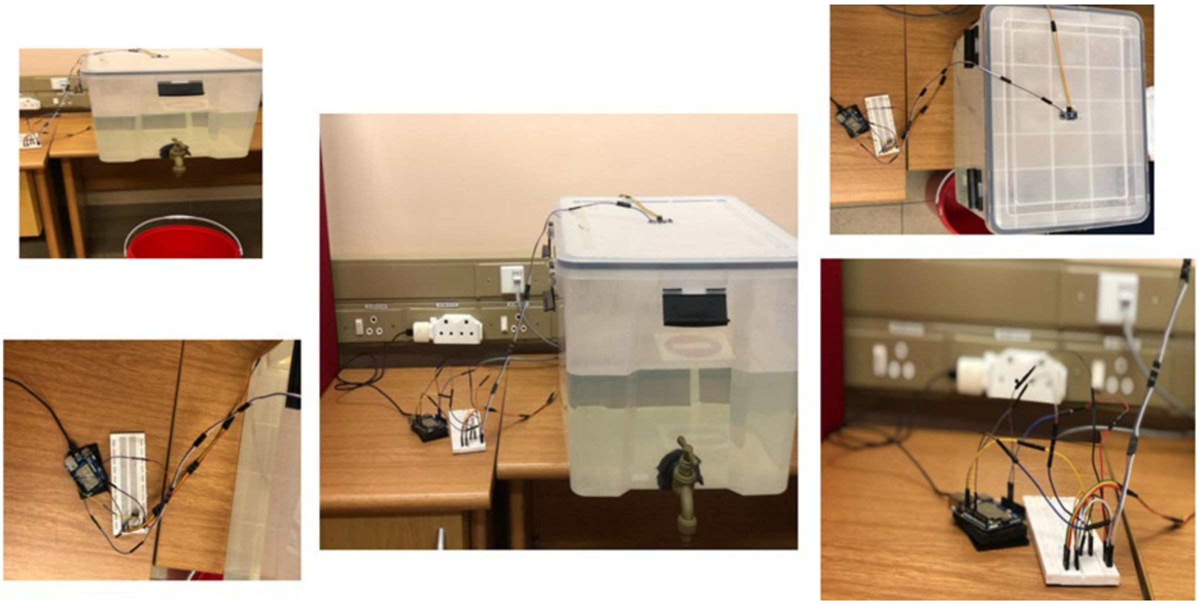

Figure 7.6: *The complete groundwater-level monitoring subsystem*

Table 7.1: *Overall costs of components used for groundwater-level monitoring subsystem*

Tools	**Prices (per unit)**
Arduino YUN	R895,00
Ultrasonic sensor	R29,00
DHT 22 sensors	R139.95
NEO-6M GPS module	R160,00
Jumper cable (50 pack)	R79,00
Solar panel 10W 18V	R395,00
Breadboard and jumper kit	R68.00
Total	**R1,765.95**

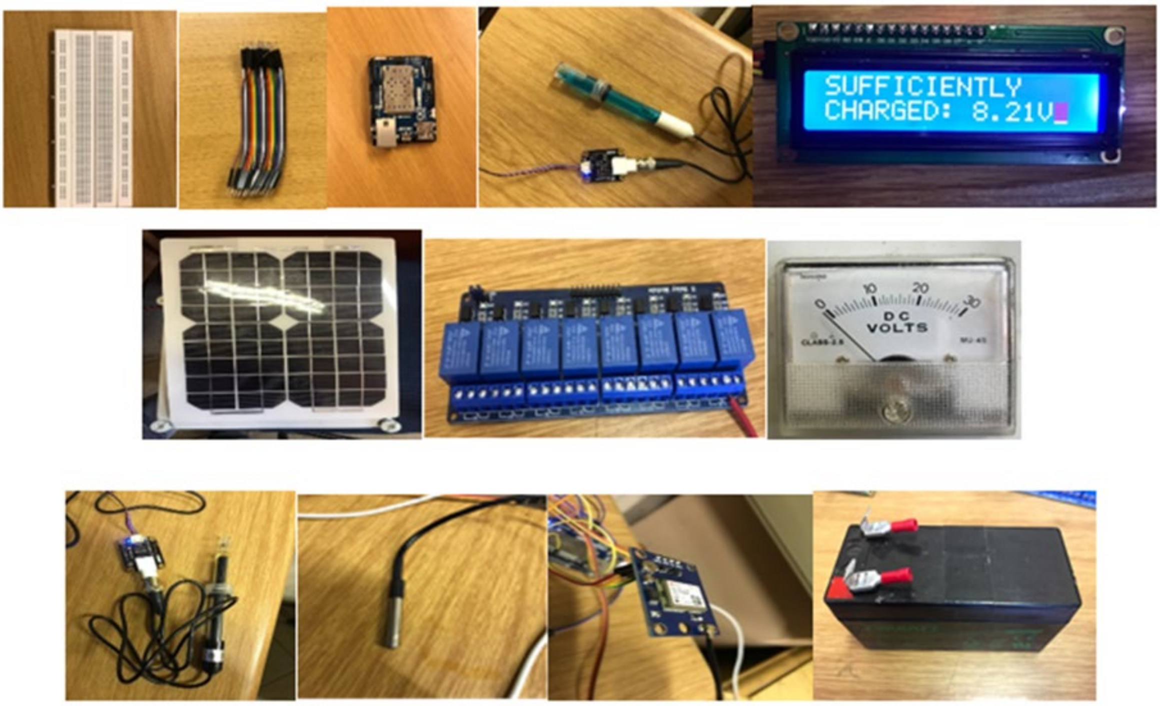

Figure 7.7: *Components used for groundwater quality subsystem development*

Figure 7.8: *Data acquisition unit for groundwater quality subsystem development*

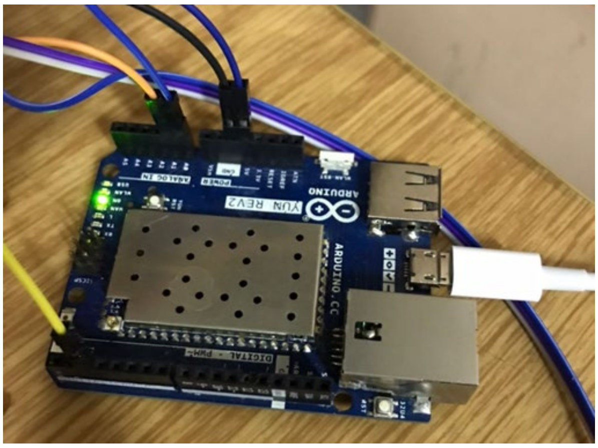

Figure 8.8 *Data transferring and processing unit for groundwater quality subsystem development*

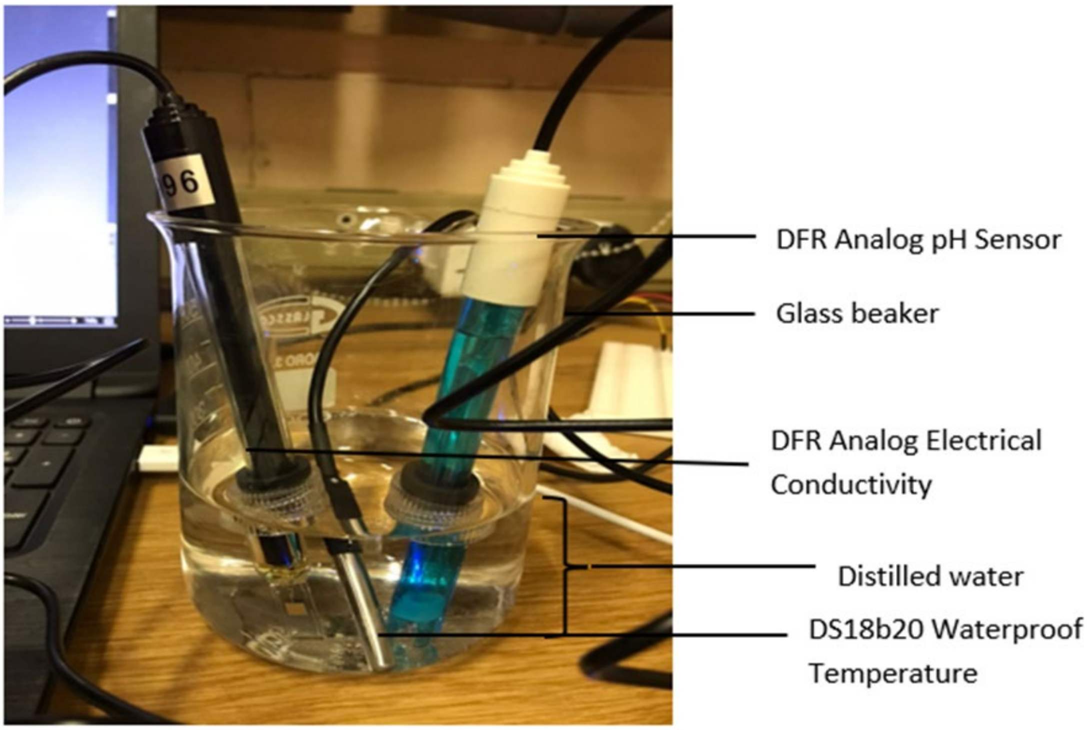

Figure 7.9: *Water quality sensors' calibration set-up*

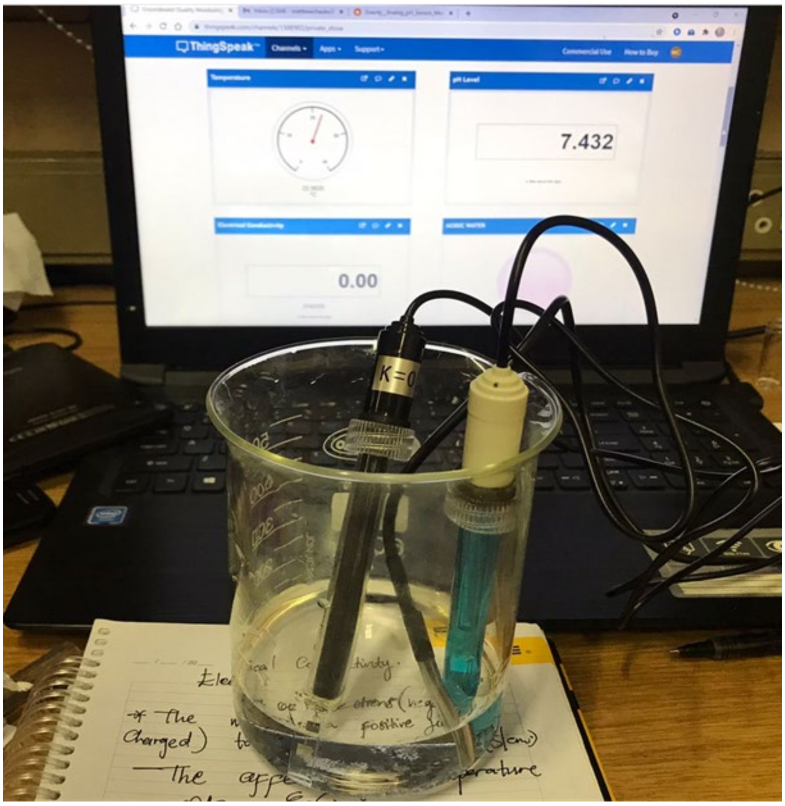

Figure 7.10: *The result of the water quality sensors' calibration set-up*

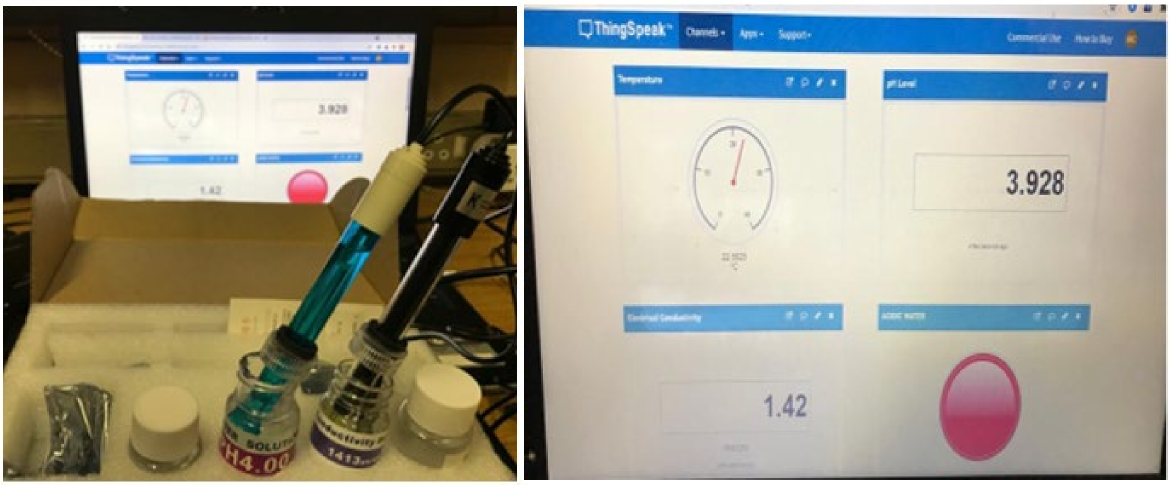

Figure 7.11: *Water quality sensors' calibration (pH = 4.00 and electrical conductivity = 1413uS/cm)*

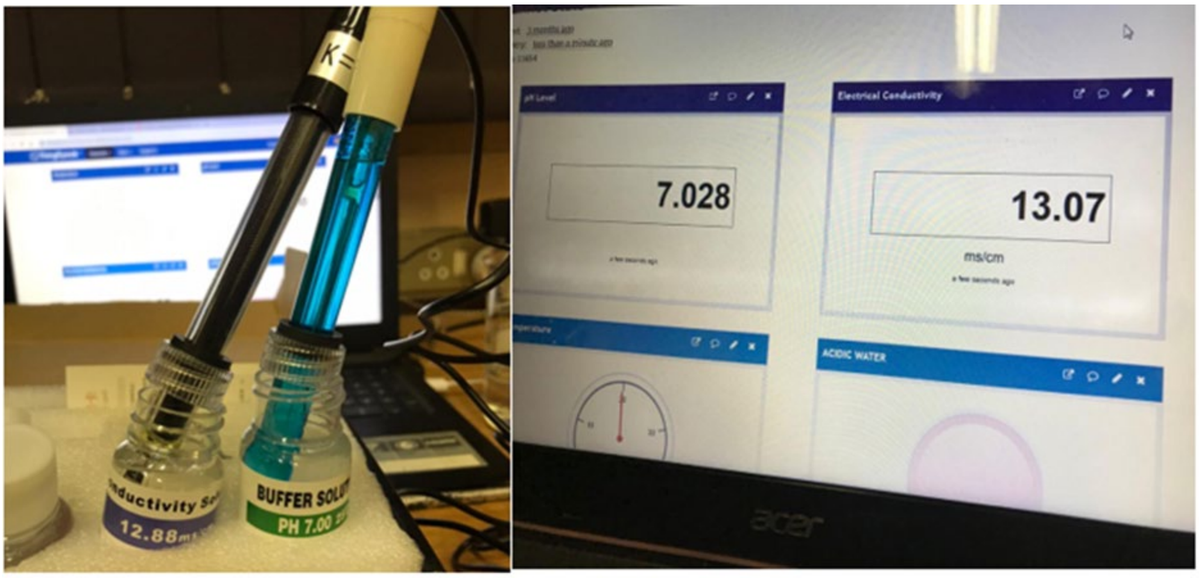

Figure 7.12: *Buffer solutions; (pH = 7.00 and electrical conductivity = 12.88 mS/cm)*

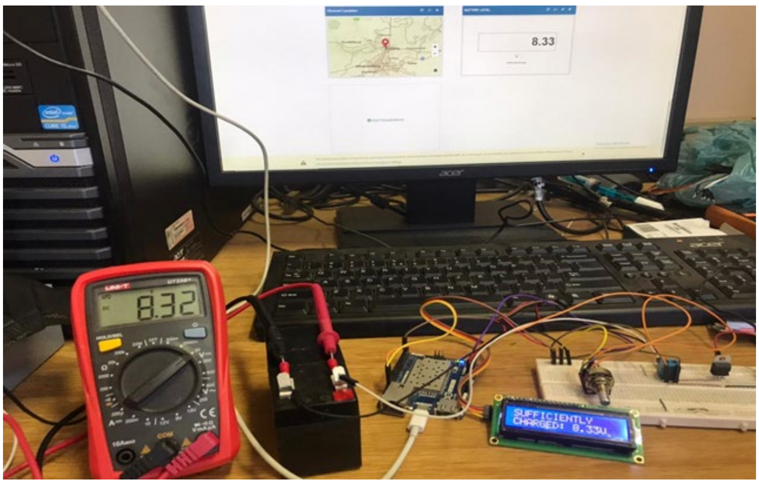

Figure 7.13: *Battery-level monitoring testing*

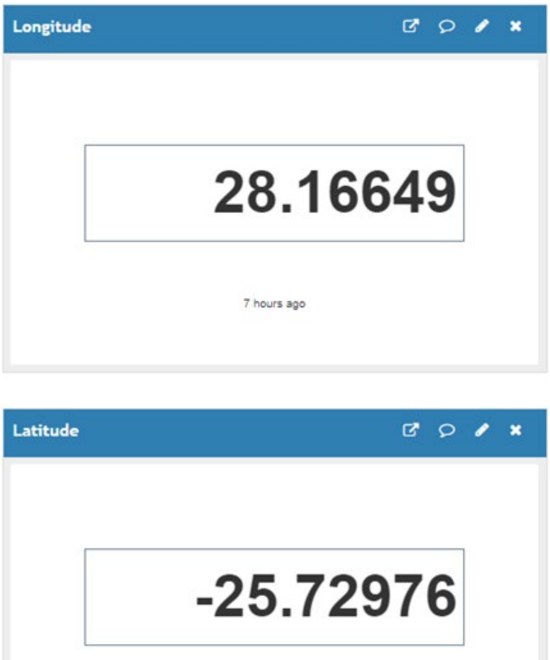

Figure 7.14: *GPS module testing*

Figure 7.15: *Nitrate concentration samples and HACH DR/890 colourimeter showing colour change, i.e. presence of nitrates*

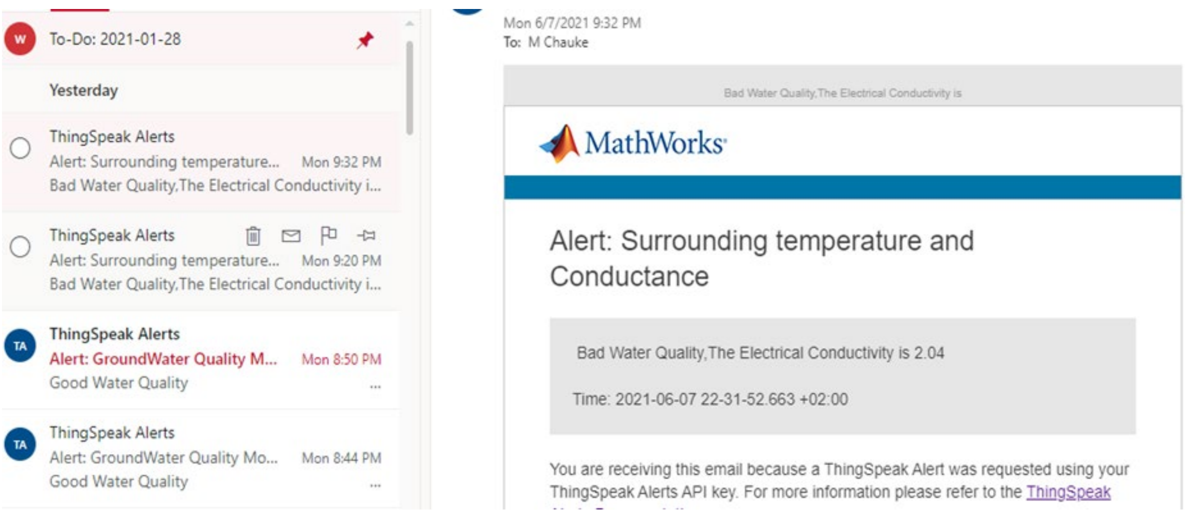

Figure 7.16: *Email notification testing*

Table 7.2: *Manganese detection from Pienaars Dam leisure resort boreholes*

MANGANESE DETECTION – PIENAARS DAM LEISURE RESORT BOREHOLES		
Name of sample	**Results**	**Comments (low range)**
Pienaarsdam Borehole 1A	0,003 mg/ℓ	Manganese levels are well below the levels for acute health or aesthetic levels. Samples had an amber colour.
	0,003 mg/ℓ	
Pienaarsdam Borehole 1B	0,006 mg/ℓ	Average 0,005 mg/ℓ
	0,004 mg/ℓ	

Sample(100ml)	pH Level	Electrical conductivity (mS/cm)
E.Coli (1)	11,229	8,56
E.Coli (2)	10,743	8,99

Figure 7.17: E. coli *testing set-up and testing*

***Table 7.3** Nitrate's results for pH level and electrical conductivity*

Nitrate concentration(mg/ℓ)	pH level	Electrical conductivity(mS/cm)
8.3	9.743	0.13
9.7	9.600	0.13
12.1	9.457	0.13
13.1	8.771	0.13
13.9	8.629	0.21
17.3	8.571	0.21
27.5	8.543	0.21
Second tests		
Nitrate concentration(mg/ℓ) At	**pH level**	**Electrical conductivity(mS/cm)**
± 1 mg/ℓ (10 ml of stock 2 into 100 mℓ nitrate) **22.7** ℃	6.52	0.14
±10 mg/ℓ (1 mℓ in 100 ml nitrate) **23** ℃	7.89	0.07
±12 mg/ℓ (2 mℓ in 90 mℓ nitrate) **23.1** ℃	8.11	0.27

***Table 7.4:** Manganese concentration electrical conductivity and pH results*

Manganese Concentration	EC Measurement (mS/cm)	pH Level
Low Range: 0.8 mg/l High Range: 5.0 mg/l (Borehole 1A)	0.18	9.110
2.3 mg/l (Borehole 1B)	0.26	9.31
5.6 mg/l (Distilled Water)	0.22	10,363

Concentrations with No Readings from a Colorimeter	EC Measurement (mS/cm)	pH Level
10 g (Borehole 1A)	0.26	12.242
1 g (Borehole 1A)	0.40	12.011
0,5 g (Borehole 1B)	0.35	11,220

Table 7.5: *Manganese standard for AAS reading*

Manganese concentration	**Electrical conductivity readings (mS/cm)**	**pH level readings**
$1001\ \mathrm{mg}/\ell \pm 6\ \mathrm{mg}/\ell$ Manganese standard for AAS (22.9 ℃)	1.92	2.11 

Figure 7.18: *Battery level results*

Table 7.6: *Overall costs of components used for groundwater quality monitoring subsystem*

Tools	**Prices (per unit)**
Arduino YUN	R1,032.41
DFR analogue pH sensor	R739.00
DFR analogue electrical conductivity sensor	R1,213.00
NEO-6M GPS module	R160.00
Jumper cable	R63.00
12 V battery	R191.60
Eight-channel relay module	R115.00
LCD	R65.00
Total	**R3,579.01**

APPENDIX 2: PROPOSALS FOR ARCHIVING DATA GENERATED DURING THE PROJECT

The project team proposes that the data generated during the project will be archived by the Tshwane University of Technology (TUT) and Water Research Commission. The data will include this Phase 1 project report and the progress reports for referencing. The developed prototype so far will be archived at TUT for further research development and pilot testing outside the laboratory environment when the project enters the next phase.

APPENDIX 3: LIST OF PUBLICATIONS AND OTHER TECHNOLOGY TRANSFER ACTIONS

List of publications

ADEREMI BA, OLWAL TO, NDAMBUKI JM and RWANGA SS (2021) Groundwater level resources management modelling: A review. Preprints **2021** 2021070227. https://www.preprints.org/manuscript/202107.0227/v1

List of technology transfer action

The project leadership is in the process of applying for Intellectual Property (IP) protection with the Directorate of Research and Innovation at TUT.

The project team is currently engaged with the rural communities through the Steve Tshwete Local Municipality in Nkangala District as part of science engagement and societal impact.

APPENDIX 4: CAPACITY BUILDING

Four postgraduate students were involved in this project. Two of the students are master's students and two are doctoral students. The involvement of the students is outlined below

- **Chauke Matthews** is a master's student enrolled in a Master of Engineering (MEng) in Electrical Engineering degree since 2020. The title of his research study is "A Geography of Things (GoT)-based scheme for real-time monitoring of groundwater quality". The research study was carried out in collaboration with the Water Research Commission project. The overall objective of this project was to develop a system for acquiring, transferring, analysing and displaying real-time information to manage groundwater level and quality resources from a geographically distributed network of wells. The student was responsible for the design and development of a low-cost, portable, real-time sensor prototype subsystem for monitoring groundwater quality in a laboratory setting. The subsystem was developed and tested in the laboratory using water samples with various impurities. The pH value and the electrical conductivity of these impurities were measured with the developed sensor subsystem. The data on the mentioned water quality parameters was transferred and displayed on the cloud-based IoT analytics platform. The system was then merged with the water level subsystem to achieve the overall goal of this project.

- **Singh Nirisha** is a master's student enrolled in a Master of Health Sciences in Environmental Health (MHealthSci – Environmental Health) degree since 2020. She is working on a Water Research Commission project titled "Detection of underground water quality through real-time remote monitoring within two boreholes in rural communities in the Steve Tshwete Local Municipality, Nkangala District jurisdiction". The student's role in the project is to assess the use of a real-time groundwater quality monitoring prototype used for the detection of underground water quality. This is to be achieved by the following objectives: (a) Simulate water in the laboratory with *E. coli*, nitrates and manganese (Mn) to be used for testing the prototype system by the electrical engineering student; (b) Test if the prototype system developed for remote sensing can detect the water quality parameters that include *E. coli*, manganese and nitrate at two rural communities in Mpumalanga within the Steve Tshwete municipal jurisdiction. This will be done by checking results in the laboratory. Currently, the first objective has been achieved, whereas the second objective is still pending field testing in Mpumalanga.

- **Aderemi Banjo** has been enrolled for his Doctorate in Engineering (DEng) in Electrical Engineering since October 2019. The title of his research study is "Computational efficient and scalable groundwater level management using Edge computing Internet of Things". He is involved with the design and development of the level subsystem of the prototype, as well as the general coordination of this project from the student's side. The design and development of this prototype was the first objective. He is currently working on gathering the groundwater historical data around the Gauteng and North West dolomite aquifer within the Steenkoppies compartment for modelling and training his model. This will be used for the second objective of his study, i.e. the groundwater level prediction. He has submitted a paper for journal publication.

- **Tladi Tsholofelo** is enrolled for a Doctorate in Engineering (DEng) in Civil Engineering. Her research study is titled "Real-time groundwater level management using integrated GIS and wireless sensor technology". The main aim of her study is to develop a real-time groundwater level management system using GIS-based wireless technology, which will support proactive decision making in cases of hydrological extremes. The study will entail the development of a decision support system, testing it in the laboratory environment and finally testing it in the field. The decision support system that will be developed in this study is centred around rainfall and lag time as a trigger to the system. She is currently in the data collection/analysis phase (for field characterisation) and is planning for the laboratory set-up. The water level sensor developed in this project will be used in her study to acquire groundwater levels that will be used in the decision support system. The student's involvement in the development of the sensor prototype was the preparation of the testing set-up and analysis of the results obtained from conducting performance evaluations for the water level sensor.