Development and Implementation of the Geography of Things-based Real-Time Groundwater Remote Sensing and Telemetry at Nkangala District Municipality, Mpumalanga

Final Report

to the Water Research Commission

by

Prof JM Ndambuki, Prof TO Olwal, Prof LS Mudau, Dr BA Aderemi, Ms TM Tladi, Ms M Masilela, Ms N Singh and Mr M Chauke
Tswane University of Technology

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EXECUTIVE SUMMARY

Rationale

The effective management of groundwater resources in dry and semi-dry regions of South Africa is of utmost importance for providing water to the country's inhabitants. However, the current manual collection of groundwater level and quality data is outdated, time-consuming, inadequate, and unreliable. Real-time groundwater level and quality data are becoming increasingly critical in far-flung remote areas. This constitutes frequent and timely data to effectively allocate groundwater resources and to prevent waterborne diseases among the inhabitants. Therefore, the availability of real-time data enables water resource managers to make informed decisions on resource allocations. This, in turn, fosters an efficient and sustainable usage of groundwater resources while improving the quality of life for the people in these regions. By developing an appropriate IoT-based real-time monitoring incorporating a Global Position System (GPS) enabled system dubbed as a Geography of Things (GoTs)-based remote sensing and telemetry to provide the needed data, an effective monitoring and management of groundwater resources in far-flung remote regions can be achieved.

Objectives

The main objective of this project was to develop and implement a real-time groundwater remote sensing and telemetry system based on the Geography of Things (GoTs) in the Nkangala District Municipality, Mpumalanga.

The main objective was divided into four (4) objectives, namely to:

1. Review literature on existing ultrasonic sensors range extension techniques for real-world wells' level monitoring, as well as biological and chemical groundwater quality monitoring techniques.
2. Develop and implement an extended range ultrasonic sensor solution as well as biological and chemical *in situ* groundwater level and quality, respectively monitoring solutions, both within the laboratory and at the selected in situ municipality wells.
3. Develop a groundwater biological quality monitoring solution for undertaking tests within the laboratory and at the selected *in situ* municipality wells.

4. Build community science engagements with communities from Nkangala District municipality through capacity-building initiatives and subsequent handing over of the project.

Aligned to the above objectives the following deliverables were submitted:

- Deliverable 1: Report on Review of literature on existing ultrasonic sensing range extension techniques. This deliverable consisted of a comprehensive report regarding the techniques in the literature for extending the range of ultrasonic sensors.
- Deliverable 2: Report on the Development of a range-enhanced remote ultrasonic sensor prototype. This deliverable consisted of the developed range-extended ultrasonic sensor prototype with associated technical drawings and lab validation results.
- Deliverable 3: Report on the development of a biological and chemical groundwater quality monitoring solution. This deliverable includes a report on the developed sensor prototype, complete with technical drawings that serve as proof of concept for remote bio-chemical sensing of contaminants. The bio-chemical contaminants for this monitoring system are *E. coli,* nitrate, fluoride and sulphates.
- Deliverable 4: Report on the field tests and associated potential risks. This deliverable consists of an integrated groundwater level monitoring system and the bio-chemical monitoring system, remote sensing and telemetry, methodologies of field testing *in situ*, field results, and associated field-testing risks.
- Deliverable 5: Report on community science engagements with the target municipality(s). This deliverable consists of skills development reporting for the communities and the science engagements, which will eventually lead to handing over the operations of the finished project to the target community(s).

Methodology

To achieve the main objective, the following method was followed:

- A comprehensive literature review was carried out to ascertain the pros and cons of existing ultrasonic sensors' range extension techniques and to determine novel approaches to improve their suitability for shallow well monitoring applications.
- The second stage involved designing the prototype in a virtual environment. A new circuit was designed using electronic components, transducers, and IoT-enabled devices to extend the existing level range, while monitoring the groundwater level. The resulting circuitry was tested for performance using Proteus software. This was necessary to determine the correct components needed to implement the monitoring system and their values.
- The simulation-based design was followed by the physical system development and implementation. This included building, construction, and overall integration of the subsystems.
- An extensive performance evaluation was carried out within the laboratory environment before the constructed system was taken out for robust field testing.
- Community science engagement was carried out. This involved an initial strategic information session with municipal management, followed by training of the end users of the technology regarding the use of the technology for groundwater level and quality monitoring.

Results

The results of comprehensive performance evaluation and field tests showed that the proposed technology can measure groundwater levels and indicate the potential presence of biochemical contaminants such as *E. coli*, fluoride, nitrate, and sulphate in real-time, efficiently, adequately and reliably. As far as groundwater level measurements are concerned, the prototype could measure up to 16 metres of groundwater level compared to the initial 4 metres.

Short summary results (Key findings)

This project developed a real-time remote sensing system to monitor groundwater levels and indicate the potential presence of quality parameters, including *E. coli*, fluoride, sulphate, and nitrate. In contrast to traditional monitoring systems, this system monitors:

- Groundwater levels are monitored with contactless sensors to prevent rusting noticed in conventional contact measuring instruments. Chemical pollutants in groundwater, including fluoride, sulphates, and nitrate, can be detected more rapidly in real-time than through traditional laboratory methods. Additionally, advancements have been made in measuring the potential presence of biological parameters like *E. coli.*
- Additionally, the system features a geolocation sensor that identifies the locations of the monitored groundwater levels, chemical parameters, and biological parameters above.
- Finally, a community engagement framework that supports the training of the stakeholders was also developed.

The new knowledge created will support real-time groundwater monitoring. Prompt and timely detection will guarantee safe water consumption and oversee water usage.

- The community engagement model fosters an ideal synergy between the host community and the management of water resources.
- This project produced a groundwater monitoring system (a prototype) and a community engagement model.
- We designed, developed, and implemented the prototype in the laboratory. At the time of writing, this product was being tested in the field of study. Our product is unique in detecting the potential presence of those chemical and biological contaminants mentioned above and monitoring groundwater levels.
- The users and beneficiaries of this product are water managers and communities at large.
- During our community engagement with the Nkangala district municipality, they expressed readiness to adopt this technology.

Benefits of the system

The proposed real-time groundwater remote sensing and telemetry system offers a range of benefits, including the ability to monitor groundwater levels in real-time, identify potential issues such as contamination or depletion, and provide early warning regarding potential problems. The system would also provide valuable data to stakeholders and decision-makers, enabling them to make informed choices about water use and management in a real-world application. Comprehensive benefits of the system can be outlined below:

- Continuous monitoring and detection of every fluctuation.
- Biochemical contamination early detection.
- Climate change adaptation through early warning.
- Reduced labour hours through remote monitoring.
- Sustainable water supply.
- Reduced pumping costs.
- As compared to existing monitoring systems in the market, this prototype has the following innovations, to the best of our knowledge.
- As demonstrated, this system can monitor the level and some biochemical parameters of groundwater in near real-time or real-time.
- This system is equipped with a geography of things (GoTs) and can thus show its location by providing the location's longitude and latitude coordinates.
- This system is equipped with a battery monitoring system.
- Remote and easy access to groundwater data in the cloud.
- Using an IoT analytical platform to monitor the quantity and quality of groundwater remotely also provides convenient and user-friendly ways of monitoring groundwater, making the process easier for you.

Conclusions

The goal of creating a groundwater monitoring system in a laboratory setting has largely been met. Additionally, the system has undergone field testing. The system uses a contactless ultrasonic sensor to monitor groundwater level at a depth of 16 metres from the ground surface level, which is beneficial for both local and regional insights into groundwater behaviour. The data collected through this monitoring can also support research, planning, and informed decision-making. Furthermore, empowering the community (EHPs, water and sanitation technicians, and IT officials) and developing a community engagement model will assist in creating a holistic approach to groundwater monitoring that can significantly improve public health outcomes and compliance within the District Municipality.

Overall, the project achieved the main objective of developing and implementing a real-time groundwater remote sensing and telemetry system based on the Geography of Things in the Nkangala District Municipality, located in the province of Mpumalanga.

However, the primary challenge in developing and implementing the monitoring system was sourcing components locally. The necessary sensors were frequently unavailable, forcing the project team to endure prolonged waiting times before the acquisition of required sensors.

Future developments and recommendations

This developed monitoring system is a work in progress; thus, future development will include:

- Monitoring of additional water quality parameters should be explored.
- Exploring utilisation of other non-contact sensor technologies other than ultrasonic sensors, such as radar for groundwater level measurement.

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LIST OF ABBREVIATIONS

ATC	Automatic Temperature Compensation
DDM	District Development Model
DNRA	Dissimilatory Nitrate Reduction to Ammonium
DO	Dissolved Oxygen
E. coli	Escherichia coli
EC	Electrical Conductivity
EHP	Environmental Health Practitioner
GIS	Geographic Information Systems
GWL	Groundwater Level
IoT	Internet of Things
IT	Information Technology
LCSN	Low-Cost Sensor Networks
MHS	Municipal Health Services
NDM	Nkangala District Municipality
NGO	Non-Governmental Organization
NTU	Nephelometric Turbidity Units
ORP	Oxidation Reduction Potential
pH	Potential of Hydrogen
SANS	South African National Standards
TUT	Tshwane University of Technology
UN	United Nations
WHO	World Health Organization
WSN	Wireless Sensor Networks

1 INTRODUCTION

1.1 Background

According to a report by the United Nations, access to freshwater is becoming increasingly scarce, and by 2050, at least one in four people is likely to live in a country affected by chronic or recurring shortages (Shah et al., 2016). The report highlights several global water scarcity facts and figures, revealing the alarming scale of the problem. Over 40% of the world's population is already affected by water scarcity, which is projected to increase. More than 1.7 billion people live in river basins where water use exceeds recharge, leading to groundwater depletion. The lack of essential sanitation services, such as toilets or latrines, is a significant challenge for 2.4 billion people. More than 80% of wastewater from human activities is discharged into rivers or seas without any pollution removal, resulting in an enormous pollution burden on water bodies and marine life. Moreover, preventable water and sanitation-related diarrhoeal diseases cause the death of nearly 1,000 children every day, highlighting the critical importance of clean water and sanitation; which requires real-time water quality monitoring for early detection of any contaminants in water before it reaches the communities On the other hand, hydropower is the most important and widely used renewable energy source, accounting for 16% of total electricity production worldwide as of 2011. Nevertheless, the overuse of water resources for irrigation, which accounts for approximately 70% of all water abstracted from rivers, lakes, and aquifers, poses a significant threat to the availability of freshwater resources. Water-related disasters, such as floods, are a significant cause of natural disasters, accounting for 70% of deaths. This emphasises the need for effective water management policies, practices, and infrastructure to ensure access to clean, safe, and sufficient water for all.

The availability of surface water is rapidly decreasing, which has made it challenging to manage groundwater effectively. To establish an effective groundwater management system, it is crucial to implement groundwater monitoring (Verma and Singh, 2013; Singh, 2014). Currently, most locations use hand-held tape to measure groundwater levels only once or twice a year (Anumalla et al.,2005). However, in a few hundred locations, groundwater levels are measured using pressure transducers and recorded hourly to daily (Anumalla et al.,2005). Despite the value of this data in understanding resource usage, it is not available frequently enough for water resource managers to make informed decisions, which can lead to the community and water managers being caught off guard. The lack of timely information can result in a lack of awareness regarding the sustainability of groundwater, which can impact planning and adaptability (Anumalla et al.,2005). As the world progresses towards development and urbanisation, it is becoming increasingly clear that the sustainability of water resources is under threat. The continued expansion of irrigation development, urbanisation, and public water supplies is causing the magnitude of future droughts to intensify. The alarming water consumption trends are a cause for concern as global water consumption increased by 6% between 1990 and 1995, twice the rate of population growth (Shalini et al., 2020). According to the Tearfund water report, by 2025, two-thirds of the world's population may experience water shortage (T.W. Report, 2002). Hence, developing an improved monitoring system to study water resource availability and usage has become crucial. This system must track water usage patterns, detect shortages and manage water resources. Only by taking such steps can we hope to ensure the sustainability of our water resources for future generations.

On the other hand, according to Singh et al. (2018), Water quality monitoring assists in evaluating the nature and extent of pollution control required for the effectiveness of pollution control measures. Despite traditional groundwater monitoring programmes, Important new technologies and practices are developing. Due to the general lack of *in situ* data, the new technologies can help extrapolate knowledge from regions with good data to areas with less information, giving an understanding of potential risks and vulnerabilities. In this regard, effective and efficient groundwater monitoring systems are required to keep up with the pace.

With the advancement of technology, ultrasonic sensors, in conjunction with Internet of Things (IoT) enabled devices, have been developed to monitor groundwater resources. There are various practical applications of ultrasonic sensors in the literature to measure the level of water in tanks, pipes and groundwater as well as to measure the levels of the waterbed in rivers or seas (Song et al., 2017; Wang et al., 2012; Kumar et al., 2008; Bandini et al., 2017). Over the years, ultrasonic sensors have proven to be more economical, contactless, and non-invasive solutions for liquids, foams and bulk solids level measurement (Lynnworth, 2013). Consequently, various ultrasonic sensors designed using certain design factors such as costs, level of accuracy, precision and operating range are available in the market (Rocchi, 2019).

Wireless sensor networks have grown in popularity since they offer potential benefits such as reduced logistics challenges, high costs, water quality data inconsistencies, and power consumption (Chauke et al., 2022). In contrast, municipal water quality monitoring and surveillance which is still using traditional monitoring procedures that have been proven to be ineffective, laborious, time-consuming, and lack real-time results to promote proactive responses to water contamination (Pule et al., 2017). Thus, WSN offers continuous monitoring of the quality of water, which is helpful in determining rapid changes in the water for quick reactions.

On the other hand, ultrasonic sensors have been applied to various water-level sensing and monitoring processes. A low-cost IoT-based real-time groundwater level monitoring network was built to monitor 11 groundwater sites in Nova Scotia, Canada (Drage and Kennedy, 2020). A customised ultrasonic sensor-based monitoring system was designed and implemented to measure the groundwater level alongside an IoT-enabled technology to transmit the data in real-time operation to keep the costs low. Also, an ultrasonic sensor-based monitoring system was designed and implemented to measure water depth across overhead tanks and groundwater reservoirs by Kumar et al. (2015). The authors used sub-GHz radios to connect the gateway that can upload the data online for visualisation and analytics, as well as the range extension of the ultrasonic sensor to about 10 m using the Extended Butterworth-Van Dyke Model. In another related work, a real-time water balance monitoring system using an ultrasonic level sensor was proposed by Kudva et al. (2015). The design and the implementation of the real-time monitoring system by Kudva et al. (2015) consist of an ultrasound level sensor, a 16-bit microcontroller, and a sub-gigahertz radio to set up a hub and spoke system. The real-time data from the sensors is pushed to a server on the cloud to log and perform analytics. The device's industrial design allows for flexible mounting on various tanks. However, the initial contactless sensing range of this monitoring system was limited to 4 m, which has now been improved in this project to 16 m. The original range was unrealistic considering typical depths of monitoring shallow wells, ranging from at least 10 m. Furthermore, a Rapid Adaptive Needs Assessment (RANA) kit for monitoring water quantity was developed for military purposes in disaster-hit locations by Angello et al. (2012). Their design has been optimised for short-duration deployments (about 3 days) for places that don’t have adequate cellular coverage. A monitoring system to acquire information from the flood based on IoT technology was designed by Satria et al. (2018). The prototype design used an ultrasonic sensor and rain sensor to acquire the water and rain levels, while this data was processed using an Arduino microcontroller. Thus, the system could provide flood altitude and rainy weather information in real-time using an Ethernet module as a web server integrated with a wireless router as a gateway path to the user. However, the system could only access one flood detector or one flooded location. Also, an ultrasonic-based monitoring system was developed by Dewi et al. (2017) using web-based output and GSM-based disaster, including a prototype fire monitoring information system building GSM Module. This prototype was used for disaster communication and information purposes. Stoianov et al. (2007) developed Pipenet to collect data into a cluster head from various regions of the pipe network using the network of sensors. The data measured was used to analyse pipe bursts and signal leakages (Stoianov et al., 2007).

A study of the resonance characteristics of low-frequency ultrasonic transducers is presented in this work by Papageorgiou and Laopoulos (2003). The effect of the influence of the equivalent output resistance of the driving circuits on the shape of the frequency response and the sensitivity of the transducer was investigated. As highlighted in their study, this method is useful in determining the ultrasonic sensor's frequency. However, this method does not work when two resonant peaks are very close to each other because, in that case, the series resonant frequency of the second peak would be ambiguous (Kudva et al., 2015; Angello et al.,2015). Rocchi et al. designed and implemented a non-contact ultrasonic sensor system capable of measuring the water level in the marine environment. (Rocchi, 2019). This system is part of a low-cost device developed to detect water pollution by non-conductive liquids (i.e., hydrocarbons floating in the sea), exploiting the different conductivities of fluids involved. While equipment and techniques currently used for monitoring marine water pollution are costly, this report focuses on the characterisation of a low-cost SRF05 ultrasonic sensor and its implementation inside a floating organ, because of data obtained from laboratory tests. Moreover, changes in climatic conditions, such as temperature and humidity, were monitored in a climatic chamber, aiming to establish the best operating range in terms of sensor resolution and the architecture of a buoy.

However, the sensor showed signal anomalies at regular distance intervals due to anticipated flight times. This led to the adoption of a sensor system consisting of a combination of more SRF05 sensors to optimise the measurement system. In addition, it presents an analytical method based on ultrasonic signal reconstruction to improve the accuracy of the measurement method. The final device is managed to have a sensibility of about 1 mm.

Furthermore, the major limitation of most of these ultrasonic-based monitoring systems is the depth they can measure. Hence, most are normally deployed to a shallow well or to control floods. However, most groundwater monitoring wells are deep, so there is a need for a long-range ultrasonic-based groundwater monitoring system and real time water quality monitoring in communities The study conducted by Quinn and his colleagues (Quinn et al., 2022), on the applications of Geographic Information Systems (GIS) and remote sensing in public participation and stakeholder engagement for watershed management, indicates that although water sensors have been in use from the past decade, the full potential for stakeholder engagement through the utilization of GIS and remote sensing in the field of watershed management is still limited and poised for significant development.

1.2 Rationale of the project

Groundwater monitoring is a crucial aspect of water resource management, especially in areas where water is scarce. While several groundwater monitoring systems utilise ultrasonic sensors, their range is often limited. Typically, commercially available systems can only measure up to 6 metres. Unfortunately, this range is inadequate for deep-well monitoring purposes, which require sensors that can measure depths beyond 6 metres. The depth measurement obtained through ultrasound sensors can reach up to 16 metres, which is still classified as a shallow well, but the limited range that you can find for groundwater level using IoT. In addition, municipal water quality monitoring and surveillance is still generally using traditional monitoring procedures that have been proven to be ineffective, laborious, time-consuming, and lack real-time results to promote proactive responses to water contamination. Thus, WSN offers continuous monitoring of the quality of water, which is helpful in determining rapid changes in the water for quick intervention.

1.3 Project overall objectives

The objectives of this project are:

1.3.1 To review the literature on existing ultrasonic sensing range extension techniques.

1.3.2 To develop a range-enhanced remote ultrasonic sensor prototype.

1.3.3 To develop a biological and chemical groundwater quality monitoring solution

1.3.4 To conduct field tests and associated potential risks.

1.3.5 To conduct a community science engagement with the target municipality(s).

1.4 Project overall deliverables

Aligned to the above objectives are the following deliverables submitted:

- Deliverable 1: Report on Review of literature on existing ultrasonic sensing range extension techniques. This deliverable consisted of a comprehensive report regarding the techniques in the literature for extending the range of ultrasonic sensors.
- Deliverable 2: Report on the Development of a range-enhanced remote ultrasonic sensor prototype. This deliverable consisted of the developed range-extended ultrasonic sensor prototype with associated technical drawings and lab validation results.
- Deliverable 3: Report on the Development of a biological and chemical groundwater quality monitoring solution. This deliverable includes a report on the developed sensor prototype, complete with technical drawings that serve as proof of concept for remote sensing the potential presence of bio-chemical contaminants. The bio-chemical contaminants for this monitoring system are *E. coli,* nitrate, fluoride and sulphate.
- Deliverable 4: Report on the Field tests and associated potential risks. This deliverable consists of an integrated groundwater level monitoring system and the

biochemical monitoring system, remote sensing and telemetry, methodologies of field testing in situ, field results and associated field-testing risks.

- Deliverable 5: Report on community science engagements with the target municipality(s). This deliverable consists of skills development reporting for the communities and the science engagements, which will eventually lead to handing over the operations of the finished project to the target community (s).

2 DEVELOPMENT AND IMPLEMENTATION OF RANGE-ENHANCED ULTRASONIC SENSOR

2.1 Literature review on existing ultrasonic sensing range extension techniques

2.1.1 Introduction

In the recent past, the over-exploitation trend for groundwater level resources has precipitated the need to quantify the amount of groundwater level within the aquifer (T.W. Report, 2002). As one of the sources of clean drinking water, groundwater is an important resource and, as such, needs to be measured and monitored on a timely basis (Song et al., 2017). This enables constant determination of the status and trend of the quantity of groundwater stored within the aquifers. Several conventional methods constitute monitoring groundwater levels through data measurement of monitored wells using a flowmeter such as a vertical flowmeter (Wang et al., 2012). Data from monitored wells using vertical flowmeters is analysed further to provide qualitative and quantitative characteristics of the aquifer. However, often data points are sparse due to only a few wells, which are widely distributed from each other, being built owing to their high cost of construction. This implies little knowledge of spatial water flows (Song et al., 2017; Kumar et al., 2008) . Consequently, there is a need to explore innovative techniques for monitoring groundwater levels (GWL).

There are various types of flowmeters used in measuring groundwater levels based on their basic requirements, such as low cost, resistance to corrosion, low sensitivity to dirty particles, high accuracy and resistance to erosion (Khumar, 2020). These are classified as vortex, mechanical, magnetic, and ultrasonic flowmeters (Wang and Luo, 2012; Bandini et al., 2017; Lynnworth, 2013; Rocchi et al., 2019). With advantages such as low cost, user-friendliness, and insensitivity to ambient light, dust, or electromagnetic interference, ultrasonic-based flowmeters have become the fastest-growing technology within the field of instruments for monitoring and measurement of groundwater levels (Drage and Kennedy, 2020). The principal component constituting the ultrasonic-based flowmeters is known as the ultrasonic sensor.

An ultrasonic sensor is a transducer that can realise the mutual conversion between high-frequency mechanical energy and electrical energy (Rocchi, 2019). Generally, ultrasonic transducers can be classified into three categories, namely the magnetoelastic category, the piezoelectric category, and the capacitive category (Drage and Kennedy, 2020;Bandini, 2017). All these categories of ultrasonic sensors are utilised in the measurement fields such as flow monitoring systems, ultrasonic therapy, non-destructive testing, sonar, distance measurement, and medical imaging (Wang, 2012; Kumar, 2015). As a transducer, ultrasonic sensors have the following advantages: relatively low hardware requirements, high precision, low-cost, and non-contact distance measurement (Rocchi, 2019). These advantages make ultrasonic sensors useful for object shape recognition, derived two-dimensional positioning, multi-sensor fusion trajectory measurement, high-precision contactless level measurement, small range measurement, and three-dimensional positioning (Allevato et al., 2020; Carotenuto, 2020; Xia et al., 2019 Patkar, 2016; Fu et al., 2016). Hence, the ultrasonic sensor has applicability in groundwater-level monitoring systems. Furthermore, the most common HC-SR04 low-cost, contactless ultrasonic sensors' range is not more than 400 cm (Rocchi et al., 2019; Lynnworth, 2013;). This limitation in contactless range poses distance constraints when measuring the groundwater levels for realistic wells deeper than 4 metres from the ground surface. This shortfall necessitates the need to develop an extended range ultrasonic sensors using low-cost sensors available off-the-shelf.

2.1.2 Water level flow measurement systems (flowmeters)

In the literature, there are four types of water level flow measurement (flowmeters) used in groundwater monitoring systems. These include the Vortex flowmeters, which contain a sensor tab that can bend and flex from side to side as the vortex passes through and measure the vortices (Wang, 2012). A diagram of a vortex flowmeter is shown in Figure 1. In vortex flowmeters, the bend and flex action produce the corresponding frequency that is proportional to the volume of the flow. Campero and Vigil (1997) developed a Particle Image Velocimetry (PIV) based vortex flow measurement to use in Taylor-Couette flow pattern experiments. However, due to moving parts, vortex flowmeters experience a loss in signal flow during measurement, making them less accurate.

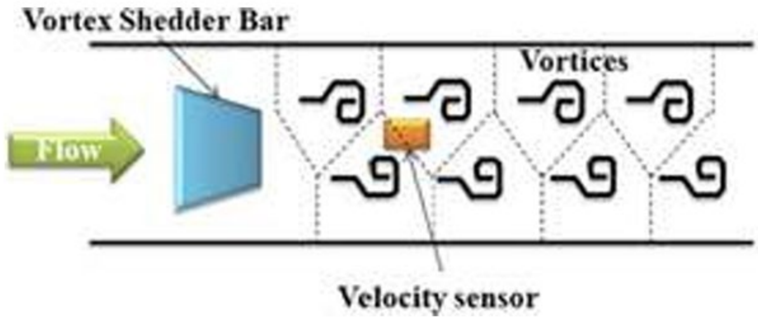


Figure 1: Vortex flowmeters

Secondly, there are mechanical flowmeters that contain rotational devices such as a paddle wheel and a propeller. In mechanical flowmeters, liquid flow causes the rotation of the inner paddle wheel, which, in turn, produces a flow rate that is directly proportional to the rotational speed of the paddle wheel. With these moving parts, the accuracy and lifetime of the mechanical flowmeters are less due to the moving parts (Kumar et al.,2020). An example of a mechanical flowmeter is shown in Figure 2.

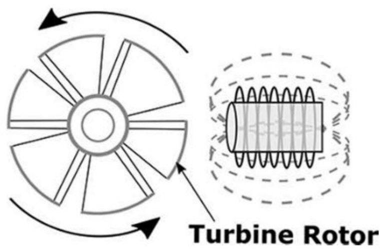


Figure 2: Mechanical flowmeter

Thirdly, there are magnetic flowmeters, which are volumetric meters with no moving parts. These magnetic flowmeters are water-based or conductive without any moving parts; hence, they are one of the best choices for water flow measurements. The working operation of these flowmeters is based on Faraday’s law. The measured voltage is a direct function of the average velocity of the liquid, the length of the conductor, or the distance between the electrodes, as well as the strength of the magnetic field. Although the magnetic flowmeter is simple to implement, it only works for conductive measurements (Wang, 2012). A diagram of a magnetic flowmeter is shown in Figure 3.

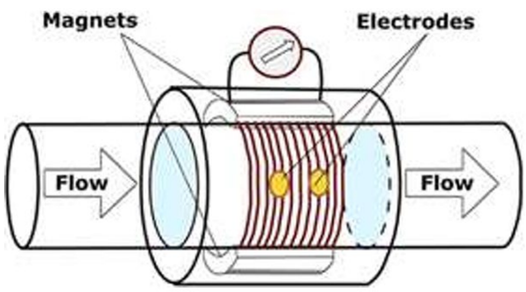


Figure 3: Magnetic flowmeter

Lastly, there are ultrasonic flowmeters that transmit ultrasonic signals downstream in the direction of the flow, while an echo signal is transmitted upstream to the receiver. In ultrasonic flowmeters, the differential time is used to evaluate the velocity of the liquid in the medium over the given distance (Wang, 2012; Drage and Kennedy, 2020). Hence, the calculated velocity over the distance is then used to evaluate the volumetric flow. Ultrasonic meters have many advantages over conventional meters; however, it is limited in range. Figure 4 presents a diagram of an ultrasonic flowmeter. Table 1 shows the summary of the characteristics of these measurement flowmeters, while Table 2 summarises the surveys related to measurement flowmeters and their applications. Based on Table 1, magnetic and ultrasonic measurement flowmeters have better performance characteristics than vortex and mechanical measurement flowmeters.

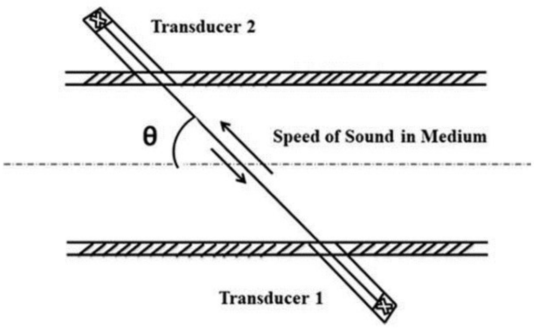


Figure 4: Ultrasonic flowmeter

Table 1: Summary of Water Level Measurement Flowmeters

Characteristics/Principle	Vortex	Mechanical	Magnetic	Ultrasonic
Measurements objects	Liquid and gas	Liquid and gas	Conducting Liquid	Liquid and gas
Moving parts	No	Yes	No	No
Range ability	1:50	1:20	1:100	1:20
Accuracy	More Accurate	Most Accurate	Most Accurate	More Accurate
Effect of non-uniform flow	No	Yes	Yes	No
Effect of solids	No	No	Yes	Yes
Effects of adhesion	No	No	Yes	Yes

Table 2: Summary of Some Applications of the Related Surveys on Flow Measurement Meters

Types of Flowmeters	Application	Merits	Demerits
Magnetic (Kumar et al.,2020; Yao et al., 2017; Yan et al., 2018; Ameran et al., 2016; Fan et al., 2016)	Multiphase flow monitoring system, Blood flow measurement, Two-phase liquid flow measurement and transit-time flow	These papers provide comprehensive modern technologies in the process of tomography, soft computing, palm oil flow monitoring system, metering, and clinical usage	They can only measure the liquid flow of conductive medium, and cannot measure the flow of non-conductive medium, such as gas and water, for better

	measurements, Eddy current flowmeter		heat treatment. Accuracy is only in the range of ± 1% over a flow rate range of 5%. The size and cost of the field coils and circuitry do not increase in proportion to their size of the pipe bore.
Vortex (Venugopal et al.,2011; Pankanin, 2005)	Particle Image Velocimetry (PIV)	These papers provide a few aspects of design and problems concerning the vortex flowmeter	Vortex flowmeters require turbulent flow to operate and will cease to read as the fluid transitions from the turbulent flow regime to the transitional or laminar flow regime. Vortex flowmeters may have a limited turn-down ratio. It cannot be used to measure pulsating flow because of the pressure pulsation, the measurement won't be accurate.
Mechanical (Wan, 2018; Kuthada, 2013;	Airflow measurement, Coriolis flowmeter, Capillary	Provided a consistent summary of available works for mechanical flow meters	They are costly. Maintenance is difficult. It is not suitable for small

McWilliams, 2002)	flowmeter, Doppler flowmeter		pipes or pipes that have a small diameter.
Ultrasonic (Wang et al., 2019; Peng et al., 2018; Rajita and Mandal, 2016)	Evaluation method for ultrasonic flowmeter	These presented important developments in transit-time ultrasonic flowmeters and custody, as well as an accurate analysis of measurement in the flow slurries	Ultrasonic flowmeters are not suitable for fluids that do not contain bubbles or suspended particles. Ultrasonic flowmeters are not suitable for fluids that contain high levels of gas. Ultrasonic flowmeters are not suitable for fluids that contain high levels of impurities.

2.1.3 Ultrasonic-based groundwater level monitoring system

There are various practical applications of ultrasonic sensors in the literature. Various devices have been developed to measure the level of water in tanks, pipes and groundwater as well as to measure the levels of the waterbed in rivers or seas (Song, et al., 2017; Wang and Luo, 2012; Kumar et al., 2008). There are many types of devices available for water level measurement, such as mechanical, capacitive as well as inductive systems, ultrasonic, acoustic and optical devices (Paczesny, 2015). However, over the years, ultrasonic sensors have proven to be more economical, contactless and non-invasive solutions for liquids, foams and bulk solids level measurement (Lynnworth, 2013). Consequently, various ultrasonic sensors are available in the market based on costs, level of accuracy, precision, as well as operating range (Rocchi, 2019).

Ultrasonic sensors have been applied to various water-level sensing and monitoring processes. A low-cost IoT-based real-time groundwater level monitoring network was built to monitor 11 groundwater sites in Nova Scotia, Canada (Drage and Kennedy, 2020). To make the costs low, a customised ultrasonic sensor-based monitoring system was designed and implemented to measure the groundwater level as well as IoT-enabled technology to transmit the data in real-time operation.

Also, an ultrasonic sensor-based monitoring system was designed and implemented to measure water depth across overhead tanks and groundwater reservoirs by Kumar et al. (2015). The authors used sub-GHz radios to connect the gateway that can upload the data online for visualisation and analytics as well as the range extension of the ultrasonic sensor to about 10 m using the Extended Butterworth-Van Dyke Model.

In another related work, a real-time water balance monitoring system using an ultrasonic level sensor was proposed by Kudva et al. (2015). The design and the implementation of the real-time monitoring system by Kudva et al., (2015) consist of an ultra-sound level sensor, a 16-bit microcontroller and a sub-gigahertz radio to set up a hub and spoke system. The real-time data from the sensors is pushed to a server on the cloud to log as well as perform analytics. The industrial design of the device allows for flexible mounting on a variety of tanks. However, the sensing range of this monitoring system is limited to 4 m. This makes it unsuitable for monitoring typical wells with a distance between the groundwater surface and the ground surface being more than 4 m.

Furthermore, a Rapid Adaptive Needs Assessment (RANA) kit for monitoring water quantity was developed for military purposes in disaster-hit locations by Angello et al. (2012). Their design has been optimized for short-duration deployments (about 3 days), for places that don’t have adequate cellular coverage. A monitoring system to acquire information from the flood based on IoT technology was designed by Satria et al. (2018). The prototype design used an ultrasonic sensor and rain sensor to acquire the water level as well as rain levels, while the processing of this data was carried out using an Arduino microcontroller. Thus, the system can provide flood altitude and rainy weather information in real-time using an Ethernet module as a web server integrated with a wireless N router as a gateway path to the user. However, the system can only access one flood detector or one flooded location.

Also, an ultrasonic-based monitoring system was developed by Dewi et al. (2017) using web-based output, and GSM-based disaster, including a prototype fire monitoring information system Building Based GSM Module. This prototype is used for disaster communication and information purposes. Stoianov et al. (2007) developed Pipenet to collect data into a cluster head from various regions of the pipe network using the network of sensors (Stoianov et al., 2007). The data measured is used to analyse pipe bursts and signal leaks.

A study of the resonance characteristics of low-frequency ultrasonic transducers is presented in this work by Papageorgiou and Laopoulos, (2003). The effect of the influence of the equivalent output resistance of the driving circuits on the shape of the frequency response and the sensitivity of the transducer was investigated. As highlighted in their study, this method is useful in determining the ultrasonic sensor's frequency, however, this method does not work when two resonant peaks are very close to each other, because, in that case, the series resonant frequency of the second peak would be ambiguous (Kumar, 2015; Kudva 2015).

The design and implementation of a non-contact ultrasonic sensor system capable of providing the water level in the marine environment was carried out by Rocchi. et al. (2019). This system is part of a very low-cost device developed to detect water pollution by non-conductive liquids (i.e., hydrocarbons floating in the sea), exploiting the different conductivities of fluids involved. While equipment and techniques currently used for monitoring marine water pollution are very expensive, this paper focuses on the characterization of a low-cost SRF05 ultrasonic sensor and its implementation inside a floating organ because of data obtained from laboratory tests. Moreover, changes in climatic conditions, such as temperature and humidity, were monitored in a climatic chamber, aiming to establish the best operating range in terms of sensor resolution and the architecture of a buoy. However, the sensor showed signal anomalies at regular distance intervals due to anticipated flight times, which led to the adoption of a sensor system consisting of a combination of more SRF05 sensors to optimize the measurement system. In addition, it presented an analytical method based on ultrasonic signal reconstruction with the aim of improving the accuracy of the measurement method. The final device managed to have a sensibility of about 1 mm the monitoring system, the weaker the echo produced. Consequently, this weak echo can be easily missed by the monitoring system.

2.1.4 Development of range-enhanced ultrasonic sensor

To increase the contactless range of ultrasonic sensors, higher signal energies need to be transmitted. Thus, the key requirement to achieve range extension of an ultrasonic sensor is to model this transducer using the Extended Butterworth-Van Dyke model (EBVDM). Using EBVDM, a typical HC-SR04 ultrasonic can be extended from 400 cm to 1000 cm (Qiu et al., 2022; Kumar et al., 2015). Furthermore, higher signal energies needed for transmission can be achieved by increasing the amplitude voltage of the excitation of the transmitter. Increasing the voltage may not provide an increase in signal strength; consequently, the number of pulses transmitted should be increased instead. Therefore, increasing the number of pulses would allow the corresponding base receiver to see a larger signal energy. Thus, the transducer characterisation would be obtained to increase the frequencies of the pair of ultrasonic sensors using resonant frequency equations. After obtaining the resonant frequencies, the next step is to transmit the frequencies at the maximum energy level; hence, range extension for an ultrasonic sensor would be achieved.

Technique I: The ultrasonic sensor range extension range can be modelled using Extended Butterworth-Van Dyke Model (EBVDM) (Kumar et al., 2015). However, these ultrasonic sensors are found to have multiple resonant frequencies, which is the reason EBVDM is chosen. Furthermore, each RLC branch represents one resonant frequency. To derive the values of components in the model, each ultrasonic sensor is characterised using an impedance analyser for frequencies between 1 kHz to 100 kHz at 800 points. At frequencies well above the resonant frequencies, R_S, L_S, and C_S have negligible influence on the impedance curve, and the impedance equals C_O. At the series resonant frequency, L_s and C_s cancel each other out, and the impedance equals the parallel combination of R_S and C_O.

Using (1-2), the needed resonant frequencies can be obtained, which must be between 40 kHz and 52 kHz for series resonance and parallel resonance, respectively. Hence, Figure 5 represents the equivalent circuit diagram to obtain series and parallel resonance, respectively.

Series resonance: $\omega_S = \frac{1}{\sqrt{L_s C_s}}$ (1)

Parallel resonance $\omega_P = \frac{1}{\sqrt{L_s C_{eq}}}$ where $C_{eq} = \frac{L_O C_S}{C_O + C_s}$ (2)

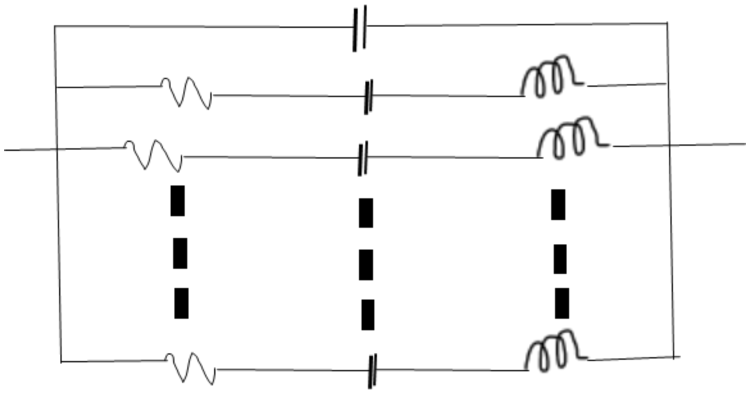


Figure 5: Equivalent circuit diagram for EBVDM

Consequently, to maximise energy efficiency, it is important to transmit at the resonant frequencies obtained using (1-2). In Figure 5, the impedance curve of the piezoelectric transducer shows two peaks and deals with only the electrical properties of the transducer. Some part of the electrical energy dissipated across the resistor gets converted to acoustic waves. Through simulations of the derived model suggested that power transmitted at the two resonant frequencies should be similar, which is practically observed using (3);

$$\frac{P_{TX}(52kHz)}{P_{TX}(40kHz)} \neq \frac{P_{RES}(52kHz)}{P_{RES}(40kHz)} \tag{3}$$

where P_{TX} is the power transmitted into the medium and P_{RES} is the power dissipated across the resistor. This indicates that there is a difference in the efficiency of electrical to mechanical energy conversion at different resonant frequencies due to mechanical loading.

To increase the range, higher signal energies need to be transmitted. This can be achieved by increasing the voltage amplitude of the excitation of the transmitter. However, increasing the voltage beyond a certain point does not provide a commensurate improvement in the received signal strength. Instead, the number of pulses transmitted should be increased so that the correlation-based receiver can see a larger signal energy. Increasing the energy level of the transmit pulse will increase the level of the echoes and thus their detectability. Using (4), the energy content of a pulse can be determined.

$$E = \rho\omega^2 A^2 t_p \quad (4)$$

where A is the amplitude, ω is the frequency, t_p is the duration and the density of the medium is ρ.

In this range extension design, a pair of ultrasonic transducers must be used; one at the transmitter circuit and another at the receiver circuit. The distance between the pulse transmitter and the wave-reflecting object is obtained by multiplying the Time-of-Flight (TOF) by the speed of sound and dividing by two. Figure 6 represents the equivalent circuit diagram for the transmitter circuit of EBVDM. In this transmitter circuit, a suitable driver circuit, such as the Totem Pole output (push-pull-out driver), must be chosen. Thus, an LC matching circuit must be used for matching the transducer and switching network. The component values for the matching circuits are derived from the EBVDM for the 40 kHz branch.

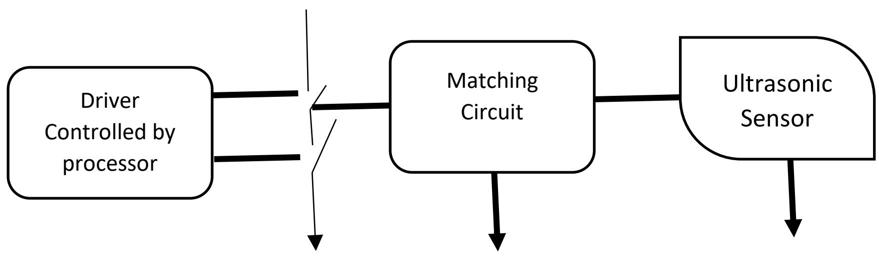


Figure 6: Equivalent transmitter circuit

Figure 7 represents the equivalent receiver circuit. In this receiver circuit, a two-stage voltage-controlled amplifier (VCA) must be used. The VCA consists of a Low-Noise Preamplifier (LNP) and a Voltage Gain Amplifier (VGA). At the transmitter circuit end, a controllable gain is needed because the amplifier will saturate under high gain if the reflecting surface is close to the transmitter. Furthermore, when the reflecting surface is far and the gain is low, the amplifier will not amplify the signal above the noise floor. Therefore, the differential output of the amplifier is converted to a single-ended signal and sent to a passive low-pass filter (RC), which can also be considered as an AM demodulator for envelope detection. The RC filter also serves as an anti-aliasing filter.

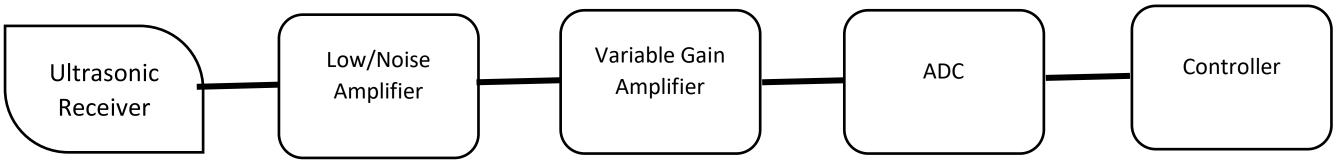


Figure 7: Equivalent receiver circuit

Technique II: The second technique which can be used to increase the range of a low-cost ultrasound sensor for deep well application, is by combining many of these ultrasonic sensors until the desired water level is reached. The proposed method is illustrated in Figure 8. The cascaded method can be used to obtain the total level.

```
        if Sensor1 <= 0.5
      x1 = 400
      else
     x1 = Sensor 1
end
if Sensor2 <= 0.5
 x2 = 400
else
    x2 = 400 + Sensor 1
end
if Sensor 3 <= 0.5
 x3 = 400
Else
 x3 = 400 + Sensor 1 + Sensor 3
End for
  return: round (Total Level)
End Function
```

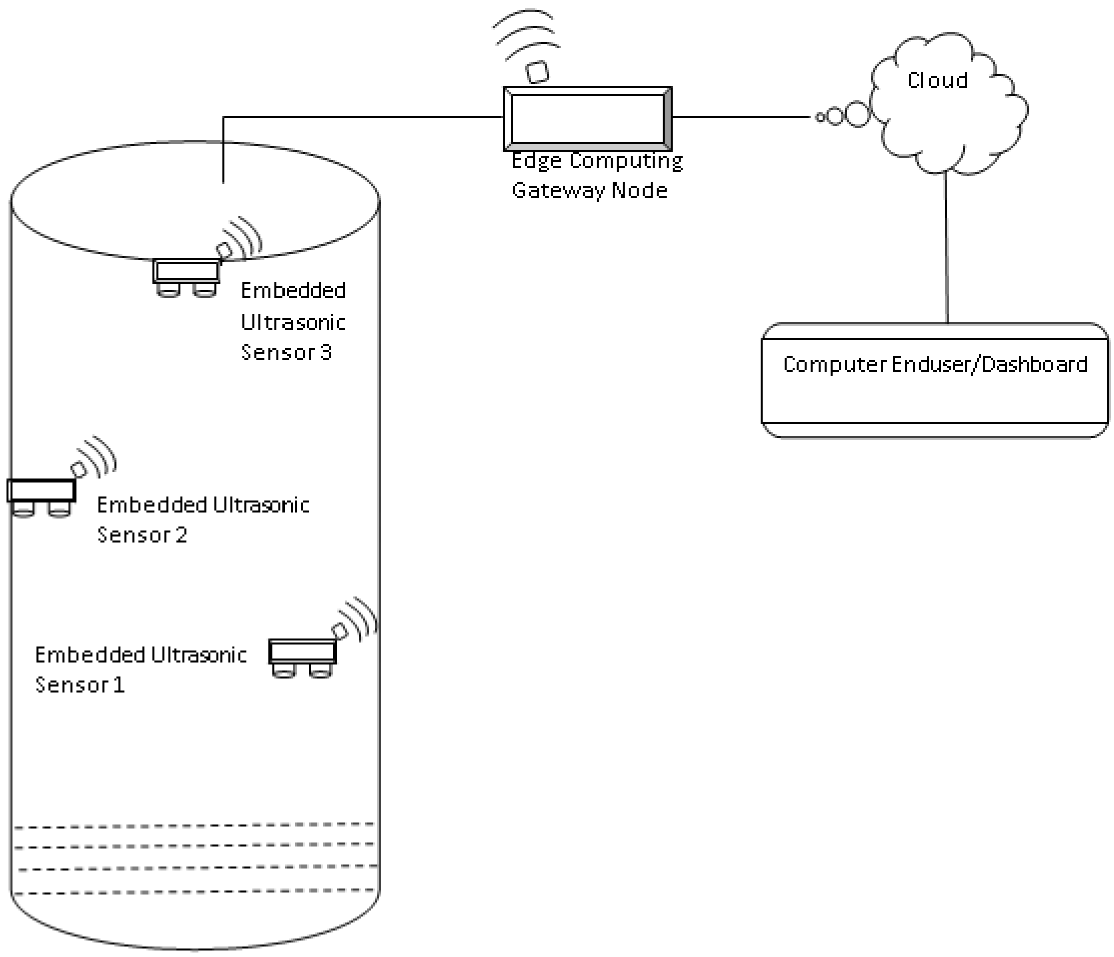


Figure 8: Proposed Cascaded Groundwater Monitoring System

Thus, the total level is obtained by;

Total level (T_L) = $S_1 + S_2 + S_3$

Also, the controlling flowchart is represented in Figure 9.

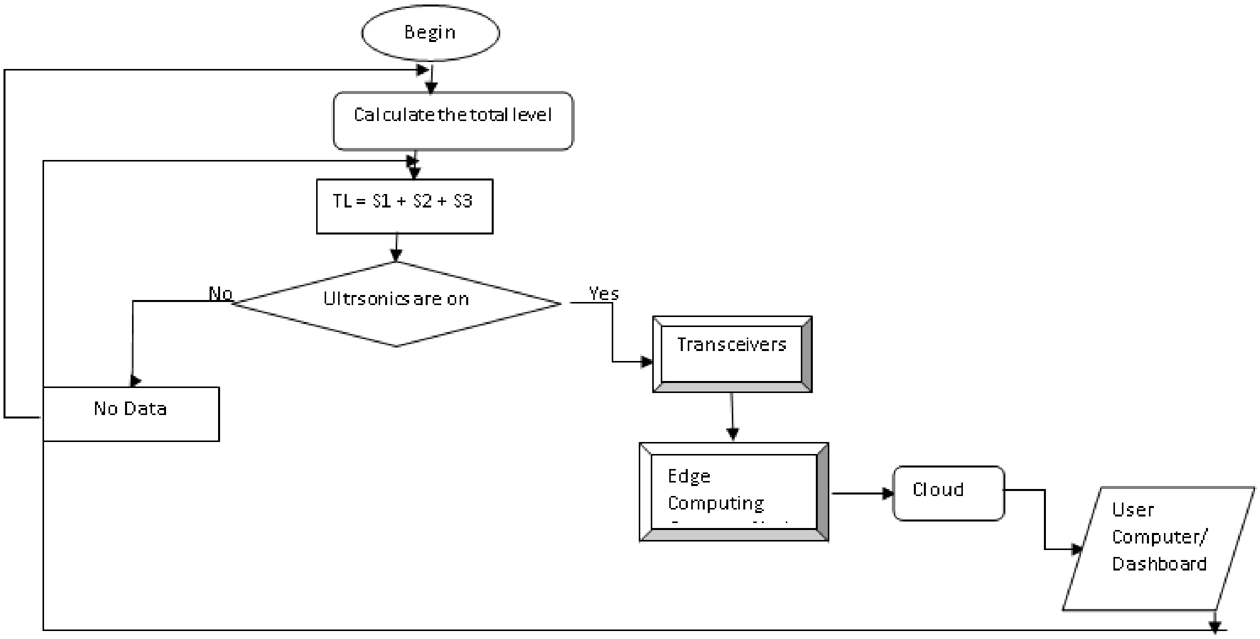


Figure 9: Flowchart of Cascaded Groundwater Monitoring System

2.1.5 Open issues and way forward for future works

In conclusion, this review has presented the literature review on the few existing available materials on ultrasonic sensors and their range extension technique. To the best of our knowledge, the idea of extending sensing range for ultrasonic sensors in relation to groundwater level monitoring applications is limited in the literature. From the literature reviewed, there are open issues and research challenges that need to be examined. Firstly, the low-cost ultrasonic sensors that are available in the market have a limited range of about 400 cm. Based on the previous research, it is necessary to develop a low-cost, innovative long-range IoT-based groundwater level monitoring system for a deeper well network. Secondly, the amplitude of a pulse is limited by the capability of the ultrasonic sensor, which is limited by size. Consequently, ultrasonic wave propagation in air is subject to exponential loss with increasing frequency, due to the compressibility of air, which limits the frequency range that can be used. This leaves increasing pulse duration as the principal means of increasing echo detectability. However, for a threshold detection system, when the pulse duration is increased, the echoes from closely spaced objects will overlap, making them indistinguishable. This reduces the spatial resolution of the system. Both the problem of overlapping echoes and the energy level of the pulse can be overcome by introducing pulse compression, originally developed for RADAR, that makes high spatial resolution possible using longer pulses to allow for weaker echoes to be detected (Frenkel, 2008). Lastly, increasing the energy level of the transmit pulse will increase the level of the echoes and thus their detectability, but poses technical challenges, such as the first echo may not be from the monitoring object, thus giving a false reading. Additionally, the farther the object with a small profile is from

2.2 Methodology and implementation within the laboratory

In this section, a prototype for measuring groundwater levels in a well was developed. This involved the circuit development, modelling and the choice of a suitable component for the development of a groundwater monitoring system which can measure up to 17 metre depth. This involved the integration of different components into a single monitoring prototype. Thus, the overall objective of this section is to develop a prototype with the different integrated units, such as a sensor, microprocessor, as well as IoT-enabled devices to measure groundwater level within a laboratory environment. This is a continuation of the developed prototype that can monitor both the groundwater level as well as quality. However, this can measure beyond 4-metre depth using an ultrasonic sensor.

Hence, the developed sub-system should demonstrate acceptable levels of the user's requirement specifications as shown in Table 3.

Table 3: Groundwater level sensor and data transmission specifications

FUNCTIONALITY	**DESCRIPTION**
1. Application and Technical Details of the Sensor	
1.1 Application	Groundwater level monitoring
1.2 Monitoring Media	A borehole with a 160 mm diameter
1.3 Geo-referencing	Location of the well to be observed in real-time
1.4 Measuring depth range	4 meters to 17 metres depth

1.5 Recording frequency	Real-time to near-real time (30 seconds), 5 minutes, hourly to daily
1.6 Sensor accuracy	0.5%
1.7 Sensing technology	Contactless (provide an alternative if a contactless one is not available). Advanced, IoT-enabled technology
1.8 Sensor mounting	Provide specifications
1.9 Robustness and reliability	Sensor robust to withstand environmental conditions
2. Technical Details for Data Logging and Transmission	
2.1 Recording frequency	Real-time to near-real-time (30s), 5 minutes, hourly to daily
2.2 Data transmission	Real-time data transmission and display, (send real-time data at remote locations through wi-fi)
2.3 Data logger	• No loss of data due to power failure or signal loss. • Ability to download data without ceasing measurement
2.4 Scalable	The data acquisition system must be adaptable to a larger scale without sacrificing performance.
2.5 Modular design	Subsystems and components need to accommodate new technologies without affecting the design of others
2.6 Power supply	Internal or external battery and a solar panel. The lifespan of the battery should be at least one year

2.7 Security	Components are to be packaged in a manner that the monitoring system will be less vulnerable to theft and vandalism
2.8 Lightning protection	Required
2.9 Connecting cables	Required
2.10 Wi-fi connection	Wi-fi router required
2.11 Mobile Connection	Mobile internet such as 5G/4G/Satellite connectivity is a major requirement

2.2.1 Modelling of range-enhanced ultrasonic sensor circuit

In this sub-section, the design and modelling of the range-enhanced ultrasonic prototype circuit in SIMULINK will be presented.

Figure 10 shows the designed trigger or transducer (ultrasonic) circuit diagram of the range-enhanced ultrasonic sensor prototype. The circuit designed is meant to work in conjunction with an ultrasonic sensor as the main transducer. This circuit contains different components arranged and soldered together. These components are:

- Capacitors
- Resistors
- Integrated Circuits
- Transistors
- Diodes
- Breadboard
- Ultrasonic Transducers
- Oscilloscope
- Signal generator

After Figure 10 was designed, it was modelled using the SIMULINK/MATLAB 2022 version platform. This is to calibrate and simulate the correct values of the components that will be required to develop the range enhancer circuit.

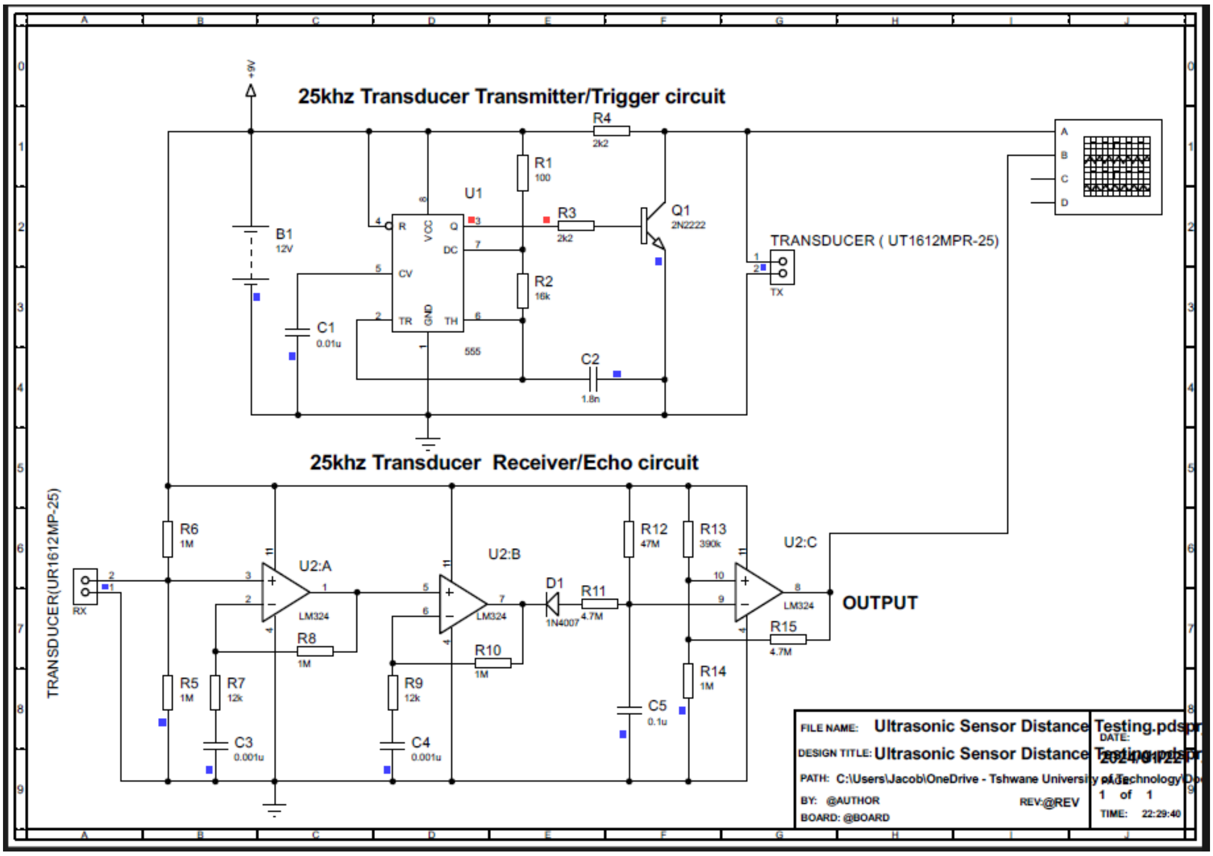


Figure 10: Circuit diagram of the range enhanced ultrasonic sensor circuit

The circuit simulation was performed in the SIMULINK environment and tested to confirm the required frequency. After the circuit simulation was performed, the components were arranged on the breadboard and tested. The frequencies of both transmitter and receiver were measured using an oscilloscope after the circuit was triggered using a signal generator. The SIMULINK design and model using these components are depicted in Figure 11.

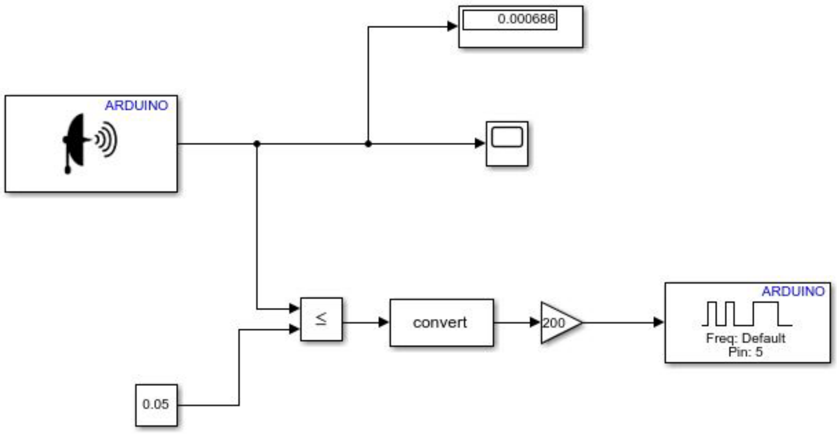


Figure 11: The simulated model of range-enhanced ultrasonic sensor

The model simulation frequency results were displayed on Figure 11. Also, Figure 11, shows the corresponding groundwater level variable experimented with changes in time variables. Figure 12 shows the flow chart diagram for the prototype. This flow chart governs the working of this prototype in such a way that it tells the prototype how the data should be measured. At the start of the prototype's operation, all sensors measure their data per minute (which can also be reduced or increased based on how frequently the data is needed). Sensors measure the data in analogue mode; however, the data needs to be converted to a calibrated digital format for display on the monitoring unit. The sent data continues every time (as instructed) and also goes back to sleeping mode.

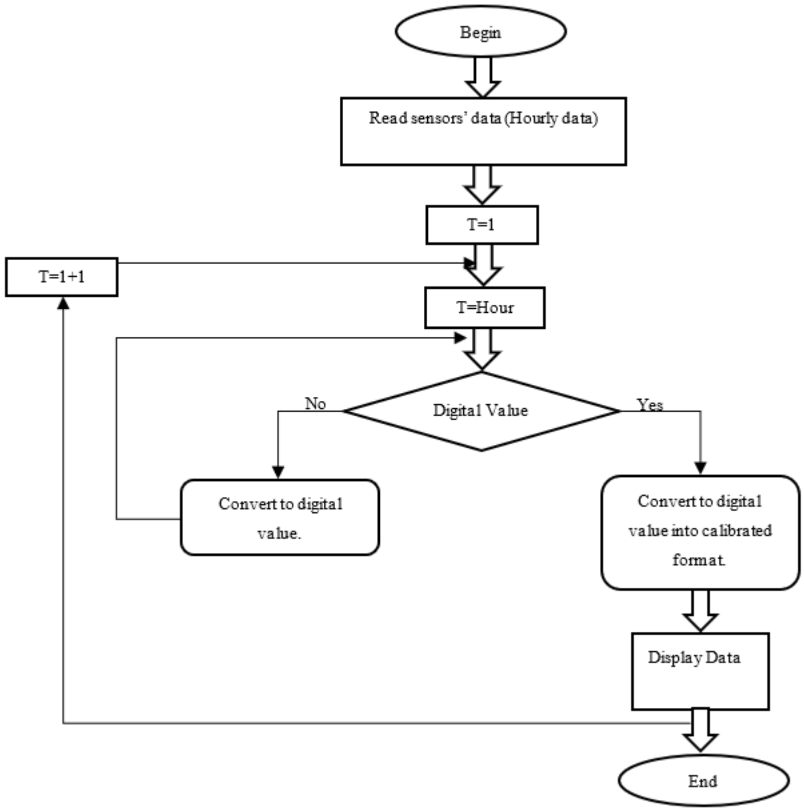


Figure 12: Groundwater level monitoring system flowchart diagram

Furthermore, performance testing was done to determine the range of the ultrasonic sensor prototype using the developed range-enhanced circuit. Figure 13 shows the diagram of the performance test using the signal generator and oscilloscope used to record the result. This was carried out to determine if the desired range can be reached using the transducer. As shown in Figure 13, the sensory circuit with ultrasonic transducer was connected to both the signal generator and the oscilloscope. A signal generator was used to provide the electric signal in the circuit, while the oscilloscope was used to measure the frequency as the circuit was triggered.

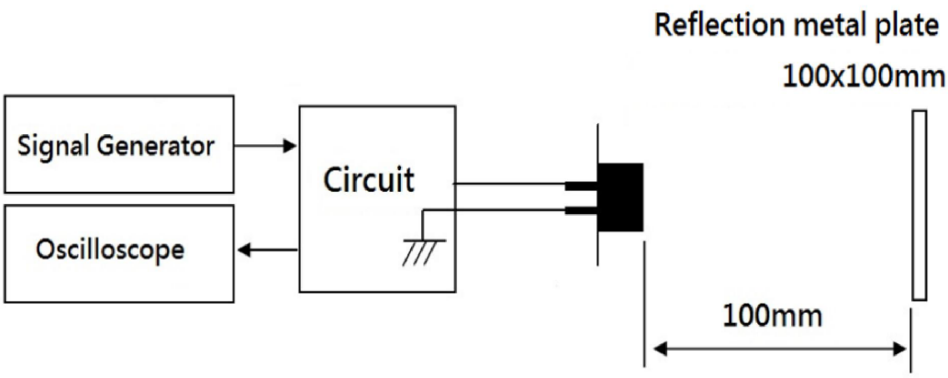


Figure 13: Performance testing diagram

Figure 14 shows the results on the oscilloscope. Figure 14 also shows 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 greater than 100 seconds.

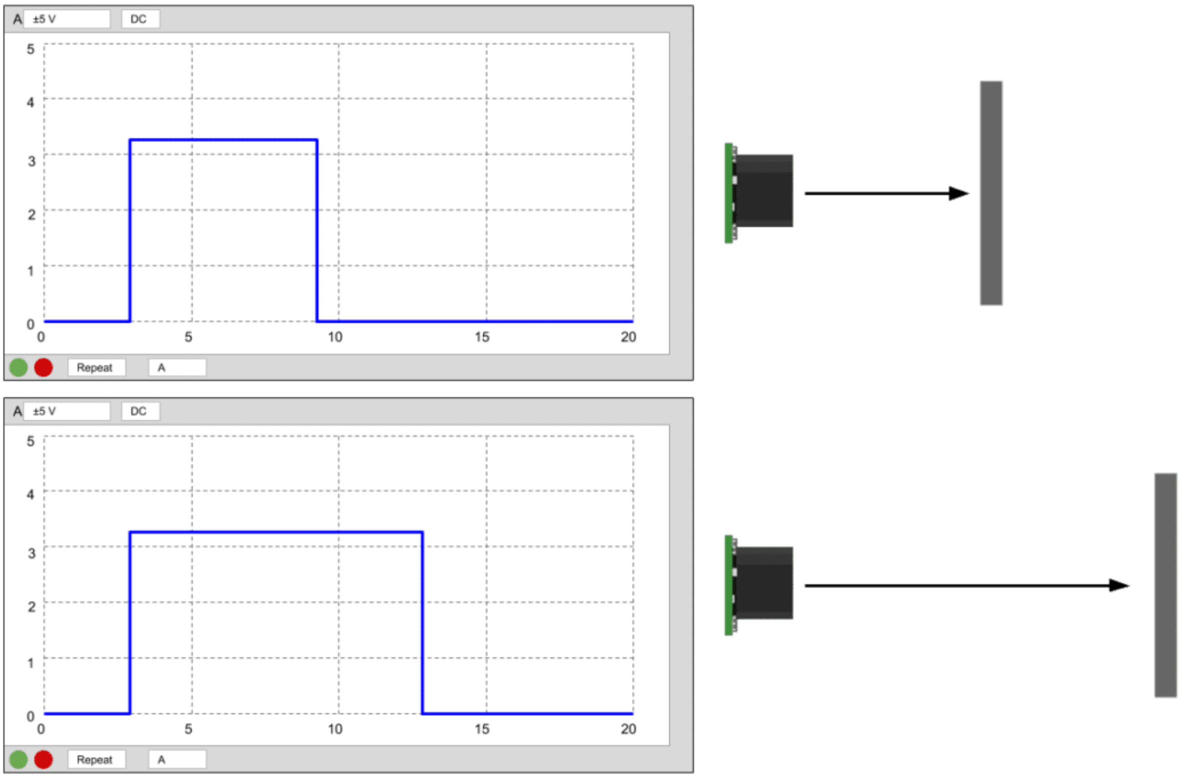


Figure 14: SIMULINK scope

At the end of this designing and modelling exercise, the designed model and the simulated results clearly show the possibility of deploying this range-enhanced circuit with a suitable ultrasonic sensor for groundwater level monitoring capability.

2.2.2 Ultrasonic input data capturing unit

The data input capturing unit consists primarily of sensors, a circuit board and a microprocessor. The ultrasonic sensors that were used in this system are an HC-SR04 ultrasonic low-cost sensor, JSN-SR04T, and MaxBotix MB7853. To compensate for temperature and humidity shortcoming, a DHT 22 sensor will be included to compensate for this shortcoming. Although there are many water sensors, however, these sensors were chosen for this project because they are a non-contact sensor, have an accuracy of $\pm$ 0.5, and power consumption of 5V.

Figure 15 shows the schematic block diagram of the data capturing unit of the prototype. The sensors were connected to the breadboard and ATmega328P microcontroller. The Arduino-based processing module contains a set of written code. This is used to perform the processing of raw data, storage of codes and transfer of processed captured data into the cloud via the use of internet access.

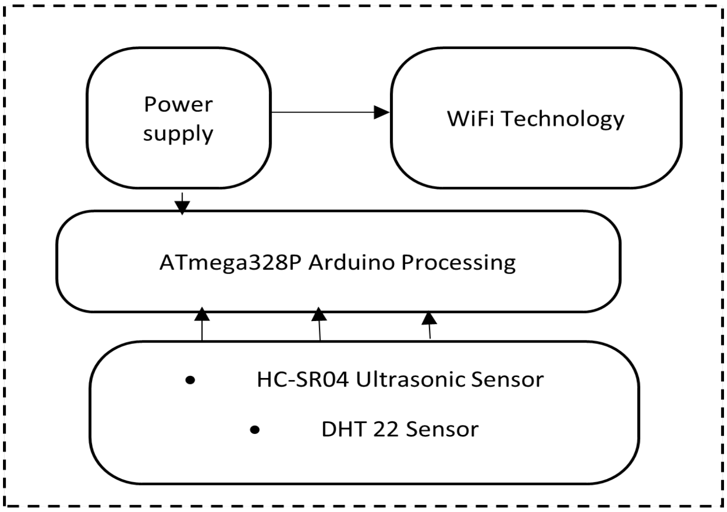


Figure 15: Schematic diagram of data capturing layer

These ultrasonic sensors use 40KHz sound pulses to measure distance. It consists of a transmitter and a receiver that can also be combined into a transducer. The distance here is calculated using the time delay between the object and the transducer. An ultrasonic distance sensor works by sending out ultrasound waves. These ultrasound waves get reflected by an object, and the ultrasonic sensor detects them. By measuring how much time passed between sending and receiving the sound waves, you can calculate the distance between the sensor and the object.

$$\text{Distance (cm)} = \text{Speed of sound (cm/}\mu\text{s)} \times \text{Time (}\mu\text{s)} / 2$$

Where Time is the time between sending and receiving the sound waves in microseconds. At 20 °C, the speed of sound is roughly 343 m/s or 0.034 cm/μs.

In this project, three ultrasonic sensors were tested with the designed range-enhanced circuit to determine the most suitable for this system. These ultrasonic sensors are HC-SR04, JSN-SR04T, and MB7853. The HC-SR04 and JSN-SR04T are both ultrasonic distance sensors that can measure distances between 0.002 metres and 4 metres using ultrasonic pulses. However, they have some key differences in terms of physical size, waterproofing, cables, power consumption, and cost.

- HC-SR04 is a non-waterproof sensor that has two transducers, one for transmitting and one for receiving ultrasound waves. It can measure distances from 0.02 metres to 4 metres with an accuracy of 0.0003 metres.
- Waterproof ultrasonic sensors, such as JSN-SR04T or JSN-SR04T-2.0, are designed to be used in wet or moist environments. They have only one transducer that acts as both transmitter and receiver. They can measure distances from 0.025 metres to 4.5 metres with an accuracy of 0.0001 metres.
- The main advantages of waterproof sensors are that they are more durable, reliable, and suitable for outdoor projects or projects that involve water level measurement. The main disadvantages are that they are larger, more expensive, and have a longer minimum distance than non-waterproof sensors.

Table 4: Summary of features of HC-SR04 and JSN-SR04T

Feature	**HC-SR04**	**JSN-SR04T**
Physical size	Smaller	Larger
Waterproofing	No	Yes
Cables	One module	Two parts (sensor and logic board)
Power Consumption	Lower	Higher

Figure 16 shows the diagram of JSN-SR04T sensor while Figure 17 shows the diagram of HC-SR04T sensor.

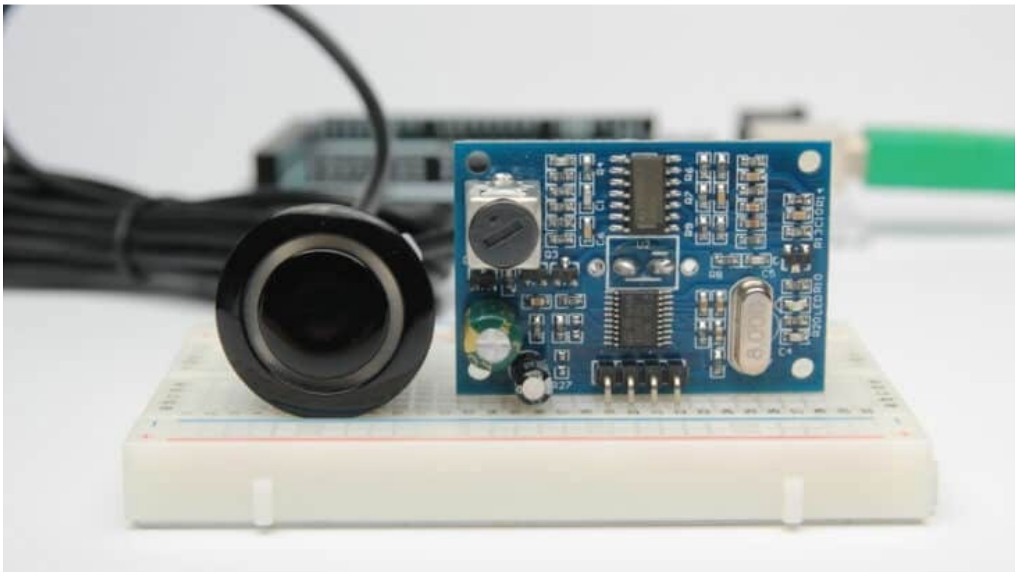


Figure 16: Diagram of JSN-SR04T sensor

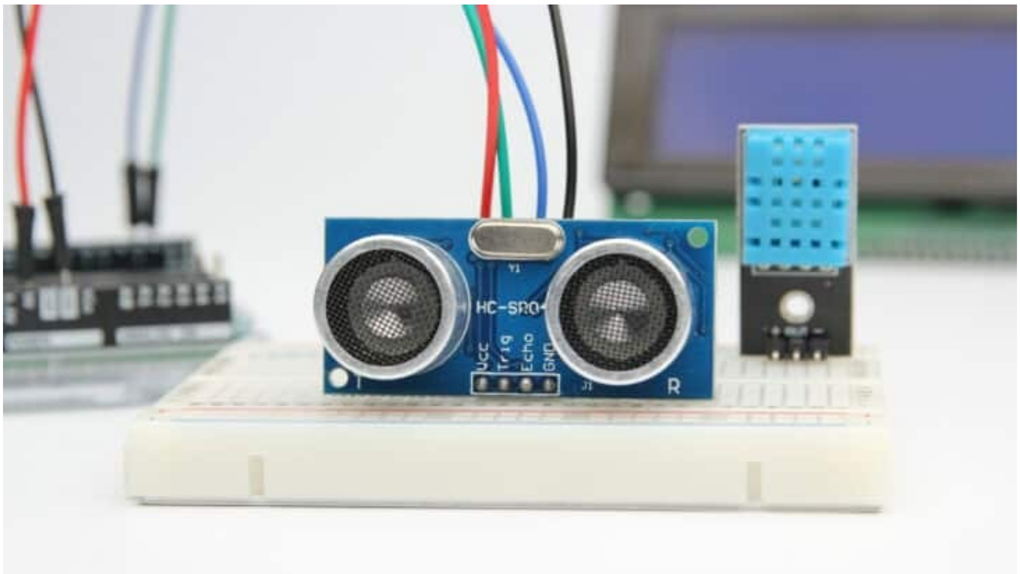


Figure 17: Diagram of HC-SR04 sensor

The third sensor used in this project is MB7853 manufactured by MaxBotix. MB7853 sensors are non-contact object detection and ranging sensors that detect objects within a defined area. These sensors are designed for use in the air. They are not affected by the colour or other visual characteristics of the detected object. They use high-frequency sound to detect and localise objects in a variety of environments. They measure the time of flight for sound that has been transmitted to and reflected from nearby objects. Based on the time of flight, the sensor then outputs a range reading. The MB7853 is a weather-resistant ultrasonic distance sensor with a range of 30 to 1680 cm and a resolution of 1 mm. This sensor is ideal for outdoor applications such as water tank or bin level measurement. It has a very small beam angle and can also be used for robot applications. MaxBotix does not call their sensors 'waterproof', but the sensors are properly tested and rated with an IP67 weather-resistance rating. Furthermore, it is worth noting that the speed of sound strongly depends on the temperature and humidity of the air. Consequently, the speed of sound in air increases about 0.006 metres per second per degree centigrade. Unlike many other sensors, the MB7853 features on-board internal temperature compensation. This means that the sensor will automatically compensate for the speed of sound changes and continue to give accurate readings. As it was in the previous prototype, an external temperature and humidity sensor, such DHT22 can be installed for even more accurate temperature and humidity compensation. Figure 18 is the diagram of MB7853 sensor while its features and benefits are:

- Long range detection and outputs
- High acoustic power output
- Readings can occur up to every 829ms, 1.2Hz rate
- Triggered operation provides the range reading as desired
- Fast measurement cycle
- Quality narrow beam characteristic
- Low cost, long range IP67 sensor
- Approximately 20-mm resolution from 300-mm to 500-mm
- 1-mm resolution from 500-mm to 5000-mm
- 10-mm resolution from 5000-mm to 16500-mm

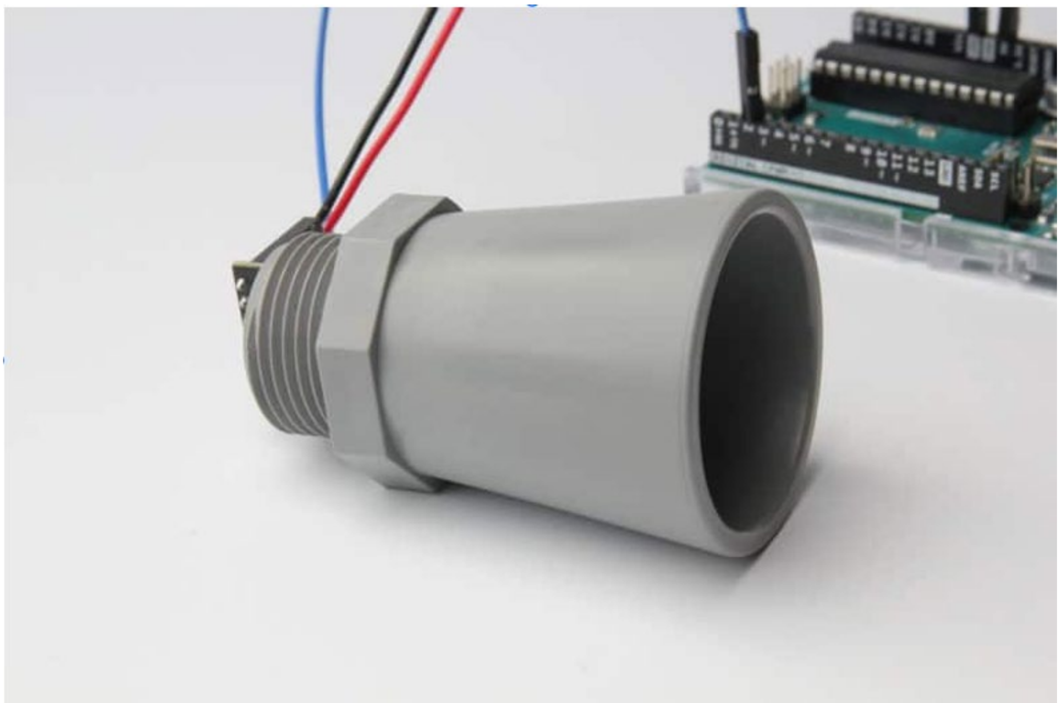


Figure 18: Diagram MB7853 sensor

As a result of the desired long-range application, MB7853 was chosen in this system because it was able to work with the range-enhanced circuit built. Furthermore, during the implementation and testing stage of this system, both HC-SR04 and JSN-SR04T sensors attenuated beyond 4 m and 6 m, respectively. This made them not suitable for groundwater well monitoring applications.

2.2.3 Construction and implementation of the prototype

The construction and implementation of the range-enhanced ultrasonic prototype monitoring system will be discussed in this section. This includes the choice of the sensor, the constructed circuit, the microcontroller, installation, and testing.

Hardware assembly and implementation of the prototype

As discussed earlier, in this system, the main sensor employed for this long-range groundwater level monitoring system is the ultrasonic MaxBotix MB7853 sensor. This is because the sensor is contactless and has long-range detection output. From the datasheet provided, it uses 3-5V input, the resolution of the Analogue Voltage output on the Tank Sensor line is limited to 1024 discrete steps, yielding a scale factor of Vcc/1024 per 2 cm for MB7853. The output is buffered and corresponds to the most recent range data. The scale factors expressed in terms of millivolts per centimetre are in 2.44mV/cm 2-centimetre resolution. The constructed circuit, hardware and the components were assembled within the laboratory.

After this, the level monitoring system was designed and simulated for the value of each component needed for the prototype development using Proteus software. Figure 19 shows the overall circuit design for this prototype built and simulated using Proteus software. This allows the opportunity to visualise the work of the circuit board before the arrangement of the circuit board and printed. The design in Figure 20 also contains other IoT-enabled devices required for remote monitoring and data transfer between the monitoring well and the personnel in charge of water management.

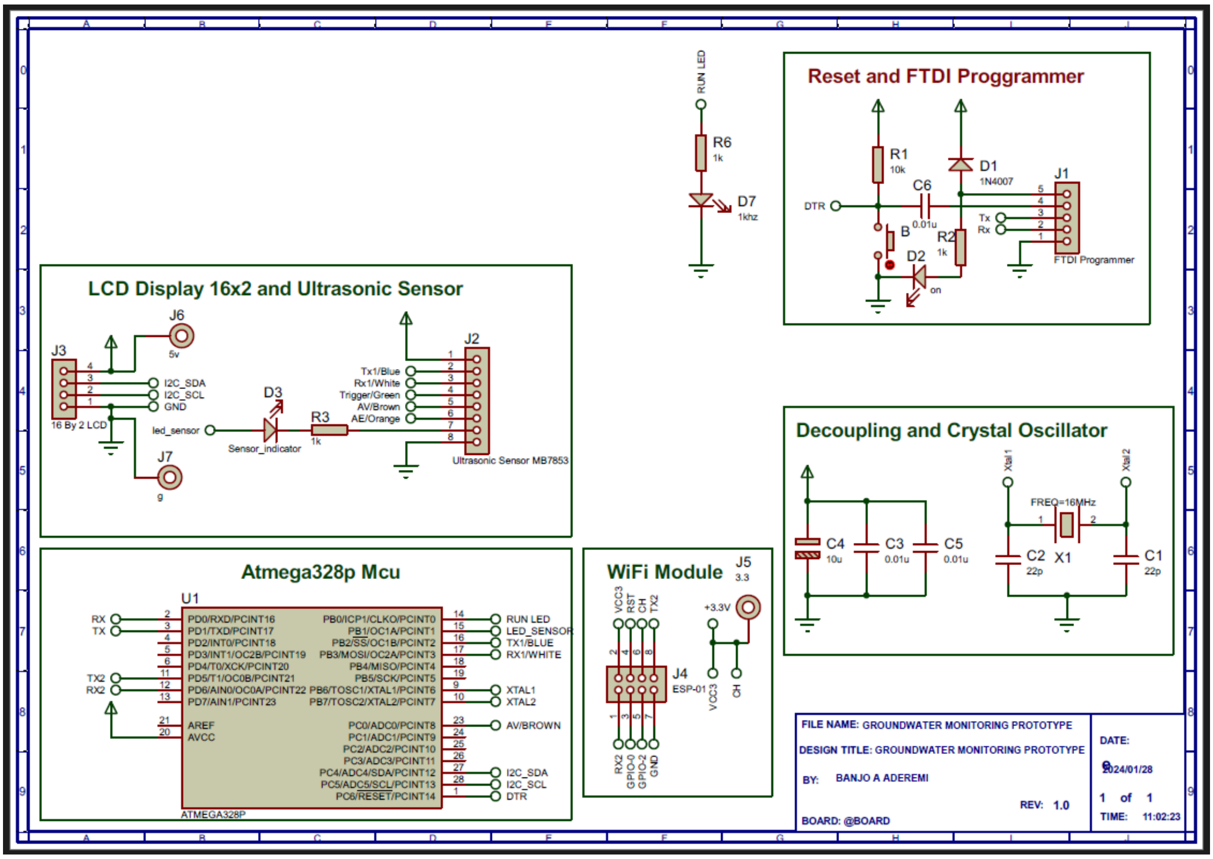


Figure 19: The simulated circuit of designed prototype using proteus software

Figure 19 and Figure 20 show the printed PCB board layout and 3D board for this prototype, respectively.

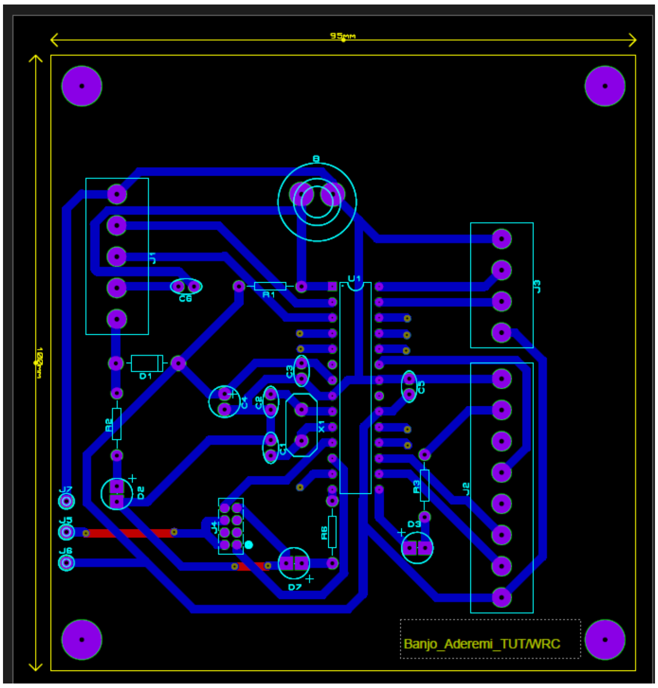


Figure 20: The printed PCB layout for the prototype

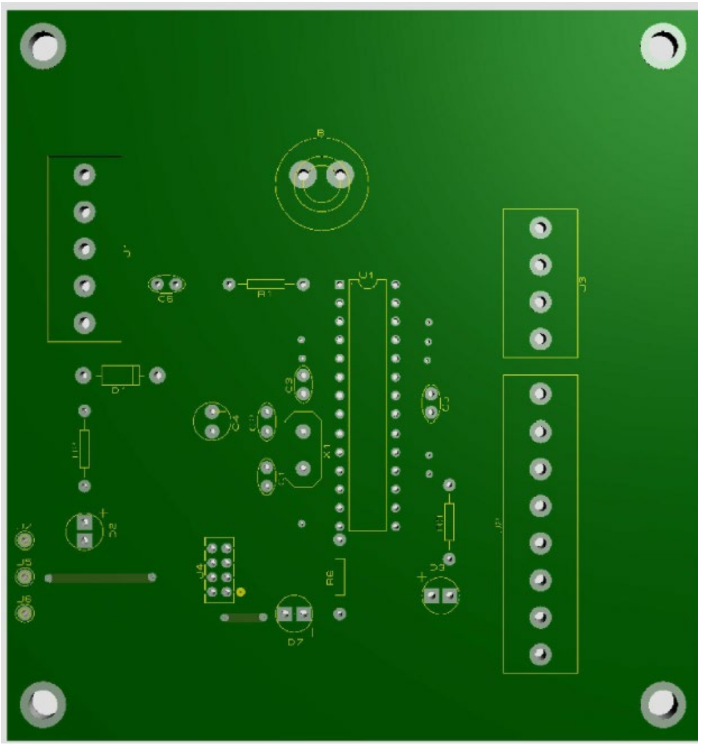


Figure 21: 3D Board layout for the prototype

Figure 22 is the diagram of the MB7853 ultrasonic sensor used as a transducer in this prototype. Therefore, the circuit was programmed with a set of commands and codes written in C++ programming language. The written code was uploaded to the circuit and the board performed the following functions:

- Supply power to the ultrasonic sensors and (other to be attached sensors), and
- Controls the activities of the ultrasonic sensors based on the uploaded written codes.

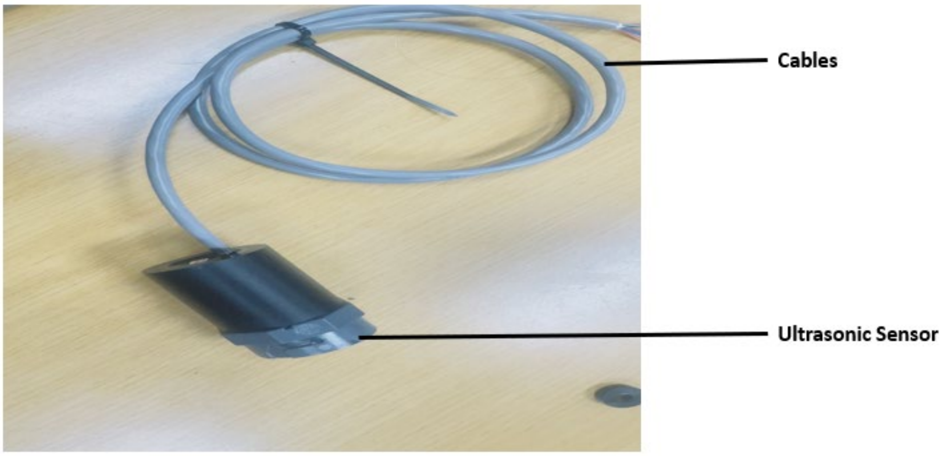


Figure 22: MB7853 sensor

In a laboratory environment, these hardware and software were assembled to form the developed range-enhanced ultrasonic sensor prototype monitoring system. Furthermore, the MB7853 ultrasonic sensor was mounted on a calibrated cylindrical tube to represent the monitoring well. This was done to represent a groundwater well. The measurements of the sensor were then verified by the physical reading obtained from the calibrated cylinder. Figure 23 shows the diagram of the MB7853 ultrasonic sensor mounted on the measurement tube.

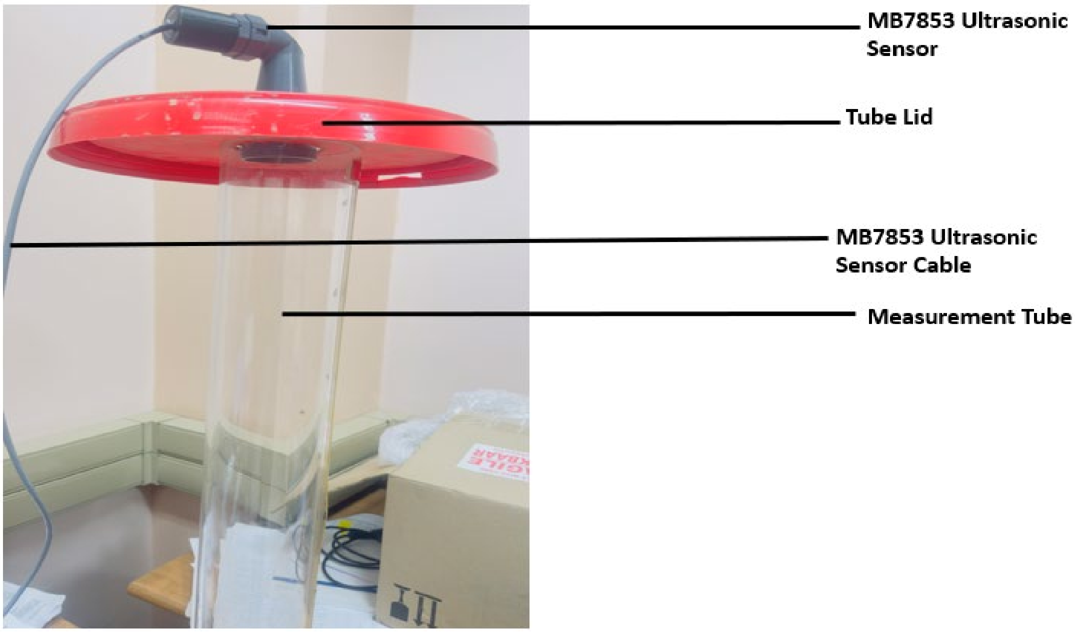


Figure 23: Ultrasonic sensor mounted on a measuring tube

Testing and results of range range-enhanced ultrasonic sensor

After construction, assembling and the physical implementation of the monitoring system, its testing was conducted within the laboratory environment to determine:

- The working condition, and
- Accuracy

After several tests were conducted, the results showed that the system is working as well as providing accurate measurements. Figure 24 and Figure 25 show the screenshot results on the monitoring display. The figures indicate the results of level measurements taken at different ranges to determine the prototype's ability to measure different levels.

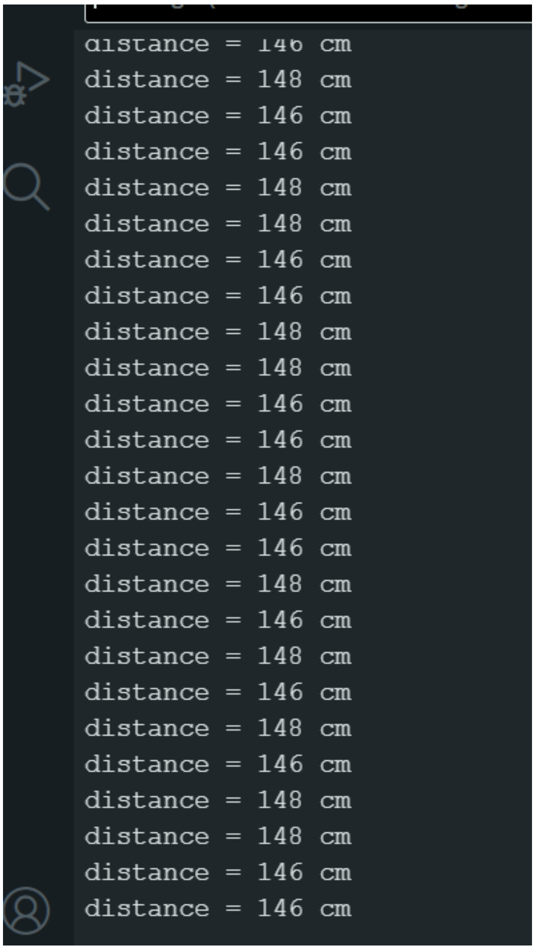


Figure 24: Results of the developed groundwater monitoring prototype 1

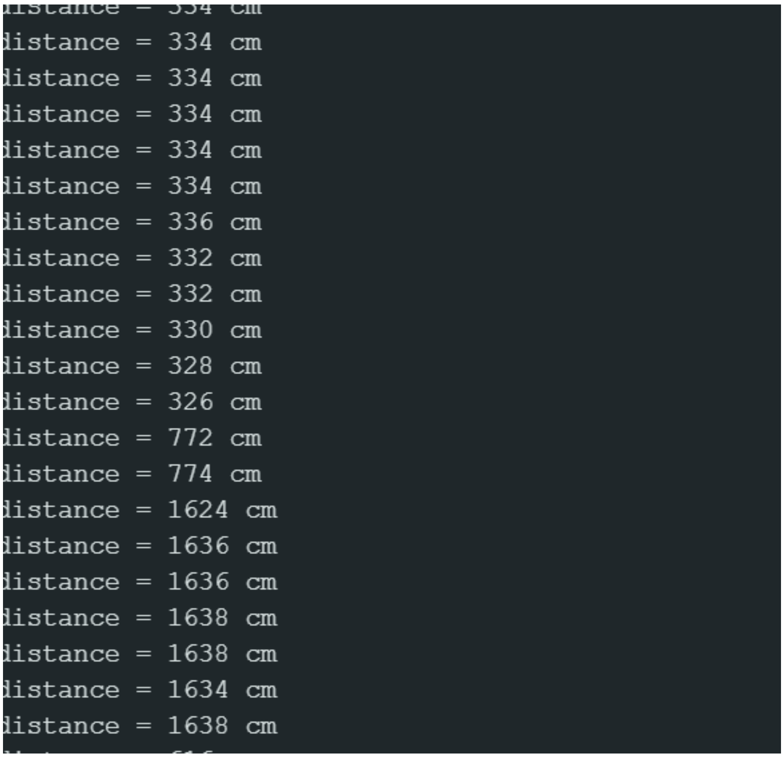


Figure 25: Results of the developed groundwater monitoring prototype 2

Application and testing of the HC-SR04 sensor in the laboratory

The HC-SR04 sensor was also tested in the laboratory environment in a setup depicted in Figure 26. Figure 26 is an artificial hydrogeological system, consisting of wells, a sand bed, an outlet and a rainfall simulator. Rainfall was selected, since it serves as a main source of aquifer recharge, and thus as it rains, the fluctuations from the well were observed using the ultrasonic sensor. The rainfall was measured using a Misol tipping bucket rain gauge, which was also integrated into the monitoring system. The measurements obtained from the well were compared with the measurements obtained from a dipstick that was inserted in the well.

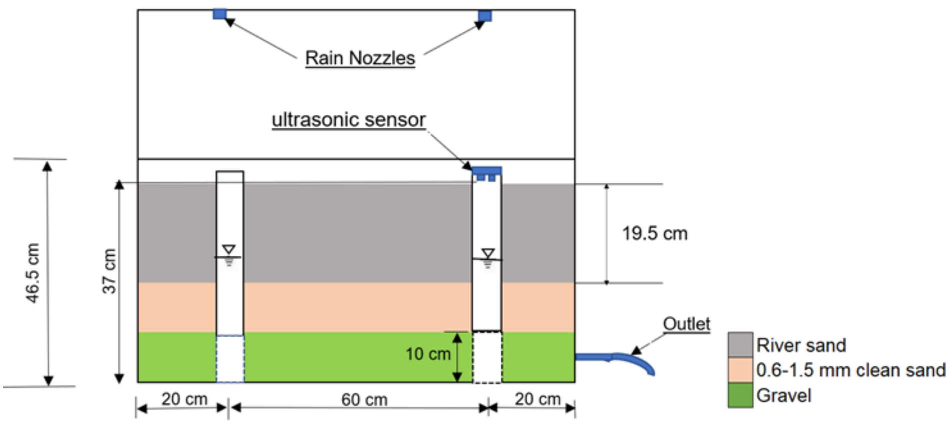


Figure 26: Artificial aquifer in the laboratory

The long-term measurements obtained from the setup in Figure 26 are depicted in a hydrograph and hyetograph in Figure 27.

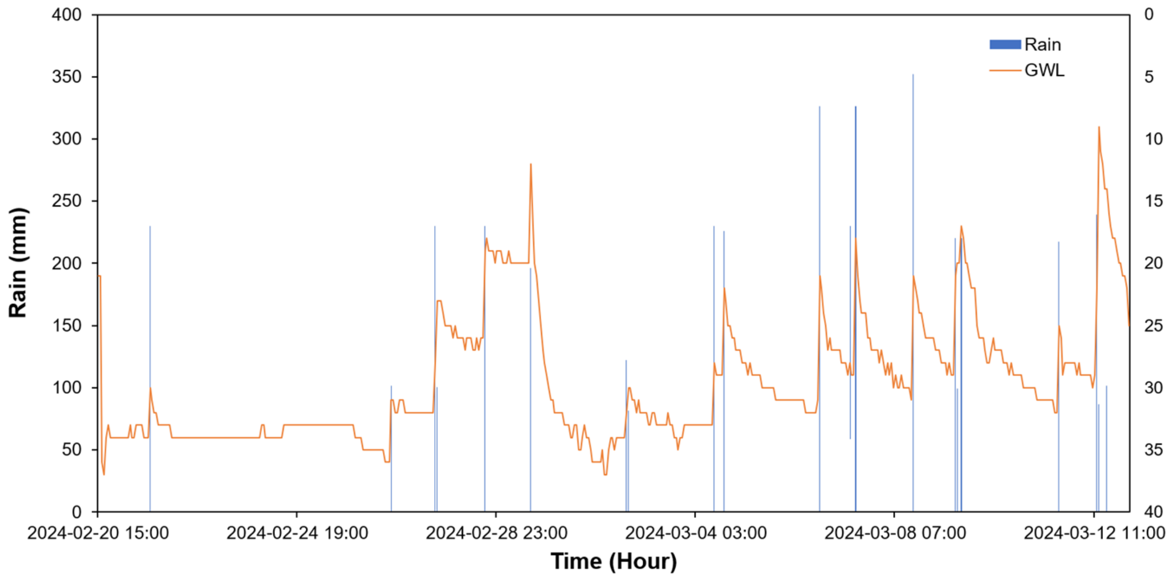


Figure 27: Aquifer response to rain events

Figure 27 shows the relationship between the groundwater level and the simulated rainfall within the laboratory. By systematically varying the water levels and the rainfall, successive measurements were taken with the aim of validating the functionality and reliability of the groundwater monitoring system. This comprehensive testing assisted in identifying any discrepancies between measured and remote readings, ensuring the integrity of the prototype before potential real-world applications. As depicted in Figure 27, aquifer response to rain events can be better understood through real-time monitoring. The groundwater levels rise after a rain event.

Consequently, Figure 28 presents the measured parameters displayed on the ThingSpeak cloud IoT platform, which is an analytic and display tool for monitoring environmental data. This platform provides a user-friendly visual interface that highlights various metrics related to groundwater conditions. By utilising this visual display, water managers can quickly and effectively evaluate the status of groundwater resources, allowing them to make well-informed decisions regarding resource management and conservation efforts. The accessibility of real-time data and clear visual representations enhances the ability to respond proactively to changes in groundwater levels.

Figure 28: ThingSpeak display

2.3 Field tests and associated risks

These field tests were aimed at evaluating the effectiveness of using the developed geography of things-based real-time groundwater remote sensing and telemetry prototype for monitoring groundwater parameters. This included testing the accuracy, reliability, and ease of use of the sensors in collecting and transmitting data in real-time.

2.3.1 The apparatus

Figure 29 shows the block diagram of the developed monitoring prototype. The block diagram illustrates three subunits: the data acquisition unit, the data transfer and processing unit, and the application and display unit. The data acquisition unit consists of sensors connected to the designed circuit. This unit is based on a microcontroller microprocessor and includes written codes for processing raw data, storing codes, and transferring processed captured data to the cloud via internet access using ESP32. The sensors used in this system include an ultrasonic sensor, a location module, and a DHT 22 sensor. The ultrasonic sensor was chosen for its non-contact with the groundwater surface nature, accuracy of ± 0.5, and low power consumption of 5V. Additionally, the system includes a rain gauge, pH level, electrical conductivity, temperature sensors, and GPS modules connected to the microcontroller as input peripherals. The primary function of the microcontroller is to convert analogue data to digital data, which is then sent to the cloud server via a wireless communication gateway. The data is retrieved from an IoT analytical platform called ThingSpeak by a computer located at the back-end office and displayed on the PC. The operation of the unit involves the execution of steps and required tasks occurring inside the microcontroller and communicating with the connected I/O peripherals.

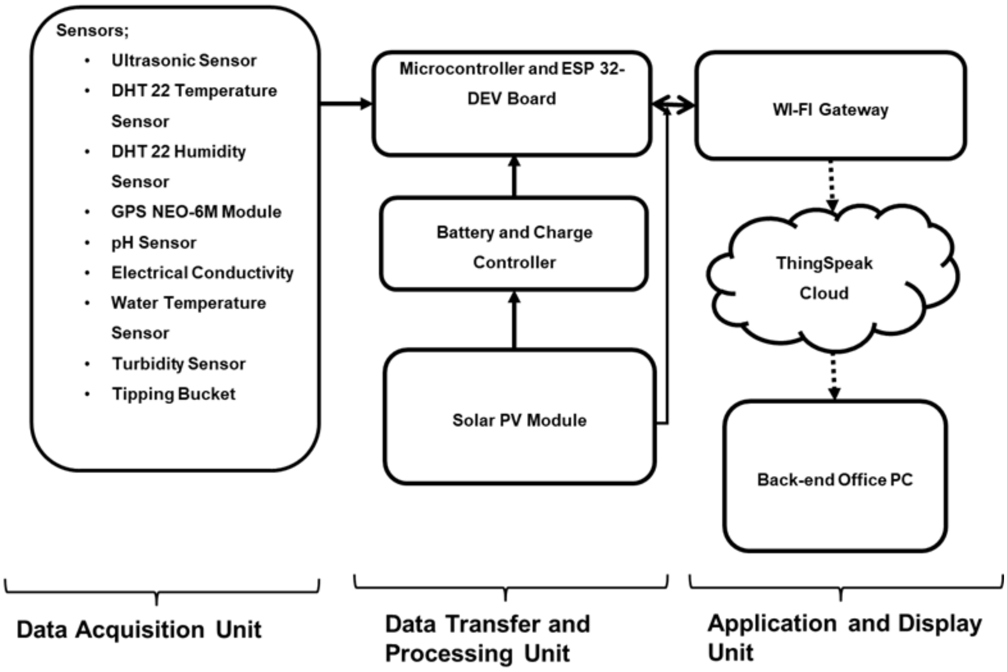


Figure 29: Block diagram of groundwater monitoring prototype

Furthermore, the communication unit utilises Wi-Fi technology to establish communication between the data and processing unit and the application and display unit. It is outfitted with an ESP32 module to facilitate this connection. This unit plays a crucial role as it enables real-time operation of the groundwater monitoring system through effective internet communication, which is made possible by the communication unit. The communication unit ensures the transfer of the measured processed data into the cloud platform. The cloud platform used is ThingSpeak. This cloud platform ensures real-time display on the monitoring system. Therefore, the groundwater parameters, quality, and quantity can be monitored anywhere so the water manager can make an informed decision.

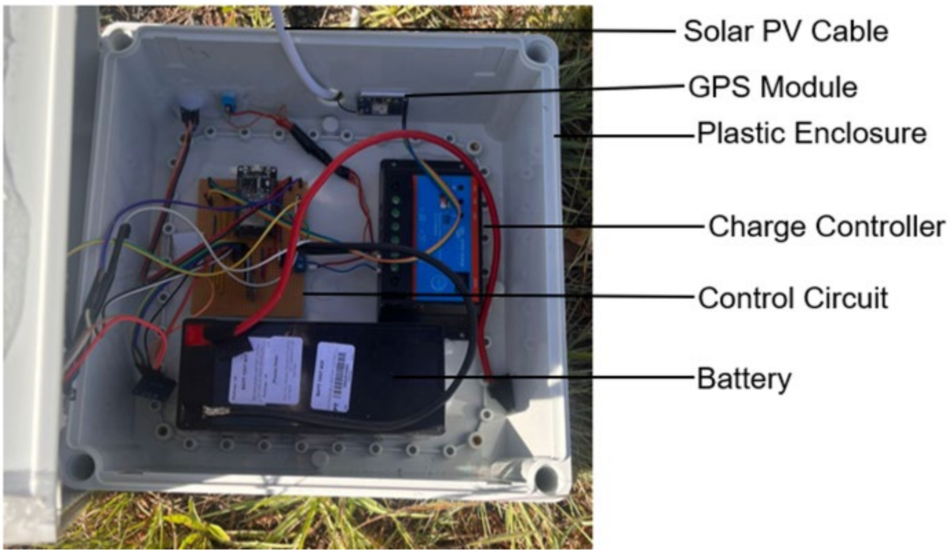


Figure 30: Cross-sectional inner of the overall prototype

The rear side of the prototype is represented in Figure 30.

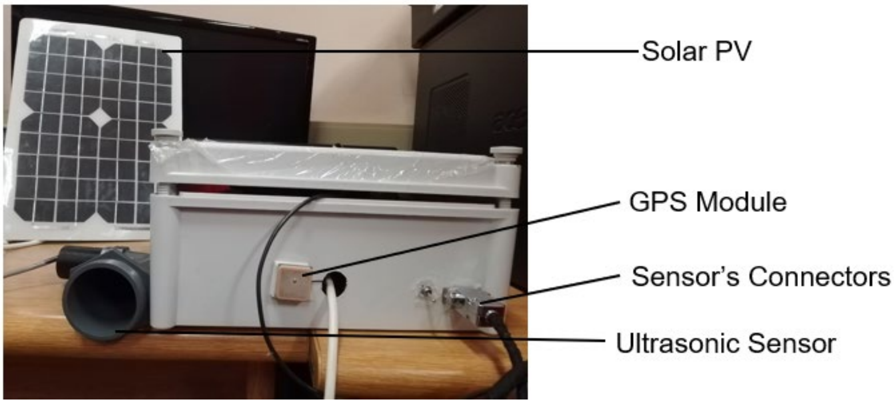


Figure 31: Rear side of the overall prototype

2.3.2 Field testing procedure

Site selection

The site selected was the Department of Water and Sanitation testing facility in Pretoria West. This site was chosen because it already has constructed testing wells, the depths of the wells are less than 5 m and the site is close to the Tshwane University of Technology (TUT) campus.

Calibration and measurements

Groundwater level measurements were taken manually with a measuring tape as shown in Figure 32 or a contact gauge shown in Figure 33. Then the sensor measurement was taken as shown in Figure 34 . The manual and the sensor reading were then compared.

Figure 32: Measuring tape and sensor measurements

Figure 33: Contact gauge

Figure 34: Sensor mounted on a well

Monitoring and comparison

The prototype setup was monitored onsite and via the cloud/server through the display unit. The IoT-enabled ThingSpeak platform monitors the data at regular intervals. The data recorded on-site and the one displayed on the ThingSpeak platform in real time were compared to check for any discrepancies. These data were stored in the cloud for further analysis.

2.3.3 Field results

The prototype demonstrated commendable response levels at the cloud end (ThingSpeak) and the tape measurement at the laboratory and field tests. The parameters measured, including geographical coordinates, groundwater levels, temperature, and humidity, yielded satisfactory results. Figure 35 showcases the water level graphical results obtained during the first field test, visually representing the capability of the sensor. During this first test, some of the challenges that were encountered were locating the sensor in the centre such that a precise level could be measured, and there was also a poor signal for the data to be transmitted through WIFI to ThingSpeak. As a result, some data was lost, and the few available records were used to plot Figure 35. The spikes in Figure 35 are attributed to the instability of the sensor while trying to obtain a stable position to locate the sensor and are largely attributed to an underground pipe leakage near the borehole. The water from the leakage emerged from the surface after approximately one year from the date of the observations in Figure 35. This thus highlights the essence of continuous GWL monitoring; it could also aid in early pipe leakage detection for underground pipes.

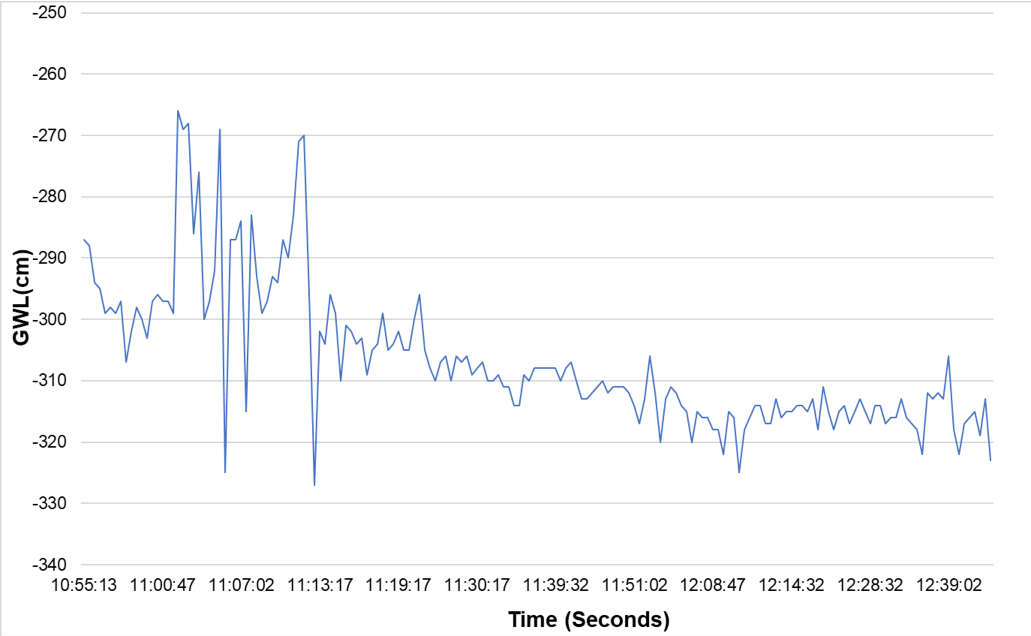


Figure 35: Groundwater levels measured first field test

The sensor was then taken to the laboratory for further development and brought back to the field for testing. Some of the developments that were made when the sensor was brought back for further site testing included incorporating a memory card into the system as a backup in cases of data loss. Improvements on the coding were carried out so that the sensor can reach the targeted levels. The results obtained from the second field test are depicted in Figure 36.

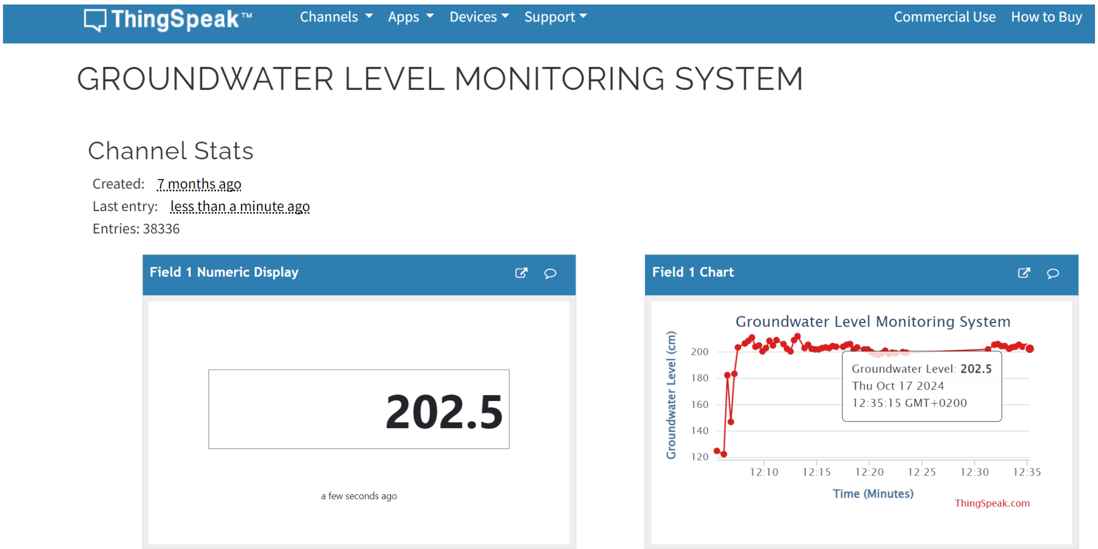


Figure 36: ThingSpeak display for the second field test

The groundwater level reading obtained during the second field testing was around 202 cm (shown in Figure 36) which agreed with the measurements taken using manual measurements (the measuring tape). The lower values (between 120 cm and 200 cm in Figure 36) are the readings that the sensor took while it was being adjusted to a stable position. Once the sensor had stabilised, it started to take constant readings within an error of around 0.5 cm.

The results of the third field test in Pretoria West are depicted in Figure 37. The groundwater level on this field test once again agreed with the manual measurements at a groundwater level of 267 cm, similar to Figure 36, the first measurements of 260 cm were the measurements of the sensor prior to a stable location being established, then it is followed by a constant 267 cm reading, which was adopted as the correct groundwater level reading.

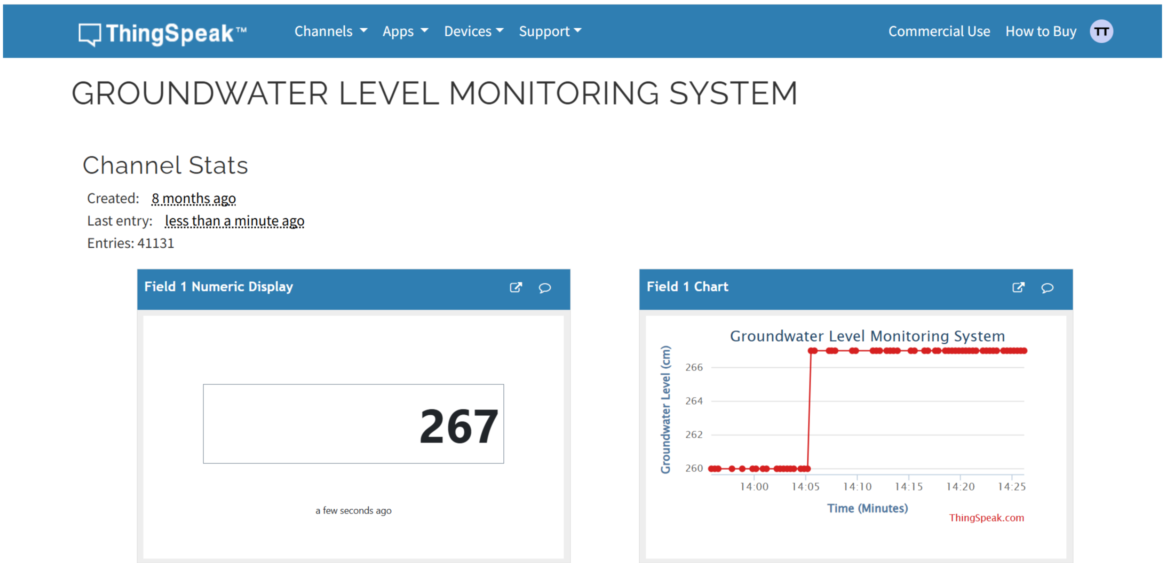


Figure 37: ThingSpeak display for the third field test

The fourth test (among a total of ten tests) that is reported is the test taken at the Sterkfontein caves monitoring well, and the results are depicted in Figure 38. This site was selected since it was the nearest accessible monitoring well at groundwater levels around 16 m to the Pretoria West area. The sensor reported constant groundwater levels at 1 607 cm, which agreed with the manual measurements. Thus, it was established that the sensor can measure up to 16 m in a real well.

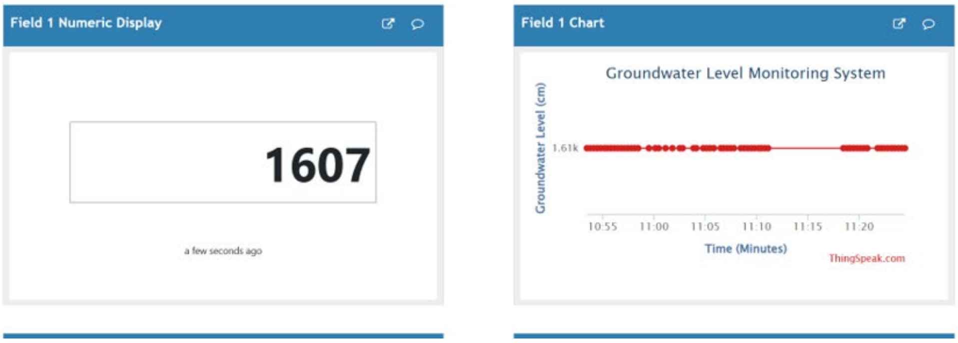


Figure 38: ThingSpeak display for groundwater level at the Sterkfontein monitoring well.

The prototype is currently deployed on site for observing real-time groundwater levels in the Department of Water and Sanitation testing site to observe long-term measurements for at least a year. The results obtained from this well will then be used in compiling a technical manual for this prototype. Figure 39 depicts the IoT groundwater monitoring system deployed in a well.

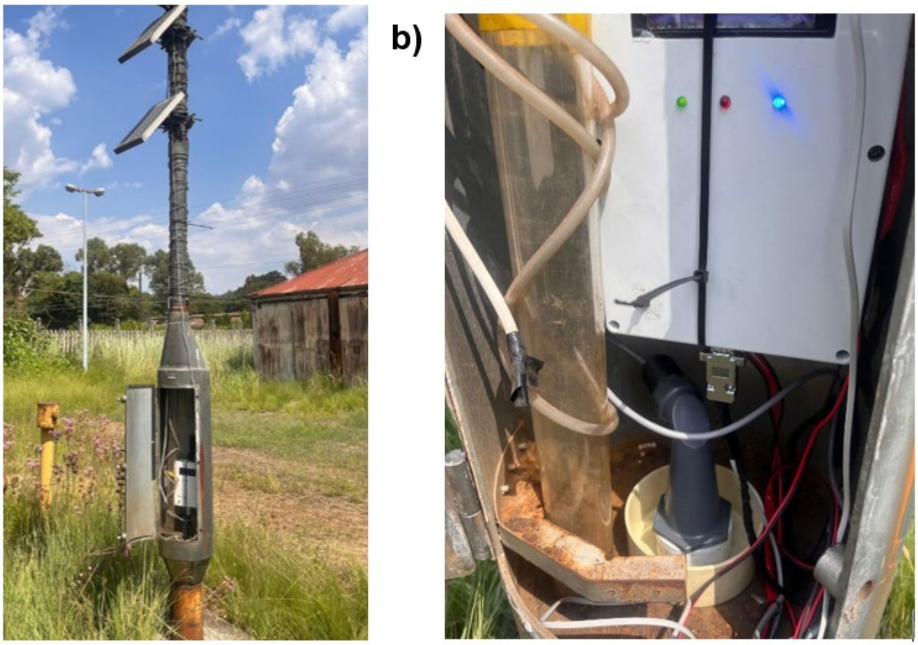


Figure 39: The IoT GWL Monitoring System a) The steel casing where the equipment where stored b) The sensor and the control system.

To the best of our knowledge, this well serves as the first well that has been equipped with the groundwater level IoT monitoring system, observing rainfall, humidity and temperature as well in this study area. The total cost of this monitoring system is approximately R30 000, including labour (the detailed costs are attached in Appendix 6). This cost will reduce due to mass production. The costs for the HC-SR04 sensor are also included in the Appendix, which can also be used in water storage tanks that are not more than 4 m deep.

2.4 Associated potential risks

As with any developed prototype, there are inherent risks associated with this groundwater IoT-based monitoring prototype.

2.4.1 Potential risks

The potential risks that are associated with this prototype can be categorised into the following:

Technical risks:

- Hardware malfunction: During the field test, the prototype may experience hardware malfunctions, leading to inaccurate data collection or complete system failure. Furthermore, because of the ultrasonic technology, the signal sometimes hits the wall of the well, especially if it is narrow.
- Connectivity issues: The prototype relies on a stable internet connection to transmit data to the central monitoring system. Any connectivity issues could impact the data collection and analysis.
- Power outages: If the prototype is not equipped with a backup power source, it may experience power outages, leading to data loss and interruptions in the monitoring process.
- Software glitches: The software used to collect and analyse the data may have glitches or bugs, resulting in incorrect data readings.

Environmental risks:

- Weather conditions: Extreme weather conditions such as heavy rain, lightning, or high winds can damage the prototype and impact its functionality.
- Physical obstructions: If installed in a narrow-walled well, physical obstructions could block the signal, affecting its performance.
- Vandalism or Theft: The prototype may risk vandalism or theft, especially when installed in a remote location.
- Chemical contamination: Although the technology of the level monitoring unit is ultrasonic, which makes it contactless in its operation, the quality unit has to make contact with the groundwater. Therefore, the quality unit is prone to chemical contamination, damage, and malfunction. Furthermore, since the

prototype cannot self-clean, the residue from the previous reads can lead to false readings and negative results.

Financial risks:

- Lack of ROI: If the prototype does not perform as expected or does not provide valuable data, it may result in a lack of return on investment.
- Cost of equipment: The cost of the prototype and its installation can be significant, and any damage or malfunction could result in a financial loss

Identifying and addressing these risks is important to ensure a successful and safe field test and the deployment of the prototype.

2.4.2 Mitigation of potential risks

To mitigate these risks, thorough testing and quality control before the field test are important. The prototype should also be regularly maintained and monitored during the field test period. Adequate insurance coverage should be obtained, and contingency plans should be in place for unforeseen circumstances. The following procedures have been identified for risk mitigation.

Mitigation against technical risks:

- Regular maintenance and calibration: The monitoring prototype should be regularly maintained and calibrated to ensure accurate and reliable readings of groundwater parameters. This will help in identifying any potential issues or malfunctions in the system. Further improvements are also needed in the quality unit to enhance its performance and accuracy.
- Backup power source: It is important to have a backup power source for the monitoring prototype in case of power outages or failures. This will ensure continuous monitoring and data collection even during power disruptions. In this case, solar PV and rechargeable batteries have been used.
- Data validation and quality control: The collected data should undergo a validation process to check for any anomalies or errors. Quality control measures should also be implemented to ensure the accuracy and integrity of the data.

- Security measures: The monitoring prototype should have appropriate security measures in place to protect the data from unauthorized access. This includes encryption of data, restricted access to the system, and regular backups of data.
- Professional handling: This prototype should be handled and maintained by professionals to prolong its usage.

Mitigation against environmental risks:

- Consumable: Replacement sensors should be made available to replace damaged sensors.
- Collaborative monitoring: Collaborating with local authorities and communities can provide valuable insights and help identify potential risks and mitigation measures. This can also help build trust and support for the monitoring project and mitigate against theft.
- Field testing: Before deploying the monitoring prototype for long-term use, it is important to conduct field testing in different locations to ensure its effectiveness and reliability. This will also help in identifying any potential issues or improvements that need to be made. This will also assist in mitigating physical obstructions
- Emergency response Plan: It is important to have an emergency response plan in place in case of emergencies or adverse events. This plan should include clear protocols for notifying relevant authorities and taking appropriate actions to mitigate risks.

Mitigation against financial risks:

- Regular communication: Regular communication with stakeholders and relevant authorities is crucial for the success of the monitoring prototype. This will help in identifying any potential risks and taking timely actions to mitigate them.
- Continuous improvement: The monitoring prototype should be continuously monitored and evaluated for its effectiveness. Any necessary improvements or

upgrades should be made to ensure optimal performance and accuracy in monitoring groundwater parameters.

2.5 Conclusion

The objective of developing a prototype for monitoring groundwater parameters in a laboratory environment has been primarily achieved. The field tests have also been done. The field test results showed that the prototype could accurately measure and monitor groundwater parameters in real time. The data collected from the sensors was consistent and comparable to that collected through manual sampling and laboratory analysis. The sensors could also quickly detect changes in groundwater parameters, allowing for timely intervention and management.

One of the main advantages of using this prototype for groundwater monitoring is the ability to access real-time data remotely. This enables quick decision-making and reduces the need for frequent site visits, which can be time-consuming and costly. Additionally, using this prototype eliminates the risk of human error and provides more excellent spatial coverage for monitoring.

This developed monitoring prototype is a work in progress; thus, future development will include:

- Field test of this system in a real groundwater monitoring well (currently ongoing in Pretoria West).
- More field tests at the Nkangala site before installation and regular maintenance after the installation.

3 DEVELOPMENTS OF GROUNDWATER QUALITY SENSORS AND IMPLEMENTATION

3.1 Literature review on groundwater quality monitoring and remote sensing

The sustainability of aquifers across the world is increasingly threatened by factors such as population increase, climate change, and the excessive extraction of groundwater, all of which adversely impact water quality. To safeguard essential water-dependent ecosystems, it is imperative to implement efficient and data-driven management strategies for groundwater resources. Unfortunately, current groundwater management practices are hindered by a lack of cost-effective, accessible, and reliable monitoring systems that are crucial for collecting essential data on groundwater quality (Calderwood et al., 2020). Groundwater resources are susceptible to a variety of both natural and anthropogenic contaminants that pose serious risks to public health and environmental integrity (Thaw et al., 2022). These contaminants can permeate aquifers, each exhibiting distinct characteristics and behaviours that necessitate specialized expertise for effective management (Izinyon et al., 2019). Consequently, groundwater quality is influenced by multiple factors, including the initial quality of water, its interactions with surrounding environments, and the potential effects of human activities, such as urban development and mining operations (Lapworth et al., 2017).

The integration of Edge computing and IoT technology has transformed the monitoring of groundwater quality, which provides early warning systems. Researchers have developed a water quality prediction sensor that utilizes real-time and historical data to aid in decision-making processes. In a separate study, a team utilized an STM32F103 as the processing core, an A7139 RF chip with a wireless communication module, and various sensors to monitor parameters such as dissolved oxygen, pH, ammonia nitrogen, and temperature over a 100-day period (Venkatesh et al., 2024). Their findings indicated that sensor nodes and GPRS technology with IoTs are optimal for monitoring drinking water quality. In addition, the critical analysis conducted by Adu-Manu et al. (2017) focused on comparing conventional water quality monitoring methods with advanced techniques. They highlighted recent improvements in sensor devices, data collection systems, communication networks, and power management systems. The use of mini boats, probes, and Wireless Sensor Networks (WSNW) for reservoir water quality monitoring, which was found to be more cost-effective, portable, and practical compared to traditional methods. It is acknowledged that modern sensors are now affordable, compact, and highly accurate, making them ideal for monitoring water quality parameters.

According to Calderwood et al. (2024), low-cost sensor networks (LCSNs) are becoming increasingly popular due to their affordability, ability to provide real-time data, and superior performance compared to conventional laboratory measurements. However, sensor hardware alone is not sufficient for a monitoring system; this software is also required to manage, clean, store, and visualize the data collected by sensors. Many commercial sensor network applications integrate real-time data streams with online analytics and visualizations to monitor human safety. Thus, groundwater chemistry has been widely utilised to assess water quality for drinking and irrigation purposes (Varol and Davraz, 2014).

Various factors influence groundwater quality, including the dissolution of rocks, precipitation, evaporation, and water recycling in irrigated areas (Shabbir and Ahmad, 2015). Additionally, the variation in groundwater quality is greatly influenced by geological formations and anthropogenic activities (Belkhiri and Mouni, 2012). To measure the potential or possibility of chemical and biological contaminants being present in the groundwater, the oxidation/reduction potential (ORP) is commonly utilized. The ORP is a device that measures the electron activity and serves as an indicator of a solution's ability to transfer electrons. It plays a crucial role in regulating the chemical composition of natural waters and sewage, depending on the level of solubility and reactivity (Račys et al., 2010). This reaction is particularly evident in water with high concentrations of nitrates, sulphides, and fluorides. It is concluded that the ORP values tend to rise in waters with elevated levels of sulphides, while they exhibit lower values in waters with high fluoride and manganese. The author (Račys et al., 2010) further indicated that the optimal oxidation-reduction potential (ORP) for drinking water is typically 250mV, with a pH range of 6.5-8.5. The ORP level should not exceed 300mV. Elevated levels of pH or ORP may indicate contamination by pollutants and the presence of Escherichia coli (*E. coli)* bacteria, rendering the water unsafe for consumption.

The key biological water quality monitoring parameters include *E. coli* bacteria and Faecal coliforms serve as a superior indicator of faecal contamination compared to other coliform bacteria. Its presence suggests the possible existence of harmful bacteria and pollutants. Detecting *E. coli* is a straightforward, quick, and cost-effective process that boasts high sensitivity. Laboratory experiments have shown that reporting bacterial concentration can take up to 24-48 hours (Khan and Gupta, 2020). To improve bacterial strain detection, more efficient and cost-effective techniques are necessary. Therefore, faecal indicator bacteria play a significant role in online monitoring efforts (Pachepsky and Shelton, 2011; Khan and Gupta, 2020). Furthermore, water quality regulators uses the level of *E. coil's* concentration to regulate the quality of water for drinking, irrigation, and other activities (Pachepsky and Shelton, 2011). Therefore, the existence of various pathogenic *E. coli* (e.g., enteropathogenic, enterotoxigenic, enterohemorrhagic *E. coli* strains) makes the choice of *E. coli* as a major contaminant even more appropriate. Hence, *E. coli* and faecal coliforms are the most crucial biological parameters for water quality that must be monitored. Notably, chemical parameters such as fluorides and sulphur are common groundwater pollutants in the Mpumalanga area due to active mining operations within the region. Thus, understanding the origin and composition of groundwater is fundamental for addressing water quality challenges and safeguarding public health and environmental integrity.

Drinking contaminated water, especially microbiologically contaminated water, has been linked to episodes of waterborne and water-related diseases, epidemics, and pandemics, leading to the transmission of diseases such as diarrhoea, cholera, dysentery, typhoid, and polio (Malebatja and Mokgatle, 2022). According to the WHO, the likelihood of contracting a waterborne disease rises with the level of contamination from pathogenic microorganisms. In the same way, the UN-Water (2018) reports that drinking contaminated water is linked to 80% of all diseases and over one-third of deaths in developing nations, with water-related illnesses resulting in losing one-tenth of a person's productive time. In addition, the presence of microbial contaminants in water sources has been associated with outbreaks of waterborne diseases, posing significant health risks to individuals and communities (Wang et al., 2020). Thus, real-time water monitoring is essential to provide an early warning signal that will assist in the prevention of outbreaks.

Quinn et al. (2022) identified that the GIS software within the systems facilitates that analysis and evaluation of spatial and temporal trends in water quality across a given watershed. Furthermore, the data obtained from the GIS software can furnish the necessary information for characterising the diverse loads emanating from urban and suburban land areas, support the creation of cognitive maps for stakeholders, and demonstrate the impact of their actions on water quality. Therefore, the use of IoTs for water quality monitoring using the real-time prototype sensors requires minimal start-up and maintenance costs, making them a suitable option for many municipalities that are faced with budget constraints on water monitoring.

3.2 Methodology and implementation within the laboratory

This section outlines the methods used to validate the accuracy of remote sensing of the groundwater quality prototype sensor for physical, chemical and biological parameters and its implementation. Both conventional laboratory methods and prototype remote sensors for groundwater quality detection were used. The conventional method for water quality monitoring is popular and used for monitoring of key parameters such as pH, temperature, electrical conductivity (EC), turbidity, fluorides, nitrates, sulphate and *E.coli*. The conventional water quality monitoring was used to validate the results detected through the remote sensing water quality prototype to determine its accuracy. The following methods and materials were used.

3.2.1 Detection of physical and biological parameters using conventional methods

A 1L water sample from a tap and a borehole was collected using a sterile water bottle. Distilled water was used to test the validity of all the equipment used, including the procedure to assess biological parameters. To detect physical parameters, a multi-electric electrode-HQ40D HACH, portable turbidity meter- HACH 2100P was used to detect the pH, temperature, electrical conductivity (EC) and turbidity. To detect chemical parameters, which are fluoride, sulphate and nitrate, a HACH DR/890 colorimeter was used following the manufacturer's instructions. Conversely, biological parameters such as *E,coli* were assessed. The 500 ml sterile sampling bottle was used to collect borehole and tap water for the detection of *E. coli*. The water was then put inside the cooler bag with an ice pack of less than 4 °C and transported to the laboratory and analysed within 6 hours. The water samples were then analysed using IDEXX Colilert 18 method and the manufacturer's instructions were followed.

3.2.2 Detection of water quality parameters using real-time remote sensing water quality prototype

The water sample that was initially used to detect physical and chemical parameters through conventional methods was also utilized to identify biological and chemical parameters through prototype sensors for water quality remote sensing. This innovative prototype was developed by the researchers within the laboratory setting and its components is represented in Table 5. The following equipment and materials were used.

Equipment and materials required:

- Groundwater quality sensor
- Calibrating solutions for pH, EC, and ORP sensors
- Distilled water for sensor cleaning
- Sterile glass beakers (250mL–500mL) for sample collection
- Magnetic stirrer (optional) to maintain sample uniformity.
- Laboratory gloves and safety goggles for contamination prevention
- Data logging software (if applicable)

Table 5: Key features of the groundwater quality monitoring system

FUNCTIONALITY	DESCRIPTION
1. Application and technical details of the proposed groundwater quantity monitoring system	
1.1 Application	Groundwater quantity parameters monitoring (*E.coli*, Fluorides, and Sulphur)
1.2 Monitoring Media	A borehole with a 160 mm diameter
1.3 Geo-referencing	Location of the well to be observed in real-time
1.4 Measuring depth range	4 meters to 17 meters depth (Validation within the laboratory)
1.5 Recording frequency	Real-time; 1-second minimum intervals
1.6 Sensor accuracy	0.5% digital and optical sensors
1.7 Sensing technology	Contact sensor with advanced, IoT-enabled technology
1.8 Sensor mounting	Inserted within the monitoring well
1.9 Robustness and reliability	Sensor robust to withstand environmental conditions
10.0 Multiparameter	*E. coli*, Fluorides, and Sulphur
11.0 Portability	5 kg/10lbs
12.0 Self-cleaning	Low maintenance
2. Technical Details for Data Logging and Transmission	
2.1 Recording frequency	Real-time to near-real-time (1s), 5 minutes, hourly to daily
2.2 Data transmission	Real-time data transmission and display, (send real-time data at remote locations through wi-fi

2.3 Data logger	• No loss of data due to power failure or signal loss. • Ability to download data without ceasing measurement
2.4 Scalable	The data acquisition system must be adaptable to a larger scale without sacrificing performance
2.5 Modular design	Subsystems and components need to accommodate new technologies without affecting the design of others
2.6 Power supply	Internal or external battery and a solar panel. The lifespan of the battery should be at least one year
2.7 Security	Components are to be packaged in a manner that the monitoring system will be less vulnerable to theft and vandalism
2.8 Lightning protection	Required
2.9 Connecting cables	Required
2.10 Wi-fi connection	Wi-fi router required
2.11 Mobile connection	Mobile internet, such as 5G/4G/Satellite connectivity, is a major requirement

The prototype was set up in the laboratory and was able to measure the correct values of groundwater pH level and electrical conductivity from different water samples. The following procedure and apparatus were used to calibrate the sensors:

- DFR Analog pH Level and Electrical conductivity sensors
- DS18b20 waterproof temperature sensor
- Glass beaker
- Distilled water and buffer solutions
- Computer

Three sensors for water quality pH, electrical conductivity, temperature and ORP were cleaned and calibrated by immersing them in distilled water and buffer solutions, with their input probes linked to a microcontroller. The pH, turbidity, electrical conductivity and ORP (Chemical/biological) sensors were connected to the analogue ports, while the temperature sensor was attached to the digital port of the microcontroller. The data collected was presented on the IoT analytical platform, ThingSpeak. The setup of the monitoring prototype is illustrated in Figure 40. This prototype was designed to incorporate the pH, turbidity, electrical conductivity, and temperature sensors, along with an ORP sensor, which serves as an indicator for the presence of sulphides, nitrate, fluoride, and *E. coli* in groundwater. The prototype developed is shown below.

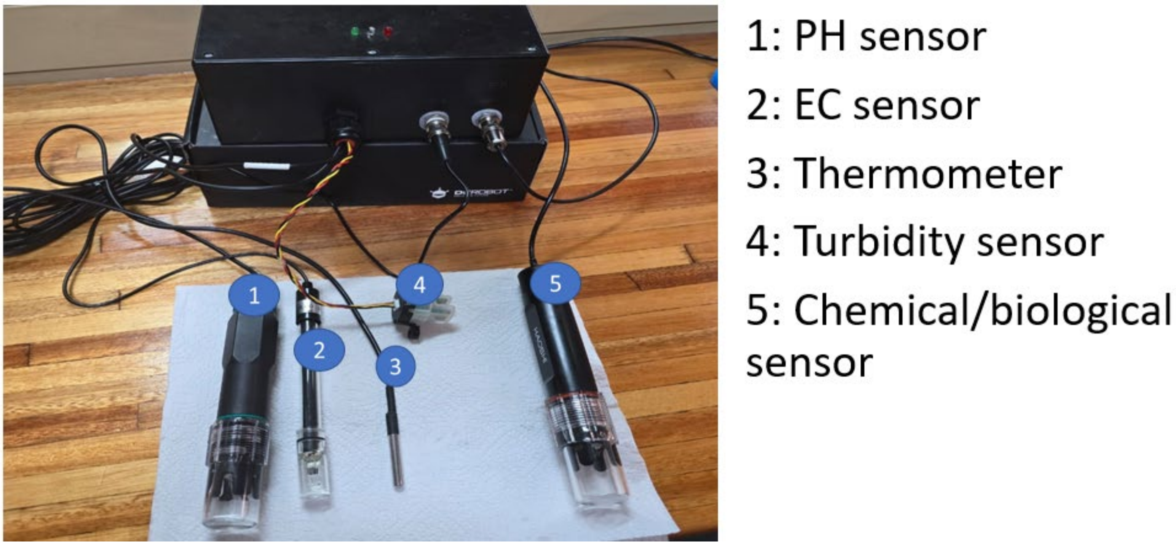


Figure 40: Water quality monitoring prototype

3.2.3 Calibration and implementation of water quality remote sensor in the laboratory setting

Sensor calibration and setup

To set up the prototype, sensors were connected to the main control unit using the designated ports, ensuring a secure and stable connection. The power was then switched on the system. The probes were cleaned with distilled water before placing them into the water source, to remove any contaminants. The sensor was then submerged into the water, positioning it correctly for accurate and consistent measurements. Finally, the readings appear on the computer dashboard, where the data is be displayed in real time using the ThingSpeak program.

3.2.4 Calibration procedure for the sensors used to detect physical parameters

pH Calibration

To calibrate a remote pH sensor (pH meter or probe), a standard pH buffer solution with known and stable pH values is used to ensure accurate measurements. The Standard pH Calibration Solutions were used as shown in Table 6 followed by calibration steps 1 to 6.

Table 5: pH sensor calibration values

Buffer Solution	pH Value at 25°C	Purpose
pH 4.00	4.00	Acidic calibration point
pH 7.00	7.00	Neutral calibration point
pH 10.00	10.00	Alkaline calibration point

Step 1: To calibrate a pH sensor, prepare fresh, high-quality pH buffer solutions. Ensure that the solutions are not expired or contaminated. The small amounts of the buffer solution are poured into separate clean beakers at a temperature of 25°C. Then the pH probe is rinsed with distilled water and gently blotted dry with a lint-free tissue to avoid static interference.

Step 2: Then the sensor is immersed in the first buffer solution, starting with pH 7.00 (neutral), and stirred gently to remove any trapped air bubbles.

Step 3: Observe and allow the reading to stabilise for 30–60 seconds, then adjust the meter if necessary to match the exact pH of the buffer.

Step 4: Rinse the probe with distilled water before moving on to the next buffer solution, typically pH 4.00 (acidic) or pH 10.00 (alkaline), and repeat the process, adjusting as needed.

Step 5: Finally, confirm calibration by testing the sensor in a known buffer or sample to verify its accuracy.

Step 6: Important pH calibration considerations. To determine accurate pH measurements, always use fresh buffer solutions, as pH buffers degrade over time and may lead to inaccurate readings. Since temperature affects pH measurements, it is recommended to use a meter with automatic temperature compensation (ATC) to ensure precision. Regular calibrations are essential, with daily calibration for high-precision applications and weekly calibration for general use. Proper storage of the pH electrode is crucial—always keep the sensor moist in a specialized storage solution, as storing it in distilled water can damage the probe and affect performance.

Turbidity calibration

To calibrate a turbidity sensor. distilled water is used for zero calibration, and a known turbidity solution is used for verification. The standard turbidity calibration solutions were used as outlined in Table 6. followed by calibration from step 1 to 3.

Table 6: Turbidity calibration values

Calibration Standard	Calibration Standard	Calibration Standard
0 NTU (Distilled Water or Formazin Dilution)	0 NTU (Distilled Water or Formazin Dilution)	0 NTU (Distilled Water or Formazin Dilution)
1 NTU Standard	1 NTU Standard	1 NTU Standard
10 NTU Standard	10 NTU Standard	10 NTU Standard
100 NTU Standard	00 NTU Standard	00 NTU Standard
800 NTU Standard	800 NTU Standard	800 NTU Standard

Step1. Prepare the calibration standards

To achieve accurate turbidity measurements, it is essential to use fresh, high-quality turbidity standard solutions. These solutions should be carefully handled to maintain their integrity and reliability. Before use, ensure that they are well-mixed by gently inverting the container rather than shaking it, since excessive agitation may introduce air bubbles that can interfere with readings. Additionally, it is important to store and use the solutions at room temperature, between 20 and 25°C, to prevent fluctuations in turbidity values due to temperature variations.

Step 2. Rinse and clean the sample cell

To maintain the accuracy of turbidity measurements, it is important to keep the cuvette clean and free of any contaminants. Use lint-free wipes to carefully remove fingerprints, dust, or residues that could interfere with light transmission and affect readings. Additionally, rinse the cuvette with distilled water before use to prevent contamination from previous samples or cleaning agents.

Step 3: Important pH calibration considerations

For accurate turbidity calibration, it is essential to use a standard formazin turbidity solution, such as 920 NTU or 100 NTU. Ensure that the sensors are thoroughly cleaned with distilled water before and after calibration, to remove any contaminants or residues. To ensure Zero and high-range calibration, steps 1 to 4 are followed.

Step1: Zero calibration (0 NTU)

For a zero-range calibration, fill the sample cell with either distilled water or a standard solution with a range of 0.02 to 0.1 NTU. Insert the cuvette into the turbidity meter and adjust the reading to zero NTU to establish a baseline. Next, proceed with the primary calibration point using a 10 NTU standard. Fill the cuvette with the standard solution, insert it into the meter, and allow it to stabilise. If necessary, adjust to ensure accurate calibration.

Step 2: High-range calibration (e.g., 100 NTU or 800 NTU)

For a high-range calibration, the zero-range calibration should be repeated with a higher NTU standard. Further measures should be taken to ensure that the readings match the expected values.

Step 3: Verify calibration

After calibration, the probe should be measured with a known standard (e.g., 1 NTU) to check accuracy.

Step 4: Important calibration considerations

To maintain accurate and reliable turbidity measurements, it is crucial to use fresh calibration standards. When preparing and handling the cuvette, take care to avoid air bubbles, as they can artificially increase turbidity values and lead to incorrect results. Additionally, handle cuvettes with caution, ensuring they remain free of fingerprints, scratches, or residues that could interfere with light scattering and compromise measurement accuracy. Regular calibration is essential, with daily calibration recommended for high-precision monitoring and weekly calibration sufficient for general use. Adhering to these best practices ensures consistent and dependable turbidity readings.

3.2.5 Calibration procedure for the sensors used to detect chemical and biological parameters

ORP calibration

Use distilled water to clean the tip of electrode and place the electrode into the first standard. immediately when the voltage reading is displayed, and the data-collection program stabilises, enter the mV value of the first ORP standard, which is 100.

To determine the second calibration point, first remove the electrode from the first standard, rinse it with distilled water, and place it into the second standard until the voltage stabilizes. Then, enter the mV reading of the second standard which is 300. Rinse the electrode with distilled water and place it into the water sample for accurate results. The ORP standard is shown in Table 7 followed by calibration step 1 to 2

Table 7: ORP standard values

Temperature ^{0}C	ORP value	Temperature ^{0}C	ORP value
0	277	30	251
5	272	35	247
10	269	40	242
15	264	45	237
20	260	50	232
25	260	55	227

Step 1: Sample collection

The drinking water sample collected uses ORP/ temperature standard values as shown in Table 8. Measures should be taken to ensure that samples are collected in sterile glass beakers to prevent contamination. The temperature should remain constant to avoid fluctuating readings.

Step 2: Sample handling

When multiple parameters are measured, ensure continuous stirring using a magnetic stirrer. Further measures should also be taken to avoid exposing samples to direct sunlight to prevent chemical changes.

3.2.6 Implementation for data acquisition, logging and analysis

After the calibration of pH, EC, pH, turbidity, and Oxidation-Reduction Potential (ORP) sensors, the water samples were analysed using the multi-prototype sensor to provide real-time measurements as outlined from step 1 to step 5.

Step 1: Immerse the sensor probes

The sensor probe is submerged 5 cm below the water surface for accurate readings. Further measures should be taken to ensure that no air bubbles are trapped around the probe.

Step 2: Data logging and analysis

An automated data logging software for real-time monitoring and analysis is used for data logging and analysis. In this regard, ThingSpeak is used for real-time monitoring. The results are then compared to the data obtained from conventional analysis. All the results obtained are then compared with the water standard following water quality guidelines (e.g., WHO, SANS).

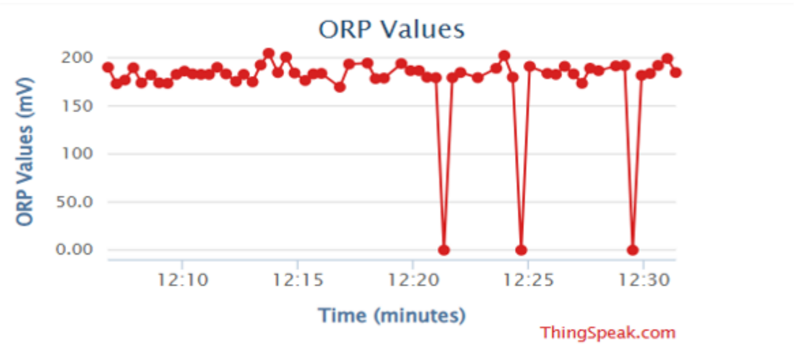
Step 3: Data recording and interpretation

To obtain data records, readings are permitted to stabilise for at least 30–60 seconds before recording. Record the temperature, pH, EC, turbidity, and ORP values and repeat the measurements at least three times for accuracy. Values of pH, EC, turbidity from conventional methods are the same as those measured from the sensors. However, ORP shows both values for chemical and biological measurements as explained in Table 8 and Figure 41.

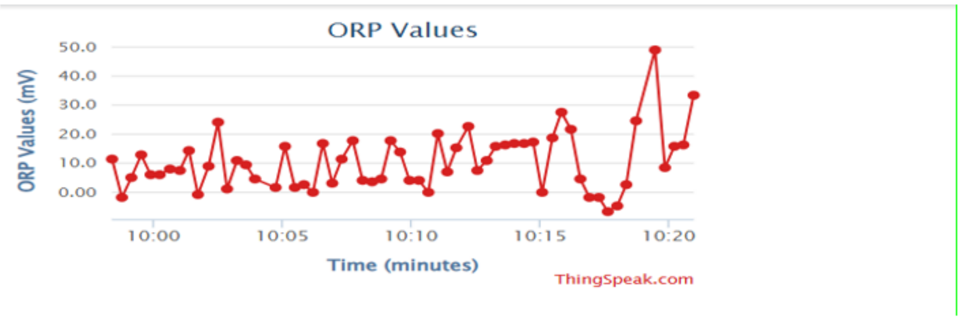
Table 8: Chemical measurements from ORP sensor

Fluoride	**Chemical value**	**Interpretation**
1mg/L	332.73mV	Higher Chemical prototype levels above 459mV indicate high levels of fluoride
1,5mg/L	459.8mV	
2mg/L	583.88mV	
Nitrate		
10mg/L	469.45mV	Chemical prototype levels below 200mV indicate high levels of Nitrates
50mg/L	457.73mV	
80mg/L	179.3mV	
Sulphates		
100mg/L	415.73 mV	Chemical prototype levels below 300mV indicate high levels of sulphates
250mg/L	454.8 mV	
500mg/L	288.98 mV	

High Oxidation-Reduction Potential (ORP) values exceeding 459 mV may indicate higher fluoride concentration levels. Conversely, low ORP values ranging between 200 and 300 mV may suggest a likelihood of elevated nitrate and sulphate levels, which can have adverse health effects. When these ORP values are detected, it is essential to conduct a laboratory analysis to confirm the actual concentrations of *E. coli*. fluoride, nitrate, and sulphate and assess any potential health risks.



ORP values with low concentration of *E-Coli* contaminated water



ORP values with low concentration of *E-Coli* contaminated water

Figure 41:E.Coli Measurements from ORP

- 1 mL of contaminated water was added to the distilled water. The ORP values remained relatively high, ranging between 150 and 200 mV, indicating a more oxidising environment with some microbial influence.
- In Figure 41, a higher contamination level was introduced, with 10 mL of contaminated water added. This resulted in a significant reduction in ORP, with values dropping to between -10 and 50 mV, suggesting a strongly reducing environment favourable for bacterial activity.

These results indicate that higher concentrations of *E. coli* lead to lower ORP levels, likely due to increased microbial respiration and oxygen consumption, which create reducing conditions in the water.

Step 4: Cleaning and storage

Ensure that the probes are cleaned with distilled water and are dried properly. Probes should be stored in appropriate storage solutions (e.g., KCl solution for pH probes).

Step 5: Quality assurance and troubleshooting

To do a quality assurance and troubleshooting performs a weekly calibration check. Cross-validate the results using secondary laboratory methods (e.g., titration for pH and DO). If the sensor readings fluctuate abnormally, conduct troubleshooting as per manufacturer's instructions.

The objective of the water quality field tests was to assess the performance and dependability of the IoT groundwater quality monitoring prototype in real-world settings. The prototype is designed to measure physical, chemical, and biological water quality parameters. This water quality prototype was tested in borehole water tanks across five strategic locations. The purpose of the field test was to evaluate the prototype's accuracy in tracking groundwater quality parameters i.e. physical, chemical, and biological, across diverse environmental conditions. Beyond performance evaluation, these field tests were crucial in identifying practical operational challenges, such as sensor functionality, data transmission efficiency, and the system's vulnerability to external factors like vandalism and inclement weather

3.3 Field test methods and implementation

To assess the functionality and reliability of the IoT groundwater quality monitoring prototype, a field test was conducted. The main control unit of the prototype was connected to a battery power source and linked to a Wi-Fi network to enable real-time data transmission. The sensors for were securely attached to the main control unit. Subsequently, all sensors for temperature, electrical conductivity, pH, ORP and turbidity, were submerged in the borehole water tanks as shown in Figure 40. The prototype sensors were submerged in water for four hours, allowing continuous data collection. Throughout the testing period, the sensor readings were monitored and recorded via the ThingSpeak IoT platform, enabling remote access to real-time data.

3.3.1 Description of test field site

The field tests were conducted within the Nkangala District Municipality, Mpumalanga province, South Africa. Nkangala District municipality consist of six local municipalities (Figure 42), which include Emakhazeni, Steve Tshwete, Emalahleni, Victor Khanye, Thembisile Hani, and Dr. JS Moroka, as shown in Figure 42. Among these, Emalahleni Local Municipality has the largest population, estimated at 395,466, representing 30% of the total population within the district. This is followed by Thembisile Hani Local Municipality, with a population estimate of 310,458, or 23.7%. Dr. JS Moroka Local Municipality accounts for approximately 249,705 residents, which is 19% of the total, while Steve Tshwete Municipality has a population of 229,831, comprising 18%. Furthermore, Victor Khanye Local Municipality has 75,452 people, or 5.8%, and Emakhazeni Local Municipality is the smallest, with a population of 47,216, constituting 3.6% of the total. Collectively, the district municipality distance area is approximately 16,892 square kilometres. The field tests were conducted at the Steve Tshwete local municipality where pilot study was conducted. The other sites: Thembisile Hani, and Dr. JS Moroka were chosen by the municipality officials because the areas rely on borehole water for drinking and other activities.

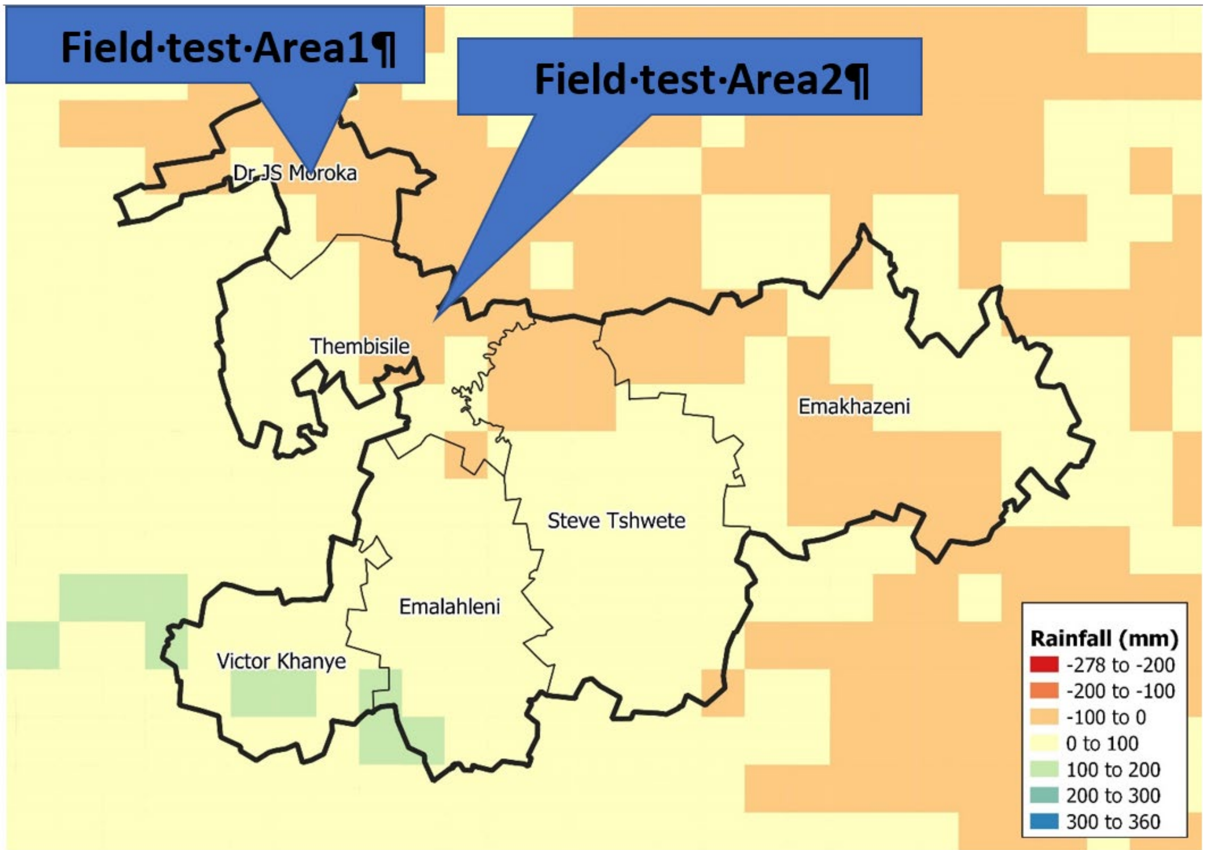


Figure 42:Nkangala District Municipality Map (Municipalities South Africa Maps. 2020)

3.3.2 Farm field test

The first site visit was at the farm shown in Figure 42 which is one of the areas using borehole for water for consumption within Steve Tshwete local municipality. The site was previously used in an earlier study phase and was again identified as a pilot location for the current project. The selection was based on several key factors:

- Inconsistent water quality findings: Prior research has revealed variable water quality in the area.
- Significant occupancy and activity: Despite being privately owned, the location serves a diverse group of individuals, including both local and international visitors. Additionally, it provides housing for community members employed on the farm and adjacent agricultural properties.
- Agricultural operations: The area features a crop farm that relies on the same borehole water for its irrigation needs.

The first field pilot tests were conducted on a farm that relies on borehole water for drinking and farming activities. The prototype was assessed for its functionality and reliability within the area. Figure 43 shows the position of the main control unit and how the sensors were submerged in the water tank.

Figure 43:Farm water tanks and borehole

3.3.3 Nkangala District Municipality Field Test Sites

The municipal area where field tests were conducted included Nokaneng and Libangeni fire station within the DR JS Moroka local municipality; Moloto Community Health Centre and Ndzudza Mabusa Tribal Offices situated in Thembisile Hani local municipality as shown in Figure 44. The water in both fire stations was not stable as it was being transferred to the other tank.

a) Nokaneng Fire Station

b) Libangeni Fire Station

c) Moloto Community Health Centre

d) Ndzundza Mabusa Tribal offices

Figure 44: Municipal Field tests sites

In Moloto Community Health Centre, the borehole pumps water into the water tank positioned on the ground, which feeds the elevated tank. Ndzudza Mabusa tribal was the only one which was fitted with filters before the water was pumped to the elevated tanks as shown in Figure 44 All filled tests sites visited use boreholes and wells drilled on the site.

3.4 Field test results

3.4.1 Farm field test

The first pilot field test aimed to evaluate the functionality and reliability of the IoT groundwater monitoring prototype under real-world conditions and was conducted in the farm. Water was tested for temperature, electrical conductivity, pH, ORP, and turbidity. The results from ThingSpeak are depicted in Figure 45.

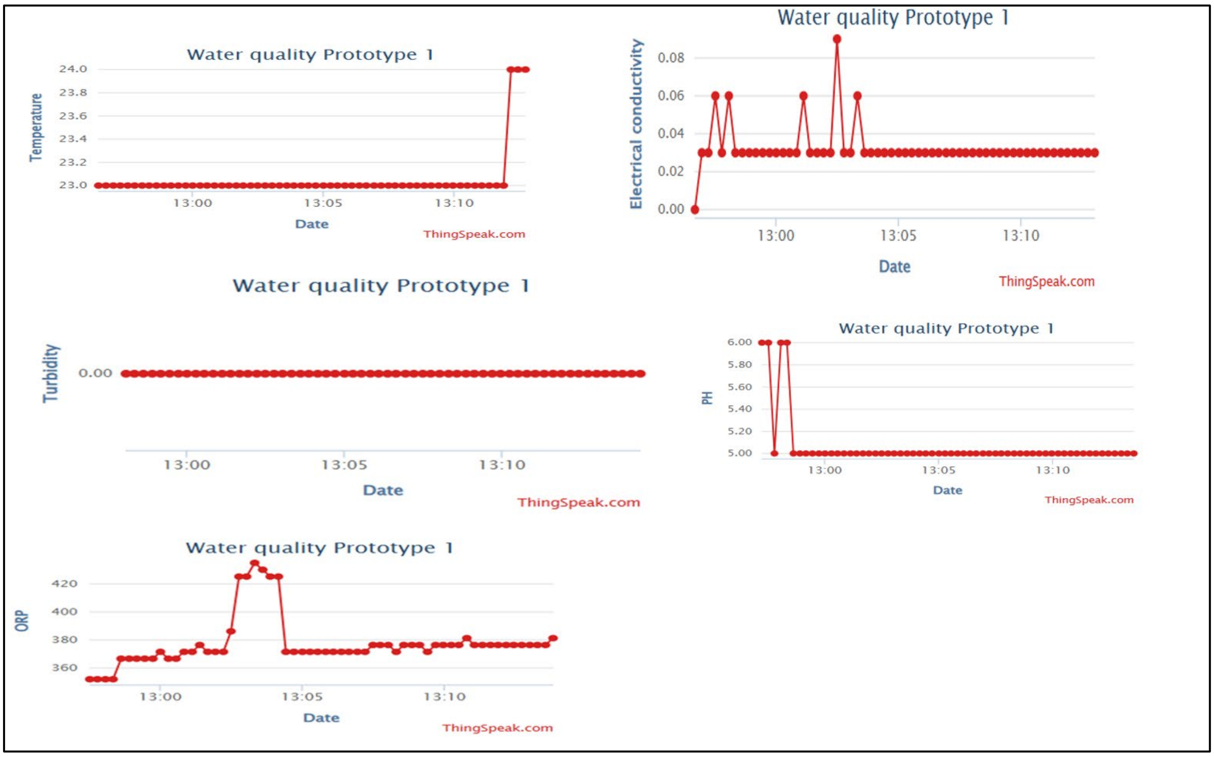


Figure 45:ThingSpeak display for the farm tank

Temperature

The temperature in farm water tanks remained stable Figure 45 at 23.0°C for most of the recorded period. However, there was a sudden spike around 13:10, jumping from 23.0°C to 24.0°C as the area was becoming warmer. This spike indicate that the sensor can sense changes in water temperature.

Electrical conductivity

As reflected in Figure 45 EC started at a low value of 0.00 and rose sharply to about 0.03 before 13:00. This suggests an initial adjustment phase of the sensor when submerged in water. Between 13:00 and 13:05, there are multiple spikes, with the highest reaching 0.08. After 13:05, the EC readings become more stable, maintaining a consistent value around 0.04.

This suggests that the prototype sense the changes when there was a movement of water to the other tanks and when there was no movement of water in the tank. The water Electrical conductivity become stable after variations because the water was stable (See Figure 45).

pH

The pH readings indicated in Figure 45 display sharp fluctuations between 5.0 and 6.0 before stabilising. Furthermore, the fluctuations in the pH value could be due to water movement, as the borehole pump was operating during the measurement.

Oxidation-reduction potential (ORP)

The ORP values started at 360 mV and remain relatively stable for a brief period. A sharp spike reaching 420 mV occurs around 13:03 to 13:05, followed by a rapid decline. After the spike, the ORP values stabilise around 380 mV, indicating that the water has reached a balanced oxidation-reduction state following the fluctuation due to water movement Figure 45.

Turbidity

As shown in Figure 45, the value of turbidity remained constant at 0.00 NTU.

General observations and interpretation of results

- Visible fluctuations in temperature suggest that the sensor is able to detect variations correctly.
- Spikes in electrical conductivity may indicate: (i) the adjustment of the sensor to the water conditions, resulting in unstable initial readings; (ii) disturbances in the water, such as movement or bubbles from the borehole pumping water into the tank, alongside minor variations in dissolved ions due to the mixing of the tank water and the pump water.
- The Ph level of 5 suggests that the water is slightly acidic in nature.
- The ORP values indicate an oxidising environment, with levels stabilising around 380 mV after an initial fluctuation. The final stable readings suggest reliable data collection once the system settled.
- Constant 0.00 NTU suggests that water has no detectable suspended particles or sediment.

3.4.2 Nokaneng fire station field test

The second field test was conducted at Nokaneng Fire Station. The results obtained in Nokaneng are depicted in Figure 46.

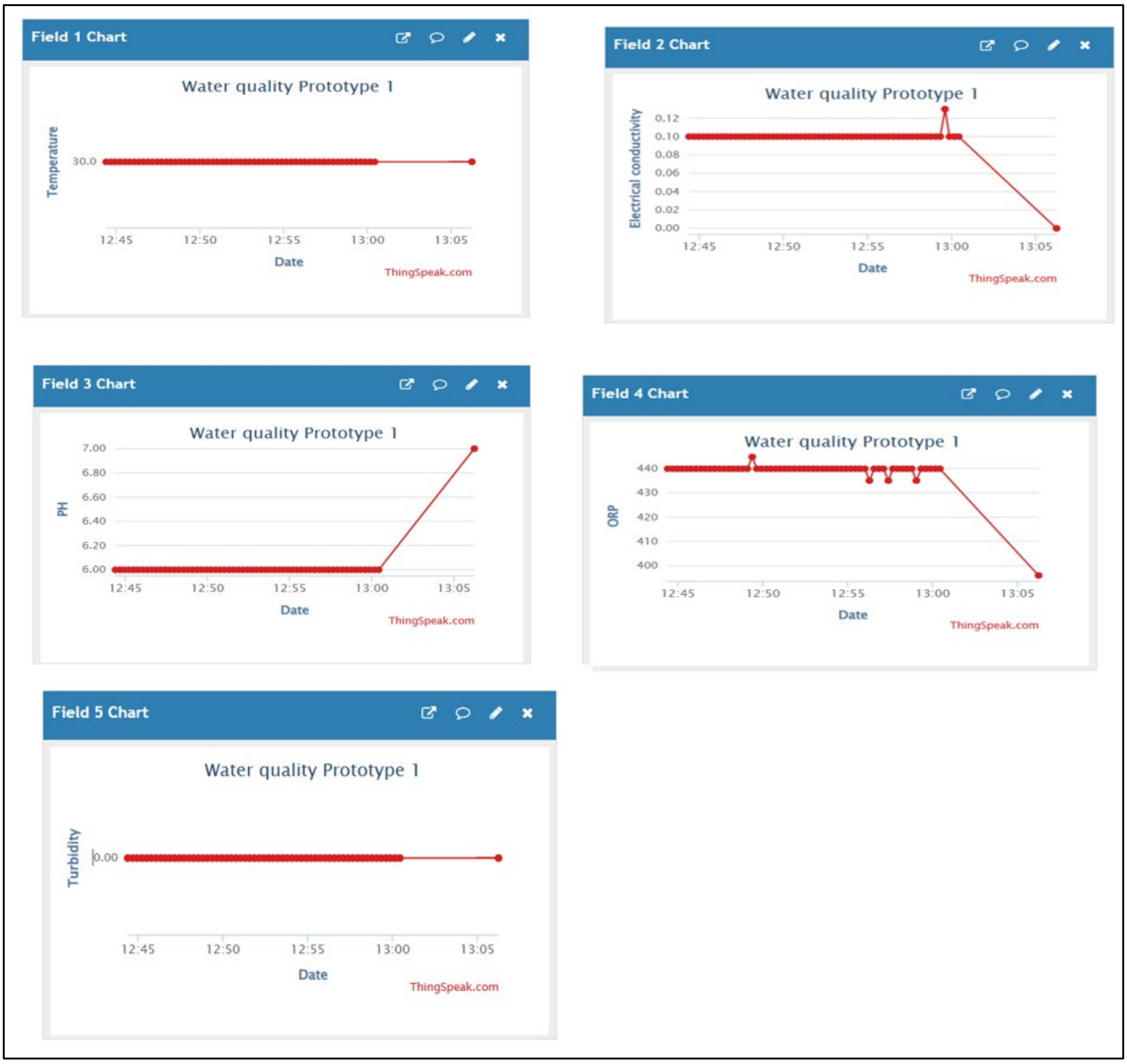


Figure 46:ThingSpeak display for Nokaneng

Temperature

As shown in Figure 46 recorded a stable temperature of 30.0°C over the entire observation period.

Electrical conductivity

As depicted in Figure 46 the electrical conductivity remained consistent at 0.10 for most of the recorded time except between 13:00 and 13:05 where there was a sudden decline.

pH

As shown in Figure 46, the pH remained steady at 6.0 throughout most of the recorded period. However, at 13:00, the sensor registered a flat line, followed by a sudden spike in pH.

Oxidation-reduction potential (ORP)

As shown in Figure 46 the ORP remained stable at approximately 440 mV throughout most of the recorded period. However, at 13:00, a sharp decline occurred, dropping from 440 mV to 400 mV.

Turbidity

The turbidity remains constant at 0.00 NTU throughout the recorded period as appeared in Figure 46.

General observations and interpretation of results

- The prototype lost connectivity between 13:00 and 13:05. Further investigation is needed to determine connectivity issues.
- The temperature remained constant throughout the sampling period, and this could be due to the water tank being housed in a controlled environment. The straight line between 13:00 and 13:05 suggests a possible lack of connectivity or data transmission failure. Further checks on the sensor and network stability are recommended to confirm the cause.
- The initial stable electrical conductivity (EC) readings indicate a consistent level of dissolved ions in the water, suggesting a stable water composition. However, the sudden drop to 0.00 suggests a complete loss of conductivity readings, which could be due to sensor disconnection or a technical malfunction. Further investigation is required to determine the cause of this sudden decline.
- The initial stable pH of 6.0 indicates that the water was slightly acidic and remained consistent over time. However, the sudden spike to 7.0 suggests a rapid shift in water chemistry or a possible sensor anomaly. Further investigation is required to determine whether this change reflects an actual alteration in water composition or a technical issue with the sensor.
- The sharp decline in ORP near 13:00 indicates a sudden disturbance in readings, which may be due to sensor disconnection.

3.4.3 Libangeni fire station field test

The ThingSpeak results obtained at Libangeni are shown in Figure 47.

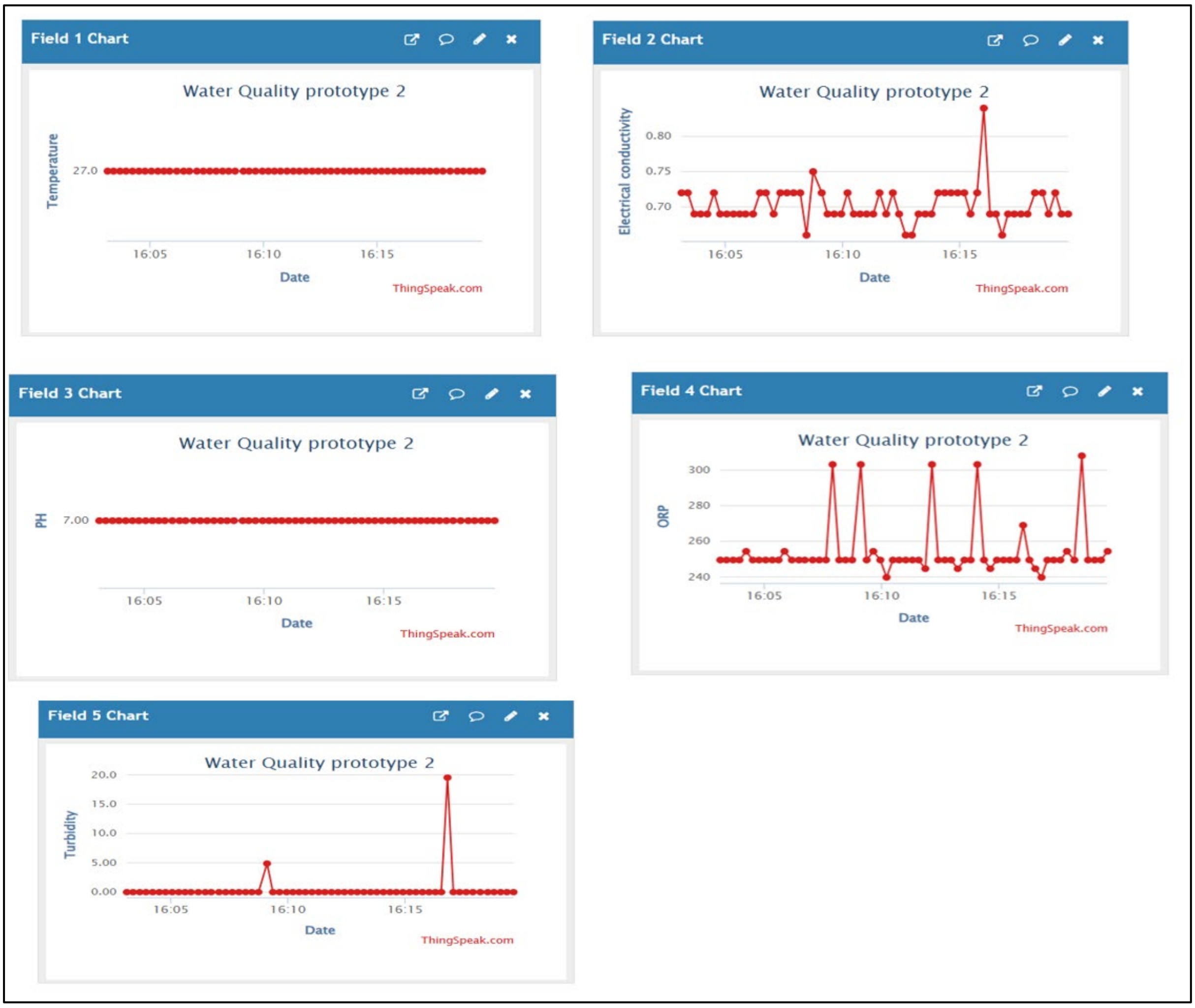


Figure 47:ThingSpeak display at Libangeni

Temperature

Figure 47 shows a constant temperature throughout the recorded period, at 27.0°C.

Electrical conductivity

As shown in Figure 47 the electrical conductivity (EC) fluctuates throughout the recorded period, reflecting variations in ion concentration. The readings predominantly range between 0.70 and 0.75 mS/cm, indicating dynamic water conditions with continuous changes in dissolved ion levels.

pH

The pH levels remained constant at 7 throughout the recorded period

Oxidation-reduction potential (ORP)

As shown in Figure 47, the ORP value of the sensor fluctuates between 300 and 240, with the average readings at 250mV.

Turbidity:

Turbidity levels, as in Figure 47, show constant levels on 0.00 NTU, with minor spikes.

General observations and interpretation of results

- Constant temperatures in the external environment may indicate a lack of mixing or water movement, leading to a uniform temperature distribution within the system.
- The continuous fluctuations in EC indicate dynamic water conditions with varying ion concentrations. Further investigation is needed, and extended observations will help determine whether these fluctuations follow a consistent pattern or are isolated anomalies.
- The average ORP baseline of 250 mV indicates moderate oxidation activity, however, the frequent spikes and drops suggest potential instability. Further investigation is required to determine whether these fluctuations are natural variations in water chemistry or sensor-related anomalies.
- Spikes on the turbidity sensor require further investigation into its accuracy.

3.4.4 Moloto Community Health Centre field test

The ThingSpeak results obtained at Moloto Community Health Centre are shown in Figure 48.

Figure 48:ThingSpeak display at Moloto

Temperature

Displays a consistent temperature of 30.0°C for most of the recorded period, with intermittent straight lines suggesting possible data transmission gaps or sensor stability issues.

Electrical conductivity

Figure 48 shows consistent Electrical conductivity with frequent spikes. The readings range between 0.11 and 0.14. the graph further shows connectivity issues between 16:00 and 16:05, and just before 16:10.

pH

The pH remained stable at 6.00 throughout the recorded period, indicating a slightly acidic water condition with no significant fluctuations as shown in Figure 48.

Oxidation-reduction potential (ORP)

As depicted in Figure 48 the ORP value starts at around 200 mV, indicating moderate reduction potential in the water. Several fluctuations were also observed, along with loss of connectivity.

Turbidity

As observed in Figure 48, there is a sharp increase in turbidity at 15:50, reaching 5.00 NTU. After the spike, turbidity drops back to 0.00 NTU and remains constant for the rest of the recorded period.

General observations and interpretation of results

- The prototype showed regular loss of connectivity, Further investigation is required to check the loss of connectivity,
- The straight lines on the temperature graph show that the IoT system experienced a brief power fluctuation or connectivity issue.
- Fluctuations on Electrical Conductivity require further investigation to determine if natural water variations or sensor-related issues cause them.
- Fluctuations on ORP require further investigation to determine whether these variations result from natural water chemistry changes or sensor-related issues.
- The spike in the turbidity indicates a sudden introduction of sediments or bubbles, in the water tank which could be due to the mixing of water because of water movement.

3.4.5 Ndzundza Mabusa Tribal offices field test

The measurements obtained at Ndzundza Mabusa are shown in Figure 49.

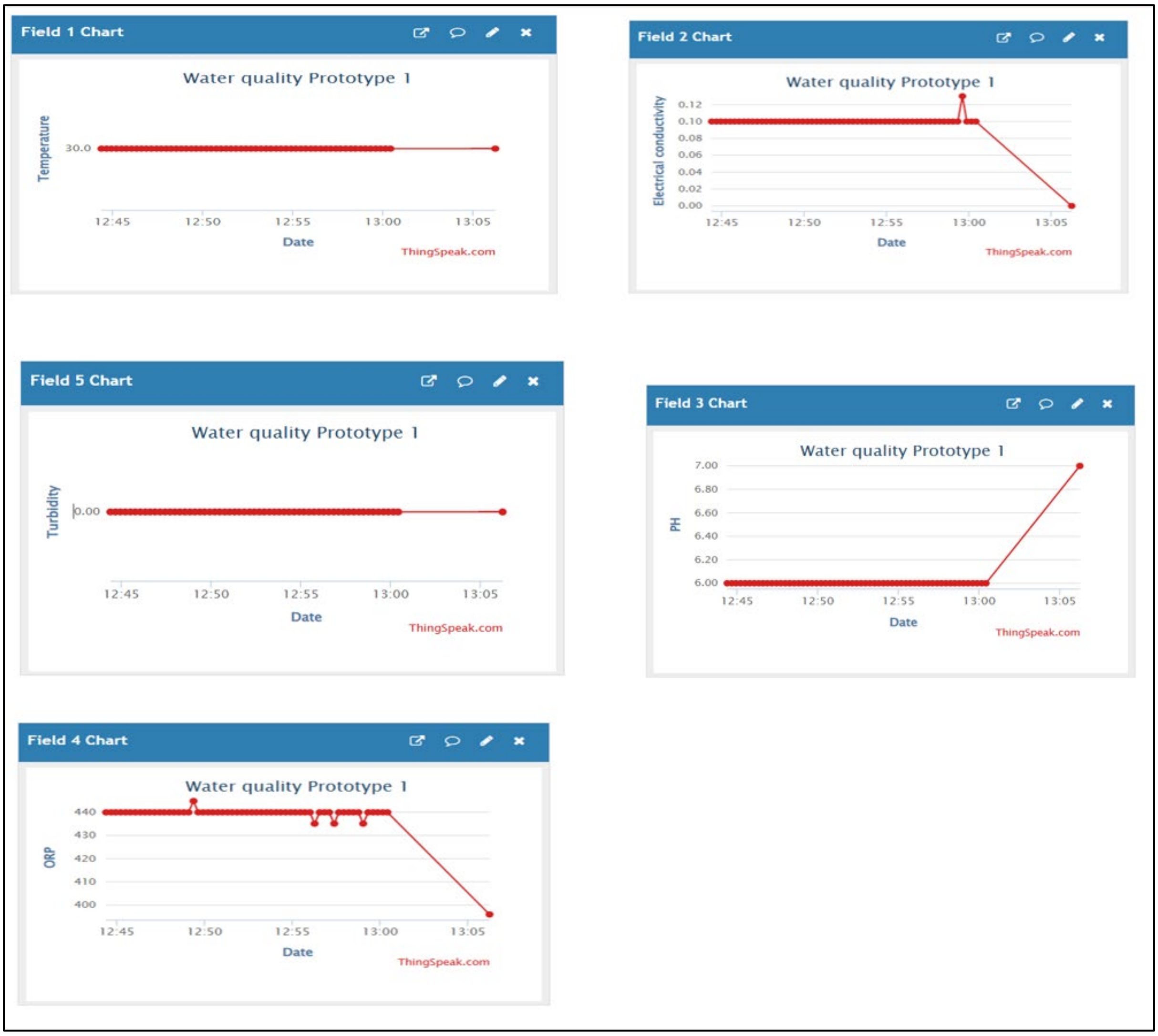


Figure 49:ThingSpeak display at Ndzundza Mabusa

Temperature

As shown in Figure 49, the water temperature at Ndzundza Mabusa Tribal offices remained stable at 30.0°C throughout the recorded period, except for the interval between 13:00 and 13:05, where there was no network access.

Electrical conductivity

Figure 49 shows a stable Electrical Conductivity at 0.10 mS/cm for most of the recorded period.

pH

As shown in Figure 49, pH remained constant at 6.00 throughout most of the recorded period. Suggesting a slightly acidic water condition.

Oxidation-reduction potential (ORP)

Figure 49 shows a stable ORP of around 440 mV for most of the recorded period. It further shows a loss of connectivity from 13:00 followed by a sudden drop from 440 mV to 400 mV at 13:05,

Turbidity

The turbidity remains constant at 0.00 NTU throughout the recorded period as in Figure 49.

General observations and interpretation of results

- The sensor had consistent values until it loses connectivity at 13:00. It is recommended that further investigations be conducted to check the cause of conductivity loss.
- The stable pH of 6.00 suggests initial water acidity, but the sudden jump to 7.00 indicates a significant shift in water chemistry or sensor behaviour. Further investigation is required to determine whether this change was due to natural causes or technical errors.
- Further investigations are required to determine the loss of connectivity.

3.5 Associated field risks of prototype sensors

As with any developed prototype, there are inherent risks associated with this groundwater quality IoT-based monitoring prototype.

The potential risks that are associated with this prototype can be categorised into the following:

Technical risks:

- Hardware malfunction: During the field test, the prototype may experience hardware malfunctions, leading to inaccurate data collection or complete system failure.
- Connectivity issues: The prototype relies on a stable internet connection to transmit data to the central monitoring system. Any connectivity issues could impact the data collection and analysis.

- Power outages: If the prototype is not equipped with a backup power source, it may experience power outages, leading to data loss and interruptions in the monitoring process.
- Software glitches: The software used to collect and analyse the data may have glitches or bugs resulting in incorrect data readings.

Environmental risks:

- Weather conditions: Extreme weather conditions such as heavy rain, lightning, or high winds can damage the prototype and impact its functionality.
- Physical obstructions: The stability of the measurements fluctuate when there is a movement of waters in the tank or pipe.
- Poor positioning and stability of the water prototype can cause damage to prototype
- Vandalism or theft: The prototype could be at risk of vandalism or theft, especially when installed in a remote location.
- Chemical contamination: Therefore, the quality unit is prone to chemical contamination, damage, and malfunction. Furthermore, since the prototype cannot self-clean, the residue from the previous readings can lead to false readings and negative results.

Financial risks:

- Lack of return on investment: If the prototype does not perform as expected or does not provide valuable data, it may result in a lack of return on investment.
- Cost of equipment: The cost of the prototype and its installation can be significant, and any damage or malfunction could result in a financial loss.

Identifying and addressing these risks is essential to ensure a successful and safe field test and prototype deployment.

3.5.1 Mitigation of potential risks

To mitigate these risks, thorough testing and quality control before the field tests is essential. The prototype should also be regularly maintained and monitored during and after the field tests the field test period. Adequate insurance coverage should be obtained, and contingency plans should be in place for unforeseen circumstances. The following procedures have been identified for risk mitigation.

Mitigation against technical risks:

- Regular maintenance and calibration: The monitoring prototype should be regularly maintained and calibrated to ensure accurate and reliable readings of groundwater parameters. This will help in identifying any potential issues or malfunctions in the system. Further improvements are also needed in the quality unit to enhance its performance and accuracy.
- Backup power source: It is important to have a backup power source for the monitoring prototype in case of power outages or failures. This will ensure continuous monitoring and data collection even during power disruptions. In this case, solar PV and rechargeable batteries have been used.
- Data validation and quality control: The collected data should undergo a validation process to check for any anomalies or errors. Quality control measures should also be implemented to ensure the accuracy and integrity of the data.
- Security measures: The monitoring prototype should have appropriate security measures in place to protect the data from unauthorized access. This includes encryption of data, restricted access to the system, and regular backups of data.
- Professional handling: This prototype should be handled and maintained by professionals to prolong its usage.
- Height of the tanks: Most borehole tanks are elevated, which poses challenges related to accessibility, maintenance, and potential exposure to harsh environmental conditions.
- Solution: Implementing a secure yet accessible mounting structure
- Solar system theft: Given the reliance on solar power to operate the IoT prototypes, there is a significant risk of theft or vandalism involving solar panels and their associated components.
- Solution: Installing tamper-proof enclosures and securing the solar panels with theft-resistant mounting brackets. Additional strategies may include connecting to the electricity supply and adjusting power to accommodate the prototype.

- Short cables: The length of cables for sensors measuring temperature, electrical conductivity, and turbidity was identified as a concern. This limited the flexibility in the deployment of the prototype.
- Solution: Extending the length of sensor cables to allow for greater flexibility in positioning the monitoring equipment
- Rusting of the turbidity meter when submerged in water: It is essential to ensure that the turbidity meter is waterproof to maintain its durability and functionality in various water conditions.
- Solution: Applying waterproof coatings or protective casings to turbidity meters to enhance their longevity and functionality.

Mitigation against environmental risks:

- Consumables: Replacement sensors should be made available to replace damaged sensors.
- Collaborative monitoring: Collaborating with local authorities and communities can provide valuable insights and help identify potential risks and mitigation measures. This can also help build trust and support for the monitoring project and mitigate against theft.
- Field testing: Before deploying the monitoring prototype for long-term use, it is important to conduct field testing in different locations to ensure its effectiveness and reliability. This will also help in identifying any potential issues or improvements that need to be made. This will also assist in mitigating physical obstructions.
- Emergency response plan: It is important to have an emergency response plan in place in case of emergencies or adverse events. This plan should include clear protocols for notifying relevant authorities and taking appropriate actions to mitigate risks.
- Environmental protection and equipment limitations: The prototype requires protection from environmental elements such as rain and extreme weather conditions.
- Solution: Developing a waterproof and durable enclosure to protect the device from rain, dust, and other environmental factors.

Mitigation against financial risks:

- Regular communication: Regular communication with stakeholders and relevant authorities is crucial for the success of the monitoring prototype. This will help in identifying any potential risks and taking timely actions to mitigate them.
- Continuous improvement: The monitoring prototype should be continuously monitored and evaluated for its effectiveness. Any necessary improvements or upgrades should be made to ensure optimal performance and accuracy in monitoring groundwater parameters.

3.6 Benefits of the groundwater quality monitoring prototype

The following are the benefits of this prototype

- Real-time data: The prototype provides real-time data on groundwater parameters, allowing for quick decision-making.
- Cost-effective: IoT technology significantly reduces the cost of monitoring groundwater compared to traditional methods. The procurement cost of the IoT-based water quality monitoring system components is approximately R20,000, whereas a ready-made commercial device costs around R350,000. This substantial cost difference highlights the affordability and cost-effectiveness of IoT-based solutions, making them a more accessible and scalable option for groundwater quality monitoring.
- Accurate and reliable: The sensors used in the prototype provide accurate and reliable data, ensuring the quality of the information.
- Remote monitoring: The prototype can be accessed through a web or mobile application, allowing remote groundwater monitoring.

3.7 Economic case of the product

The table below shows the approximate development costs for the proposed GoT-based remote sensing and telemetry system for monitoring groundwater level and quality in real-time.

Material / Component	For physical parameters	For chemical parameters	For biological parameters	Approximated Cost per unit (R)
BMT waterproof ultra sonic sensor	√			189
Ultrasonic sensor	√			39
Microcontroller Arduino UNO Wi-Fi module	√	√	√	500
Arduino pro-gateway loRa	√	√	√	6000
AZL solar panel charger 20 W, 12V, 415mAh	√	√	√	150
12 V solar battery	√	√	√	2400
ORP		√	√	2700
Open PCB board	√	√	√	200
Temperature	√			540
EC	√			1950
pH	√			1278
Turbidity	√			250
GPS receiver module	√	√	√	800
	Physical (Approx)	Chemical (Approx)	Biological (Approx)	Hybrid (Approx)
TOTAL	R 14 300	R 12 750	R 12 750	R 17000
Commercial solutions	R40 000 Onsite	>R40 000 Onsite	>R 40 000 Onsite	>R 100 000 Onsite

Sections 3.6 and 3.7 demonstrates that the proposed solution offers many advantages including relatively cheaper cost, early warning and remote telemetry and sensing system of groundwater level and quality in real-time.

3.8 Further developments

The following outlines further developments required in the project.

Completion of Field Testing at Kwaggafontein Clinic – A final round of field testing will be conducted at the Kwaggafontein clinic to assess prototype performance under real-world conditions.

The prototype will be deployed at five identified sites: Nokaneng Fire Station, Libangeni Fire Station, Moloto Community Health Centre, Ndzundza Mabusa Tribal Offices, and Kwaggafontein Clinic.

Further research should be conducted to determine the optimal frequency for cleaning and servicing the prototype. This will ensure long-term operational efficiency and accuracy.

4 COMMUNITY SCIENCE ENGAGEMENTS

This section outlines the community engagement concept and activities, which encompass the introduction of ultrasound and remote water quality sensors to the local community. It details the identification of field test sites and the training of officials within the Nkangala District Municipality. Four meetings were conducted to present the remote sensors and offer comprehensive information to political representatives and officials. Additionally, a training workshop on the operation of real-time ultrasound and prototype water quality remote sensors took place at the Nkangala District Municipality.

4.1 Review of literature on groundwater monitoring technology system within the framework of community engagement science

South Africa has faced growing challenges in effectively managing groundwater resources in recent years due to contamination risks and over-extraction, particularly in rural areas like the Nkangala District Municipality. Traditional methods of monitoring groundwater quality, which involve manual measurement of water quantity, sampling and laboratory testing, are labour-intensive, time-consuming, and prone to delays in detecting contamination. These limitations underscore the need for more efficient, real-time monitoring solutions to safeguard water quality and public health. One such solution which aim at assisting the local government on effective water management, is the implementation of Internet of Things (IoT) remote sensor technology, which offers continuous, real-time data on groundwater quantity and quality on parameters such as electrical conductivity, turbidity, pH, temperature, fluoride, sulphate, nitrates, and *E. coli* (Zhou et al., 2021).

Community-based groundwater monitoring networks, coupled with a community engagement approach, have proven to be effective and cost-efficient methods for sustainable water resource management. This is particularly relevant as governments increasingly depend on local municipalities for watershed management and planning, as indicated by Little et al. (2015). Effective groundwater resource management necessitates meticulous and intentional planning, which includes establishing long-term objectives, back casting, and implementing adaptive management strategies, as highlighted by Gleeson et al. (2011). It is essential to recognise that insufficient involvement from communities and civil society in advancing activities related to the Sustainable Development Goals (SDGs) may lead to mere discussions without actionable initiatives that directly benefit individuals. Thus, acknowledging the vital role of communities in achieving improved outcomes for all is crucial, as emphasised by the WHO (2020). Consequently, there is a pressing need to formulate management strategies that foster community engagement within the local government framework, where services are provided

In the context of local governance, the significant impact of community engagement has been underscored (Moscibrodzki et al., 2022). Crucially, such engagement enables local authorities to effectively tackle social challenges while simultaneously cultivating strong leadership capabilities and improving resource accessibility (Nabatchi & Amsler, 2014). This holistic strategy for addressing critical issues has demonstrated its ability to enhance public services and strengthen the relationship between citizens and democratic processes (Ku-Mahamud et al., 2021). Furthermore, the community engagement quality framework (WHO, 2017b) enhances the building of partnerships with the community creates a climate of trust and understanding, which in turn fosters enthusiasm and commitment, laying a solid groundwork for additional educational initiatives, including the promotion of water and sanitation activities for the development of healthy hygiene practices (WHO, 2017b).

The effective deployment of IoT technology in groundwater monitoring extends beyond mere technological improvements; it requires robust community involvement and the participation of essential stakeholders to maintain sustainable monitoring practices. Although IoT sensors can yield vital data, the challenge lies in the interpretation of this information and its incorporation into decision-making, particularly in settings where indigenous knowledge and local traditions significantly influence water resource management (Roekmi et al., 2018).

This initiative seeks to create a community engagement framework that merges IoT remote sensing technology with indigenous insights and local values to improve groundwater quality monitoring in the Nkangala District Municipality. By involving municipal staff, this research enhances the effective application of IoT technology for real-time water quality assessments while promoting collaboration and skill development within the community. The overarching objective is to empower local governments to manage groundwater resources sustainably, thereby ensuring access to safe drinking water for both present and future populations.

Stakeholder engagements

This section outlines four briefing meetings that were conducted with Nkangala District Municipality for community intake on groundwater quality monitoring study.

4.2 Community engagement 1: Initial briefing

The initial briefing meeting took place online with the municipal manager and the officials within Nkangala District Municipality. This purpose of the meeting was to introduce the study to the municipality through the Municipal Manager. The Key participants in the meeting included the following officials:

- Ms MM Skosana, Municipal Manager
- Ms N. Mnisi, Municipal Manager's Secretary
- Ms Thokozile Zulu, General Manager: Community Services
- Mr Solly Links, Manager: Municipal Health Services (MHS)
- Ms Nirisha Singh, Chief Environmental Health Practitioner and master's Student, Environmental Health
- Prof LS Mudau, Associate Professor, Tshwane University of Technology: Environmental Health
- Dr Banjo Aderemi, Tshwane University of Technology: Electrical Engineering,
- Ms MP Masilela, PhD Student, Environmental Health

During this meeting, Ms. Skosana granted approval for the study to be conducted within the Nkangala District Municipality. She further instructed the General Manager of Community Services, Ms Thokozile Zulu, to identify key stakeholders and invite them to a follow-up briefing session.

4.3 Community engagement 2: Briefing to various departments

The TUT team, comprising Prof L.S. Mudau, Dr. Banjo Aderemi, and Ms Mapula Masilela (see the attached attendance register in Appendix 1), led the second briefing session. This session was held in the Nkangala District Municipality boardroom (Figure 52). It included key stakeholders, such as the General Manager of Community Services, the Manager of Municipal Health Services, and Chief Environmental Health Practitioners (EHPs) from the six local municipalities within Nkangala District. Additional attendees included representatives from the Water and Sanitation Department and a community member whose borehole had been used as a study site in a previous research project.

Figure 50: Second community engagement briefing

In this meeting, three local municipalities, Steve Tshwete, Thembisile Hani and Dr JS Moroka, were chosen for the study due to their sustained dependence on boreholes for water supply. However, Steve Tshwete was chosen as a pilot study area to verify the usability of ultrasound and water quality prototype centre. The Chief Environmental Health Practitioners in these municipalities were assigned the responsibility of identifying the boreholes to be included in the research. After the second briefing session, five sites were identified as shown in Figure 44 and visits were carried out across all three local municipalities: Steve Tshwete, Dr JS Moroka, and Thembisile Hani.

4.4 District Development Model (DDM) – Political development meeting

The third and fourth community briefings were done in District Development Model (DDM) meetings, a strategic initiative aimed at enhancing cooperative service delivery within South Africa’s local governments. Launched by President Ramaphosa in 2019, the DDM seeks to address persistent challenges such as ineffective governance, limited resources, and insufficient intergovernmental coordination that have historically hindered local municipalities. This model serves as a platform for developing innovative solutions to local development issues while improving the state's capacity to deliver services efficiently.

Two briefings were organized involving both the technical and political teams of the DDM. The technical team consists of senior municipal officials, managers, community representatives, private sector partners, NGOs, and academics, focusing on the practical implementation of the DDM. They ensure that development projects are viable and effectively executed. The briefing was conducted online, with the study accepted for presentation to the DDM political team. This political team includes leaders from national, provincial, and local governments, as well as traditional leaders, who provide oversight and support for the DDM. They facilitate collaboration among various stakeholders, addressing political challenges and securing necessary funding. This briefing took place in person at the Nkangala District Municipality, where the TUT team presented their findings.

4.5 Workshop on IoT Groundwater Monitoring

4.5.1 The background and the aim of the workshop

A workshop was held at Pienaardam Leisure Resort in Steve Tshwete Local Municipality on 27 January 2025, representing the sixth initiative for community engagement. The main objective of the workshop was to provide training to officials from Nkangala District Municipality (NDM) on the operation of a prototype for Internet of Things (IoT) groundwater quality monitoring. Additionally, the workshop sought to collect feedback from the officials to guide the ongoing development of the prototype.

4.5.2 The participants

The workshop was facilitated by the TUT Niche Area of Climate Change, Water Security, and Disaster Management. Representatives from the Department of Environmental Health, the Department of Civil Engineering, and the Department of Electrical Engineering contributed to the session.

The facilitators included Ms MP Masilela, a doctoral student from the Department of Environmental Health, and Ms TM Tladi, a doctoral student from the Department of Civil Engineering. Seventeen officials from various municipal departments, including Municipal Health Services, Information Technology (IT), Environmental and Solid Waste Management, and Technical Services, attended the workshop.

4.5.3 The workshop programme

The workshop began with a theoretical briefing on groundwater monitoring. Ms MP Masilela focused on water quality parameters, while Ms TM Tladi addressed aspects of groundwater quantity. The session emphasised the significance of real-time monitoring, using research findings to illustrate key points. Figure 51 shows the setup for the theoretical briefing.

This was followed by an explanation of the prototype's functionality, including data collection and interpretation. An interactive question-and-answer session allowed participants to seek clarification before moving on to the practical session.

Figure 51:Theoretical briefing session

In the second session, attendees engaged in hands-on activities by setting up the prototype and performing real-time data readings, as depicted in Figure 52. The facilitators demonstrated the prototype's capabilities, allowing municipal officials to explore its practical applications in the field. The concluding session focused on evaluating the results of the workshop.

Figure 52: Practical session

4.5.4 Findings and discussions

Nkangala District Municipal officials were very much interested in the prototype, posing essential inquiries regarding its functionality, upkeep, data protection, and logistical placement. Their input proved instrumental in identifying areas for enhancement and the potential incorporation of additional features into the device.

The conversations underscored a distinct necessity for integrated groundwater monitoring systems within municipalities. The varied professional expertise of the participants, which included fields such as Environmental Health, Environmental Management, IT, and Civil Engineering, facilitated meaningful discussions on various dimensions of the prototype's use. For example, an IT expert highlighted issues concerning software licensing and data security, while a managerial representative concentrated on the financial aspects of sustaining such licenses. These multidisciplinary perspectives underscored the critical need for a cooperative strategy in groundwater monitoring.

4.5.4 Conclusions

The workshop effectively achieved its goals by providing Nkangala District Municipality officials with essential skills to utilize the IoT groundwater monitoring prototype, while also collecting valuable feedback for its improvement. The officials' engagement and input will guide subsequent enhancements, including the creation of a detailed technical manual for its operation and maintenance.

4.5.4 Recommendations

It was recommended that:

- Further training should be conducted on-site to equip officials with the necessary skills to operate the prototype.
- The prototypes will be utilized in the field for at least one year to guarantee their effectiveness and longevity.
- A minimum of a year will facilitate testing across diverse environmental conditions and seasonal variations.
- A comprehensive training manual should be developed to support the sensors.

5 OUTPUTS AND OUTCOMES

Research Outputs: As detailed in Appendix 5, the project produced 2 articles published in peer-reviewed accredited journals, 4 papers published in peer-reviewed accredited conference proceedings, and 2 papers accepted and to be presented at an international conference.

Innovative prototype: The project undertook the Development and Implementation of the Geography of Things-based Real-Time Groundwater Remote Sensing and Telemetry at Nkangala District Municipality, Mpumalanga. The literature shows little or no commercial product that integrates groundwater level and quality monitoring in real-time with relatively cheap fabrication costs.

Human Capacity Development: Three (3) PhD students trained in the fields of Engineering (2 students) and Environmental Health Sciences (1 student). One PhD student successfully completed and graduated from the project, the other two are in advanced stage to completion. Three (3) master's students trained in the fields of Engineering (2 students) and Environmental Health Sciences (1 student). All students successfully completed and graduated from the project. In addition, there were staff from the Nkangala District Municipality trained in this project via a Community Engagement Model. Five (5) females and twelve (12) males were trained.

UN sustainable development goal (SDGs alignment): This project is aligned with the 6th goal of sustainable development, which aims at ensuring the availability and sustainable management of water and sanitation for all. Relevant SDG # 6 targets that the project specifically attempted to address are:

- Achieve universal and equitable access to safe and affordable drinking water for all.
- Achieve access to adequate and equitable sanitation and hygiene for all and end open defecation.
- Improve water quality by reducing pollution, eliminating dumping, and minimizing the release of hazardous chemicals and materials, halving the proportion of untreated wastewater, and substantially increasing recycling and safe reuse globally.

The outcomes of this project include community engagements with the target municipalities, the various peer-reviewed conference presentations, regular liaison with the project reference groups in duly called meetings, project management reporting, unlocking opportunities of industry-university collaborations, possible IP generations from the project, and a framework for establishing future funding applications.

6 CONCLUSION AND FUTURE DEVELOPMENTS

6.1 Conclusion

The science of community engagement initiative presents numerous advantages, primarily aimed at improving groundwater monitoring within the Nkangala District Municipality through an innovative combination of Internet of Things (IoT) remote sensor technology and community involvement. One important benefit is the enhancement of water quality monitoring, as IoT sensors facilitate real-time assessment of water quality parameters, minimising the dependence on labour-intensive traditional testing methods.

- This advancement allows for the prompt identification of contaminants, thereby safeguarding public health.
- Additionally, the use of IoT remote sensors addresses inconsistencies in water quality monitoring, enabling municipalities to ensure sustainable resource management.
- The continuous data provided by IoT technology supports informed decision-making in water management, which is crucial for regions susceptible to waterborne diseases due to groundwater contamination.
- This real-time information fosters proactive measures to protect public health and optimise resource utilisation. Furthermore, the project encourages community and stakeholder engagement by involving municipal staff from various departments, thereby promoting collaborative water management efforts that align with local knowledge and values.
- This engagement empowers stakeholders with the necessary knowledge and tools for effective water resource management.
- Lastly, the initiative enhances financial sustainability by allowing municipalities to concentrate resources on sources exhibiting contamination signs, thus streamlining monitoring efforts and reducing unnecessary testing on consistently compliant water sources.
- This targeted strategy serves as a model for municipalities seeking to enhance water quality while managing costs effectively, and it aligns with Sustainable Development Goal 6, which aims to ensure universal access to clean water and sanitation, contributing to global sustainable water resource initiatives.

6.2 Future developments

The developed community engagement model for groundwater monitoring using an IoT monitoring system is a work in progress; thus, future development will include:

- Laboratory analysis for biological parameters.
- Field test of the system in a real groundwater monitoring well.
- Ongoing capacity building of stakeholders.
- Development of a community engagement model on IoT.

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8 APPENDICES

Appendix 1: Field test pictures



water & sanitation
Department:
Water and Sanitation
REPUBLIC OF SOUTH AFRICA
PRETORIA WEST
CONSTRUCTION EQUIPMENT
ARCHIVE STORE
DAM SAFETY
MATERIALS LAB



water & sanitation
Department:
Water and Sanitation
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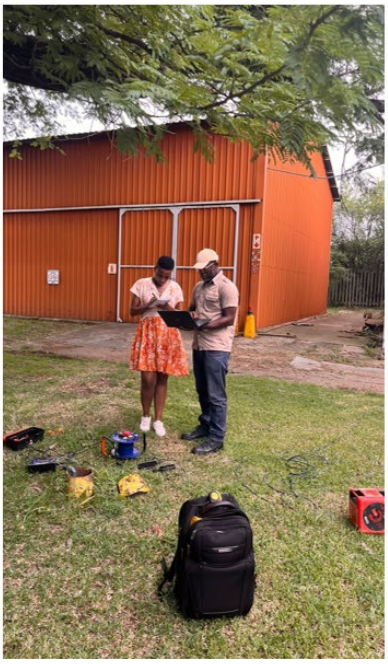
MATERIALS LAB





Appendix 2:

Tshwane University of Technology
We empower people
20 YEARS 2004-2024

Celebrating 20 years of empowering people

MEETING BETWEEN TUT AND NKAGALA DISTRICT MUNICIPALITY

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

DATE: 10 JULY 2024
VENUE: NKANGALA DISTRICT MUNICIPALITY

	Name	Organisation	Contact number	Email address	Signature
1.	Thokozile Zulu	NDM COS			
2.	Chanel Marx	NDM- MHS			
3.	Solly Links	NDM – MHS			
4.	Emmanuel Lebaba	Foreman C&S.			
5.	GG Mokhabela	NDM – MHS			
6.	Thou Jim	NDM – MHS			
7.	Alfred Magampe	NDM -MHS			
8.	Tshegofatso Mcnama	THLM			
9.	Nkhanguweni Mtuwribu	THLM			

#fromGOOD2GREAT

Tshwane University of Technology
We empower people
20 YEARS 2004-2024

Celebrating 20 years of empowering people

MEETING BETWEEN TUT AND NKAGALA DISTRICT MUNICIPALITY

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

DATE: 10 JULY 2024
VENUE: NKANGALA DISTRICT MUNICIPALITY

	Name	Organisation	Contact number	Email address	Signature
10.	Nikisha Singh	NDM-MHS- TUT			
11.	Banjo A. Adeyemi	TUT			
12.	MP Masilela	TUT			
13.	MJ Meyer	Pienaardam			
14.	Mudau L.S.	TUT			
15.					
16.					
17.					
18.					

#fromGOOD2GREAT

Appendix 3: DDM technical agenda

"District of Excellence and Climate Smart Innovation"

NKANGALA DISTRICT MUNICIPALITY

District Development Model Technical

17 September 2024

Time: 10h00

Venue: Virtually on Microsoft Teams

Programme Facilitator: Municipal Manager (MM Skosana)

Opening and Welcome	NDM Municipal Manager
Introduction and apologies	All
Announcements • DDM Council/ IDP-PMS Forum 19 September 2024	All
Minutes of the previous DDM Technical Meeting 10 June 2024	All
PRESENTATIONS BY EXTERNAL STAKEHOLDERS	
Tshwane University of Technology (TUT)	Project on Remote Groundwater Quality Monitoring Using the Internet of Things (IoT)
ISSP	The Energy Revolution: Clean Green Power with Guaranteed Storage
MTPA	Catalytic projects and programmes
Department of Education	Catalytic projects and programmes

The NDM is committed to the improvement of the physical, socio-economic and Institutional environment in order to address triple challenges through sustainable development and service excellence

Appendix 4: DDM Political agenda (Meeting 4)

"District of Excellence and Climate Smart Innovation"

NKANGALA DISTRICT MUNICIPALITY

District Development Model Council

19 September 2024

Time: 10h00

Venue: Council Chamber

SCAN ME

For presentations

1

"District of Excellence and Climate Smart Innovation"

Programme Facilitator: Executive Mayor Cllr. T.D. Ngwenya

Opening and Welcome	**NDM Executive Mayor** **Cllr. T.D. Ngwenya**
Introductions and application for leave of absence	**All**
Acknowledgement of Traditional Authorities	**CoGHSTA**
Minutes of the Previous DDM Council and Matters Arising from Previous DDM Council Meeting on the 20th of June 2024	**All**
Progress on resolutions	**General Manager: PED** **Mr JP Mangani**
PRESENTATIONS BY EXTERNAL STAKEHOLDERS	
Tshwane University of Technology	Project on Remote Groundwater Quality Monitoring Using the Internet of Things (IoT)
Nkangala Economic Development Agency	Progress on catalytic projects and programmes
Department of Public Works, Roads and Transport	Progress on catalytic projects and programmes
Department of Education	Progress on catalytic projects and programmes
Department of Cooperative Governance, Human Settlements and Traditional Affairs	Progress on catalytic projects and programmes
Department of Health	Progress on catalytic projects and programmes
Departments of Culture, Sports and Recreation	Progress on catalytic projects and programmes .
Mpumalanga Tourism and Parks Agency	Progress on catalytic projects and programmes
Department of Agriculture, Land Reform and Rural Development	Progress on catalytic projects and programmes
Discussions, Questions and Comments	All
Presentation by clusters/working groups chairpersons	• Basic Services and infrastructure development • Economic Development Growth & Job Creation • Spatial Transformation and Sustainable Human Settlements • Governance Administration and ICT • Financial Management Systems, internal auditing and Risk Management • Security and social services environmental and Disaster Management
Discussions, Questions and Comments	All
Final Remarks by the Executive Mayor/DDM Political Champion	NDM Executive Mayor **Cllr. T.D. Ngwenya**
Vote of thanks	NDM Council Whip **Cllr C. Nkalitshana**
Date of next meeting	DDM Council 19 November 2024
Closure	NDM Executive Mayor **Cllr. T.D. Ngwenya**

Appendix 5: Research outputs

The following are research outputs that emerged directly from the project:

Published outputs:

Tladi, T.M., Ndambuki, J.M., Olwal, T.O., Rwanga, S.S., "Groundwater level trend analysis and prediction in the upper crocodile sub - basin, South Africa," MDPI Water, 2023, 15, 3025. Published 12 August 2023, DHET Scopus and WoS Indexed. IF: 3.4, ISSN: 2073-4441, https://doi.org/10.3390/w15173025.

Aderemi, B.A, Olwal,T.O, Ndambuki, J.M and Rwanga, S.S ., "Groundwater levels forecasting using machine learning models: a case study of the groundwater region 10 at Karst Belt, South Africa" Elsevier, Systems and Soft Computing, formally known as Soft Computing Letters, Vol. 5, December 2023, 200049. Accepted 8 February 2023. DHET DOAJ Included, Scopus Indexed. DOI: https://doi.org/10.1016/j.sasc.2023.200049 . ISSN: 2772-9419.

Aderemi, B.A, Olwal, T.O, Ndambuki, J.M and Rwanga, S.S., "A review of groundwater management models with a focus on IoT-based systems," MDPI Sustainability 2022, 23 Dec. 2021, 14, 148. https://doi.org/10.3390/ su14010148, pp. 1-30, WoS IF = 3. 251.ISSN: 2071-1050.

Chauke, M., Olwal, T.O., and Migabo, E.M. "A Geography of Things-based groundwater quality management system" in Proc IEEE of the International Conference on Electrical, Computer and Energy Technologies (ICECET2022), 20-22 July 2022, Prague-Czech Republic. ISBN: 978-1-6654-7087-2.

Aderemi, BA., Olwal, T.O., Chauke, M., Tladi, TM., and Ndambuki, JM "Climatic Parameters Based Groundwater Level and Quality Monitoring System Using Internet of Things," in Proc SATNAC 2023 27-29 September 2023, Champagne Sports Resort, Drakensberg Central, KZN, South Africa.

Tladi, TM., Aderemi, BA., Ndambuki, JM., Olwal, TO and Rwanga, SS., "A Prototype design and implementation of a real-time rainfall-based groundwater level monitoring system using the internet of things," in Proc the Mediterranean Geosciences Union Annual Meeting (MedGU-23), Springer, 26-30 November 2023, Istanbul, Turkey.

Tladi, T.M., Aderemi B.A., Ndambuki J.M., Olwal T.O. and Rwanga S.S, 2024. *Application of Internet of Things (IoT) in Selecting Time Lag for Groundwater Level Prediction.* Machakos, Kenya, Machakos University 6TH Annual International Conference.

Accepted for presentation at International Conferences:

Chauke, M., Olwal, TO., and Migabo, EM., “Investigation of physical parameters for groundwater quality using a geography of things-based system,” in Proc IST Africa 2025, 28-30 May 2025, Nairobi, Kenya.

Aderemi, BA., Olwal, TO., Tladi, TM., Ndambuki, JM., Masilela, MP., and Mudau, LS., “Design and implementation of a real-time groundwater monitoring system using IoTs,” in Proc IST Africa 2025, 28-30 May 2025, Nairobi, Kenya

Appendix 6: Development costs of groundwater level sensing and telemetry

Component	Quantity	Unit Price (R)	Total (R)
DHT 22 sensors	1	133.1	133.1
GPS Module	1	126.09	126.09
ESP 32	1	147.2	147.2
Precision module	1	55.2	55.2
Wifi Router	1	999	999
Ultrasonic sensor **(MB7853, 16 m range)**	1	5388.38	5388.38
Connectors	1	261.45	261.45
Solar panel 10W 18V	2	395	790
Rechargeable battery	1	385	385
Enclosures	1	285	285
Rain gauge	1	619.9	619.9
Charge controller	1	399	399
LCD screen	1	77.39	77.39
Total (Including VAT)			**9666.71**
Labour	1	20000	20000
Total (Including labour)			**29589.32**

Component	Quantity	Unit Price (R)	Total (R)
DHT 22 sensors	1	133.1	133.1
GPS Module	1	126.09	126.09
ESP 32	1	147.2	147.2
Precision module	1	55.2	55.2
Wifi Router	1	999	999
Ultrasonic sensor **(JSN-SR04T, 4 m range)**	1	135.16	135.16
Connectors	1	261.45	261.45
Solar panel 10W 18V	2	395	790
Rechargeable battery	1	385	385
Enclosures	1	285	285
Rain gauge	1	619.9	619.9
Charge controller	1	399	399
LCD screen	1	77.39	77.39
Total (Including VAT)			**4413.49**
Labour	1	20000	20000
Total (Including labour)			**24336.1**

Component	Quantity	Unit Price (R)	Total (R)
DHT 22 sensors	1	133.1	133.1
GPS Module	1	126.09	126.09
ESP 32	1	147.2	147.2
Precision module	1	55.2	55.2
Wifi Router	1	999	999
Ultrasonic sensor **(HC-SR04, 4 m range)**	1	30	30
Connectors	1	261.45	261.45
Solar panel 10W 18V	2	395	790
Rechargeable battery	1	385	385
Enclosures	1	285	285
Rain gauge	1	619.9	619.9
Charge controller	1	399	399
LCD screen	1	77.39	77.39
Total (Including VAT)			**4308.33**
Labour	1	20000	20000
Total (Including labour)			**24230.94**