

Transition to Novel Internet of Things Technology for Management of Groundwater Resources– Case of Cape Town, South Africa



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Abstract

Groundwater is significant for humans and nature due to its varying extent, prevalence and natural quality. Effective management and protection of groundwater resources is essential and requires detailed knowledge and quantitative/qualitative characterisation of the aquifer. It is vital to confirm the groundwater parameters during hydrogeological investigations as groundwater depends on factors like geology, climate, lithology, slope and many others. However, there needs to be sufficient data to conduct these investigations and develop models for decision support in managing groundwater resources.

In this study, Internet of Things (IoT) technology was applied to collect groundwater level data from a borehole to solve the problem of insufficient hydrogeological data. IoT provided consistent data collection, appropriate capacity to deal with immense records and ensured speedy and accurate information analysis. The interval resolution of collecting the IoT-based data was changed from 15 minutes to 24 hours to increase the battery life of the water level sensor to have continuous communication between the gateway and sensor. A combination of MODFLOW Software, Geographical Information System (GIS) and Analytic Hierarchy Process (AHP) techniques was then adopted to assess the groundwater processes related to Managed Aquifer Recharge (MAR) in the study area.

This research investigates the workability of using IoT technology to collect groundwater level data to assess the processes that occur in the Cape Flats Aquifer around a stormwater pond catchment area. The study area in the Mitchells Plain West Catchment comprises the catchment areas of two stormwater ponds and covers an area of 0.315 km². The AHP and GIS techniques were used to produce a groundwater recharge potential zone map of the study area to develop a numerical groundwater model in MODFLOW. Recharge rates, hydraulic conductivities and other groundwater parameters were assigned and varied with estimated boundary conditions during model development. It was carried out based on acceptable ranges for the study area from previous studies and water resources management agencies of South Africa. The model was run and calibrated using the IoT-based groundwater levels collected at the monitoring borehole at Green dolphins pond.

The study determined that the stormwater ponds were located in areas with very high groundwater recharge potential that covered 10.6% of the total study area. They are located in a flat area with quaternary deposits, low drainage density and high lineament density, which increase water infiltration rate, thus promoting groundwater recharge. The impact of the groundwater recharge was evaluated using the water budget, as there was an increase of 0.86 m between the observed head value and simulated head value at the monitoring borehole. It was observed that varying the recharge rates and hydraulic conductivity influences the fluctuations in the water table and the outflows presented in the water budget tables. Therefore, the increase in the water table at the borehole shows the importance of stormwater ponds as a water source for MAR.

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Glossary of Terms

This glossary consists of terms related to internet of things technologies, stormwater management, groundwater management and engineering and geographical information systems used in this dissertation. The sources of these terms were: Woods-Ballard et al., 2007; Adelana, 2010; Vice, 2011; Carden et al., 2018.

Aquifer is a sub-surface zone or formation of rock or soil containing a body of groundwater.

Catchment refers to the area contributing surface water flow to any specific point on a watercourse. It can be divided into sub-catchments.

Catchment Delineation is the process of creating a boundary that represents the contributing area for a particular control point.

Climate Change is the increasing evidence that the earth's climate is changing e.g. as a result of temperature increases due to anthropogenic emissions.

Confined Aquifer is an aquifer enclosed by formations that are less permeable or impermeable media.

Conveyance is the movement of water from one location to another.

Detention – the slowing down of surface flows before their transfer downstream.

Detention pond/basin is a vegetated depression that is normally dry except following large storm events when it temporarily stores stormwater to attenuate flows. It may also allow infiltration of stormwater into the ground.

Digital Elevation Model (DEM) is a digital cartographic dataset that represents continuous topographic elevation data of terrain or overlaying objects.

Evapotranspiration is the process by which water is transferred from the land to the atmosphere through evaporation from soil and other surfaces plus transpiration of moisture from the surface membranes of leaves and other plant surfaces.

Groundwater is the water that is below the ground in the saturation zone.

Hydrology refers to the physical, chemical and physiological sciences of the water bodies of the earth including: occurrence, distribution, circulation, precipitation, surface runoff, stream-flow, infiltration, storage and evaporation.

Hydrogeology is the study of the water below the ground surface and geological aspects of surface water.

Infiltration is the process of penetration of rainwater into the ground. Infiltration is the soaking of water into the ground.

Managed Aquifer Recharge is the purposeful recharge of water to aquifers to subsequently recover the environmental benefits (Dillon, 2009).

Monitoring/Observation Borehole is a borehole drilled at a location to measure groundwater parameters like water levels, water quality and pressure changes.

Permeability is the ability of a material to allow water to flow through it when fully saturated and subjected to an unbalanced pressure.

PCB is a medium used in electrical engineering to connect components to one another.

Recharge is the addition of water to the groundwater system by natural or artificial means.

Retention pond is a pond where runoff is detained for a sufficient time to allow settlement and biological treatment of pollutants.

Sensor is a device that produces an output signal for the purpose of sensing a physical phenomenon.

Stormwater is water resulting from natural precipitation and/or accumulation and includes rainwater, groundwater and spring water.

Stormwater pond is a facility that stores excess stormwater runoff temporarily to reduce flood peaks.

Stormwater runoff is the portion of rainfall that flows to the surface drainage system.

SuDs – Sustainable Drainage Systems is an approach to surface water management that combines a sequence of management practices and control structures designed to drain surface water in a more sustainable fashion than some conventional techniques.

Unconfined Aquifer - is an aquifer that is open to receive water from the surface.

Watershed is the upper boundary of a specified catchment area for rainfall that contributes to a given drainage area.

Water Table is the point where the surface of groundwater can be detected. It may change with the seasons and the annual rainfall.

Wetland refers to land transitional between terrestrial and aquatic systems where the water table is at or near the surface and would support vegetation typically adapted to life in saturated soil. This includes lakes, salt marshes, coastal lakes, swamps, ponds, pans and artificial impoundments.

Symbols

A	-	(1,2,3...X) Thematic map
B	-	(1,2,3...Y) Thematic map sub-classes
ET ₀	-	Reference evapotranspiration (mm day ⁻¹)
e _s	-	Saturation vapour pressure (kPa)
e _a	-	Actual vapour pressure (kPa)
e _s - e _a	-	Saturation vapour pressure deficit (kPa)
g	-	Gravity acceleration (m ³ /s)
G	-	Soil heat flux density (MJ m ⁻² day ⁻¹)
kg	-	kilogram
km	-	kilometre
km ²	-	square kilometre
km ³	-	cubic kilometre
m	-	metre
mm	-	millimetre
n	-	number of parameters
P	-	Pressure of the liquid
P ₀	-	Atmospheric pressure at liquid surface
R	-	Maximum range of height (m)
R _n	-	Net radiation at the crop surface (MJ m ⁻² day ⁻¹)
T	-	Mean daily air temperature (°C)
V	-	Voltage output signal (volts)
V _{h₀}	-	Voltage output corresponding to a depth of 0m
V _{h₅}	-	Voltage output corresponding to a depth of 5m
X	-	Weight of the thematic layers
Y	-	Rank of the sub classes of the thematic layer
ρ	-	Density of the liquid (kg/m ³)
λ _{max}	-	Principal Eigenvalue
%	-	Percent
°C	-	Degrees Celcius

u_2	-	Wind speed at 2 m height (m s^{-1})
Δ	-	Slope vapour pressure curve ($\text{kPa } ^\circ\text{C}^{-1}$)
Γ	-	Psychrometric constant ($\text{kPa } ^\circ\text{C}^{-1}$)

Acronyms and Abbreviations

ADC	-	Application Delivery Controller
AHP	-	Analytic Hierarchy Process
AI	-	Artificial Intelligence
API	-	Application Programming Interface
ASR	-	Aquifer Storage and Recovery
ASTR	-	Aquifer Storage Transfer and Recovery
CCT	-	City of Cape Town
CFA	-	Cape Flats Aquifer
CI	-	Consistency Index
CR	-	Consistency Ratio
CSV	-	Comma-separated Values
DWA	-	Department of Water Affairs
DWAF	-	Department of Water Affairs & Forestry
DEM	-	Digital Elevation Model
EPC	-	Electronic Product Code
GIS	-	Geographic Information System
GCTMA	-	Greater Cape Town Metropolitan Area
GND	-	Ground
GWPZ	-	Groundwater Potential Zone
HTTP	-	Hyper Text Transfer Protocol
IERC	-	European Research Cluster on the Internet of Things
IGN	-	Department of Geosciences and Natural Resource Management
IoT	-	Internet of Things
IP	-	Internet Protocol
IPCC	-	Intergovernmental Panel on Climate Change
ITU	-	International Telecommunication Union
IWRM	-	Integrated Water Resources Management
LED	-	Light-emitting Diode
LoRaWAN	-	Long Range Wide Area Network

LPWAN	-	Low Power Wide Area Network
LULC	-	Land Use/Land Cover
MAP	-	Mean Annual Precipitation
MAR	-	Managed Aquifer Recharge
MATLAB	-	Matrix Laboratory
MCU	-	Microcontroller Unit
M2M	-	Machine to Machine
MQTT	-	MQ Telemetry Transport
NFC	-	Near Field Communication
PaWS	-	Pathways to Water Resilient South African Cities
PCB	-	Printed Circuit Board
PWC	-	Pair-wise Comparison
RCI	-	Random Consistency Index
REST	-	Representational State Transfer
RFI	-	Radio Frequency Interface
RFID	-	Radio Frequency Identification
SAWS	-	South African Weather Service
SIM	-	Subscriber Identity Module
SOA	-	Service Oriented Architecture
SRTM	-	Shuttle Radar Topography Mission
SuD	-	Sustainable Drainage Systems
TCP	-	Transmission Control Protocol
TMG	-	Table Mountain Group
TTN	-	The Things Network
UCPH	-	University of Copenhagen
UCT	-	University of Cape Town
UPS	-	Uninterruptible Power Supply
USGS	-	United States Geological Survey
VCC	-	Voltage Common Collector
VDC	-	Vehicle Dynamic Control

WC	-	Wireless Communication
Wi-Fi	-	Wireless Fidelity
WSN	-	Wireless Sensor Network
4G LTE	-	Fourth Generation Long-term Evolution

1. Introduction

1.1 Background

South Africa is in a semi-arid region, resulting in unreliable and uncertain water availability (Ebrahim *et al.*, 2020). The water resources are minimal due to a relatively low Mean Annual Precipitation (MAP) of 450 mm per year, which is below the world average of about 860 mm per year. The combined runoff of 49 billion cubic metres per year is less than half that of the Zambezi River, the fourth-largest river in Africa (Basson, 2011).

Surface water resources are the most common water sources for urban, industrial and irrigation requirements in South Africa. Diversifying away from the dominant investment focus on surface waters towards an integrated range of alternatives like groundwater is necessary to remedy the current scarcities and meet future demands (Cobbing & Hiller, 2019). The City of Cape Town has access to several groundwater resources, namely; Albion Springs, the Atlantis Aquifer, the Table Mountain Group (TMG) Aquifer, the Cape Flats Aquifer (CFA) and the Newlands aquifer (Mauck, 2017).

Groundwater resources represent the most extensive available source of fresh water lying beneath the ground, thus a need to target the potential zones and conserve this critical resource. The overlying unsaturated zone protects groundwater; thus, the resource is more resilient to climate change and less susceptible to pollution than surface water (DWA, 2010a). Identifying suitable sites for artificial recharge is crucial to sustaining groundwater systems and avoiding their depletion due to insufficient natural recharge (Keifer & Effenberger, 1967).

Groundwater is integral to water resources and must be managed sustainably (DWA, 2010a). Effective management and protection of groundwater resources require detailed knowledge and quantitative/qualitative characterisation of aquifers. Therefore, modelling and planning of the groundwater through modern technologies and approaches is highly prioritised in this direction (Kouli *et al.*, 2008).

There have been attempts to provide groundwater recharge estimates across Sub-Saharan Africa to promote Integrated Water Resources Management (IWRM). However, insufficient data and information on groundwater recharge have limited these attempts (Xu & Beekman, 2019). Therefore, there is a need for the application of Internet of Things (IoT) technology to generate immense data on local groundwater conditions. It is faster than conventional manual data collection and provides real-time temporal and spatial data using connected devices like sensors. Sensor equipment is continually decreasing in cost, increasing in accuracy and has the potential to improve the groundwater data collection capabilities in Southern Africa (Gaffoor *et al.*, 2020).

Estimating recharge is essential in the management of groundwater resources. It is vital to identify all the recharge mechanisms and estimate the magnitude of the different components of recharge (Segun *et al.*, 2010). In this study, IoT-based collected data was used to calibrate a model developed with MODFLOW software and used to estimate the quantity of groundwater

banked in an aquifer, an approach commonly referred to as Managed Aquifer Recharge (MAR). A water level sensor was installed in a borehole within the study area to collect and monitor groundwater level data to determine the net infiltration associated with recharge.

1.2 Problem Statement

The availability of groundwater resources in an area depends on several factors, including local geology, topography and climate. The groundwater resources in a given area are often spatially variable, thus requiring investigations and high-quality data to estimate viability and potential as a water source. (Cobbing & Hiller, 2019). Unfortunately, the data in most developing countries could be more extensive in both temporal and spatial resolution, which affects the development of groundwater models needed to manage the resource. The high variability in the availability of hydrogeological data is generally due to inadequate monitoring efforts and ineffective transformation of data to information (Gaffoor *et al.*, 2020), and where data is available, it is not easy to access (Cobbing & Davies, 2011).

1.3 Research Objectives

1.3.1 Main Objective

The main objective is to investigate the transition to the novel internet of things technology for groundwater resource management and Managed Aquifer Recharge in the Cape Flats Aquifer using stormwater.

1.3.2 Specific Objectives

The specific objectives are as follows.

- i. **Groundwater level data collection and monitoring:** This specific objective is to implement an IoT monitoring system to collect accurate and real-time groundwater level data in the study area. This provides a comprehensive understanding of the aquifer's behavior and enable informed decision-making for groundwater resource management. The data collection process was completed within a period of almost five months.
- ii. **Estimation of stormwater storage and recharge potential:** This objective aims to quantify the volume of stormwater that can be stored within the Cape Flats Aquifer and assess its recharge potential using a MODFLOW model. The model considers estimated boundary conditions and provide insights into the feasibility and efficiency of utilizing stormwater for Managed Aquifer Recharge. The estimation and analysis process conducted was within a specified timeframe of two months.

- iii. **Identification of groundwater potential zones:** The objective is to identify groundwater potential zones within the study area, based on geological, hydrological, and other relevant data. By analyzing factors such as aquifer characteristics, groundwater availability, and recharge potential, this objective aims to delineate specific areas with high potential for sustainable groundwater resource management. The identification process was completed within three weeks.
- iv. **Assessment of groundwater recharge rates and processes:** This objective focuses on assessing the rates and processes of groundwater recharge occurring in the Cape Flats Aquifer. It aims to determine the recharge mechanisms, quantify the recharge rates, and understand the factors influencing groundwater recharge through data analysis, modelling, and field investigations. This assessment process was conducted within three months.

1.4 Justification

In evaluating of groundwater resources in Cape Town, the estimation of recharge into the Cape Flats Aquifer is very important. Due to the limited water availability to satisfy the increasing demand, there is an urgent need for rapid reconnaissance technologies to assess groundwater over large areas, although there may be only limited secondary data (Kouli *et al.*, 2008). The ability to monitor the groundwater resources in South Africa needs to be improved as the focus for water supply is mainly on surface water resources. Therefore, adequate capacity building should be implemented through practical, in-service training programmes on groundwater monitoring and management in public institutions and the private sector (DWA, 2010a).

1.5 Chapter Outline

This research report has six (6) chapters consisting of the following.

Chapter 1 comprises the introduction of the research, which includes the background, problem statement, research question and objectives, justification and the scope and limitations of the project.

Chapter 2 entails the literature review that summarises previous studies on the research topic. It also provides an overview of the concept of groundwater augmentation around MAR for sustainable groundwater development, stormwater harvesting, internet of things technologies and groundwater modelling, among others,

Chapter 3 describes the methodology employed in the development of the project. It includes the criteria followed in the study area selection, collection of existing datasets, groundwater potential zone mapping, collection of groundwater level data using IoT and groundwater flow modelling using MODFLOW.

Chapter 4 presents results from the groundwater potential zone mapping process using Geographic Information System (GIS) and Analytic Hierarchy Process (AHP) techniques. It includes detailed descriptions of the thematic layers used in the mapping process and the delineation of the zones.

Chapter 5 provides the outputs from collecting groundwater level data using Internet of Things (IoT) technologies. It presents the calibration of the collected water level depths into groundwater levels above the mean sea level appropriate for usage in the groundwater flow modelling model.

Chapter 6 focuses on the results from the groundwater flow modelling process using MODFLOW, model calibration and validation.

Chapter 7 presents the conclusions and recommendations from the research project. It includes all the essential findings and clearly states recommendations based on the various findings from the thesis.

2. Literature Review

2.1 Introduction

This chapter covers the overview of the characteristics of the study area, stormwater harvesting, assessment of groundwater augmentation with stormwater and groundwater modelling. The chapter presents the identified gaps and proposals, which, when implemented, would improve the management of groundwater resources.

2.2 The Study Area - Cape Flats

2.2.1 Location and Topography

The Cape Flats area covers an area of approximately 630 km² in the City of Cape Town, South Africa. The topography of the Cape Flats is marked by changes in elevation, ranging from low-lying sandy plains to rocky mountains with a series of peaks, rising to a height of 1,086 m above sea level on Table Mountain (Adelana *et al.*, 2010; Mauck, 2017; Axelson, 2023). It drops down to the sea in many parts of the peninsula, with the mainland positioned between 33°30' and 34°10' south-latitude and between 18°20' and 19°00' east-longitude (Adelana *et al.*, 2010). The hydrology of the Cape Flats is associated with wetlands or seasonal wetland conditions due to its flat topography (Mauck, 2017).

The area extends from False Bay in the South to the Tygerberg Hills in the northeast and Milnerton in the northwest. It is also bounded by Table Mountain in the West and the hills of Kanonkop at Brackenfell in the East (Hay & Seyler, 2008). The Cape Flats comprise numerous dunes with a south-easterly orientation, a maximum and average elevation of 65 m.a.s.l. and 30 m.a.s.l. (Adelana & Jovanovic, 2006). This research covers a catchment area of two stormwater ponds, the school pond and the green dolphins pond, located in the Mitchells Plain Western Catchment, as shown in **Figure 2-1** below.

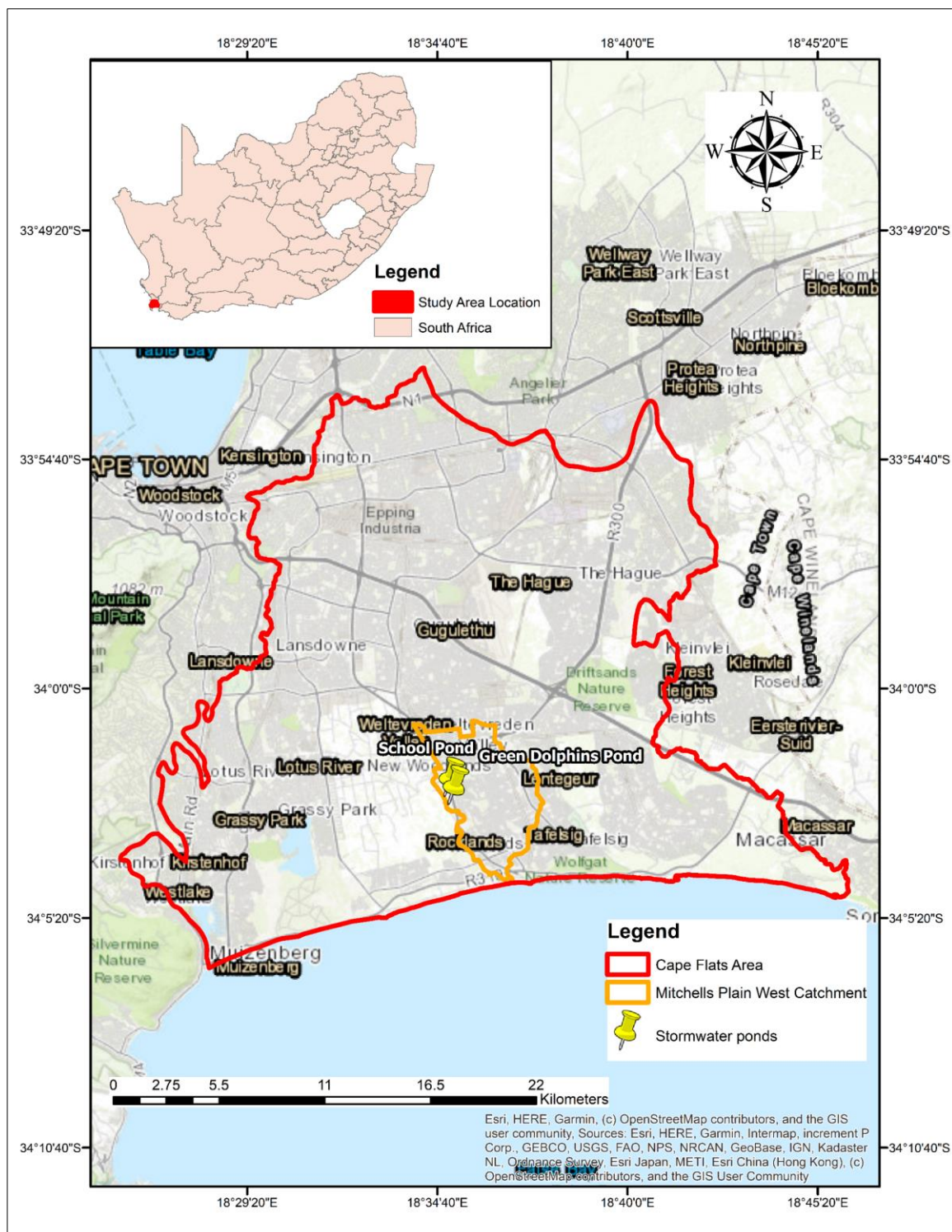


Figure 2-1: Location of the Cape Flats Area, Mitchells Plain West Catchment, and the Stormwater Ponds

2.2.2 Land Use

The main land use types over the Cape Flats are informal and formal residential settlements and general urban use with small pockets of agriculture and natural vegetation in some protected areas. Most of the residential areas consist of low to medium-income informal settlements occupied by the ‘blacks’ and ‘coloured’ people who were forced to live away from the Cape Town City Centre in the late 1970s and early 1980s during the apartheid planning (Mauck, 2017).

2.2.3 Climatic Conditions

The South African climate is largely arid to semi-arid due to its location in the high-pressure belt of the Southern Hemisphere, located around 30°S latitude. The pressure belt is split into two cells, one on the Atlantic side and the other above the Indian Ocean, due to the unequal heating of the land during summer and winter (Schalke, 1973). Cape Town weather experiences strong winds: the prevailing southeast trade winds in summer are replaced by the northwest anti-trade in winter (Adelana, 2010). The deviation of the westerly cold ocean current towards and along the west coast of Africa, known as the Benguela current, is caused by the continental margin of South Africa (Schalke, 1973).

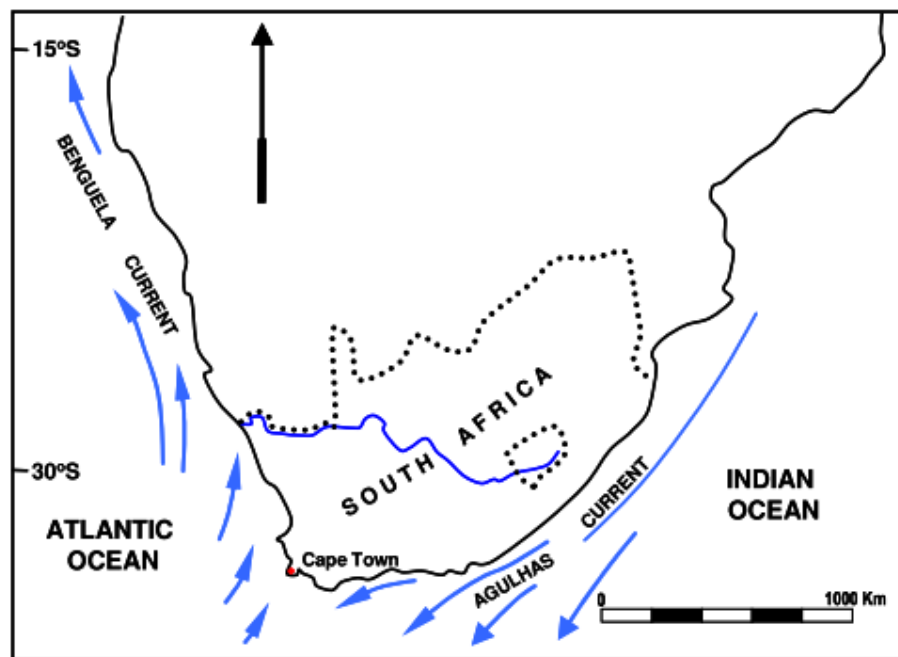


Figure 2-2: Principal Ocean Currents along the Southern Coast of Africa

(Adelana, 2010)

The climate of the CFA is influenced by geographical and topographical features, which result in highly localised microclimates. The climate grades into semi-desert in the north of the Western

Cape, become less seasonal to the east and tends towards sub-tropical on the coast (Segun *et al.*, 2010). The annual precipitation of the Cape Flats area varies between 400 mm and 800mm towards False Bay, with an arid period from November to April, and the mean annual temperature is approximately 17°C (Adelana *et al.*, 2010). According to the annual climate report by SAWS (2020), the average minimum and maximum temperature in Cape Town was 11.9°C and 22.4°C respectively. **Table 2-1** illustrates the climate overview for the periods; 1951 to 2020 and 1981 to 2020 for the temperature and rainfall of Cape Town, respectively.

Table 2-1: Climate Overview of Cape Town

(SAWS, 2020)

Rainfall (mm) overview of some climate stations for 2020 (1981-2020)									
Station	Total 2020	Normal (1981-2010)	Highest Annual Total (since 1981)	Lowest Annual Total (since 1981)	Highest Daily Total 2019	Highest Daily Total (since 1981)	Number of days with rainfall >=1mm (2020)	Average number of days per year with rain >=1mm (1981-2010)	
Cape Town	382	542	707(1996)	323(2010)	34	94 (1993-04-11)	54	68	
	Average 2020	Normal (1981-2010)	Rank (Highest since 1951)	Highest Annual Average (since 1951)	Lowest Annual Average (since 1951)	Highest Daily 2020 (date)	Highest Daily (since 1951)	Lowest Daily 2020 (date)	Lowest Daily (since 1951)
	Maximum Temperature (°C) overview of some climate stations for 2020 (1951-2020)								
	22.4	22.2	21	23.4 (1999)	20.9 (1954)	36.8 (2020-02-25)	42.3	11.4(2020-08-31)	9.4
	Minimum Temperature (°C) overview of some climate stations for 2020 (1951-2020)								
	11.9	11.7	22	12.6 (2014)	10.0 (1951)	20.2 (2020-01-15)	22.4	1.8 (2020-07-27)	-1.9

2.2.4 Hydrogeology and Geology

The formation of the Peninsula sandstones has been linked to that of the eastern fringe of the Cape Flats. The low-lying sand-covered coastal plain connecting the Peninsula to Tygerberg and Stellenbosch was formed by the river and wind erosion and deposition caused by the Palaeozoic. This led to the removal of the Table Mountain Group between False Bay and Table Bay, creating the Cape Flats (Harris *et al.*, 1999). The basement of the Cape Flats is composed of Precambrian and Palaeozoic rocks belonging to the Cape granite, the Malmesbury Formation, and the Table Mountain Sandstone. Raised beaches have been found as evidence of former fluctuations in sea level along the coast of the Cape Peninsula and on sites where a cliff coast is present (Schalke, 1973). The meta-sediments of the Precambrian Malmesbury Group are the oldest rocks in the Western Cape and consist of metamorphic rocks like phyllitic shale, quartz and schist, siltstone, sandstone, and greywacke. These occupy the coastal plain between Saldanha and False Bay in the west and the first mountain ranges in the east (Adelana *et al.*, 2010).

The Cape Flats has sediments of Quaternary and comprises the 'late-tertiary and recent sands' unit overlying the Malmesbury Shale. (Theron *et al.*, 1992). **Figure 2-3** shows the geology of the southwestern part of the Cape Flats with various section lines drawn based on previous studies (Henzen, 1973; Gerber, 1981; Vandoolaeghe, 1989).

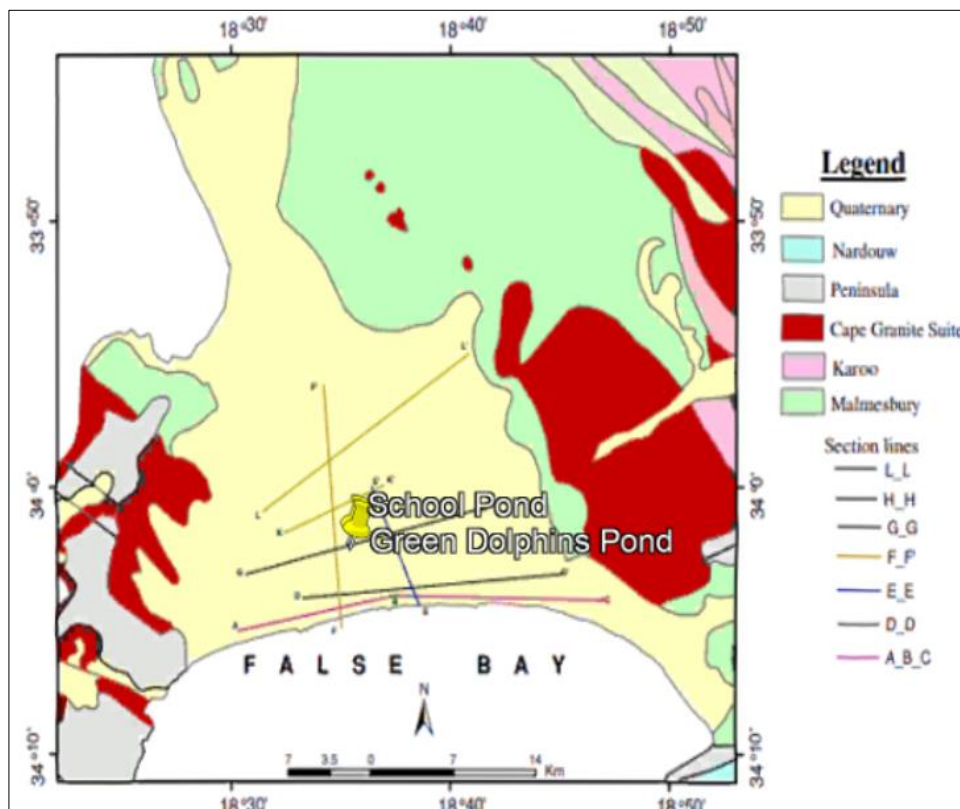


Figure 2-3: Geological Map of the Cape Flats Area

(Adelana *et al.*, 2010)

The study area of this thesis comprises the Quaternary sediments of the Sandveld group, made by the Witzand and Langebaan formations, and lies along section line G-G as shown by the location of the stormwater ponds, therefore, comprises sand overlying Malmesbury shale as shown in **Figure 2-4**.

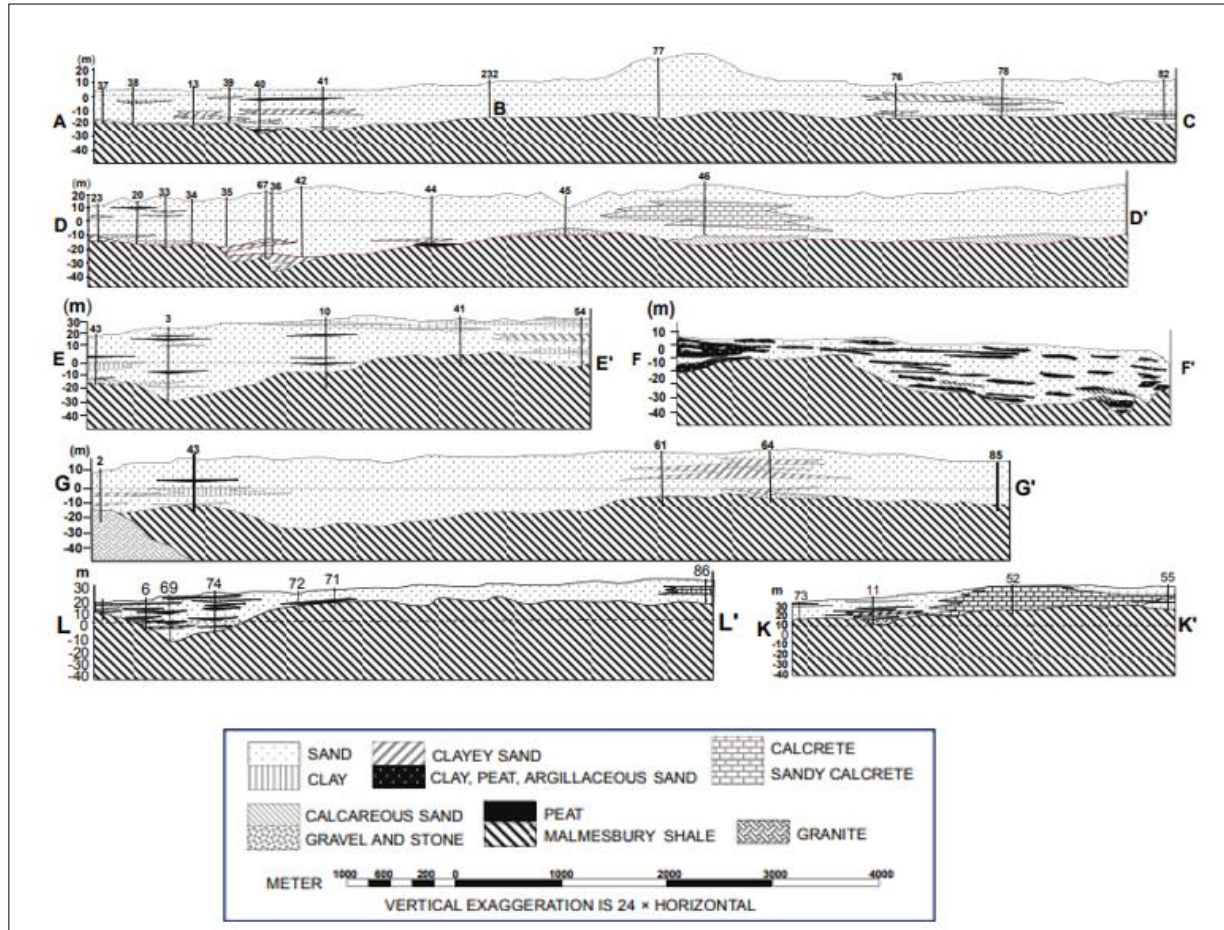


Figure 2-4: Geological Cross-sections (indicated in the figure above) showing the Inter-relationship of Sediments in the Cape Flats

(Adelana *et al.*, 2010)

2.2.4.1 Quaternary Deposits

1. Witzand Formation

The Witzand Formation forms the youngest subdivision of the Cenozoic Sandveld Group. It is widely distributed along the southwest coast and comprises fine to coarse calcareous sand with shells forming vegetation-bound coastal dunes (Roberts *et al.*, 2009; Browning & Roberts, 2015; Gxokwe & Xu, 2017). The Witzand formation overlies the Langebaan formation, and its

thickness is variable but usually less than 30m thick, and the dune snail *trigonephrus globulus* is ubiquitous. Detrital carbonate comprises 20 to 85 % of the sands, derived from crashed sea shells but also echinoid spicules and dune snails (Rogers, 1980; Browning & Roberts, 2015).

2. Langebaan Formation

The Langebaan Formation is a Limestone Member of the Bredasdorp Group, which has been incorporated into the Quaternary sediments of the Sandveld Group. The limestones overlay various older units and are found from sea level to above 200 m (Theron *et al.*, 1992). The formation is characterised by very fine to medium calcareous sandstones containing cross bedding along the coast (Gxokwe & Xu, 2017).

2.2.4.2 Conceptual Hydrogeological Model

Adelana (2010) developed a conceptual hydrogeological model of the CFA using existing data on potential controls of recharge like climate, hydrology, geomorphology, lithology, groundwater fluctuations, qualitative fluctuations and geology to describe the location and mechanisms of recharge into the aquifer as shown in **Figure 2-5**. It is believed that the CFA carries recharge water laterally a few hundred meters to a few kilometres, which could result in the ageing of the recharged water as illustrated by the wells AB-7 and BA-6 being located a distance away from the source of recharge.

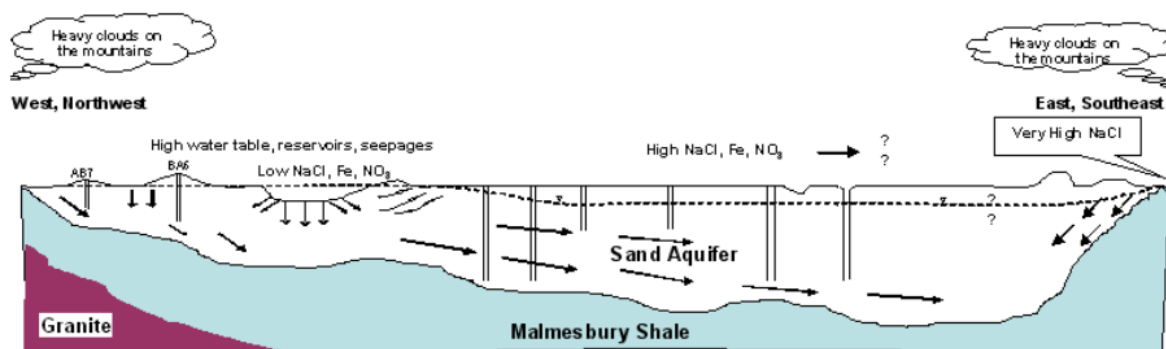


Figure 2-5: A Hydrogeologic Model of the Cape Flats Area

(Adelana, 2010)

Similarly, Gxokwe & Xu (2017) developed a three-dimensional (3D) regional hydrogeological model of the cape flats aquifer using the Golden surfer software. It was determined that the groundwater in the CFA flows from the northern, eastern and western sides towards the southwestern part of the aquifer, i.e., from high elevations to low elevations. Recharge (Re) in the aquifer is mainly from precipitation and occurs on the surface. Groundwater leaves the aquifer

through evapotranspiration (ET) and abstraction (Abs) in the Phillipi horticultural area, where it is used for irrigation.

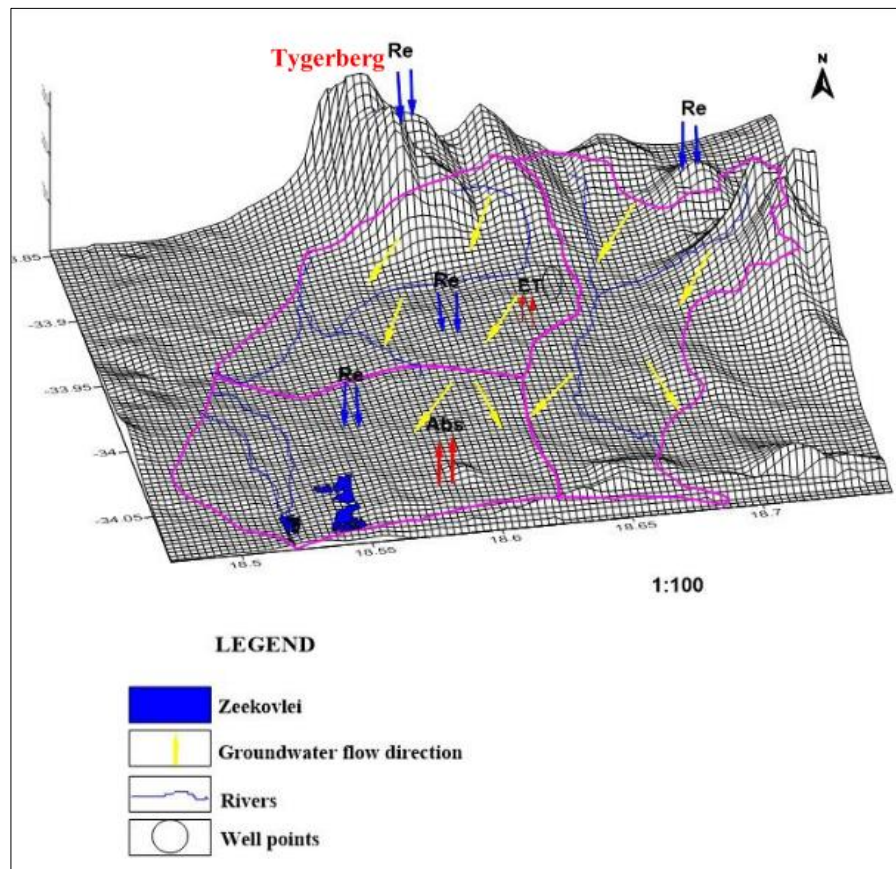


Figure 2-6: 3D Regional Hydrogeological Model of the CFA

(Gxokwe & Xu, 2017)

2.3 Groundwater Recharge, Storage and Discharge

2.3.1 Groundwater Recharge

Groundwater Recharge is the downward flow of water reaching the water table, forming an addition to the groundwater reservoir (Lerner *et al.*, 1990). Adams *et al.* (2004) define groundwater recharge as the flow of the portion of rainfall that reaches the saturated zone by either direct contact in the riparian zone or by downward percolation through the unsaturated zone. The fraction of precipitation that becomes groundwater is determined by soil characteristics and surface vegetation. When soil is eroded, rainwater runoff increases, which reduces the rate at which precipitation infiltrates and recharges groundwater in aquifers. Changes in the vegetation cover and modifications in the landscape also impact the amount of water infiltrating

the aquifer. The Cape Flats Aquifer is located in a peri-urban city where groundwater recharge is due to water supply leakages, urban irrigation return flows and urban drainage (Gxokwe and Xu, 2017).

Groundwater movement occurs naturally or artificially. The recharge of aquifers can be enhanced artificially by increasing the availability of the water supply for recharge to store and treat water in aquifers. Xu & Beekman (2019) broadly define groundwater recharge as the addition of water to the saturated zone and further distinguish four main recharge modes, as follows.

- i. Downward flow of water through the unsaturated zone reaching the water table.
- ii. Lateral and/or vertical inter-aquifer flow.
- iii. Induced recharge from nearby surface-water bodies resulting from groundwater abstraction.
- iv. Artificial recharge i.e., from borehole injection or manmade infiltration ponds, dams, etc.

Artificial recharge of aquifers is also known as Managed Aquifer Recharge (MAR). It is a water management option that provides a means of intentionally recharging and storing water underground in aquifers for subsequent recovery and beneficial use. It provides an essential buffer against the impacts of climate variability and change, mainly when additional groundwater is recharged during wet or flooding periods for subsequent abstraction during dry or drought periods (Ebrahim *et al.*, 2020).

2.3.2 Groundwater Storage

Jia (2007) defines groundwater storage as the volume of gravitational water stored in an aquifer. It is accumulated in a long-term dynamic process of the interaction of recharge, flow, and discharge in such a way that it stabilizes when the balance between recharge and discharge is relatively stable. The long-term equilibrium of the groundwater system is maintained under certain conditions. This equilibrium refers to the amount of water that flows or leaves the system equal to or less than the amount that would be discharged from the system. The quantity of water stored in a system is always equal or varies depending on the long-term average conditions of the climate (Alley *et al.*, 1999).

The amount of discharge and recharge depends on the weather conditions and the duration of the cycle. In some instances, such as during a hydrological and meteorological cycle, the change in the rainfall may stimulate the recharge disturbing the storage and discharge accordingly; as long as the recharge is adequate, more storage helps maintain the balance between the flow and recharge (Jia, 2007).

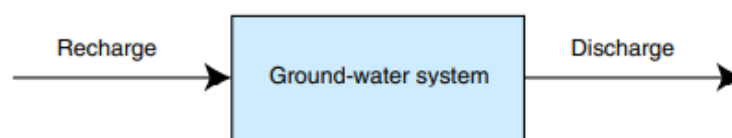


Figure 2-7: Water-budget Diagram Illustrating that Inflow equals Outflow

(Alley *et al.*, 1999)

2.3.3 Groundwater Discharge

Xu *et al.* (2006) defined groundwater discharge as the reverse of recharge, i.e., water leaving an aquifer system via natural or artificial means; a groundwater abstraction is a form of discharge. It includes natural discharge and exploitation/sustainable yield. Natural discharge is the groundwater naturally leaves the aquifer unit before or after exploitation, such as the outflux on the lower boundary of the aquifer, the evaporation from the unconfined water surface and leakage to the adjoining aquifer unit or layer. Sustainable yield is defined as the amount of water in a unit of time that can be sustainably taken from the aquifer without producing an undesirable result (Jia, 2007).

2.4 Groundwater Potential of the CFAU

The CFA is a valuable groundwater source to the Greater Cape Town Metropolitan Area. The pilot study of the Cape Flats aquifer, centred on Mitchell's plain, carried out by the geohydrology directorate of the Department of Water Affairs & Forestry, South Africa (DWAF) in the 1980s determined a potential supply of 18mm³/yr of water from the CFAU. The study indicated that the area could yield up to 30l/s of water. The recharge by rainfall for the whole CFAU was estimated as 53.4mm/yr, and the potential sustainable was equivalent to 20% of the total water supply to the Greater Cape Town Metropolitan Area (GCTMA). However, not all the CFAU is suitable for providing sustainable high-yielding groundwater for town supply purposes, but it is a valuable source of groundwater for small-scale uses, especially the irrigation of gardens (Maclear, 1995).

A study by Gxokwe and Xu (2017) on the conceptualisation of urban hydrogeology on the CFA revealed that aquifer parameters play an important role in determining groundwater potential. They provide the magnitude of influence that stress due to either groundwater abstraction or artificial recharge has on the aquifer. It was concluded that the southern part of the CFA around the Phillipi area is suitable for MAR due to the high aquifer discharge and storage observed in the area. The hydraulic conductivity of the aquifer varies between 15-50m/d, the

storativity values range from 10^{-3} to 10^{-1} and the transmissivity from $<50 - 650\text{m}^2/\text{d}$ (Gerber, 1976; Gxokwe & Xu, 2017).

2.5 Groundwater Utilization of the CFA

Surface water is the most utilised source of water in Cape Town. Groundwater is a better water source, and if well developed and utilised, it would make a far more significant contribution to the water supply. Unfortunately, its use as a resource remains negligible, supplying only just over 2% of the total demand of Cape Town. Plans are underway to augment the water supply with more groundwater to diversify water resources (Adelana, 2010; CoCT, 2018). The Cape Flats Aquifer is a very productive area with intense water use. The groundwater contained in the CFA unit is fresh (Maclear, 1995). Groundwater is essential for humans and nature due to its varying extent, prevalence and natural quality across the globe (Villholth, 2006). It is a major component of the water supply system globally as it plays a crucial role in managing various regions and climatic zones (Shahin, 2004). Coughanowr (1994) listed several unique features rendering groundwater suitable as a water supply, and these include.

- i. Groundwater has excellent natural quality. It is generally free of pathogens, color, and turbidity.
- ii. Groundwater is widely distributed and can easily be developed near communities.
- iii. Groundwater sources are dependable and are relatively unaffected by short droughts.
- iv. Groundwater can be developed incrementally, at points near the water demand, thus avoiding the need for large-scale storage, treatment, and distribution systems.

South Africa's groundwater utilization has increased significantly over the past five decades. Nationally, irrigation uses over 64% of groundwater, and domestic consumption and mining in urban areas use around 8% (Adelana, 2010). The aquifer is used for irrigating sports fields and gardens in the Mitchells Plain area (Harris *et al.*, 1999) and for agriculture in the Phillipi Horticulture Area (PHA).

The CFA is an essential potential source of groundwater for the Cape Town Metropolitan Area, as the city's water supply is impaired by climate change and freshwater scarcity due to population growth and the expansion of industries and commercial activities in the city. Therefore, the City of Cape Town is responsible for managing its groundwater resources sustainably, which requires accurate data on the recharge and output of the Cape Flats' underground sources. (Adelana, 2010).

2.6 Managed Aquifer Recharge

2.6.1 Overview

Managed Aquifer Recharge comprises purposeful recharge and storage of surface runoff and treated wastewater in aquifers. MAR is an adaptive measure used in various countries, particularly semi-arid and arid areas, to reduce vulnerability to climate change and hydrological variability.(Dillon *et al.*, 2009; IGRAC, 2016). It helps communities to invest in demand management as it enables the minimum reduction in demand to reach groundwater balance (Dillon *et al.*, 2009). MAR is more advantageous over dams as an option for water supply in such a way that its economic size can range as low as 1000 m³/a, whereas dams with surface storage require several orders of magnitude (Dillon, 2005). The primary objectives of MAR, according to Ebrahim *et al.* (2020), include the following:

- i. Secure and augment water supply (balance variation in water supply and demand).
- ii. Improve water quality.
- iii. Ameliorate groundwater level decline.
- iv. Prevent seawater intrusion.
- v. Secure water supply in drought and emergency situations.
- vi. Prevent seawater intrusion.
- vii. Enhance environmental flow.

It is very flexible and applicable on different scales and purposes. However, it is not a remedy for water scarcity as it requires suitable sources of water and aquifer conditions. Consequently, the MAR potential of an area should be assessed before any field activities are initiated (IGRAC, 2016). The factors that determine whether MAR is likely to be successful, according to Murray (2004), include:

- i. The quality, type, and reliability of the water source available for recharge
- ii. The quality of recharge water, aquifer geochemistry, the compatibility of the two waters and clogging issues
- iii. The hydraulic characteristics of the aquifer and groundwater recovery
- iv. Economics
- v. Management requirements

2.6.2 MAR Project Components

There are two main types of aquifers in which groundwater recharge can be stored: Confined and Unconfined aquifers. A confined aquifer requires a borehole/well to penetrate the aquitard/ low permeability layer in a stratigraphic sequence to inject and abstract fresh water for end use. Unconfined aquifers allow direct injection and infiltration of water through permeable soils for

recharge to be enhanced by basins and galleries as they do not have an aquitard (Dillon *et al.*, 2009; Mauck, 2017). **Figure 2-8** shows the seven components common to the types of aquifers.

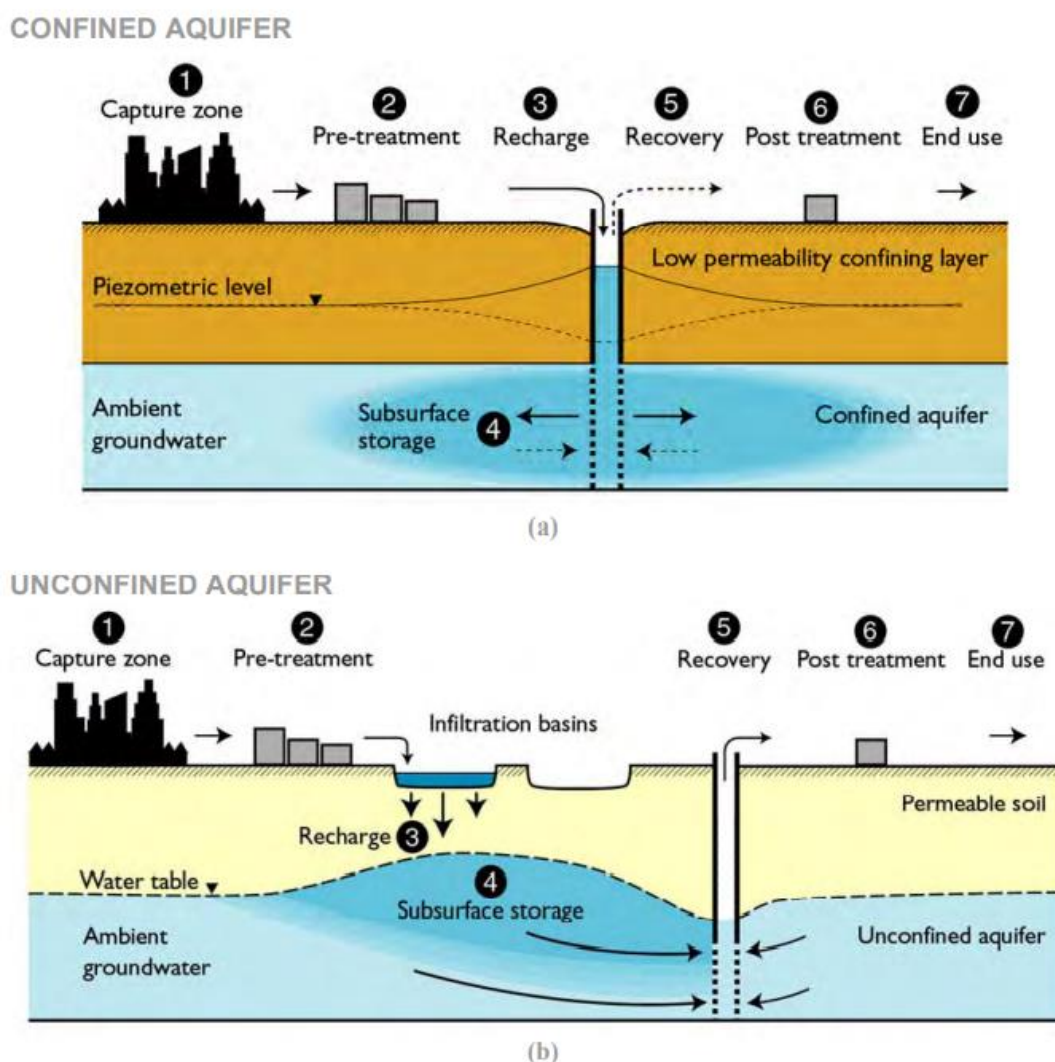


Figure 2-8: (a) Confined Aquifer and (b) Unconfined Aquifer

(Dillon *et al.*, 2009)

2.6.3 MAR Techniques

Numerous techniques/methods enhance groundwater recharge intentionally or unintentionally. Gale (2005) illustrated the categories of the intentional recharge methods as shown in **Figure 2-9**. It shows groundwater recharge methods through percolation tanks, wells, and infiltration basins like stormwater ponds. The methods were divided into spreading methods, in-channel modifications, wells, shaft and borehole recharge, induced bank infiltration and rainwater harvesting.

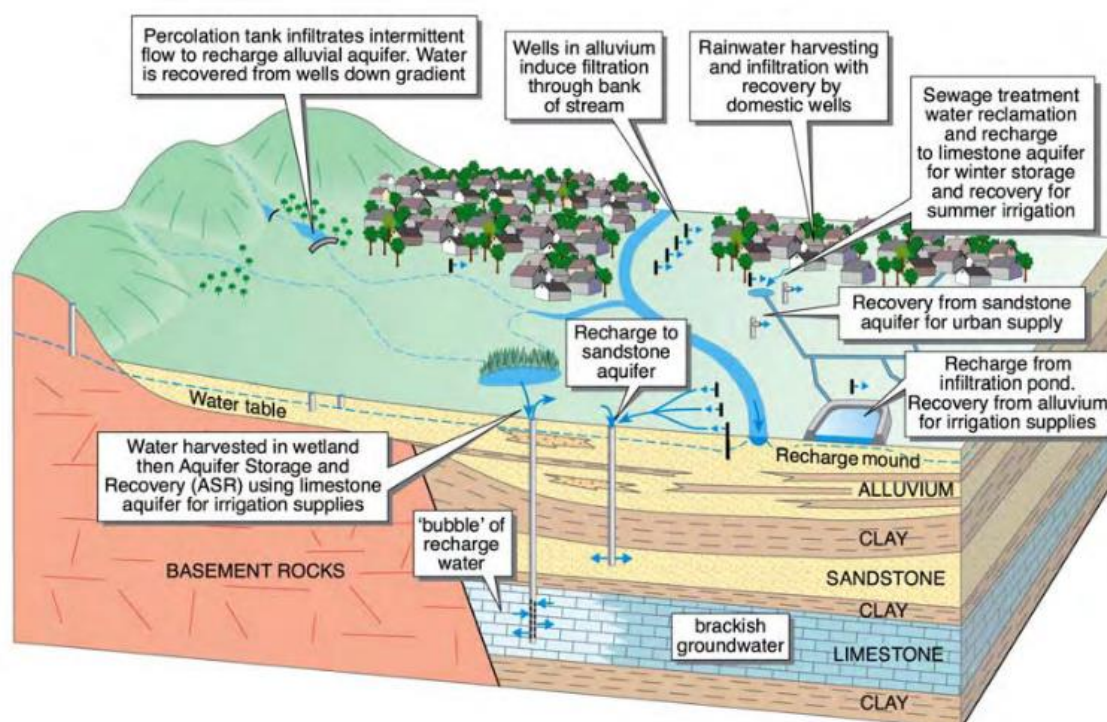


Figure 2-9: Methodologies for MAR

(Gale, 2005)

2.6.3.1 Spreading Methods

The spreading methods consist of infiltration ponds, Soil Aquifer Treatment (SAT), controlled flooding and incidental recharge from irrigation. These are applied in cases where the unconfined aquifer is at or near the ground surface, and groundwater recharge is by infiltration through the permeable layers (Gale, 2005).

2.6.3.2 In-channel Modifications

Groundwater can be recharged using sand storage dams, percolation ponds behind check dams, subsurface/underground dams and leaky dams (Gale, 2005). Sand storage dams are small dams built on and into the riverbed of seasonal sandy rivers, allowing them to trap sediments when flow occurs. The sand dams can be raised in case of floods to create an ‘aquifer’ that can be tapped by wells in the dry seasons (Dillon *et al.*, 2009; RAIN, 2012). Using percolation ponds behind check dams is an inexpensive way to recharge groundwater. A concrete spillway is constructed to avoid erosion, and bunts are built to channel surface runoff, thus reducing the

destructive energy of the intense runoff. Underground dams are used to detain water in alluvial aquifers. In ephemeral streams where basement highs constrict flows, a trench is constructed across the stream bed into the basement rocks and backfilled with low-permeability material to constrain groundwater flow (Gale, 2005).

2.6.3.3 Wells, Shafts and Borehole Recharge

This technique provides groundwater storage control or water quality improvements for industries requiring a large amount of water or water of high quality. It consists of open wells and shafts, Aquifer Storage Recovery (ASR) and Aquifer Storage and Transfer and Recovery (ASTR), whereby structures are designed to recharge water by injection or infiltration. ASR is a technique where the borehole is used for both injection and recovery of water. ASTR involves the injection of water into a borehole with recovery from another location, some distance away, to increase travel time and benefit from the water treatment capacity of the aquifer. The wells and shafts are used to recharge shallow aquifers, especially at locations where surface layers are of low permeability and spreading methods are not practical (Gale, 2005; IGRAC, 2007).

2.6.3.4 Rainwater Harvesting

These methods include collecting overland flow for productive use, like field bunds, rooftop runoff and trenches. They are used for small-scale systems, managed mostly by individuals and local communities and involve the concentration of rainfall from a larger area for groundwater recharge (IGRAC, 2007). Rooftop runoff is diverted into a well, a sump or caisson filled with sand or gravel and allowed to percolate to the water table, where it is collected from a well using a pump (Dillon *et al.*, 2009).

2.6.3.5 Induced Bank Infiltration

Induced bank infiltration comprises bank filtration and dune filtration. Bank filtration is the extraction of groundwater from a well near or under a river or lake to induce infiltration from the surface water body, thus improving the water quality recovered. Dune filtration is the infiltration of water from ponds constructed in dunes and extraction from wells or ponds at a lower elevation for water quality improvement and to balance supply and demand (Dillon *et al.*, 2009).

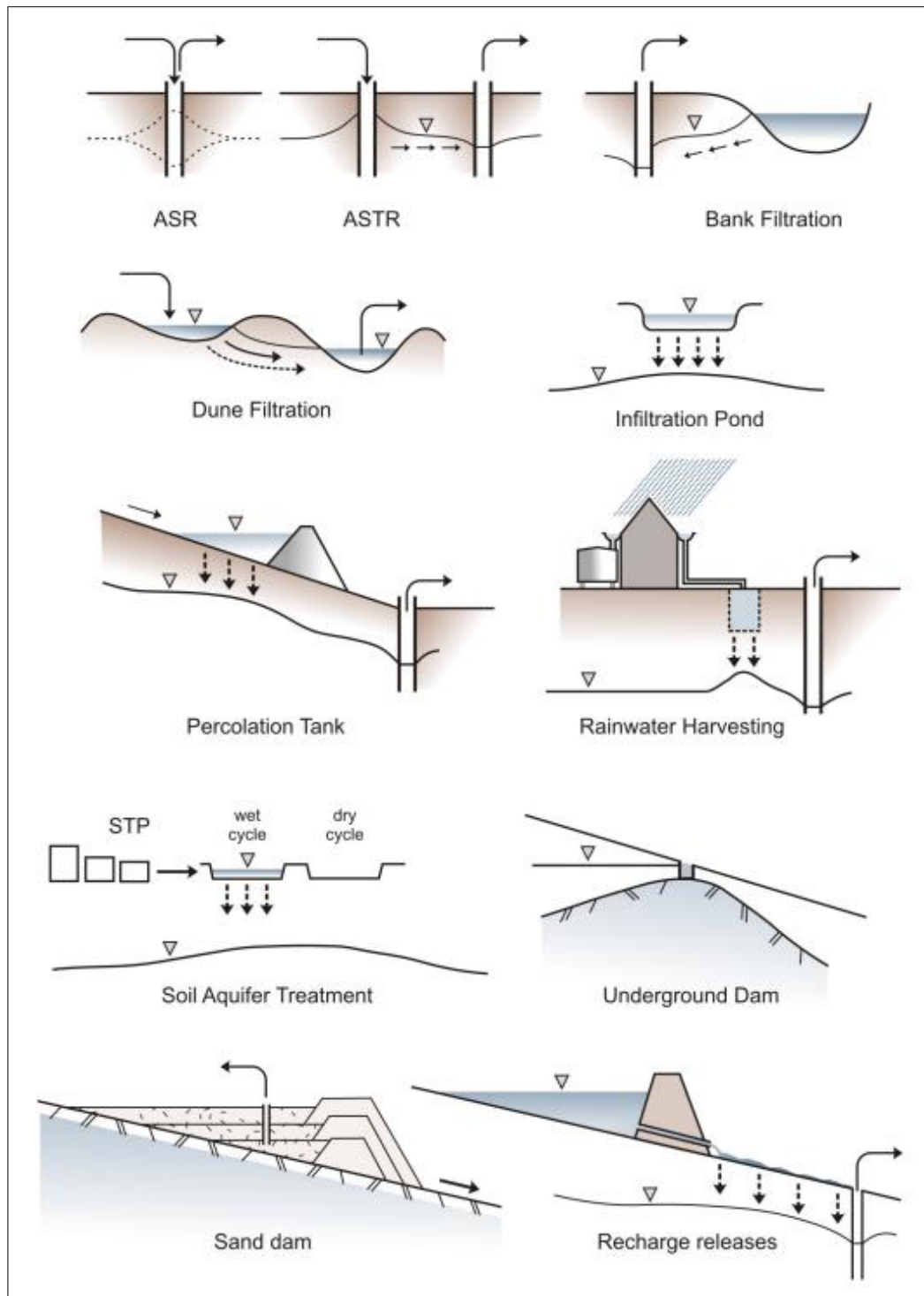


Figure 2-10: Schematic Representation of the MAR Techniques

(Dillon *et al.*, 2009).

2.6.4 MAR in Africa

2.6.4.1 MAR Case Studies

A recent study by Ebrahim *et al.* (2020) identified that it is more practised in the wealthier and drier countries where MAR technology has gained popularity. It provided an overview of the MAR progress in Africa to determine the potential of MAR for future use. A total number of 52 case studies on MAR, concentrated in nine (9) countries, were identified in the continent, with South Africa having the highest number of cases of 17 and Ethiopia with the least cases, as shown in **Figure 2-11**.

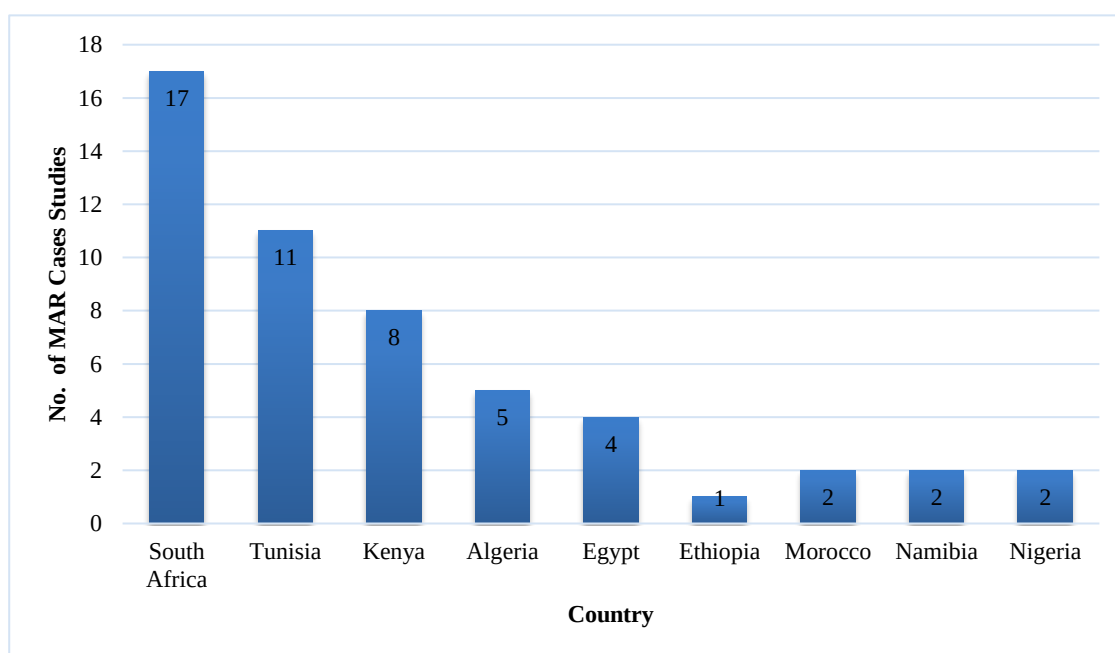


Figure 2-11: Number of MAR Case Studies in Africa per Country
(Ebrahim *et al.*, 2020)

2.6.4.2 Historical Development of MAR Cases in Africa

According to Ebrahim *et al.* (2020), MAR in Africa started in the 1960s, and the cases have increased since then. However, it has yet to be implemented in most of the African countries; hence the analysis was based on 37 new projects with known start dates. The first projects were launched in 1965 in Tunisia and Polokwane, South Africa, followed by two other MAR projects in the 1970s and three in the 1980s. A total number of seven and sixteen projects were implemented in the 1990s and 2000s, respectively. There was a decrease in the 2010s to seven cases recorded, which would have been attributed to a lag in reporting. **Figure 2-12** shows the

number of case studies per decade, categorized according to the various main MAR techniques used in Africa.

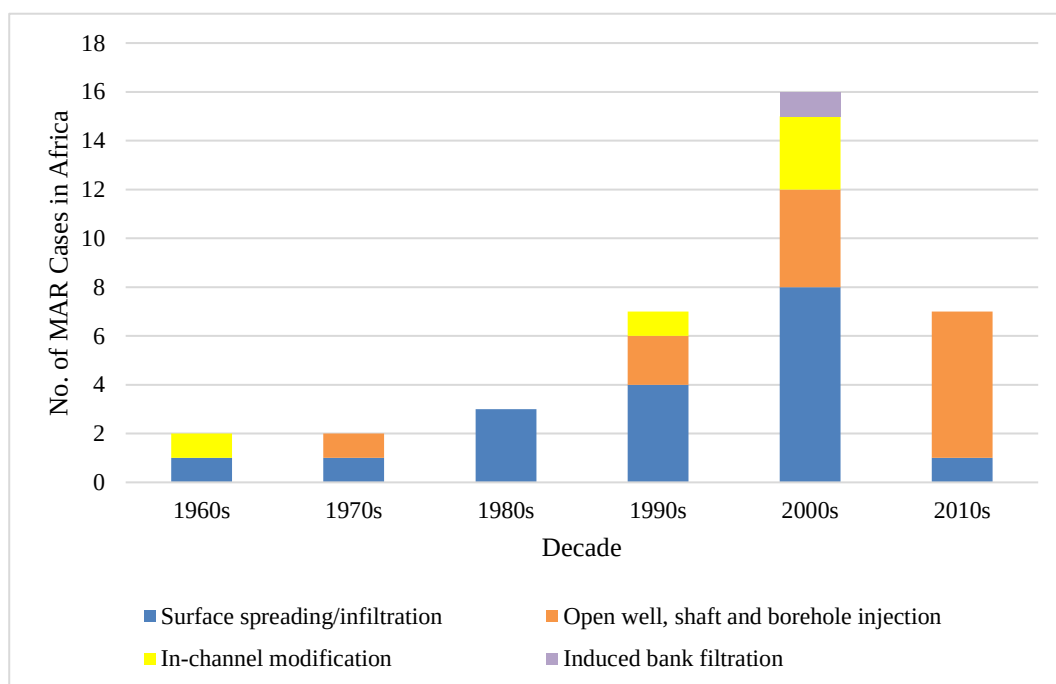


Figure 2-12: Historical Development of MAR Cases in Africa with known Starting Date.

(Ebrahim *et al.*, 2020)

In Tunisia, the first MAR project was launched in 1965 in the Soukra aquifer after creating a public irrigated perimeter to recharge groundwater from treated wastewater. After that, an experimental station was built in the Souhil river basin to recharge the Nabeul-Hammamet aquifer in 1986. The El Hajeb-Sidi Abid public irrigated area was created in 1995, and it was observed that there was a significant rising in the piezometric groundwater levels from the percolation of irrigation water into the aquifer. The aquifers of Boumerdes and Mahdia-Ksour Essef benefited from the landscaping of the riverbeds of Zrata and El Ayoun by infiltration structures in 2005. Finally, a new pilot study was constructed in 2008 in Korba-El Mida purposely to encourage groundwater recharge of the Eastern Coast of Cap Bon region using treated wastewater (Chaieb, 2014).

2.6.4.3 Main MAR Techniques used in Africa

There are four types of MAR techniques employed in Africa, according to Ebrahim *et al.* (2020). These include the following in ascending order; surface spreading/ infiltration, open well, shaft and borehole injection, in-channel modification and induced bank filtration. The sand storage dams of the in-channel modification are mostly used in Kenya, with over 500 dams constructed

since 1995 (RAIN, 2012). The spreading method is the most practised in Tunisia, and the open well, shaft and borehole injection method in South Africa. No cases of the rainwater harvesting method were recorded in the continent and only one case of the induced bank filtration method was reported in Egypt, as shown in **Table 2-2** (Ebrahim *et al.*, 2020).

Table 2-2: Number of Main MAR Techniques in Africa per Country

(Ebrahim *et al.*, 2020)

Country	Surface Spreading/ Infiltration	Open well, shaft and borehole injection	In-channel modification	Induced bank filtration
Algeria	5	-	-	-
Egypt	3	-	-	1
Ethiopia	-	-	1	-
Kenya	-	-	8	-
Morocco	1	-	1	-
Namibia	1	1	-	-
Nigeria	1	1	-	-
South Africa	4	12	1	-
Tunisia	6	2	3	-
Total	21	16	14	1

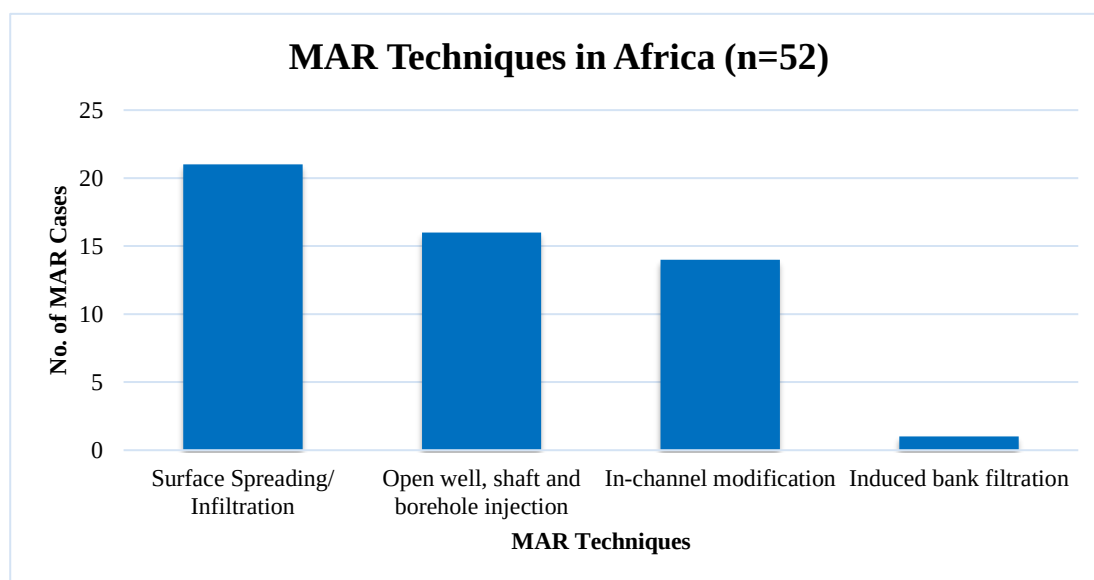


Figure 2-13: Number of MAR Cases in Africa per Technique

(Ebrahim *et al.*, 2020)

2.6.5 The Potential for MAR in South Africa

South Africa has the skills and resources to implement MAR as it is a concept that has been introduced previously in the country (Murray, 2009). South Africa's aquifers vary considerably from those with high permeability and storativity, like the primary aquifers at Atlantis and the Cape Flats, and those with low permeability and storativity, like most of the hard rocks aquifers. In areas where only hard rock exists, artificial recharge is appropriate to enhance limited natural groundwater with an average yield of 1l/s (Murray and Tredoux, 1998). MAR is one of the essential water resources management strategies to improve water security due to climate change, high rate of urbanization and population increase. It was developed to increase groundwater storage to overcome the temporal imbalance between local water demand and availability to improve the water security of the water supply (Dillon, 2009; IPCC, 2014; Zhang *et al.*, 2019).

Several pilot artificial recharge studies have been done on various aquifers to demonstrate the applicability of MAR in South Africa. There are four MAR sites where in-depth feasibility studies have been performed, including Atlantis, Polokwane, Kharkams and Calvinia (Murray *et al.*, 2007). In addition, DWA (2010b) identified other case studies around South Africa, shown in **Figure 2-15**. **Table 2-3** shows the summary of the MAR sites.



Figure 2-14: Location of MAR Sites with in-depth Feasibility Studies

(Murray *et al.*, 2007)



Figure 2-15: Location of Other MAR Sites in South Africa
(DWA, 2010b)

Table 2-3: Summary of the MAR Sites in South Africa

(Murray, 2004; DWA, 2010b)

Site	Aquifer	Managed Aquifer Recharge Method	Main purpose	Water Sources
Atlantis	Sand	Infiltration basins	Water security for the dry season, wastewater reuse, capture stormwater and prevent saline water intrusion	Municipal wastewater and Stormwater runoff
Polokwane	Sand and fractured gneiss	Infiltration into the fractured aquifer	Reuse wastewater	Treated municipal wastewater
Kharkams	Fractured granite	Borehole injection	Water security for the dry season, improve water quality, increase yield, and reduce salinity of groundwater	Ephemeral rivers, surface water runoff
Calvinia	Breccia pipe in Karoo sequence	Borehole injection	Water banking for emergency in case of droughts	Dams, groundwater (existing boreholes)
Williston	Horizontal fracture in Karoo sequence	Borehole injection	Increase yield of existing production boreholes	Adjacent aquifer compartment
Sedgefield	Sand	Dune filtration: infiltration of water through the sand dunes	Increase water supply to meet the demand	Treated effluent from wastewater treatment works
Hermanus	Shallow sands	Local rainwater harvesting	Diversion of stormwater runoff into the aquifer for recharge	Stormwater runoff
Loeriesfontein	Alluvium	Percolation tanks	Municipal water supply and irrigation	Ephemeral rivers

The Atlantis WRM Scheme near Cape Town has been operating for over 20 years, and farmers have built numerous earth dams to enhance groundwater recharge. The stormwater collection and recharge system was constructed in the late 1970s and received its first recharge water in 1979. The scheme has several boreholes and well points for monthly groundwater level and water quality monitoring. (Murray, 2009). There need to be more data at Plettenberg Bay and Prince Albert to establish how the aquifers responded to large-scale abstraction. In response, boreholes and loggers were installed at various points, and the staff was trained to improve the monitoring (DWAF, 2007).

The Polokwane scheme has been in operation since the 1960s, using treated wastewater as a water source for recharge. It depends mainly on surface water; however, it has a groundwater abstraction infrastructure that supplies domestic water to meet the daily demand and serves as a backup during the dry seasons for the municipality and irrigation purposes (Murray *et al.*, 2007).

Miriam Arinaitwe: Transition to Novel Internet of Things Technology for Management of Groundwater Resources – Case of Cape Town, South Africa

Polokwane has alluvium overlying the fractured gneisses allowing infiltration of treated municipal wastewater and the river water (Murray and Tredoux, 2002).

Kharkams is a small village in the semi-arid Namaqualand region with a mean annual rainfall of 250mm. The scheme received its first MAR activity in 1995 and mainly depended on groundwater as a water source. It is used for good quality water during the rainy seasons that would be lost to evaporation and evapotranspiration (Murray, 2004; Murray *et al.*, 2007; DWA, 2010b). The Kharkams aquifer comprises granites and gneisses cut by major faults on which high-yielding boreholes are sited. The water flows over or infiltrates the sand filter built in the ephemeral river and is gravitated to the injection boreholes. Three controlled injection runs from 1999 to 2001 reversed the declining water levels in the aquifer (Murray, 2004).

Calvinia town, on the western edge of Karoo, has a mean precipitation of 210 mm and a long history of water shortage, thus using MAR to augment the scarce water supplies. Most of the town's water is thoroughly treated from the Karoo Dam, and a small portion is derived from groundwater, which, to a large extent, is saline and has to be blended with surface water for potable (Murray and Tredoux, 2002). Secondary aquifers underlie Calvinia; thus, high-quality water is needed for borehole injection. The scheme can provide a back-up supply for two months; however, the recharged water is unsuitable for human consumption as the subsurface medium is highly mineralised. The quality of the water can be improved by blending the dam water at a ratio of 1:8. It is also difficult to quantify the volume of the water conserved through MAR as it would equal the volume stored in the subsurface if the dam was dried up (Murray and Tredoux, 2002; Murray *et al.*, 2007).

2.6.6 MAR Potential Site Assessment and Mapping

It is challenging to identify areas suitable for managed aquifer recharge and estimate its influence on groundwater levels and flows as there may be limited data on the complex surface and subsurface conditions and flows of the region. It can be resolved by pilot studies using computation tools that allow testing of operational scenarios and hydrologic conditions (Russo *et al.*, 2015). Various studies have been carried out globally using the integration of geospatial data, multi-criteria decision analysis techniques, remote sensing and geographic information system (GIS) technology. This is a more cost-efficient and faster way to identify suitable sites for groundwater recharge potential through MAR suitability maps (Sallwey *et al.*, 2019; Achu *et al.*, 2020; Ahmed *et al.*, 2021).

Different factors/ thematic layers considered in the modelling of the groundwater recharge potential zones include but are not limited to land use, lithology, geomorphology, soil texture, lineament density, rainfall, drainage density, geology and slope (Yeh *et al.*, 2016; Achu *et al.*, 2020). The factors and their importance are compiled from previous literature, and appropriate scores are assigned to each factor to produce a final groundwater recharge potential map of the area (Yeh *et al.*, 2016). MAR suitability maps hold the potential to be integrated into sustainable groundwater plans; however, their quality depends on the quality of the input data as the

decisions of the expert (Sallwey *et al.*, 2019). In this study, seven thematic layers, described in detail below, were used to identify the groundwater potential zones of the study area.

2.6.6.1 Factors Influencing Groundwater Recharge

2.6.6.1.1 Lithology

Lithology is the study of the general physical characteristics of rocks, which is essential in the distribution of groundwater (Yeh *et al.*, 2016). Selvarani *et al.* (2017) stated that the permeability, structure and porosity of the underlying lithological units influence groundwater development. The lithology and size of the rock influence the distribution and flow of groundwater, as rocks with intense fracturing have good potential for groundwater recharge (Fagbohun, 2018).

2.6.6.1.2 Land use/Land Cover (LULC)

Land use/land cover comprises the distribution of residential areas, vegetation cover and type of soil deposits, interpreted from satellite images and land use maps. It is important as it affects runoff, recharge rate and evapotranspiration of the groundwater system. (Yeh *et al.*, 2016). Impervious surfaces like paved areas limit water infiltration, while vegetation cover favours water infiltration into groundwater storage by delaying surface runoff (Achu *et al.*, 2020). Sener & Davraz (2013) stated that the groundwater quality could be affected by the pollutants from the residential area and agricultural activities in the study area.

2.6.6.1.3 Soil

The soil type in an area is one of the major factors that play a significant role in the groundwater recharge in the aquifers, given its texture, structure, permeability and porosity (Selvarani *et al.*, 2017; Achu *et al.*, 2020). The soil controls the infiltration rate of groundwater in that clay soil has a low infiltration rate and high runoff, whereas sandy soils have a high infiltration rate, resulting in low runoff (Fagbohun, 2018). The soil type also controls the movement of contaminants in the vadose zone, which determines the vulnerability of the aquifer. Clay soil has low permeability and restricts contaminant migration to the subsurface layers (Sener & Davraz, 2013).

2.6.6.1.4 Slope

Slope is the elevation change rate that expresses the steepness of the ground surface, which influences the water infiltration rate and surface runoff (Aryanto & Hardiman, 2018; Arulbalaji *et al.*, 2019). The slope of an area affects the infiltration rate of rainfall in such a way that more extensive slopes produce a minor recharge as water rapidly flows down the steep slope compared to smaller slopes (Yeh *et al.*, 2016). Flat/gentle slopes promote groundwater recharge potential

by allowing sufficient time for infiltration, while areas with steep slopes have low infiltration rates and thus have a low groundwater recharge potential (Ahmed *et al.*, 2021).

2.6.6.1.5 Lineament Density

A lineament is a linear feature expressing an underlying geological structure like a fault, cleavages and fractures (Yeh *et al.*, 2016). Tiren (2010) described a lineament as an interpreted one-dimensional line drawn in relation to linear to semi-linear terrain forms like valleys and slopes. Various non-geological structures like channels and roads usually cause errors in assessing lineaments. Therefore geological maps and on-site investigations are used to eliminate these errors (Yeh *et al.*, 2016).

Source data for studies of lineaments consists of information on the topography of an area, e.g. topographical maps, aerial photos, multi-spectral sensing, laser, radar and thermography and geophysical data (Tiren, 2010). Lineaments represent the zones for faulting that result in increased secondary porosity and permeability that provide the pathways for groundwater movement. Lineament density reveals the groundwater potential of an area as the lineaments represent permeable zones (Magesh *et al.*, 2012). The total length of lineaments, also known as lineament density (L_d), is calculated using **Equation 1** below (Yeh *et al.*, 2016).

$$L_d = \frac{\sum_{i=1}^{i=n} L_i}{A} \quad \text{Equation 1}$$

where $\sum_{i=1}^{i=n} L_i$ is the length of lineaments (L) and A is the area of the study area

2.6.6.1.6 Drainage Density

Yeh *et al.* (2016) described drainage density as the total length of all rivers on a drainage basin divided by the total area of the basin. The quality of the network depends on lithology as it provides an important index of the rate of percolation of water into the subsurface layers. The runoff, flow and groundwater recharge are greatly affected by the nature and drainage density of a particular area (Ahmed *et al.*, 2021). The suitability of groundwater potential zones is indirectly related to drainage density, given its relationship with surface runoff and permeability. The denser the drainage network, the higher the runoff and the lower the rate of recharge (Magesh *et al.*, 2012; Fagbohun, 2018). Drainage density is an inverse function of permeability in that the less permeable the rock, the less the infiltration of rainfall (Magesh *et al.*, 2012). It is expressed by **Equation 2**.

$$D_d = \frac{\sum_{i=1}^{i=n} S_i}{A} \quad \text{Equation 2}$$

where $\sum_{i=1}^{i=n} S_i$ is the total length of drainage and A is the unit area of the study area

2.6.6.1.7 Geology

The geologic setting of an area plays an essential role in the occurrence and distribution of groundwater in any terrain because groundwater occurs in geological formations. The ability of the parent rock to store and transport groundwater is vital for its occurrence and depends on the texture, structure and mineral content of the different rocks in the study area (Selvarani *et al.*, 2017; Arulbalaji *et al.*, 2019).

2.6.6.2 Analytic Hierarchy Process (AHP)

AHP is a multi-criteria decision-making technique widely used for groundwater management (Saaty, 1980). It uses pairwise comparison questions to elicit a matrix of the relative preference between each pair of alternatives for each attribute and a matrix of judgements of the relative importance of each pair of attributes (Hopkins, 2001). Each factor is assigned a rank on a scale of 1-9 based on the pairwise comparison. The thematic layers are assigned weights to determine the recharge potential score (P_r) and subjected to weighted overlay analysis in GIS (Yeh *et al.*, 2016; Abijith *et al.*, 2020). P_r is expressed as in **Equation 3**, where w_i is the i^{th} factor weight, r_i is the i^{th} factor rate and the subscripts i refer to the individual features of a theme (Yeh *et al.*, 2016). The weight of each factor represents the proportion of its value in the potential recharge scale; thus, the higher the weight, the more significant the influence of the factor.

$$P_r = \sum w_i r_i \quad \text{Equation 3}$$

The groundwater recharge potential map is obtained and the results validated using an independent dataset (Ahmed *et al.*, 2021).

2.6.7 Water Sources for MAR

According to Dillon *et al.* (2009), there are various water sources for MAR, such as stormwater, reclaimed water, mains water, desalinated seawater, rainwater and groundwater from other aquifers. There is a need for treatment in some cases depending on the source of the water, like where reclaimed water is used for recharge. However, no treatment is necessary where river water of low turbidity is diverted into infiltration basins for irrigation purposes. Sources that provide water of poor quality need a high level of treatment before recharging in cases where:

- i) The aquifer already contains high quality water.
- ii) The water is to be recovered for higher valued uses such as drinking.
- iii) The aquifer is fine-grained and there is a need to avoid frequent or permanent clogging of the recharge basin, gallery or well.

Ebrahim *et al.* (2020) identified six water sources for MAR in Africa. The study considered 52 case studies, of which 33 used river water, 11 used treated wastewater, five used groundwater and each of the other sources three sources were used in one case study, as shown in **Figure 2-16**.

Nineteen of the 33 case studies using river water used ephemeral rivers, while the other eight relied on perennial rivers. Treated wastewater was used in countries with limited water resources, like South Africa, Namibia and Tunisia. Four of the five case studies using groundwater were in South Africa at Elandsfontein, Kolomela, Sishen Mine and Williston. The Williston case study transferred groundwater from an adjacent aquifer compartment to another, while the other three cases used dewatering water from mines (DWA, 2010b; Ebrahim *et al.*, 2020).

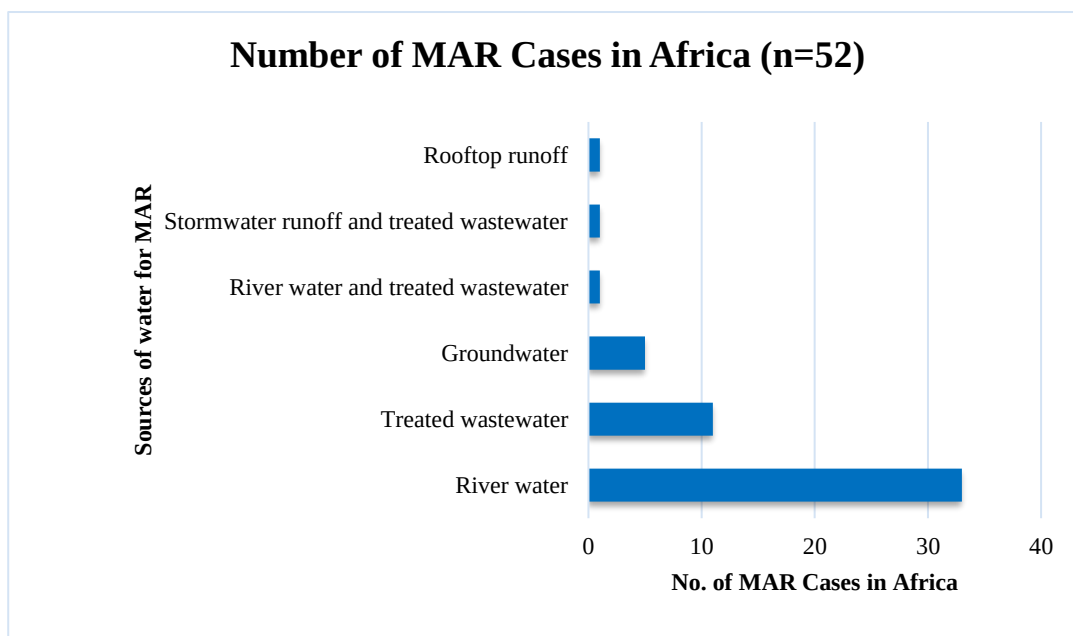


Figure 2-16: Number of MAR Cases in Africa per Water Source

(Ebrahim *et al.*, 2020)

2.6.7.1 Stormwater Runoff as a Water Source for MAR

Stormwater is the water resulting from natural precipitation and accumulation and includes rainwater, groundwater and spring water. It is an integral part of the urban environment and a potential water source, not a ‘nuisance’ by-product of urbanisation (Mitchell *et al.*, 2006; Armitage *et al.*, 2013). According to Armitage *et al.* (2013), the stormwater management infrastructure in South Africa has predominantly focused on collecting stormwater runoff, the portion of rainfall which flows to the surface drainage system and channelling it to the nearest watercourse. It has impacted the environment negatively through soil erosion, siltation and pollution, thus the need for stormwater harvesting (SWH).

Stormwater harvesting is considered in the urban water cycle as part of the Sustainable Drainage Systems (SuDs) of the Water Sensitive Urban Design (WSUD) due to their contribution to stormwater management (Armitage *et al.*, 2013). Integrating SWH into WSUD provides a

method to achieve multipurpose outcomes that assist in moving towards more integrated urban water management. SWH reduces the size of stormwater pollution management facilities by reducing pollutant loads and providing a potential solution to excess stormwater flow volumes and rates (Mitchell *et al.*, 2006).

Water sources favourable for MAR must have water suitable for ultimate use after abstraction. Stormwater runoff is used worldwide for the artificial recharge of groundwater. It usually has a suitable chemical quality. However, characteristics like sediment load and quantity variations may need consideration (Murray and Tredoux, 1998). The quantity of stormwater runoff is highly variable, with the urbanised catchment runoff being up to 50 percent more in total volume and up to 500 percent more in peak discharge than rural runoff. Infiltration and stormwater ponds, wetlands and porous pavements are recommended to lower the volume and peak discharges to avoid flooding (NRC, 1994; Batchelor, 1997).

According to the National Research Council (1994), stormwater runoff quality from residential areas is generally of acceptable quality for most recharge options. However, it is affected by several factors, like rainfall quantity and intensity and the natural characteristics of the drainage basin. Stormwater runoff from industrial areas, industrial wastewater, dry weather storm drainage flow, construction sites and commercial areas should only be regarded for artificial recharge with treatment prior to recharge. Murray and Tredoux (1998) stated two management options available to obtain high-quality stormwater runoff with little need for treatment, and these are as follows.

- i. Divert poor quality stormwater such as that occurs as a ‘first flush’.
- ii. Install natural treatment basins in the catchment area so that solid particles and trace elements are precipitated, and oils, tars and waxes are trapped.

2.7 Stormwater Ponds

The high rate of urbanisation in South Africa has led to a high conveyance of stormwater runoff during rainfall events. One of the regional controls to restore the natural hydrological cycle without hindering the urbanisation rate is the implementation of stormwater ponds (Nascimento *et al.*, 2000). There are numerous stormwater ponds in South Africa, of which Cape Town houses over 800 and 292 of these overlay the CFA. These green spaces were established to collect stormwater runoff to prevent floods, build resilience towards climate change impacts and droughts, improve water quality, preserve biodiversity, and increase groundwater storage quantity. Stormwater ponds collect and manage stormwater runoff from various developments to reduce the peak flow of a storm event. Three main stormwater ponds are used for stormwater management in South Africa, including detention ponds, retention ponds and constructed wetlands (Armitage *et al.*, 2013; Rohrer, 2014). In this study, two detention ponds were used.

2.7.1 Detention Ponds

Detention ponds are storage facilities that are ordinarily dry vegetated depressions designed to store stormwater runoff for short periods and provide flow attenuation. They also facilitate some settling of particulate pollutants and may function as a recreational facility. The stormwater runoff infiltrates the underlying layers or is drained into the downstream watercourse at a predetermined rate (Woods-Ballard *et al.*, 2007; Armitage *et al.*, 2013; Rohrer, 2014).

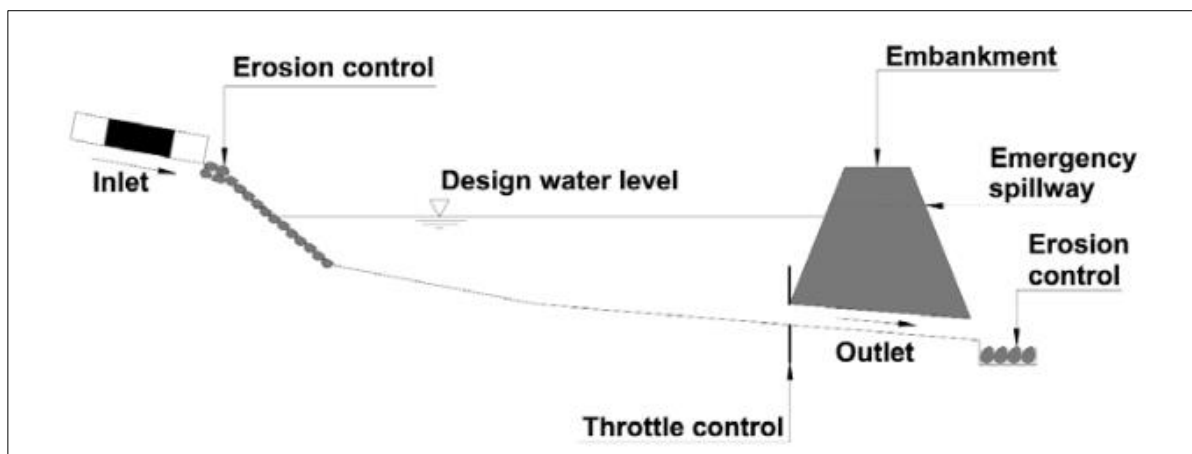


Figure 2-17: Schematic Profile of a Simple Detention Pond

(Woods-Ballard *et al.*, 2007)

2.7.1.1 Advantages of Detention Ponds

Armitage *et al.* (2013) outlined advantages of detention ponds and these include:

- i. Detention ponds temporarily store large volumes of stormwater runoff thus attenuating downstream flood peaks.
- ii. They are relatively inexpensive to construct and easy to maintain.
- iii. They serve as sports fields, play parks or commons during drier seasons.
- iv. Detention ponds add aesthetic value to adjoining residential properties when maintained well.
- v. They present fewer safety hazards than wet ponds due to the absence of a permanent pool of water.
- vi. They are used where groundwater is vulnerable, if lined (Woods-Ballard *et al.*, 2007).

2.7.1.2 Limitations of Detention Ponds

The limitations of detention ponds include (Armitage *et al.*, 2013);

- i. Detention ponds are not very good at removing dissolved pollutants and fine material.
- ii. Generally, they are not as effective in removing pathogens as constructed wetlands.
- iii. They are faced with a problem of siltation due to sediments transported by the runoff.
- iv. The floors of detention ponds can become swampy for some time after major rainfall.
- v. They occupy so much valuable land as they should have a large plan area.
- vi. Detention depths may be constrained by system inlet and outlet levels (Woods-Ballard *et al.*, 2007).

2.7.2 Retention Ponds

Retention ponds also referred to as ‘retention basins’, are permanent pools where runoff is detained for a sufficient time to allow settlement and biological treatment of pollutants. They can handle large amounts of stormwater runoff; however, they may accumulate sediments that impact the storage capacity of the permanent pool. It is recommended to have a sediment clean-out cycle of 15-25 years (Woods-Ballard *et al.*, 2007). The following should be considered:

- i. Regular partial sediment removal is most effective but may not be economic. However, where possible, sediment should not be removed from more than 50 per cent of the pond or wetland area at any one time.
- ii. Appropriate bankside working areas should be selected, and wetland and bankside habitats protected.
- iii. Sufficient vegetation should be retained to ensure rapid re-colonization of damaged areas.
- iv. Ideally, sediment removal should remove accumulated inorganic and organic sediment only but not wetland subsoil or topsoil layers. In practice, this can be difficult to achieve.

Figure 2-18 shows an on-site pond on the Cape Peninsula University of Technology (CPUT) Campus used to irrigate all the green spaces. In August 2020, the pond had to be upgraded to increase its capacity and renovate the inlet and outlet structures as the existing pond was losing much water. CPUT built a 420m long retaining wall around the circumference with drainpipes running behind the entire length of the wall during the upgrade. Currently, the pond has a green setting, leakage is curbed, capacity is greater, and more water is available for future water shortages.



Figure 2-18: On-site Retention pond located at CPUT Campus

2.7.2.1 Advantages of Retention Ponds

Armitage *et al.* (2013) outlined some advantages of retention ponds and these include the following:

- i. The incorporation of retention ponds into the natural landscape promotes biodiversity; they can also be used for recreational purposes where adequate supervision is available.
- ii. Retention ponds generally have the capacity to remove a wide range of common stormwater runoff pollutants.
- iii. Retention ponds are one of the most cost- effective SuDs options.
- iv. Stormwater runoff that is captured in retention ponds can be reused for irrigation or secondary domestic purposes where the water quality is acceptable.

2.7.2.2 Limitations of Retention Ponds

The limitations stated by Armitage *et al.* (2013) include:

- i. The permanent open pool of water creates health and safety concerns and therefore requires social impact considerations at the design stage.

- ii. If maintained infrequently or irregularly the permanent open pool of water could display unsightly floating debris and scum. Other nuisances include foul odours and mosquitoes.
- iii. Retention ponds are normally restricted to sites with shallow slopes.
- iv. Retention ponds require a baseflow or the addition of supplementary water to maintain a specified permanent water line.
- v. Retention ponds may attract birds, such as herons, whose faeces can cause an increase in phosphorous in the water.
- vi. Retention ponds are generally not as effective in removing pathogens as constructed wetlands.

Retention ponds are open water bodies that may pose a safety hazard. The embankments are lined with vegetation to improve water quality through infiltration and biological uptake. However, they are ineffective in removing pathogens from stormwater runoff and, therefore, can be a health hazard (Armitage *et al.*, 2013).

2.7.3 Constructed Wetlands

Constructed wetlands are constructed basins with shallow and marshy areas and wetland vegetation designed to treat urban stormwater runoff, enhance wildlife habitat, and offer essential aesthetics to an area. They delay the water flow for a long time to allow sediment settlement and remove contaminants by easing adhesion to vegetation and aerobic decomposition (Woods-Ballard *et al.*, 2007). The long-term performance of these wetlands is associated with vegetation density. If the vegetation covers most of the wetland, open water is confined to a few well-defined channels (Endicott & Walker, 2003). The following are some of the advantages and disadvantages, as outlined by Woods-Ballard *et al.* (2007).

2.7.3.1 Advantages of Constructed Wetlands

- i. Constructed wetlands can remove urban pollutants from water.
- ii. They are used where groundwater is vulnerable if lined.
- iii. They have high potential ecological, aesthetic and amenity benefits.

2.7.3.2 Disadvantages of Constructed Wetlands

- i. They occupy a lot of valuable land.
- ii. They are not suitable for steep sites.
- iii. The performance of the wetlands is vulnerable to high sediment flow.
- iv. Fencing and isolation is necessary due to the perceived health and safety risks.
- v. They require a supplementary water supply during the dry season to support the aquatic life.

Figure 2-19 illustrates the wetland in the heart of Century City in Cape Town. The development of Century City started in 1996; the site consisted of 200 hectares of land and a degraded wetland used by various bird species for breeding. During the planning process, the aim was to develop a site that satisfied both property development and conservation of rare and threatened vegetation, thus the birth of Intaka Island. The island is a 16-hectare wetland divided into two sections, east and west, each comprising 8 hectares. It is surrounded by canals providing a natural barrier between the built-up area and the natural environment. The water in the canals is not from the dam supplying to Cape Town, but relatively clean water is pumped from Potsdam sewage works located about 15 km away. It is pumped through a sprinkler system that aerates the water and spreads it across the first pond of four in the western section of the island (Turtle, 2020).



Figure 2-19: Wetland at Century City in Cape Town

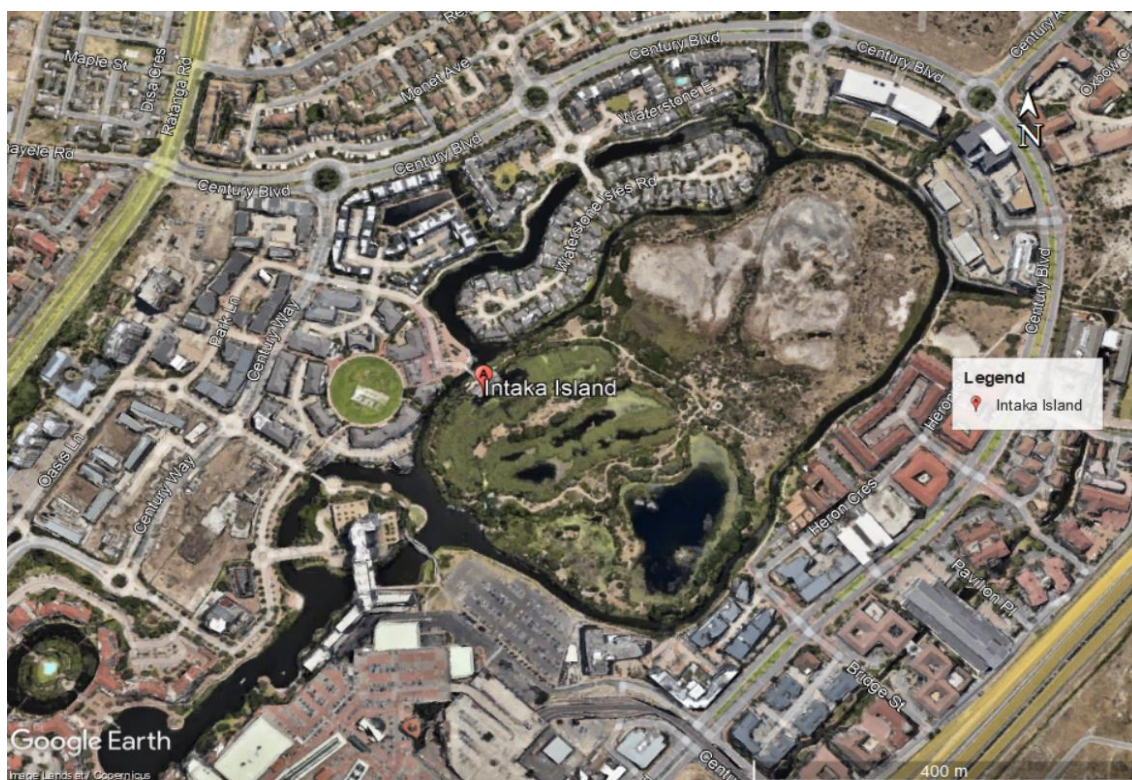


Figure 2-20: Location of Intaka Island

2.8 Climate Change Impact on Groundwater

South Africa experiences water insecurity caused by climatic change. Climate change is the increasing evidence that the earth's climate is changing (Woods-Ballard *et al.*, 2007). It is mainly caused by the anthropogenic emission of green gases, which has led to atmospheric concentrations of carbon dioxide, methane and nitrous oxide, causing global warming and long-lasting changes in all climate system components (IPCC, 2014). It is more complicated to demonstrate the impact of climate change on groundwater than on surface water (Moseki, 2018). The direct impact of climate change on groundwater varies with different combinations of soils/aquifer materials, vegetation and climate zones. Long-term groundwater monitoring provides a critical baseline to identify and evaluate the effects of future change (Jakeman *et al.*, 2016).

In recent decades, climate changes have caused impacts on natural systems as changes in precipitation or melting snow or ice are altering hydrological systems, affecting water resources in terms of quantity (IPCC, 2014). The International Panel on Climate Change (2014) projected that climate change would reduce the groundwater resources in most dry subtropical regions, thus intensifying the competition for water among sectors in the 21st century. Cave *et al.* (2003) declared that the interest in determining the impacts of climate change on groundwater resources

is increasing rapidly in Southern Africa due to the increasing scarcity of water resources. A simplistic empirical relationship between mean annual rainfall and recharge was used to quantify the impact of climate change on groundwater recharge in terms of levels and recharge. A decrease of 20% in mean annual rainfall volumes was observed to translate to an 80% decline in recharge for areas that currently receive 500 mm rainfall per annum or less, as shown in **Figure 2-21**.

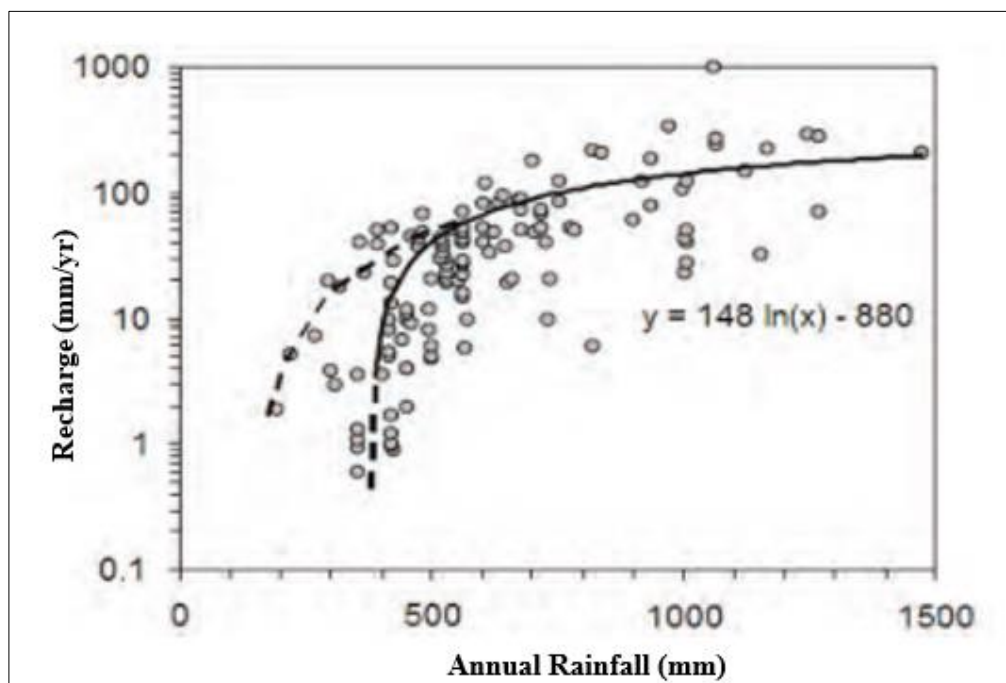


Figure 2-21: Recharge Rates in Southern Africa

(Cave *et al.*, 2003)

Climate change reduces the availability of water for groundwater recharge with consequent effects on water supplies and aquatic ecosystems dependent on groundwater (Woods-Ballard *et al.*, 2007). Groundwater recharge increases as a result of increased precipitation totals and decreases with reduced precipitation and higher evapotranspiration and temperature, which affects the water levels in unconfined aquifers (Carter & Parker, 2009; Dillon *et al.*, 2009; Duah & Xu, 2009; IPCC, 2014; Jakeman *et al.*, 2016).

Climate change mitigation and adaptation measures are developed to cope with the consequences of a changing climate and reduce future risks. They increasingly rely on the water storage capacity of the aquifer and groundwater use and management (Jakeman *et al.*, 2016). Managed Aquifer Recharge should be regarded as part of an integrated water and catchment management strategy due to its importance in mitigating and adapting to climate change (Gale, 2005). It is used to increase the storage capacity of aquifers to help water supplies cope with runoff variability in catchments exacerbated by climate change (Dillon *et al.*, 2009).

2.9 Internet of Things (IoT) Technologies

2.9.1 Overview

The Internet is evolving in several directions and technologies, such as the Internet of Things (IoT) (Azimah *et al.*, 2018). IoT is a novel paradigm rapidly gaining ground in the modern era of computing (Miazi *et al.*, 2016). The IoT technologies are very beneficial for collecting, analyzing and managing groundwater data to minimize climate change and improve the protection of water sources (Oke *et al.*, 2019). According to Dlodlo (2012), linking the IoT to sustainable water resources management is very attractive and is utilized in the region of Water Resources Management. The concept of IoT is so expansive that it is tied in with estimating and controlling remotely detached "things" that more established innovation proved unable.

IoT uses electronic devices to collect and store massive amounts of data, thus improving the accuracy of plans and practices and promoting sustainable groundwater management. These devices include sensor equipment, weather stations and smartphones continuously streaming environmental data. IoT data is the kind of data collected using electronic devices and equipment interconnected with each other and other digital systems over the internet, creating a mesh of devices producing real-time information. (Cyril *et al.*, 2014; Gaffoor *et al.*, 2020).

2.9.2 IoT Basic Concept

The IoT basic concept is developed when there are numerous things/objects, such as Radio-Frequency Identification (RFID) tags, sensors, actuators, mobile phones and many others that interact and cooperate over the internet (Miazi *et al.*, 2016). Internet of Things was previously known as the “Internet of Everything”, “machine-to-machine (M2M)”, “physical computing”, and even “ubiquitous computing” (Azimah *et al.*, 2018).

There are many accepted definitions of the Internet of Things by researchers, practitioners, innovators, developers and academicians (Madakam *et al.*, 2015). However, the initial use of the term ‘Internet of Things (IoT)’ was created by Kevin Ashton in 1999. He defined it as uniquely identifiable connected objects using RFID technology (Ashton, 2009). Similarly, the International Telecommunication Union (ITU) defined IoT as a global infrastructure for the information society, enabling advanced services by interconnecting, physically and virtually, things based on existing and evolving interoperable information and communication technologies (ITU-T, 2017). IoT comprises a world where sensors and actuators are embedded in physical objects, from roadways to pacemakers, and are linked through wired and wireless networks using the same Internet IP that connects the internet. Large volumes of data are sent to various computers using these networks for analysis (Madakam *et al.*, 2015). **Figure 2-22** shows the definition of IoT as stated by IoT European Research Center (2016).

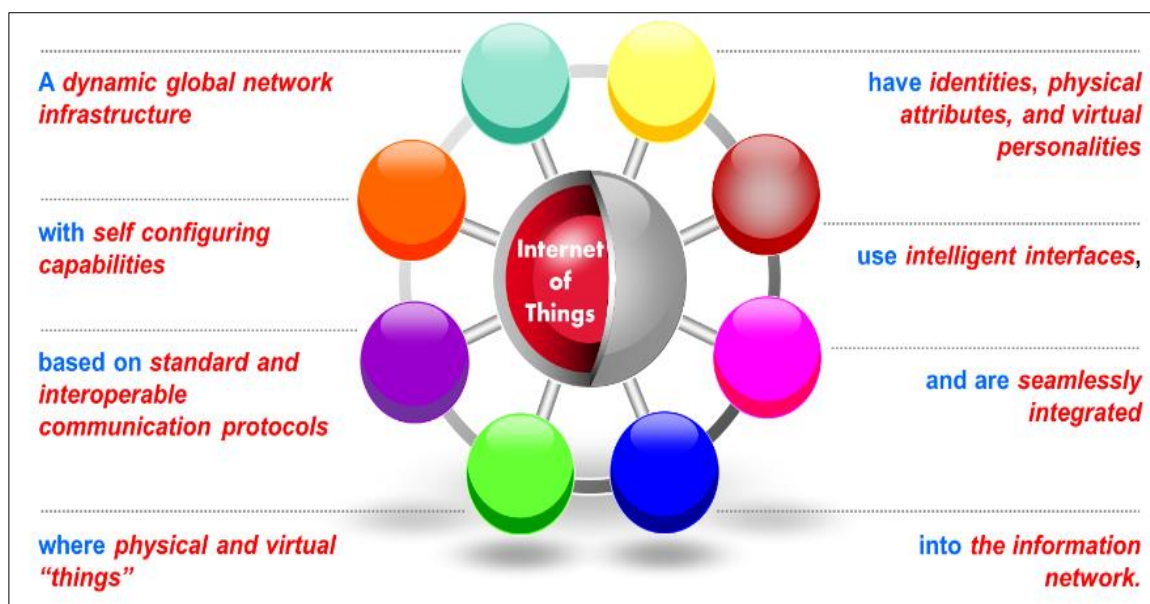


Figure 2-22: Definition of IoT

(IERC, 2016)

2.9.3 IoT Architecture

Different architectures have been proposed in the literature to establish a universal framework for IoT applications. IoT is such a broad concept, therefore, there is no proposed uniform architecture. IoT must consist of IoT devices (sensors), networking applications, communications protocols and computing technologies to work efficiently (Gigli & Koo, 2011; Djelouat *et al.*, 2018). Jia *et al.* (2012) considered an IoT system architecture consisting of three layers: perception, network and service layers. Djelouat *et al.* (2018) considered a three-layer architecture with the sensing, processing and application layers. Liu *et al.* (2014) considered an overall architecture of four layers: applications, middleware, transport layer and physical layer. Wu *et al.* (2010) believed that a five-layer architecture would best explain the features and connotations of IoT. The layers included the business, application, processing, transport and perception layers, as shown in **Figure 2-23** and **Table 2-4** below.

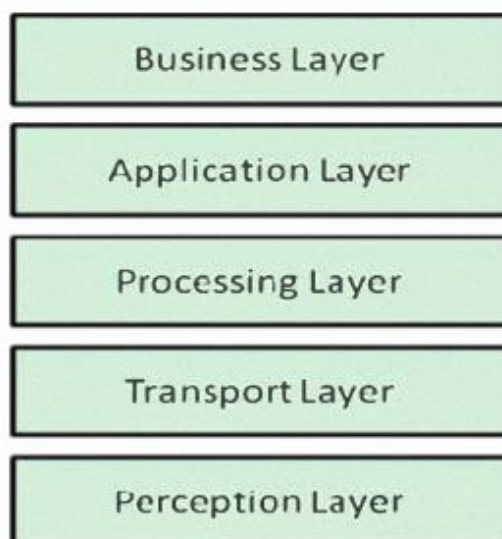


Figure 2-23: IoT Platform Architecture

(Adopted from Wu *et al.*, 2010)

Table 2-4: A Five-layer Architecture for IoT Platform

(Wu *et al.*, 2010)

IoT layer	Description
Perception layer	The layer perceives all the data by the various sensors and converts it into information to digital signals that is convenient for network transmission. The main techniques in this layer include but not limited to sensing technology, RDIF technology, 2-D barcode, GPS etc.
Transport layer (Network layer)	This layer transmits data received from the perception layer to the processing layer through a wireless or cable network or Local Area Network (LAN). The main techniques include, Wi-Fi, Zigbee, 3G etc.
Processing layer	The processing layer stores, analyses, and processes the information from the transport layer. The main techniques include database, cloud computing, intelligent processing etc.
Application layer	The task of the application layer is entirely based on the data processed in the processing layer. It plays an important role in pushing the IoT to a large-scale development as it provides all sorts of applications for each industry.
Business layer	This is the manager of the IoT system. It manages the user's privacy, the release and charging of the applications and research on business and profit models.

2.9.4 IoT Technologies

Wireless Communication (WC) provides the benefits of mobility, cableless, connectivity of devices to the network and connectivity of devices to the internet (Khutsoane *et al.*, 2017). Madakam *et al.* (2015) identified many IoT, and these include the following: Radio Frequency Identification (RFID), Internet Protocol (IP), Electronic Product Code (EPC), Barcode, Wireless Fidelity (Wi-Fi), Bluetooth, ZigBee, Near Field Communication (NFC), Actuators, Wireless Sensor Networks (WSN) and Artificial Intelligence (AI). RFID and WSN are the most foundational technologies that significantly contribute to the development of IoT. In addition, other technologies like Service Oriented Architecture (SOA), smartphones, cloud computing are being used for an extensive network for IoT support (Xu *et al.*, 2014).

2.9.4.1 Radio Frequency Identification (RFID)

RFID allows microchips to transmit identification information to a reader through wireless communication. The RFID system comprises three components: RFID tags, reader, and application system (Bang *et al.*, 2009; Jia *et al.*, 2012; Xu, He & Li, 2014). One can identify, track, and monitor any objects attached with either active or passive RFID tags/transponders automatically using readers/transceivers. The reader comprises a radio frequency interface (RFI) module and a control unit. It activates the tags, structures the communication sequence with the tag and transfers data between the application software and tags (Jia *et al.*, 2012; Azimah *et al.*, 2018). The data processing subsystem is usually the application system, depending on the application. The application software initiates all readers and tag activities (Bang *et al.*, 2009).

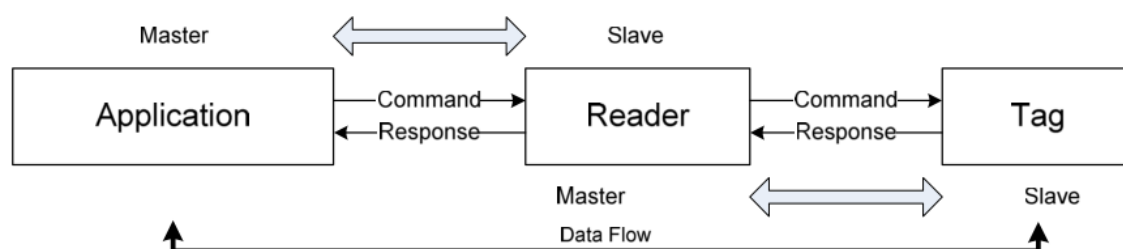


Figure 2-24: Components of the RFID System

(Bang *et al.*, 2009)

2.9.4.2 Wireless Sensor Network (WSN)

IoT was developed in parallel with Wireless Sensor Networks (WSN). Research on WSNs started in the 1980s, and it was only since 2001 that WSNs generated an increased interest from industrial and research perspectives. It was due to the availability of affordable, low-powered miniature components like sensors, processors and radios integrated into a single chip (IEC,

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2016). According to Modieginyane *et al.* (2018), a WSN comprises but is not limited to; a wireless sensor network server, routers, switches and sensor nodes depending on the design setup given its purpose. The sensor nodes collect data and send it to the gateway through field communications. The gateway sends the data through out-of-field communications using the internet to the cloud/server, where it is stored to be accessed for processing by the end user.

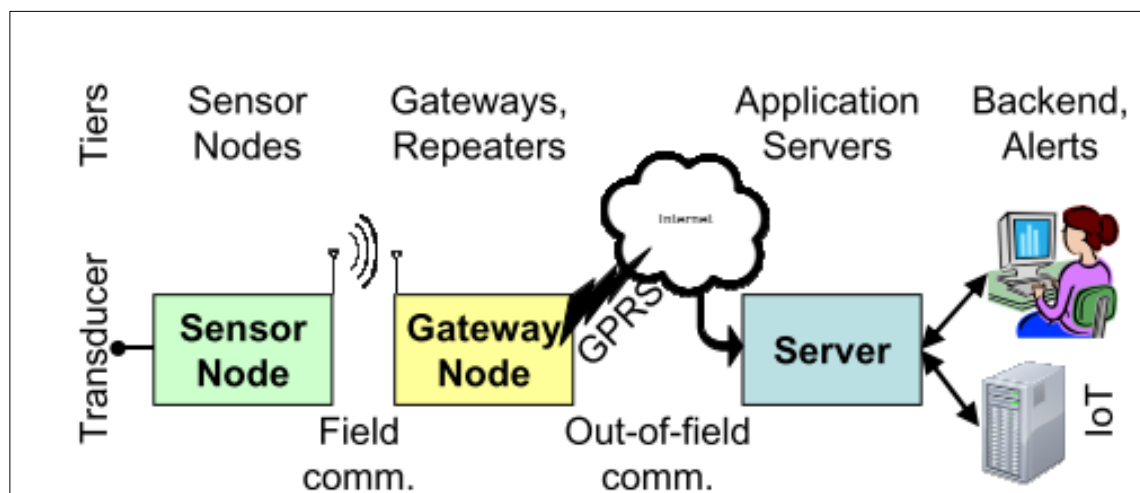


Figure 2-25: Structure of the WSN platform

(Lazarescu, 2013)

There are three main WSN topologies from which other forms of network topologies are designed, and these include the tree topology, star topology and mesh topology. **Table 2-5** shows a summary of the WSN topologies.

Table 2-5: Summary of the WSN Topologies(Modieginyane *et al.*, 2018)

WSN Network Topology	Description	Advantages	Disadvantages
Star	Sensor nodes transmit data through a sensor or gateway connected to a server. The network is considered for small networks	- Node does not affect other nodes. - Low power consumption. - Cheap to implement as nodes share one central device	- The whole network does not work if the node fails. - Low transmission
Tree	The network is divided into branches/segments	- Low power consumption. - High transmission range. - The network is easily maintained. - Cheap to maintain.	- Not resilient to node failure. - is very complex. - Uneven consumption across nodes. - The lower structure fails when the root node fails
Mesh	All the sensor nodes within the same communication range are connected. Data is transmitted through neighboring nodes to reach a device at a distance	-High fault tolerance given the various options for other sensor nodes to transmit data in case one node fails.	- High power consumption. - Increased latency. - Redundant paths. - Expensive to implement
Hybrid	This results as a combination of two or more of the topologies mentioned above.	- Low power consumption. - Fault tolerant. - Reliable, scalable, and effective communications	- Expensive to implement. - Trouble shooting and maintenance is complex

WSN-based IoT applications are divided into two categories: indoor and outdoor. Outdoor monitoring collects environmental data, which can be used in the context of smart cities. Indoor monitoring is more concerned with smart-home applications that can provide remote healthcare services (Djelouat *et al.*, 2018). WSN technology uses connected intelligent sensors for sensing and monitoring (Xu *et al.*, 2014). WSNs operate on collective networking and computing of individual sensors based on their physical sensing properties and processing capabilities. They are widely deployed in environmental monitoring, atmospheric monitoring, process monitoring and material sensing (Modieginyane *et al.*, 2018).

Lazarescu (2013) stated that WSN data acquisition for IoT environmental monitoring applications is quite challenging for open nature fields like water level monitoring for lakes and streams. These require large numbers of sensors, high reliability, low cost and long maintenance-free operation. However, field deployment may be costly and difficult to reach. Therefore, the following requirements are necessary for the long-term monitoring WSN platform.

- i. Low-cost, small sensor nodes and gateways with onboard processing, self-testing, error recovery capabilities and long-range communication.
- ii. Sufficient gateway hardware and software resources to support specific application needs (e.g., local transducers and data storage and processing).
- iii. Detection of field events onboard the gateway to reduce network traffic and energy consumption.
- iv. Fast and reliable field node deployment procedure.
- v. Remote configuration and update of field nodes.
- vi. High availability of service of field nodes and servers, reliable data communication and storage at all levels.
- vii. Node ruggedization for long-term environmental exposure.
- viii. Extensible server architecture for easy adaptation to different IoT application requirements.
- ix. Multiple-access channels to server data for both human operators and automated processing.
- x. Programmable multichannel alerts.
- xi. Automatic detection and report of WSN platform faults (e.g., faulty sensor nodes) within hours, up to a day.
- xii. 3–10 years of maintenance-free service.

2.9.5 Low-Powered Wide Area Network (LPWAN)

Low-Powered Wide Area Network (LPWAN) is a major segment of IoT applications that spans long distances. The LPWANs are resource-constrained networks with critical requirements for extended battery life, high scalability, low device, coverage and deployment costs. These networks are used in smart cities, smart environments, smart water (water quality and monitoring), smart homes and smart agriculture (Chaudhari & Zennaro, 2020).

2.9.5.1 Long Range (LoRa)

The LoRa solution is the most significant currently available example of LPWAN technology (Fernandes *et al.*, 2019). LoRa is a wireless modulation used to create long-range communication links. It is based on chirp spread spectrum modulation that maintains the low characteristics of frequency shifting keying (FSK) modulation but significantly increases the range of communication (LoRa Alliance, 2015). LoRa is used on deployments where end devices have limited energy and do not need to transmit more than a few bytes at a time and where data traffic can be initiated either by the end device, like a sensor or actuator (Augustin *et al.*, 2016). Its long-range and low-power nature makes it a suitable candidate for innovative sensing technology like environmental monitoring. Long Range Wide Area Network (LoRaWAN)

LoRaWAN is a complete communication solution around the LoRa physical layer designed to achieve the typical requirements of IoT scenarios, either mobile or mounted at a fixed location and requires a long refresh rate (Fernandes *et al.*, 2019). The basic LoRaWAN network architecture is of “a star of stars topology” with three different devices: end devices (sensor or actuator), gateway and server, as shown in **Figure 2-26** (Augustin *et al.*, 2016).

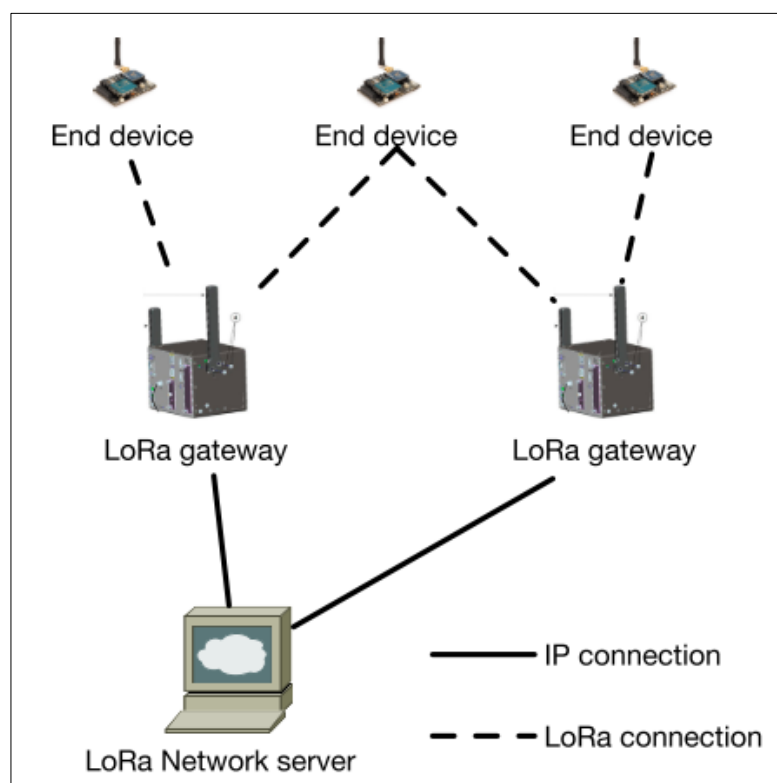


Figure 2-26: LoRaWAN Network Architecture

(Adopted from Augustin *et al.*, 2016)

The end devices communicate with the gateways using LoRa with LoRaWAN. The gateways transfer the raw data from the end devices to the LoRa network server (LNS) connected through an IP backbone, either Wi-Fi, ethernet or cellular connection: 2G, 3G, 4G networks (Augustin *et al.*, 2016). The LNS manages the entire network and establishes a connection from the end devices to the end user’s application in the cloud. Multiple gateways in the area can serve the same sensor, as there is no fixed association between an end device and a gateway. Therefore, all the gateways in the area receive the uplink packet sent by the end device, which reduces packet error rate and battery overhead and allows low-cost geolocation. (Augustin *et al.*, 2016; Semtech, 2020).

The LoRaWAN was developed by LoRa Alliance to deal with challenges faced by IoT, like long-range and low power consumption. It significantly influences the node battery lifetime,

network capacity and security (Khutsoane *et al.*, 2017). Semtech (2020) outlined several advantages of using the LoRaWAN network summarised in **Figure 2-27** below.

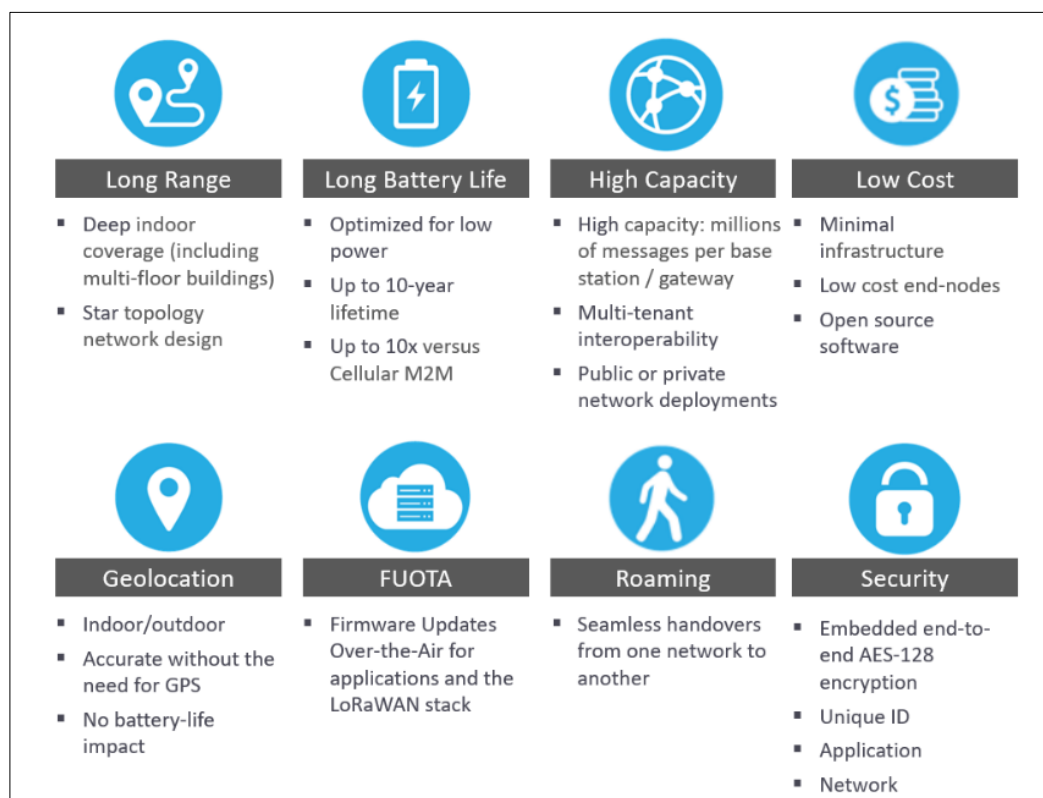


Figure 2-27: Advantages of LoRaWAN Network

(Semtech, 2020)

2.9.6 The Things Network (TTN)

The Things Network (TTN) is a global collaborative IoT ecosystem that creates networks, devices and solutions using LoRaWAN. TTN started running The Things Stack Community Edition, an open-sourced and decentralised LoRaWAN network server that allows one to build and manage LoRaWAN networks in the cloud in January 2021. The Things Stack Community Edition is accessed via the Console by selecting a cluster closest to the study area. There are currently three clusters: Australia 1, Europe 1 and North America 1. Thousands of gateways, the main building blocks of the LoRaWAN network, in 152 countries across the globe are already connected to The Things Stack Community Edition. A gateway should be set up to ensure reliable coverage even though there might already be coverage in the area. The gateways receive the data from the sensors in LoRa messages and send it to the servers where it is stored. The data is visualised on the TTN website, which allows node activity tracking. There are 196 gateways connected to TTN in South Africa, of which 12 are active sites across the City of Cape Town, as shown in **Figure 2-28** (The Things Industries., 2022).

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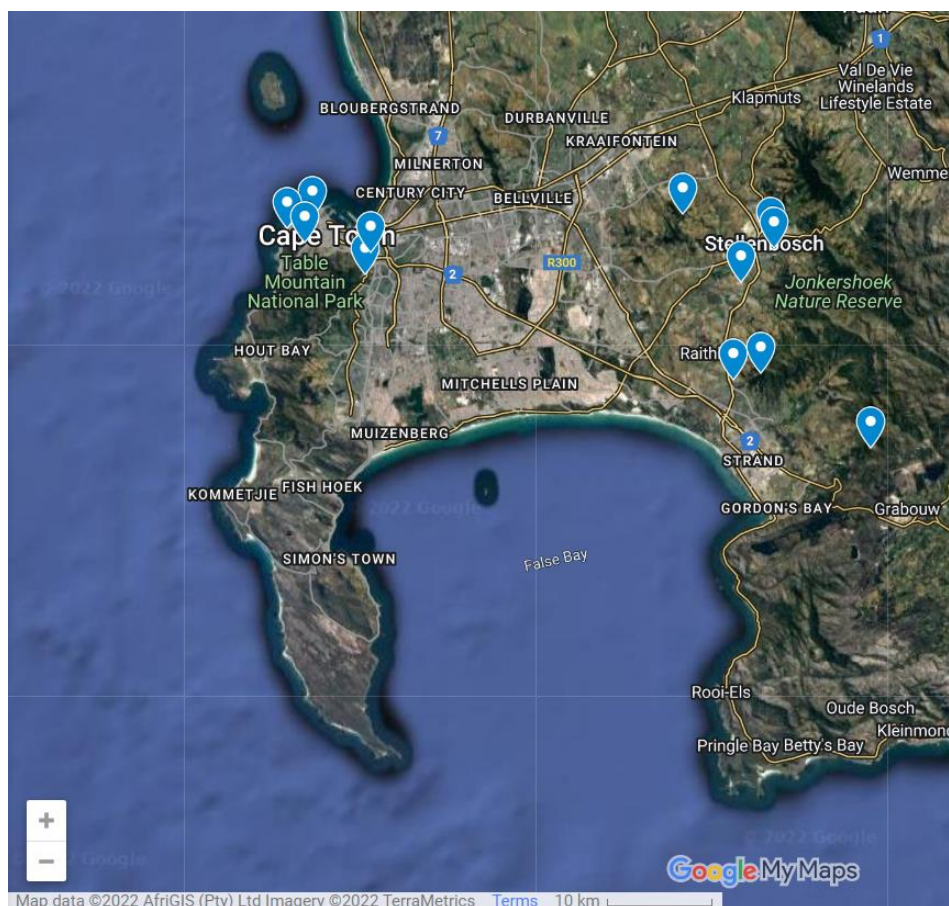


Figure 2-28: Available and Active TTN Sites in the CCT, South Africa
(The Things Industries., 2022)

2.9.6.1 ThingSpeak Platform

According to MathWorks (2021), ThingSpeak is an IoT analytic platform that visualises and analyses collected data and sends alerts privately in the cloud with MATLAB. It enables engineers and scientists to prototype and build IoT systems without setting up servers or developing web software. ThingSpeak data is stored in channels that can be viewed privately or publicly and imported or exported. A user account is created on the website to enable data storage and to graphically visualise and analyse the data in real-time. The channels can also be edited, deleted from the tab and shared with specific users.

ThingSpeak uses two API References to update the channels and chart the numerical data, i.e., Representational State Transfer (REST) and MQ Telemetry Transport (MQTT). REST is an architectural style designed as a request/response model that communicates over HTTP. It includes APIs such as GET, POST, PUT, and DELETE that are used to create a channel and update its feed, update an existing channel, clear a channel feed, and delete a channel. The MQTT

is a publish/subscribe method that runs over TCP/IP sockets or web sockets. It is used to update a channel feed and subscribe to receive messages when a channel updates (MathWorks, 2021).

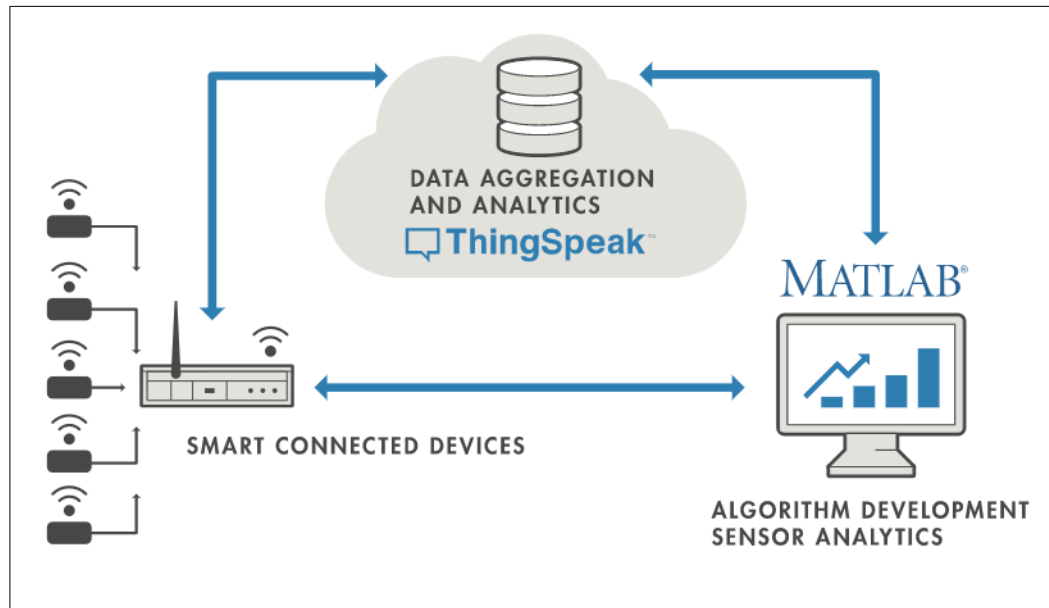


Figure 2-29: ThingSpeak IoT

(MathWorks, 2021)

2.9.7 IoT Data: Its Role in Groundwater management

Conor & Clifford (2018) showed the use of smartphones and weather stations to monitor weather patterns in Amsterdam to provide valuable data insights. Ensembled data assimilations were carried out for two case studies over the Pacific Northwest to evaluate the utility and quality of the resulting smartphone pressure observations. In both cases, the smartphone pressures improved the analyses and forecasts of assimilated and non-assimilated variables, whereby the experiments conducted with smartphones yielded improved long-term weather forecasts.

Internet of Things (IoT) technologies to collect data on groundwater conditions can improve water resource management. Malche & Maheshwary (2017) used prototype system design, implementation and description of required tools to develop a real-time IoT-based system to collect, analyze and predict water level details from a distant location for groundwater monitoring and data management in India.

Oke *et al.* (2019) presented the use of the Internet of Things for sustainable groundwater drought management in the Modder River catchment of South Africa. IoT turned out to be a standout as a groundwater data collection system. Therefore, it is recommended to explore the numerous advantages of IoT, including the ability to gather, store and share large amounts of data and simple to use to promote the concept of groundwater sustainability.

2.10 Groundwater Flow Modelling Systems

Groundwater modelling is a very complex system widely employed in analysing groundwater flow as it depends on the surface and subsurface processes. The rate of groundwater recharge, flow and storage depend on the soil characteristics, surface water, size of the aquifer and the extent of pipeline leakages (Mauck, 2017; Carden *et al.*, 2018). It can evaluate the advantages and disadvantages of implementing MAR at a proposed location when combined with specific scenarios (Zhang *et al.*, 2019)

Many researchers across the globe use groundwater modelling to assess managed aquifer recharge. It has become a standard tool for professional hydrogeologists in developing and managing groundwater resources (Khadri & Pande, 2016; Chitsazan *et al.*, 2018). It is used to combine information for aquifer characterisation, understand the groundwater balance, assess environmental impacts on groundwater and assist in developing groundwater rehabilitation measures (Mauck, 2017).

The groundwater balance and model require sets of quantitative hydrogeological data that describe the physical and hydrological framework of the basin. The physical framework data comprise topography, soil, geology, aquifer type, thickness, characteristics and boundaries and lithological variations within the aquifer. The hydrogeological data include the rate of recharge

and discharge, water table elevation and type and extent of recharge and discharge areas (Kumar, 2015). The required data under the physical, as stated by Moore (1979), include the following;

- a. Geologic map and cross section or fence diagram showing the areal and vertical extent and boundaries of the system.
- b. A topographic map at a suitable scale showing all surface water bodies and divides.
- c. Land use maps showing agricultural areas.
- d. Contour maps showing the elevation of the base of the aquifer and confining beds.
- e. Isopach maps showing the thickness of aquifer and confining beds.

The data requirements for the hydrogeological framework (Moore, 1979) include the following;

- a. Water table and potentiometric maps for the aquifer.
- b. Hydrographs of groundwater head and surface water levels and discharge rates.
- c. Maps and cross sections showing the hydraulic conductivity and transmissivity distribution.
- d. Maps and cross sections showing the storage properties of the aquifer and confining beds.
- e. Spatial and temporal distribution of evaporation rates, groundwater recharge, surface water - groundwater interaction, groundwater pumping, and natural groundwater discharge.

Pisinaras *et al.* (2007) emphasized the importance of determining boundary conditions and aquifer properties and estimating the recharge and discharge rates, as the accuracy of the model depends on these estimates to define the aquifer system numerically. The model is used to;

- a. Estimate flows and aquifer characteristics for which direct measurements are not available.
- b. Integrate and assure consistency among aquifer properties, recharge, discharge, and water levels.
- c. Identify sensitive areas where additional hydrologic information would improve understanding.

Groundwater models are applied in two distinct processes. The first process is the development model, which permits the collection of all required data in one structure resulting in a software product. The second process is where the product is applied for a specific purpose (Kumar, 2003; Lachaal *et al.*, 2012). Kumar (2003) described the logical sequence in which efficient groundwater models are developed, and this is as follows: identify model objectives, hydrogeological characterisation, model conceptualisation, software selection, model design, model calibration, sensitivity analysis and model verification. **Figure 2-30** illustrates the procedure followed in groundwater modelling studies.

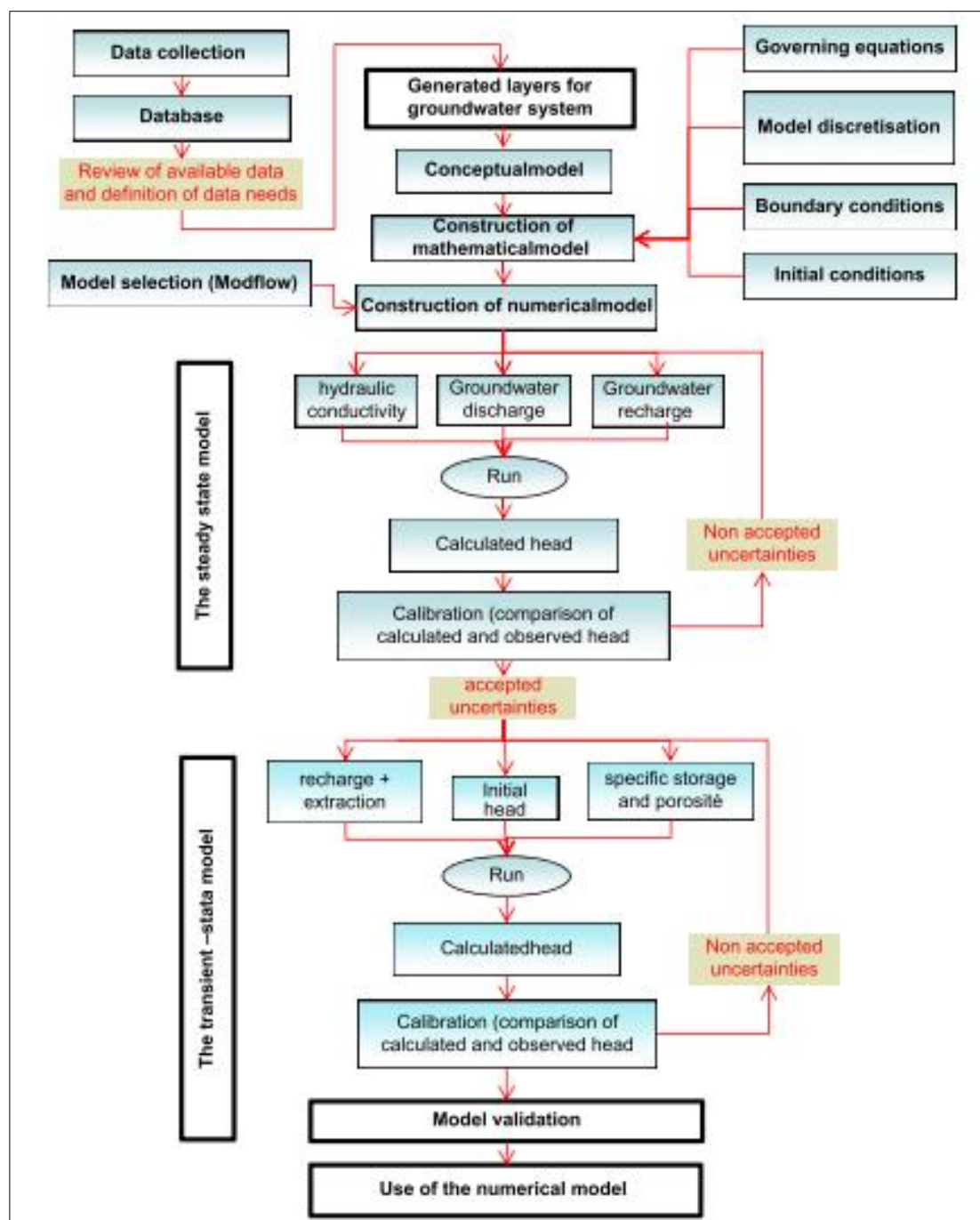


Figure 2-30: Groundwater Modelling Procedure

(Lachal *et al.*, 2012)

2.10.1 Groundwater Flow Models

Numerical modelling of interacting flow and transport between the atmosphere, land surface, vegetation, soil and groundwater is fundamental in the understanding of comprehensive processes, management of water resources and in predicting effects of management measures in semi-arid areas (Boskidis *et al.*, 2012; Kalbacher *et al.*, 2012; Khadri & Pande, 2016). The groundwater processes are represented using a combination of surface water and groundwater elements like the water balance and groundwater levels, discharge, head elevation and information from previous studies.

A groundwater model is any computational method representing an approximation of the underground system. (Kumar, 2019). Groundwater flow models are used to fill the gaps in the available data to understand better the groundwater systems (Asmael *et al.*, 2015). However, they need to be improved in their ability to represent groundwater processes, thus requiring more detailed groundwater models to address the various groundwater problems (Carden *et al.*, 2018). The combination of GIS-based analysis with the groundwater flow model allows a more detailed and quantitative assessment of MAR on the condition that the consistency of data used in the GIS and modelling are maintained throughout the entire process. (Zhang *et al.*, 2019).

There is a wide range of modelling software, each with its respective operational characteristics, capabilities, and limitations. Therefore, it is imperative to select a suitable groundwater model from the available options by considering the best code to solve the problem, data requirements, require computer hardware, cost, and accuracy of the code in representing the real world (Kumar, 2019). Kumar (2003) presented the frequently used groundwater models, including FEEFLOW, HST3D, MODFLOW, MT3D, SEAWAT, SUTRA, SWIMv1/SWIMv2, VISUAL HELP and Visual MODFLOW. MODFLOW is the most widely used program for simulating and predicting groundwater flow and has been applied in various applications like the analysis of surface water/groundwater interactions in aquifer systems (Rowan, 2001; Romero & Maddock, 2003; Mauck, 2017; Okedi, 2019).

Similarly, MODFLOW with ModelMuse, as the graphical user interface (GUI), was selected as the groundwater modelling program in this study to verify the suitability of the stormwater ponds for MAR. The model mainly focused on the detailed representation of the hydrogeological processes of the aquifer around MAR scenarios using stormwater.

2.10.2 MODFLOW as a Groundwater Modelling Program

MODFLOW is a modular, three-dimensional, finite difference and element groundwater flow hydrologic model developed in 1984 by the United States Geological Survey (USGS) (Kumar, 2019). It solves a combination of Darcy's law for the flow of water in saturated media with the mass balance equation (Boskidis *et al.*, 2012; Mauck, 2017). The structure of MODFLOW consists of a main program with a series of modules grouped in packages with specific features of the hydrologic system to be simulated, like the flow from rivers or flow into drains. It allows

independent examination of specific hydrologic features of the model and the development of additional capabilities as new packages can be added to the program without modifying the existing ones (Kumar, 2003).

MODFLOW is designed to simulate the steady state and transient conditions, as shown in **Figure 2-30** above. A steady state is where the storage term in the groundwater flow equation shown in **Equation 4** is set to zero. The transient state is provided when the equation is combined with boundary and initial conditions (Harbaugh *et al.*, 2000).

$$\frac{\partial}{\partial x} \left(K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_{zz} \frac{\partial h}{\partial z} \right) + W = S_s \frac{\partial h}{\partial t} \quad \text{Equation 4}$$

where K_{xx} , K_{yy} , and K_{zz} are values of hydraulic conductivity along the x, y, and z coordinate axes, which are assumed to be parallel to the principal axes of hydraulic conductivity (L/T); h is the potentiometric head (L); W is a volumetric flux per unit volume representing sources and sinks of water, with $W < 0.0$ for flow out of the groundwater system, and $W > 0.0$ for flow in (T^{-1}); S_s is the specific storage of the porous material (L^{-1}); and t is time (T).

The USGS has released six core versions of MODFLOW since its release: MODFLOW-84, MODFLOW-88, MODFLOW-96, MODFLOW-2000, MODFLOW-2005, and MODFLOW 6. MODFLOW 6, the newest version, contains the Ground-Water Flow (GWF) Model divided into packages as the previous versions. The Newton-Raphson formulation, based on the formulations in MODFLOW-NWT and MODFLOW-USG, can be activated for complex problems involving water-table conditions (Kumar, 2019).

The use of MODFLOW is advantageous in that it includes many facilities for data preparation, easy exchange of data in standard form, availability of source code, extended worldwide experience and relatively low price (Kumar, 2003). The major limitation of MODFLOW in groundwater recharge, as stated by Brunner *et al.* (2009), is that water does not interact with the unsaturated zone during its flow interactions.

2.10.2.1 Model Calibration and Validation

Calibration and validation of hydrogeological and hydrological models is very crucial during the modelling process to ensure that both surface and groundwater data is represented accurately (Mauck, 2017). The calibration process involves gradually adjusting the parameters of the models to produce the best fit between simulated and observed data. The calibration period is chosen based on the availability of sufficient data and groundwater observations. The validation process is carried out by testing the model under various input conditions to assess the MAR scheme, improve its performance and ensure the conceptual model is a detailed and suitable representation of the actual system (Hassan, 2004; Barnett *et al.*, 2012).

2.11 Review of Previous Groundwater Studies in South Africa

Various studies on developing various technologies, digital flow modelling and methods for groundwater recharge in South Africa have been conducted in the previous years to develop a groundwater resource relevant to the country's water supply system.

Zhang *et al.* (2019) combined GIS-based analysis with groundwater modelling to identify sites suitable for MAR implementation along the West Coast of South Africa. ModelMuse and the MODFLOW and MODPATH packages were used to verify and optimize the suitable sites for MAR. The primary water source was supposed to be the runoff of the Berg River in the rainy season. The AHP with ten thematic layers was used to improve the results from the GIS-based analysis. A MAR suitability map showed that the high suitability (Index > 0.80) sites were located southwest of Hopefield, where the aquifer thickness and the depth to the groundwater table were more outstanding than at any other place. The low suitability sites (Index < 0.60) were near the discharge area, including the Berg River and coastline.

Studies on the effects of climate change on the estimation of recharge and groundwater resource management in the TMG were carried out by Wu (2005) and Jia (2007) and yielded valuable information for groundwater resource exploitation in the Western Cape. However, the current information on the Cape Flats aquifer still needs to be improved to support resource management; therefore, further studies are needed to aid in its full development.

Harris *et al.* (1999) investigated the hydrogen and oxygen isotope hydrology of the greater Cape Town area to identify the potential use of stable isotopes as tracers to investigate the groundwater quality and quantity in the CFAU and the Culemborg-Black River aquifer. It was observed that O- and H-isotope data effectively discriminate between mains water and groundwater for most of the greater Cape Town area in the summer and autumn months.

Henzen (1973) conducted an intensive study on the hydraulic and geological properties of sand deposits in the area, and the objective of the study was to determine the feasibility of extracting and recharging the sand deposits. Maps of the area's surface and groundwater quality were prepared in the process.

2.12 Conclusion

The literature review cuts across the important topics of groundwater processes, hydrogeology, groundwater modelling and Internet of things technologies. The importance of IoT technologies for sustainable groundwater management should be emphasized. Therefore, there is a need for the application of IoT in the assessment of groundwater augmentation as it provides consistent data collection, appropriate capacity to deal with immense records and ensures speedy and exact information analysis, which would solve the problem of inadequate groundwater data.

3. Methodology

3.1 Overview

This Chapter describes the methods and processes that were employed in this study. The main aspects include data acquisition, transfer and processing. All existing geological and hydrogeological data of the study area were collected with approval from the CCT. The groundwater potential of the site was mapped with a Geographic Information System (GIS) and Analytical Hierarchical Process (AHP) techniques. Groundwater level data was collected using an IoT system to minimize the total cost of the project while at the same time providing the required accuracy. Finally, the existing data and IoT-based water level data were used to develop the numerical MODFLOW groundwater flow model of the study area.

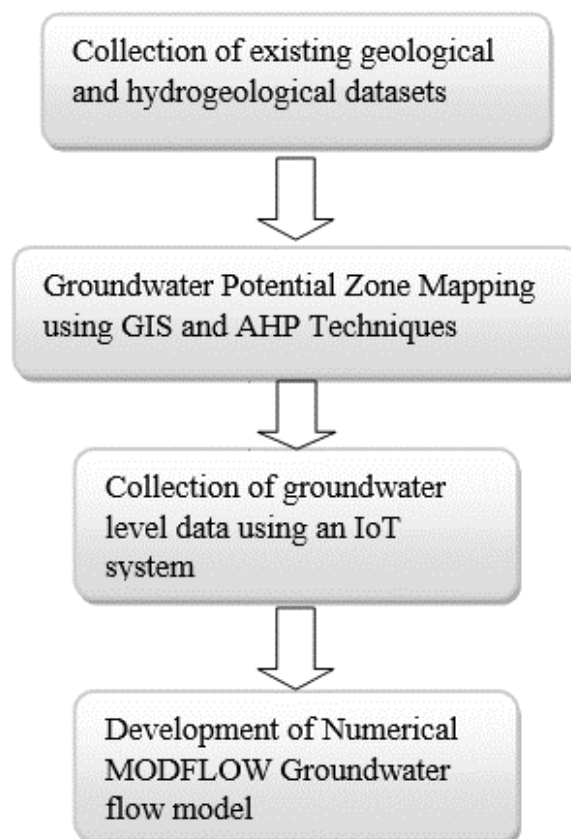


Figure 3-1: Research Methodology Flowchart

This chapter comprises eight (8) sections, including the overview of the methodology, description of the study area, site selection, suitability of the study area, available datasets, groundwater mapping using GIS and AHP techniques, collection of groundwater level data using an IoT system and modelling of groundwater flow of the site using MODFLOW Software.

3.2 Study Area Description

This research focuses on assessing the potential for IoT-based data for groundwater modelling. It uses the catchment area of two stormwater ponds in Mitchells Plain, a township, about 28 km from the Cape Town City Centre. Mitchells Plain is one of South Africa's most prominent residential areas in the Cape Flats on the False Bay coast between Muizenberg and Khayelitsha. The Mitchells Plain catchment is an urban area with low baseline groundwater levels, and its land use/ cover consists predominantly of urban and residential (Mauck, 2017). **Figure 3-2** shows the location of the study area in Mitchells plain west catchment that contains the study area.

This study is linked to the Pathways to Water Resilient South African cities (PaWS) research project funded by Danida's Window 2 programme. It explores transitioning towards water-sensitive futures in two cities in South Africa; Cape Town and Johannesburg. The project is an interdisciplinary collaboration between the University of Cape Town (UCT), Future Water Research Institute, the University of Copenhagen (UCPH) and the Department of Geosciences and Natural Resources Management (IGN). The PaWS project aims to identify opportunities for integrating nature-based approaches into the urban landscape through collaborative retrofitting an existing stormwater pond. The School pond was selected to map, evaluate, and redesign it to create infiltration areas to improve MAR. Similarly, the project has modified the functions of the pond to improve the stormwater quality and enhance the amenity and biodiversity in the environment. The contribution of this study to the PaWS project is to assess the use of IoT technologies to provide accurate and real-time data rather than conventional approaches to data collection.

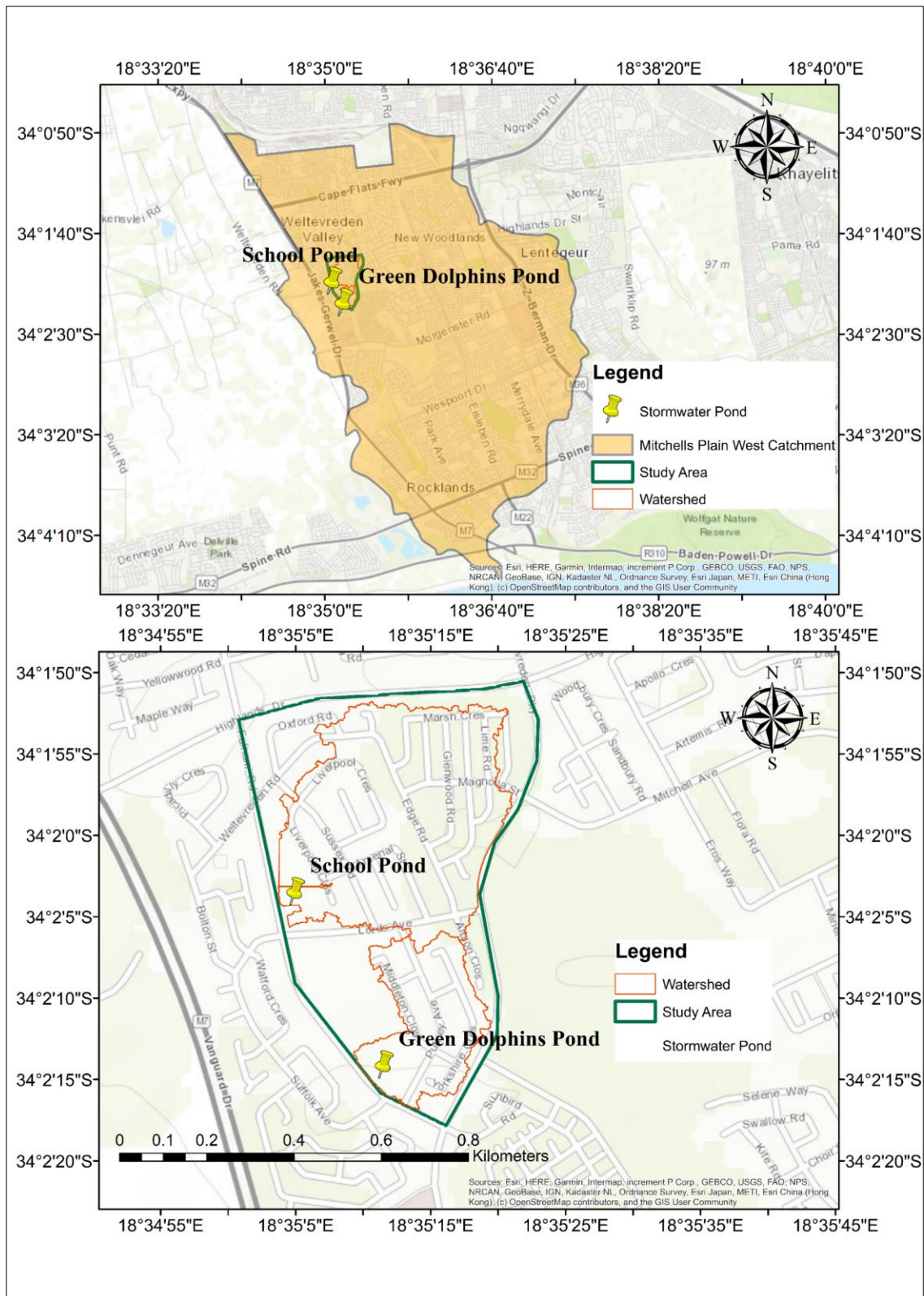


Figure 3-2: Location of the Study Area in the Mitchells Plain West Catchment, South Africa

The study area covers 0.315 km², as shown in **Figure 3-3**. The site is bound by Fulham, Highlands Dr and Weltevreden Pkwy road, and comprises two stormwater ponds. The School Pond is located at coordinates 34°2'3.0"S latitude, 18°35'4.7"E longitude, while the Green Dolphins Pond lies at 34°2'14.08"S, 18°35'11.57"E.



Figure 3-3: Study Area Location and Extent
(Google Maps)

3.3 Study Area Selection

Stormwater ponds are designed to collect stormwater runoff from the impermeable surfaces within their basins. They mitigate flooding by temporarily holding stormwater during a rainfall event and releasing it when there is capacity in the pipe network. A study by Rohrer (2014) identified that the Mitchells Plain West Catchment of 20 km² has one of the highest pond densities of 1.58 per km² due to its position within the low-lying areas of Cape Town. It has a total number of 32 stormwater ponds covering a total area of 0.174 km², 30 detention ponds and 2 retention ponds, as shown in **Figure 3-4**. Two stormwater detention ponds were selected for the study based on the availability of the hydrology and hydrogeological data to enable the development of a model of the study area.

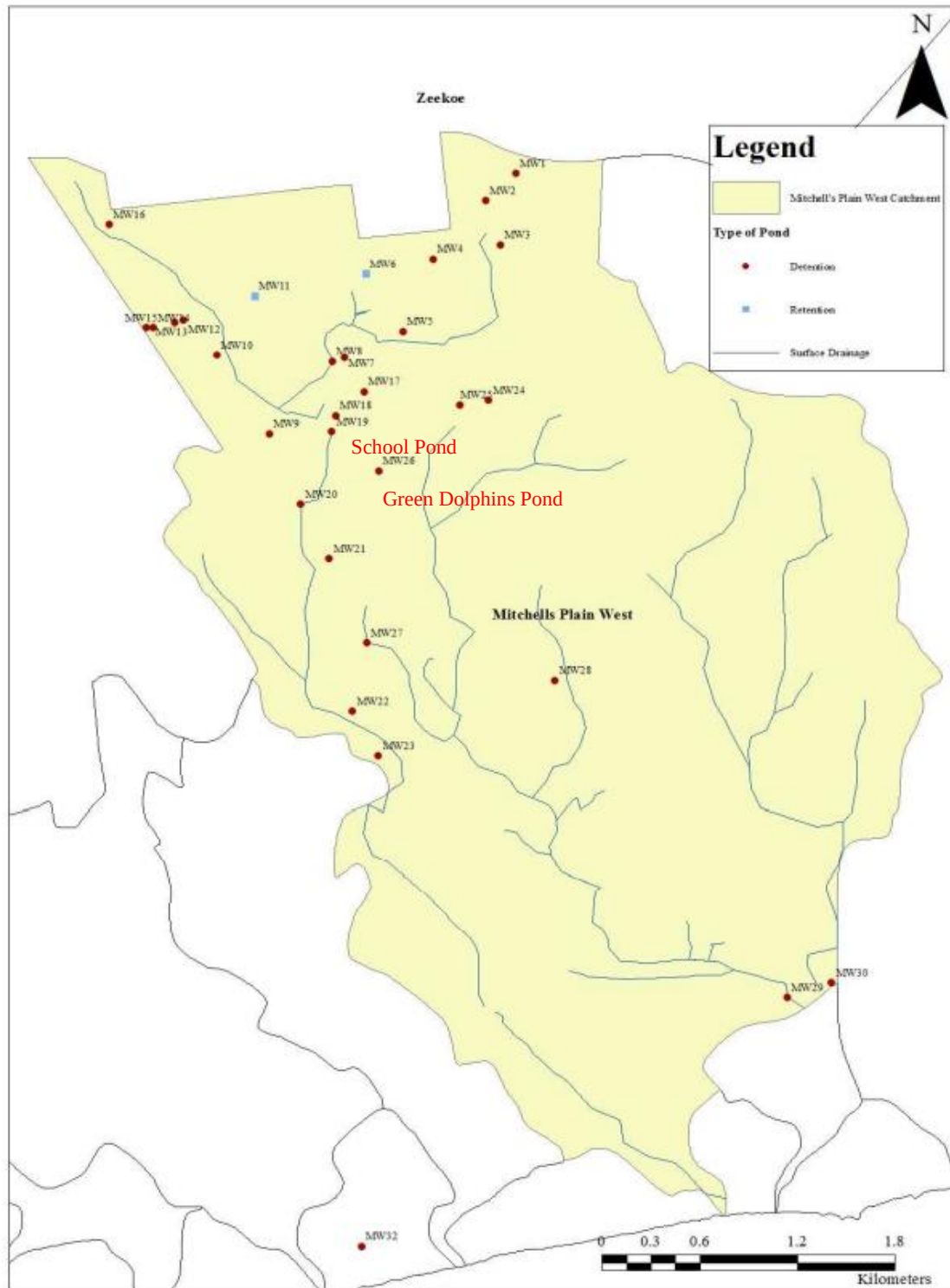


Figure 3-4: A Map showing the Distribution of the Stormwater Ponds across the Mitchells Plain West Catchment

(Rohrer, 2014)

3.3.1 Selected Stormwater Ponds

The details of the two stormwater detention ponds that were selected for this study are as follows:

Table 3-1: Selected Stormwater Ponds

ID	Name	Area (m ²)	Road Name	Suburb	Erf Number	Latitude (°)	Longitude (°)
MW20	School Pond	8744	Fulham Avenue	Weltevreden Valley	40-2136	34°2'3.0"S	18°35'4.7"E
MW21	Green Dolphins Pond	7604	Fulham Avenue	Weltevreden Valley	40-2140	34°2'14.08"S	18°35'11.57"E

3.3.1.1 School Pond

The school pond is an excavated open area next to the Leadership College-Hyde Park, connected to a stormwater system with two inlets and one outlet. It was once a vlei (shallow pool of water) that dried up due to the abstraction rates in the area. (Jones, 2019). The pond has a gentle slope that allows water to flow easily from the two outlets to its outlet. The entire pond area is covered by a wide range of biodiversity of vegetation, shrubs, flowering plants, and a few bird species.

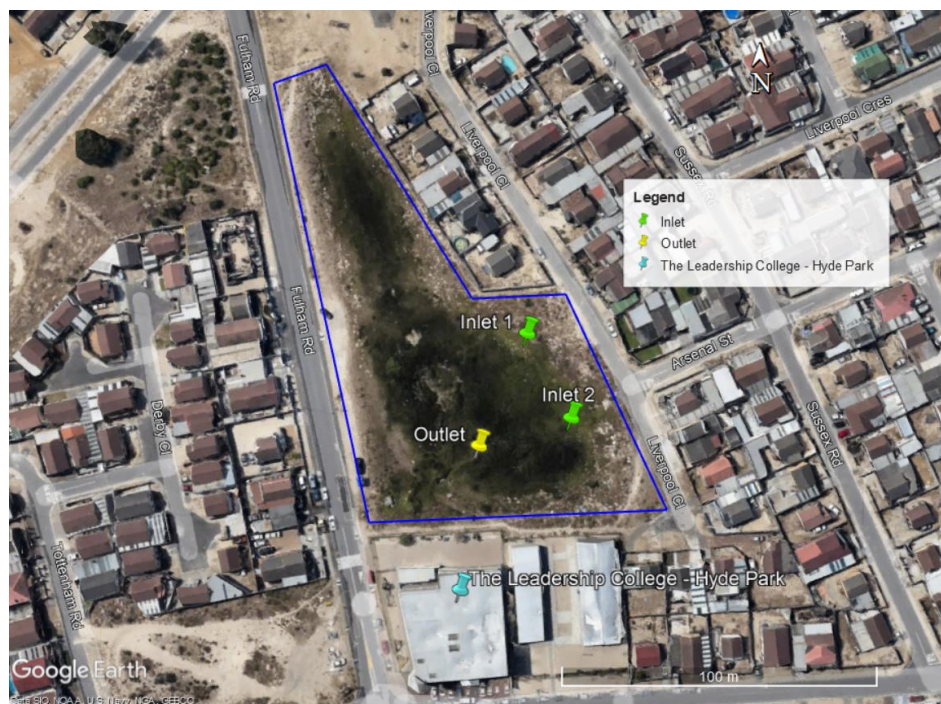


Figure 3-5: School Pond

(Google Maps)

3.3.1.2 Green Dolphins Pond

The Green dolphins pond is located along Fulham Road in Mitchells Plain, about 0.40 km south of the school pond. It is mainly covered by short grass, vegetation, shrubs, and visible soil patches. It has a CCT monitoring borehole (MON71), three inlet pipes, and one outlet close to each other, as shown in **Figure 3-6**.

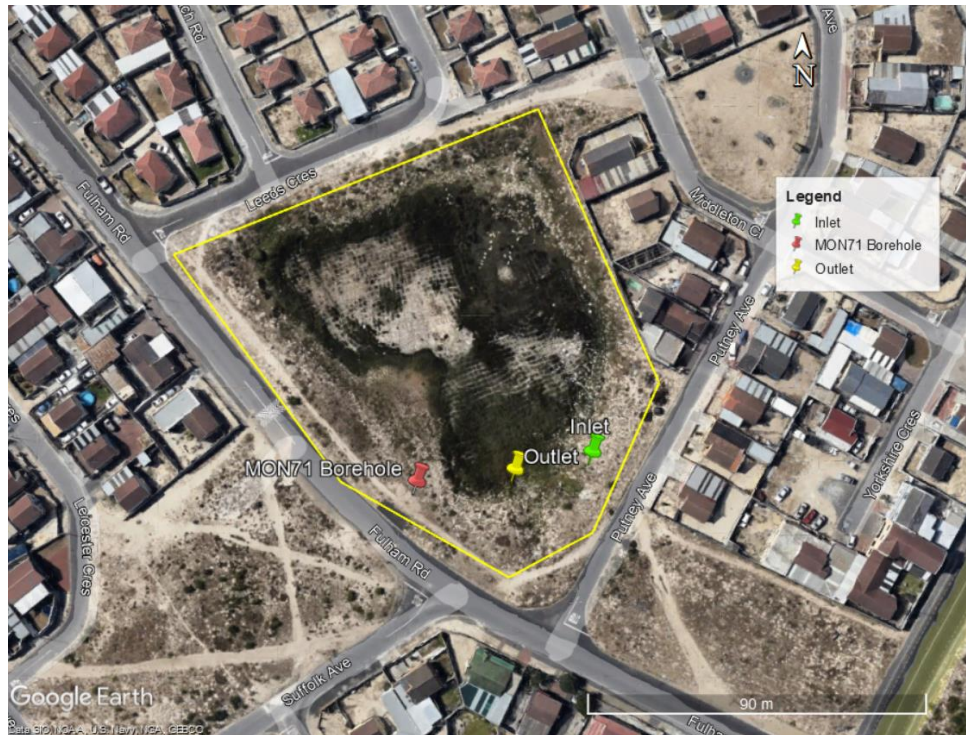
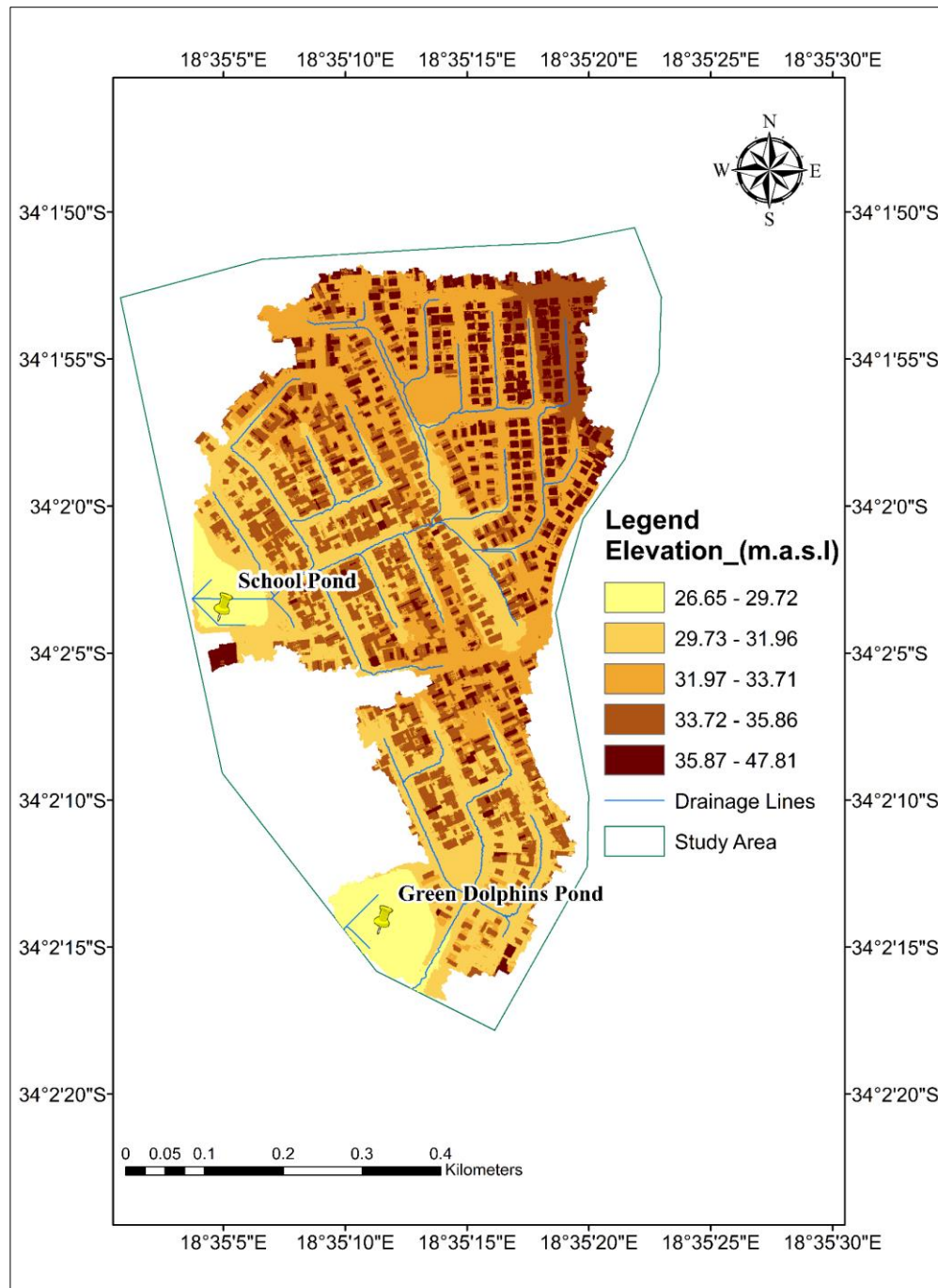


Figure 3-6: Green Dolphins Pond
(Google Maps)



3.4 Suitability of the Study area

The study area is in the Cape Flats Area in the Mitchells Plain Western Catchment. A summary of the factors considered in the selection of the study area includes the following:

- i. The watershed areas of the two selected stormwater ponds were suitable for MAR.
- ii. Location in the high aquifer productivity area of the CFA with high groundwater potential.

- iii. Availability of hydrological and hydrogeological data.
- iv. Location of the catchment in a residential area with potential groundwater users.
- v. The catchment area has a gentle slope towards the stormwater ponds that allows water to flow through the stormwater system to the ponds where it is stored for potential infiltration.

3.4.1 Study Area Catchment

3.4.1.1 Catchment Delineation

The catchment area of the stormwater ponds was delineated using ArcGIS software to determine the area that drains into each stormwater pond, as shown in **Figure 3-7**. A 0.5 m high-resolution DEM was created from a Lidar dataset from the UCT-GIS library and was used to obtain the corresponding contributing basins for each pond. The Lidar dataset captured the top of the buildings, thus the high elevation of 47.81 m.a.s.l compared to the highest ground elevation of 35.12 m.a.s.l in the study area. The school pond has a larger catchment area of 0.155 km² compared to the green dolphins pond of 0.048 km². Both the catchments are within the area bound by Fulham, Highlands Dr and Weltevreden Pkwy roads; thus, the study area was extended to those extents.

Figure 3-7: Delineated Catchments of the Stormwater Ponds

3.5 Available Datasets of the Study Area

3.5.1 Overview

Both primary and secondary data were used as the success of this study largely depended on the availability and accuracy of data collection, as it is instrumental in developing a model to assess the groundwater flow conditions. This assessment was based on the hydrogeological parameters that characterize the physics of groundwater flow in the aquifer. Primary data comprised IoT-based groundwater level data collected for almost five months using a groundwater monitoring system. The secondary data included information on surface and subsurface layers like the geology, infiltration rates, climatic conditions, soils, slope, groundwater level data, recharge rates, evaporation, pumped abstractions, land use, aquifer characteristics and boundaries. These datasets were obtained from the City of Cape Town Portal, the South African Weather Service (SAWS), and previous studies carried out in the study area.

3.5.2 Climatic Conditions of the Study Area

3.5.2.1 Analysis of Temperature and Rainfall Time Series

Daily rainfall and temperature data from the nearest weather stations to the study area, with sufficient years of time series, was obtained from the South African Weather Service (SAWS), Cape Town Automatic Weather Station (CT-AWS) and Kirstenbosch as detailed in **Table 3-2**. The CT-AWS weather station was the nearest to the study area, therefore, its time series was selected for further analysis.

Table 3-2: Weather Stations within Close Proximity to the Study Area

Weather Station No.	Weather station	Latitude (S)	Longitude (E)	Elevation	Start Year	End Year	No. of recorded monthly years	Distance from station to study area (km)
00211788	CT-AWS	-33.98	18.6	43	2002	2021	20	6.4
00207804	Kirstenbosch	-33.99	18.43	156	2002	2021	20	15.3

CT-AWS Station Dataset: The Mean Monthly Rainfall and Mean Monthly Maximum and Minimum temperatures were obtained from the dataset, and the results were plotted as shown in **Figure 3-8**. The total annual precipitation from 2002 – 2021 ranges between 249 mm and 600mm, with an average of 434 mm, as shown in **Figure 3-9**. A detailed presentation of the historical climatic data is included in **Appendix 4**. The mean monthly maximum and minimum temperatures were 35°C and 2°C, respectively, while the Mean Maximum Monthly Rainfall (MMMR) was 93.2 mm in June, and the Maximum monthly rainfall recorded during the period of the record was 167.6 mm in August 2013.

Table 3-3: Mean Monthly Temperature and Rainfall (2002 -2021)

Month	Mean Maximum Monthly Temperature (°C)	Mean Minimum Monthly Temperature (°C)	Mean Monthly Rainfall (mm)
Jan	34	13	10.6
Feb	35	13	8.0
Mar	35	10	14.3
Apr	34	7	33.3
May	30	5	51.6
Jun	27	3	93.2
Jul	26	2	81.1

Month	Mean Maximum Monthly Temperature (°C)	Mean Minimum Monthly Temperature (°C)	Mean Monthly Rainfall (mm)
Aug	26	3	83.6
Sep	29	5	39.6
Oct	32	6	27.4
Nov	31	9	29.7
Dec	33	12	10.6

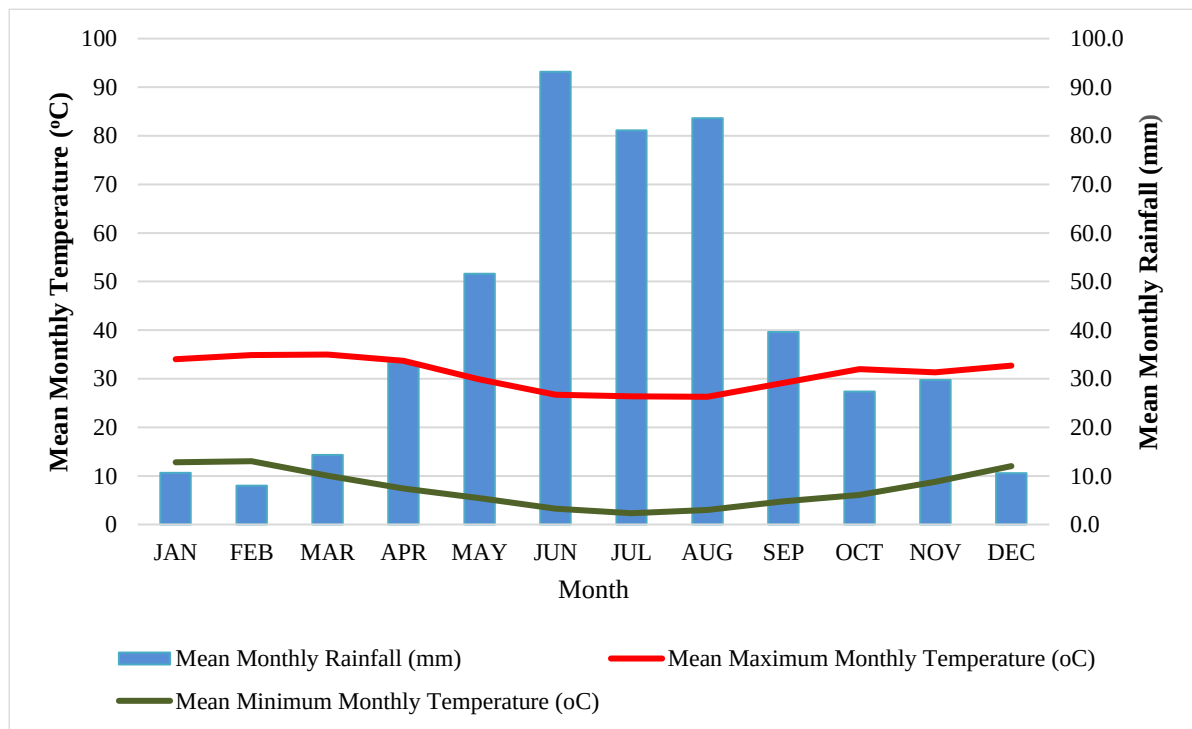


Figure 3-8: Mean Monthly Temperature and Rainfall (2002 -2021) at CT_AWT Station

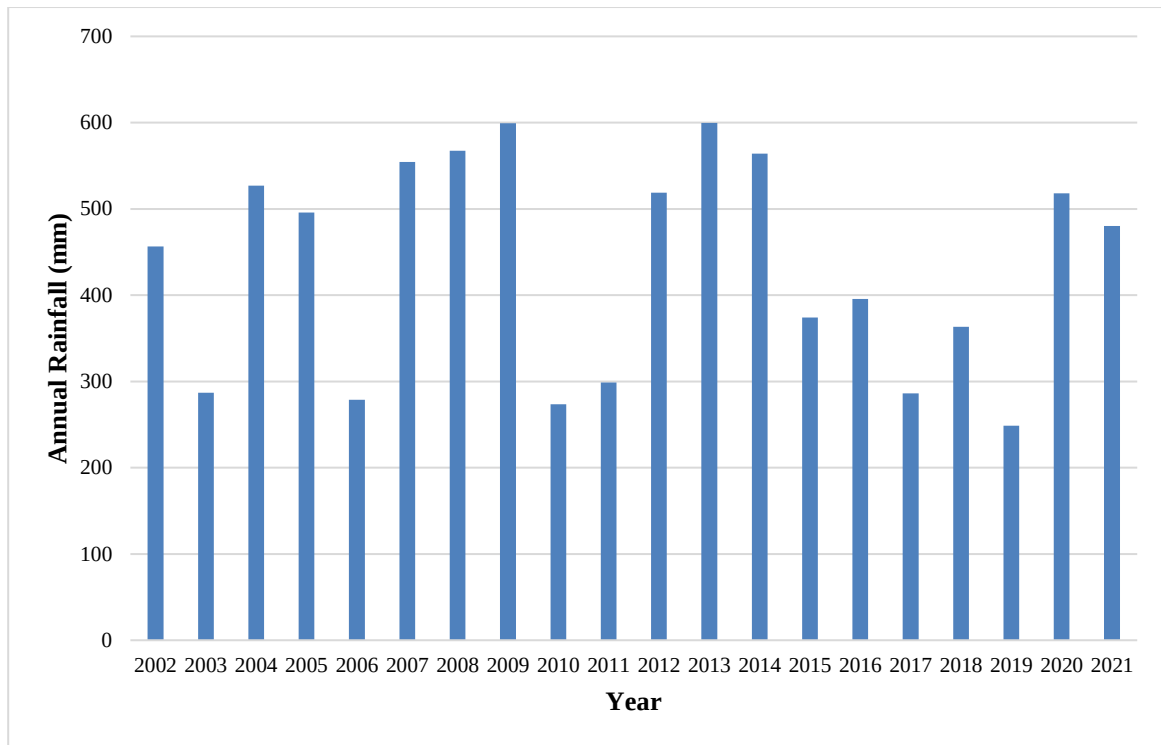


Figure 3-9: Annual Precipitation (2002-2021) at CT_AWT Station

3.5.2.2 Reference Evapotranspiration (ET_o)

The City of Cape Town set up the Phillipi weather station in the Cape Flats area in 2021 to provide meteorological data. The weather station was installed to record hydrological data including evaporation from an evaporation pan. The data was remotely collected via a cellular network, downloaded every day at midnight and stored on the Server Database (Goslin, 2021). CCT was able to closely monitor the evaporation in the Cape Flats area for four months from May to August 2021, before the station was unfortunately vandalised. The available data was used to convert the evaporation data to computed evapotranspiration (ET_o) using **Equation 5** presented by Doorenbos and Pruitt (1977).

$$ET_o = K_p \times E_{pan} \quad \text{Equation 5}$$

where ET_o is the Evapotranspiration (mm/day); K_p – Class A Pan coefficient and E_{pan} – Evaporation data (mm/day)

The pan evapotranspiration method is a method that links evaporation to the reference evapotranspiration ET_o . It is very effortless to use, data is easily interpreted and it is applicable, and suitable for areas with limited meteorological data (Milanović *et al.*, 2017). Doorenbos and

Pruitt (1977) provided the values for K_p for different weather conditions i.e., relative humidity and wind speed, for different locations of the pan as shown in **Table 3-4**.

Table 3-4: Pan Coefficient (K_p) for Class A Pan

(Doorenbos and Pruitt, 1977)

Class A Pan	Pan Placed in Short Green Cropped Area			
Wind Speed at a height of 2 m (km/day)	Windward side distance of green crop (m)	Mean Daily Relative Humidity (%)		
		<40 (40*)	40 - 70 (55*)	> 70 (70*)
<175 (175*)	1	0.55	0.65	0.75
	10	0.65	0.75	0.85
	100	0.70	0.80	0.85
	1000	0.75	0.85	0.85
175-425 (300*)	1	0.50	0.60	0.65
	10	0.60	0.70	0.75
	100	0.65	0.75	0.80
	1000	0.70	0.80	0.80
425 - 700 (562*)	1	0.45	0.50	0.60
	10	0.55	0.60	0.65
	100	0.60	0.65	0.70
	1000	0.65	0.70	0.75
>700 (700*)	1	0.40	0.45	0.50
	10	0.45	0.55	0.60
	100	0.50	0.60	0.65
	1000	0.55	0.60	0.65

*Representative mean value

The mean daily wind speed and the relative humidity data recorded at the Cape Town Airport, located about 7.2 km Northeast of the stormwater pond catchment, was obtained from a study by Okedi (2019).

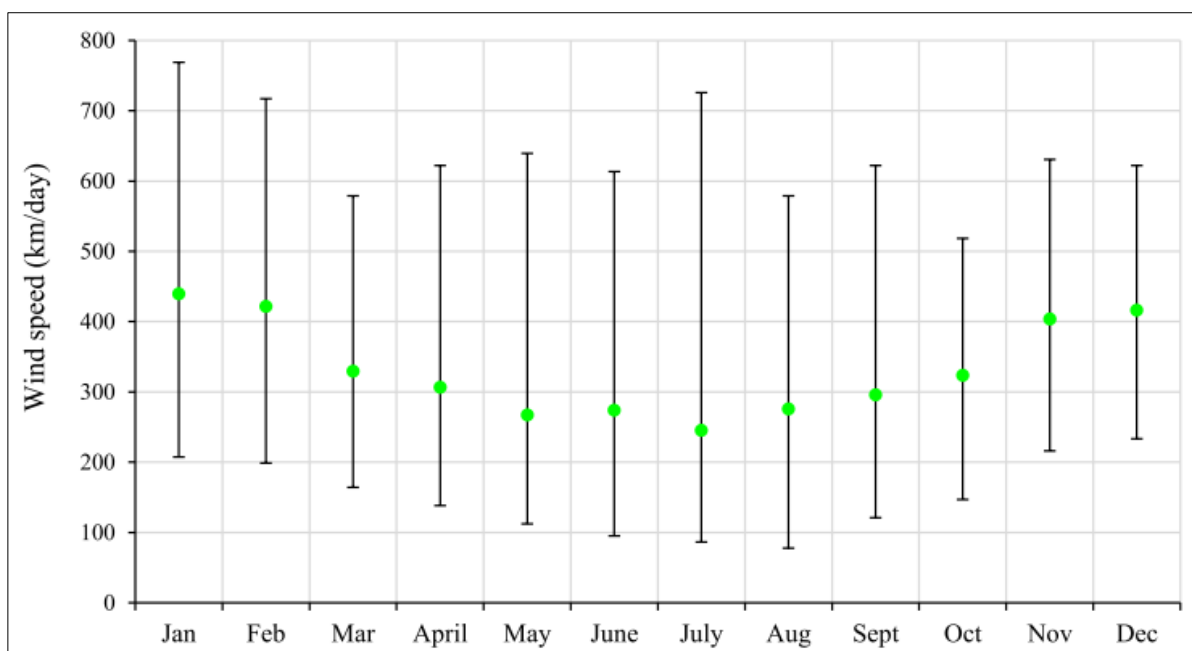


Figure 3-10: Mean Daily Wind Speeds at Cape Town Airport

(Okedi, 2019)

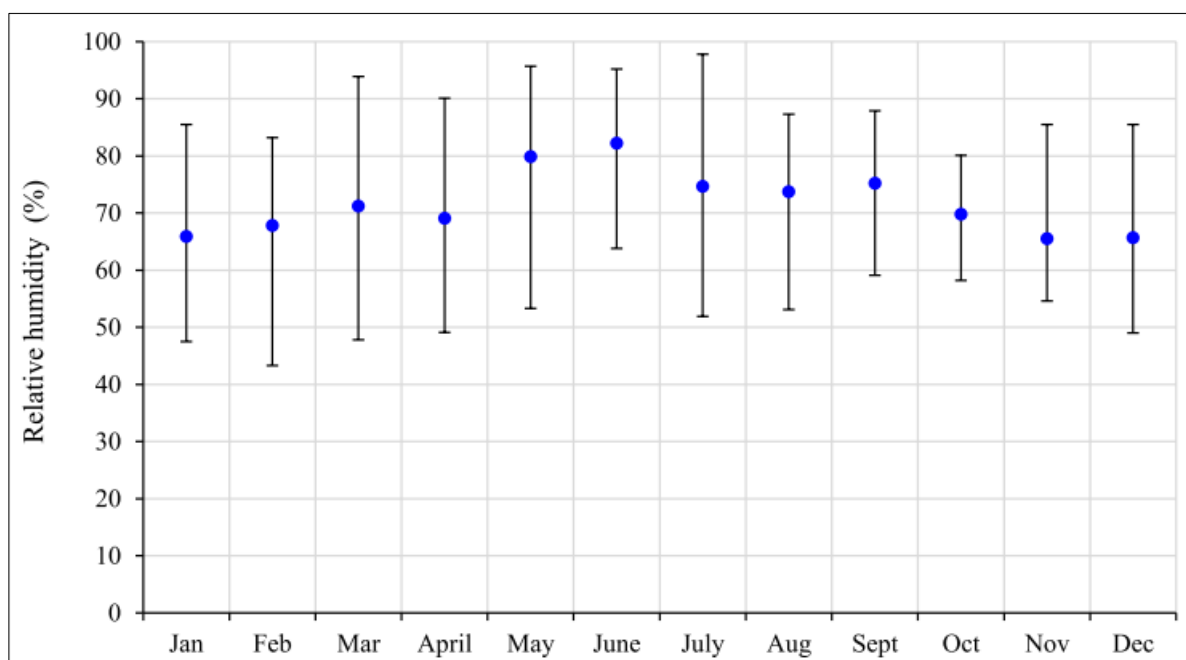


Figure 3-11: Mean Daily Relative Humidity at Cape Town Airport

(Okedi, 2019)

It is observed from **Figure 3-10** and **Figure 3-11** that the mean wind speed during May, June, July and August is between 175 km/day and 425 km/day, and the mean relative humidity is >70%. A K_p value of 0.8 was used to estimate the ET_o , given a windward distance of 1000 m. The estimated mean ET_o was determined as 1.34 mm/day, as shown in **Table 3-5**.

Table 3-5: Estimation of the Reference Evapotranspiration of the Study Area

Month	Monthly A-Pan Evaporation (mm)	Mean Monthly A-Pan Evaporation (mm/day) E_{pan}	Pan Coefficient (K_p)	Mean monthly Evapotranspiration (ET_o) (mm/day)
May	44.5	1.44	0.80	1.15
June	52.8	1.76	0.80	1.41
July	44.8	1.45	0.80	1.16
August	64.0	2.06	0.80	1.65
Average				1.34

3.5.3 Infiltration rates

A study on the evaluation of Cape Town's stormwater ponds for MAR was carried out by Jones (2019). Ten test pits were installed around each stormwater pond to determine the average infiltration rate using double ring infiltrometers. The infiltration rate at the School pond was determined to be 30.28 cm/hr obtained by taking an average of 10 test pits and 34.67 cm/hr for the Green Dolphins pond obtained by taking the average of results from 8 test pits, as shown in **Table 3-6**. The obtained infiltration rates exceeded the minimum required infiltration rate of 2.54cm/hr for an infiltration rate; thus, the ponds were regarded as suitable for MAR based on the geology of the soil.

Table 3-6: Infiltration Rates at the Stormwater Ponds

(Jones, 2019)

Test Pit	Infiltration rate (cm/hr)	
	School Pond	Green Dolphins Pond
Test Pit 1	33.33	33.60
Test Pit 2	75.00	46.00
Test Pit 3	31.00	No test completed
Test Pit 4	26.67	No test completed
Test Pit 5	18.46	22.00
Test Pit 6	25.20	23.00
Test Pit 7	32.00	28.29
Test Pit 8	36.00	44.57
Test Pit 9	16.36	54.55
Test Pit 10	8.73	25.33
Mean infiltration rate	30.28	34.67
	32.47	

3.5.4 Water Table

Dipped groundwater level data recorded at the MON71 Borehole at Green Dolphins pond in 2020 and 2021 was provided by the City of Cape Town. The data was analysed, and the maximum, minimum and mean groundwater levels in the study area were determined as 27.03 m.a.s.l, 25.82 m.a.s.l and 26.31 m.a.s.l, respectively.

Table 3-7: Water Level Data at MON71 Borehole

Borehole - MON71			
Year	Date and Time	Dipped water level (mbgl)	Dipped water level (mamsl)
2020	2/20/2020 12:35	2.48	25.988
	3/24/2020 11:27	2.57	25.903
	6/2/2020 11:35	2.65	25.818
	7/1/2020 10:35	2.43	26.043
	9/9/2020 10:40	1.85	26.623
	11/13/2020 13:38	1.90	26.568
	11/24/2020 8:30	1.95	26.518
	11/25/2020 12:40	1.97	26.498
2021	1/19/2021 11:56	2.20	26.268
	2/11/2021 14:24	2.26	26.208
	3/2/2021 11:45	2.33	26.138
	4/13/2021 14:05	2.29	26.178
	5/12/2021 11:28	2.35	26.118
	6/14/2021 15:02	2.21	26.258
	7/7/2021 11:19	1.60	26.868
	8/4/2021 11:25	1.44	27.028
	9/3/2021 10:45	1.37	27.098
Maximum		2.65	27.03
Minimum		1.44	25.82
Mean		2.16	26.31

3.6 Groundwater Potential Zones Mapping for MAR through GIS and AHP Techniques

A combination of GIS techniques and the Analytical Hierarchical Process (AHP) method was used to delineate the groundwater potential zones of the study area. The GIS-based method was selected as it has a powerful spatial analysis ability, and the AHP method was used because it was the most popular method for mapping suitable MAR sites from previous studies.

3.6.1 Catchment Delineation

Catchment Delineation is the process of creating a boundary that represents the contributing area for a particular control point or outlet and is based on the topography and river network

information of the area. The required catchment boundary was defined by applying the GIS tool to an appropriate high-resolution Digital Elevation Model (DEM).

3.6.2 Methods and Materials

The groundwater potential zones of the stormwater ponds catchment were delineated using geospatial techniques in the ArcGIS software using the knowledge-based factor analysis of a total of 7 thematic layers of information of the area such as geology, lineament density, lithology, slope, soil, land use/landcover (LULC) and drainage density.

The study area catchment was delineated using a 0.5 m resolution DEM with the support of the hydrology tool in ArcGIS. The Lidar dataset, obtained from the UCT GIS Support, was used to create a bare-earth DEM, minimum value inputs with a 0.5 cell size, using the LAS Dataset to Raster tool under the conversion toolbox. The DEM was used in preparing the drainage density and lineament density maps using the line density under the Spatial Analyst tool in ArcGIS Software.

Geology, Lithology and Soil shapefiles of the Cape Flats Aquifer were collected and used to extract the shapefile of the study area using the extraction by mask tool in ArcGIS software. The slope was generated from Shuttle Radar Topographic Mission (SRTM), data and the Land use/ Land cover was generated using the supervised image classification tool.

3.6.3 Multi-criteria Decision Analysis using AHP Technique

Multi-criteria decision analysis using Analytical Hierarchical Process (AHP) is the most common and well-known GIS-based method for delineating groundwater potential zones. It is an effective tool for dealing with complex decision-making in groundwater-related fields as it reduces them to a series of pairwise comparisons and then synthesises the results (Arulbalaji *et al.*, 2019). **Figure 3-12** shows the flowchart of the methodology used in groundwater potential zone mapping.

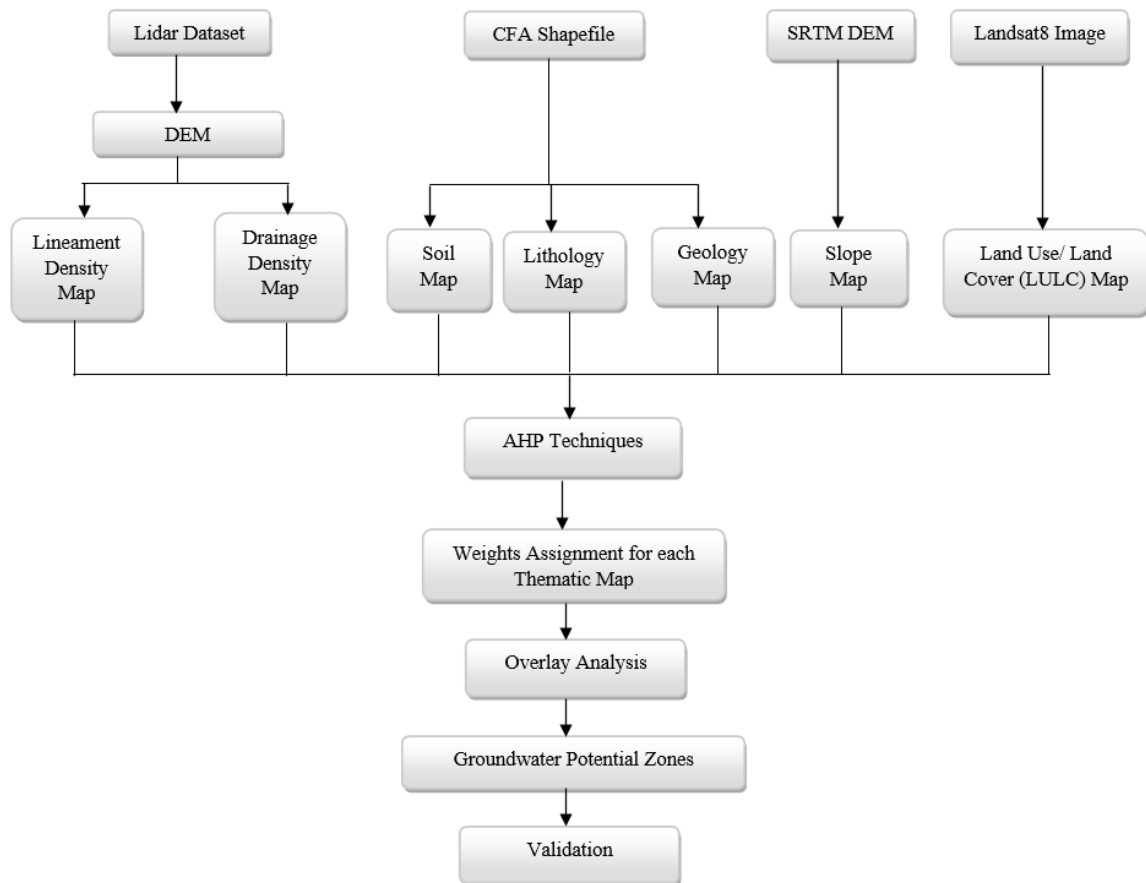


Figure 3-12: Flowchart of Methodology used in Groundwater Potential Zone Mapping

3.6.4 Groundwater Potential Zoning Factors

In this study, seven (7) thematic maps were considered as the control factors of groundwater flow and storage in the area. These influencing factors were weighted according to their reaction to groundwater occurrence, expert opinion, and consideration from the reviews from previous studies.

3.6.4.1 Scale of Relative Importance

Parameters were assigned weights according to Saaty's scale (1-9) of relative importance value shown below. This was carried out based on the importance and water-holding capacity of the layers.

Table 3-8: Saaty's Scale of Relative Importance

Intensity of Importance	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate Importance	Experience and judgement slightly favor one element over another
5	Strong Importance	Experience and judgement strongly favor one element over another
7	Very Strong Importance	One element is favored very strongly over another, its dominance is demonstrated in practice
9	Extreme Importance	The evidence favoring one element over another is of the highest possible order of affirmation
2,4,6,8 can be used to express intermediate values		

Table 3-9: Relative Importance of the Thematic layers

Criteria		More important	Scale
A	B	A/B	(1-9)
Geology	Lithology	A	1
	Slope	A	3
	Drainage Density	A	3
	Land Use	A	5
	Lineament Density	A	5
	Soil	A	5
Lithology	Slope	A	3
	Drainage Density	A	3
	Land Use	A	5
	Lineament Density	A	5
	Soil	A	3
Slope	Drainage Density	A	1
	Land Use	A	3
	Lineament Density	A	3
	Soil	A	5
Drainage Density	Land Use	A	1
	Lineament Density	A	2
	Soil	A	3
Land Use	Lineament Density	A	1
	Soil	A	3
Lineament Density	Soil	A	1

3.6.4.2 Pair-wise Comparison Matrix

The thematic layers were compared with each other using a pair-wise comparison matrix shown in Table 3-10.

Table 3-10: Pair-wise Comparison Matrix between the Applied Parameters for the AHP Model

	Geology	Lithology	Slope	Drainage Density	Land Use	Lineament Density	Soil
Geology	1	1	3	3	5	5	5
Lithology	1	1	3	3	5	5	3
Slope	1/3	1/3	1	1	3	3	5
Drainage Density	1/3	1/3	1	1	1	2	3
Land Use	1/5	1/5	1/3	1	1	1	3
Lineament Density	1/5	1/5	1/3	1/2	1	1	1
Soil	1/5	1/3	1/5	1/3	1/3	1	1
Total	3	3	9	10	16	18	21

The normalized pair-wise comparison matrix was created by dividing each cell by the sum of each column and the normalized weights for each component were calculated using the average of each row.

Table 3-11: Normalized Pair-wise Comparison Matrix and Weights of each Factor

	Geology	Lithology	Slope	Drainage Density	Land Use	Lineament Density	Soil	Weight
Geology	0.31	0.29	0.34	0.31	0.31	0.28	0.24	0.30
Lithology	0.31	0.29	0.34	0.31	0.31	0.28	0.14	0.28
Slope	0.10	0.10	0.11	0.10	0.18	0.17	0.24	0.14
Drainage Density	0.10	0.10	0.11	0.10	0.06	0.11	0.14	0.10
Land Use	0.06	0.06	0.04	0.10	0.06	0.06	0.14	0.07
Lineament Density	0.06	0.06	0.04	0.05	0.06	0.06	0.05	0.05
Soil	0.06	0.10	0.02	0.03	0.02	0.06	0.05	0.05
TOTAL	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Figure 3-13 shows the normalized principal eigenvector for each layer in percentages. The higher the normalized principal eigenvector, the greater the influence the parameter has on the groundwater potential zone in the study area. A parameter with a high weight illustrates a layer with a high impact, and a parameter with a low weight illustrates a small impact on groundwater potential (Arulbalaji *et al.*, 2019).

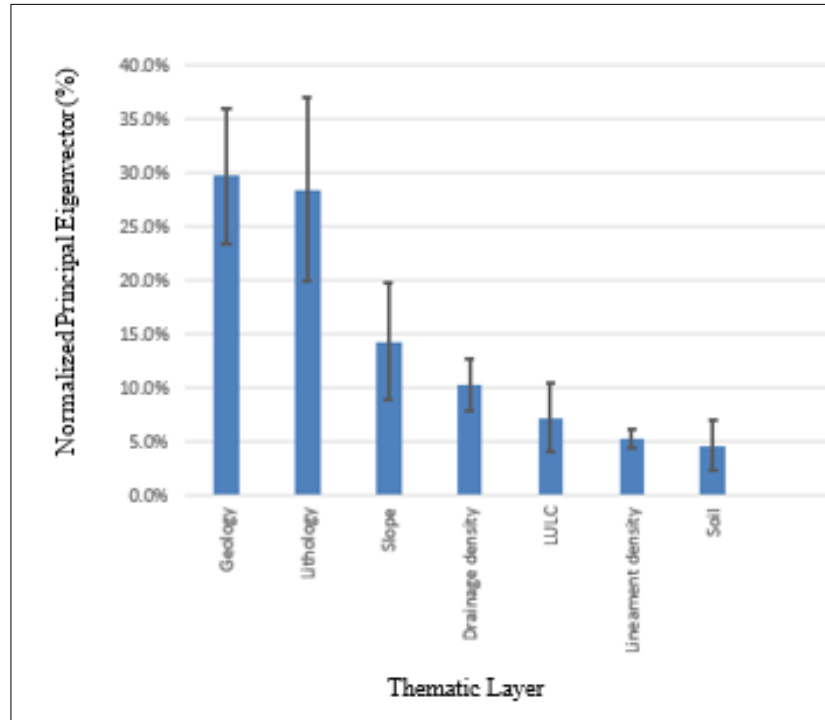


Figure 3-13: Normalized Principal Eigenvector for each Thematic layer

3.6.4.3 Consistency Ratio (CR)

The matrix was checked for consistency by determining the consistency ratio. The consistency ratio is defined as; $CR = CI/RCI$, where CI is the Consistency Index given by **Equation 6** and RCI is the Random Consistency Index.

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad \text{Equation 6}$$

Where $\lambda_{\max}$ denotes the principal eigenvalue and n represents the number of parameters. The principal eigenvalue ($\lambda_{\max}$) represents a function for the matrix divergence from consistency. Therefore, a pairwise matrix is considered consistent only when $\lambda_{\max}$ is equal to or more than the number of the layers being examined.

$$\lambda_{\max} = \frac{49}{7} = 7$$

$$CI = \frac{7 - 7}{7 - 1} = 0$$

The random consistency index (RCI) was obtained from the table below, showing Saaty's Ratio Index for the different values of N.

Table 3-12: Saaty's Ratio Index for the Different Values of N

The Consistency Indices of Randomly Generated Reciprocal Matrices												
Order of the Matrix												
N	1	2	3	4	5	6	7	8	9	10	11	12
RCI Value	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48

Therefore, the consistency ratio was given below.

$$CR = \frac{0.0}{1.32} = 0$$

Saaty (1990) stated that a CR of equal to or less than 0.1 for larger matrices is acceptable to continue the analysis. If the consistency is more significant than 0.1, the analysis should be revised to locate the inconsistencies and correct them.

3.6.4.4 Identification of Groundwater Zones

The sub-classes of the layers were re-classified using the natural breaks classification method in ArcGIS software for assigning weights and then allocated ranks on a scale of 1 to 5 according to their relative influence on groundwater development, as shown in **Table 3-13**. All seven thematic layers were integrated with the weighted overlay analysis method in ArcGIS using **Equation 7**.

$$GWPZ = \sum_i^n (X_A \times Y_B) \quad \text{Equation 7}$$

where;

- GWPZ - Groundwater Potential Zone
- X - Weight of the thematic layers
- Y - Rank of the sub classes of the thematic layer
- A - (1,2,3...X) Thematic map
- B - (1,2,3...Y) Thematic map sub-classes

Table 3-13: Weight and Ranking for the Different Sub-classes of the Thematic Layers

Parameter	Sub-Classes	Weight	Influence (%)	Rank	Area (km ²)
Geology	Quaternary	0.30	30	5	0.315
Lithology	Sand	0.28	28	5	0.315
Slope (degrees)	0 - 0.15	0.14	14	5	0.161
	0.16 - 0.47			4	0.007
	0.48 - 0.82			3	0.078
	0.83- 1.2			2	0.048
	1.3 - 1.5			1	0.020
Drainage Density (km/km ²)	0 – 27.52 (Low)	0.10	10	5	0.234
	27.53 – 55.04 (Very Low)			4	0.057
	55.05 – 82.56 (Moderate)			3	0.018
	82.57- 110.1 (High)			2	0.005
	110.2- 137.6 (Very High)			1	0.001
Land Use /Land Cover (LULC)	Bare Ground	0.07	7	1	0.008
	Stormwater Pond			5	0.019
	Vegetation			5	0.002
	Built-up Area			1	0.223
	Road			1	0.064
Lineament Density (km/km ²)	0 – 15.92 (Low)	0.06	6	1	0.261
	15.93 – 31.85 (Very Low)			2	0.033
	31.86 – 47.77 (Moderate)			3	0.016
	47.78- 63.7 (High)			4	0.005
	63.71- 79.62(Very High)			5	0.001
Soil	Sandveld	0.05	5	5	0.315

3.7 Groundwater Level Data using an IoT-based Monitoring System

South Africa is faced with a need for hydrogeological data in areas with groundwater use. This section presents a novel approach used for collecting and validating IoT-based groundwater levels to contribute towards alleviating the problem of inadequate data.

3.7.1 SenseCAP LoRaWAN Wireless Sensor Network

SenseCAP is an industrial WSN which integrates easy-to-deploy hardware and data application programming interface (API) services, enabling low-power, long-distance environmental data collection. A simple system composed of four (4) key components: a water level sensor, node, gateway, and smartphone, was set up across the study area to collect, monitor, manage and analyze the water levels within the aquifer. **Figure 3-14** shows the architecture of the WSN that was used in this study.

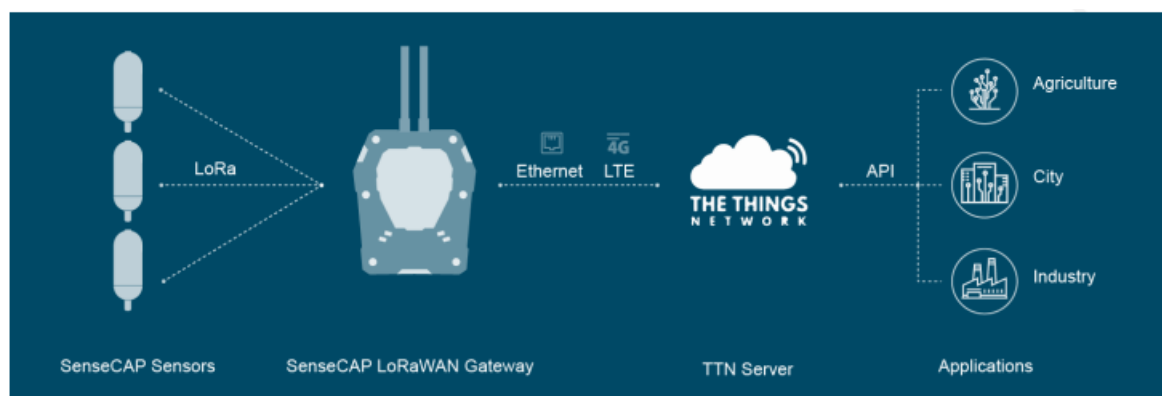


Figure 3-14: SenseCAP LoRaWAN Architecture

The WSN consists of LoRaWAN gateways and sensor nodes and can realise one-to-many, long-distance networking and bilateral communication. The Seeed SenseCAP LoRaWAN gateway can receive data from either a SenseCAP or a third-party sensor attached to a node. It then sends the data to the cloud, where it is managed on The Things Network (TTN). The Thing Speak platform converts the raw data sent by the sensor into visually displayed and analysed data.

3.7.2 Monitoring System Set up and Installation

It was imperative to have a clear line of sight distance between the gateway and the sensor to enable proper communication between the devices. A SenseCAP LoRaWAN Gateway and a Hefei WNK8010 submersible water level sensor were used in this study. The gateway was installed at The Leadership College-Hyde Park, located next to the School pond. The water level sensor was installed in the secure CCT MON71 borehole at the Green dolphins' pond at coordinates 34°2'15.42"S latitude and 18°35'11.42"E longitude, as shown in **Figure 3-15**. The borehole has a concrete cover that prevents the vandalism of the sensor. It consists of a 0.165 m wide solid PVC pipe drilled to the basement of the aquifer to a depth of 45 m and a 0.305 m solid steel casing around the PVC pipe to a depth of top 5m. as shown in **Figure 3-17**.



Figure 3-15: Location of Gateway and Water level Sensor



Figure 3-16: CCT MON71 Borehole

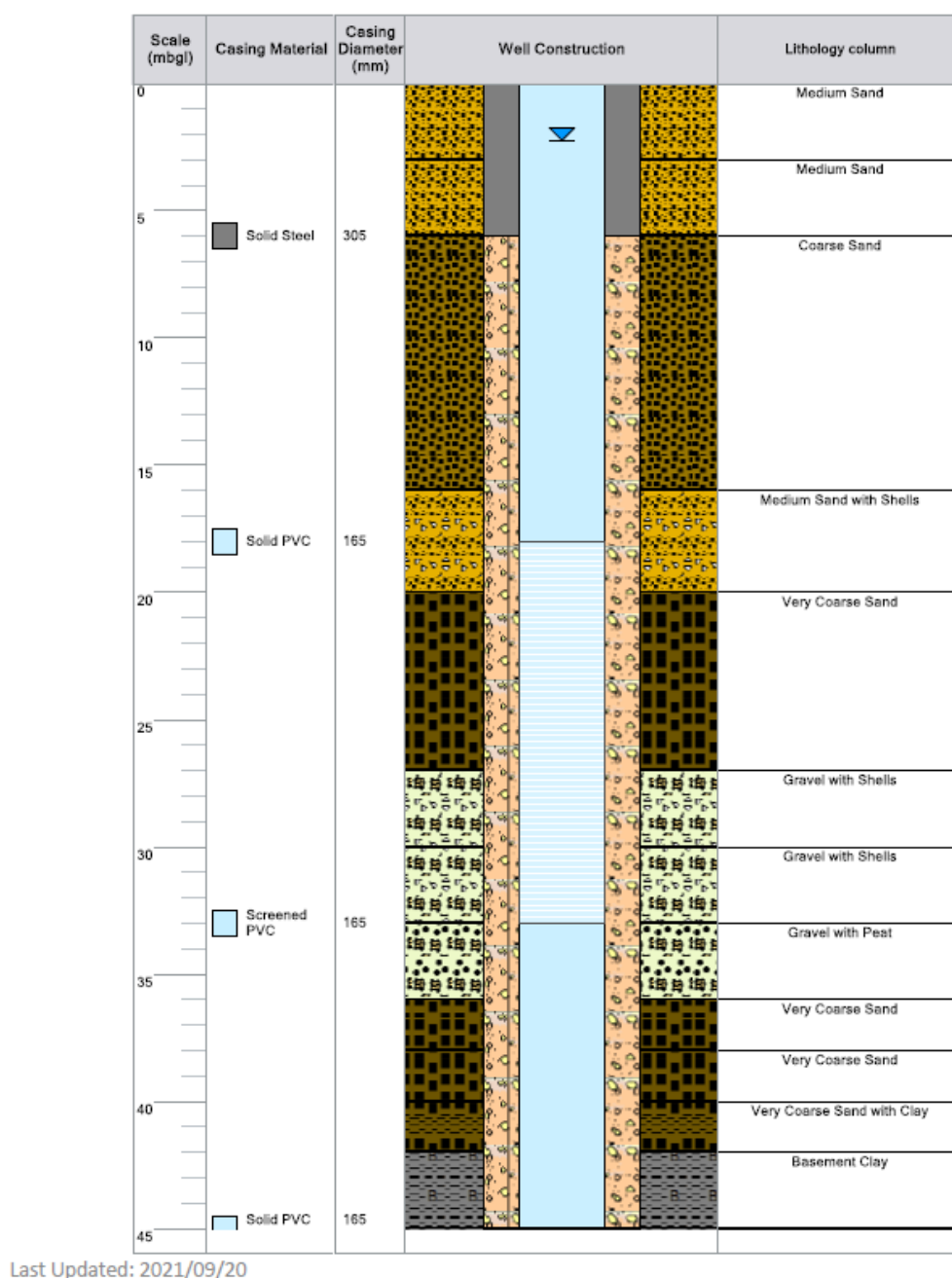


Figure 3-17: Cross-section through MON71 Borehole

3.7.2.1 Network Configuration of the Gateway

The gateway was connected to the internet using a 4G LTE micro-SIM card with a monthly subscription. The lid of the gateway was opened, the card was installed correctly into its socket, and the lid was closed with the screws.

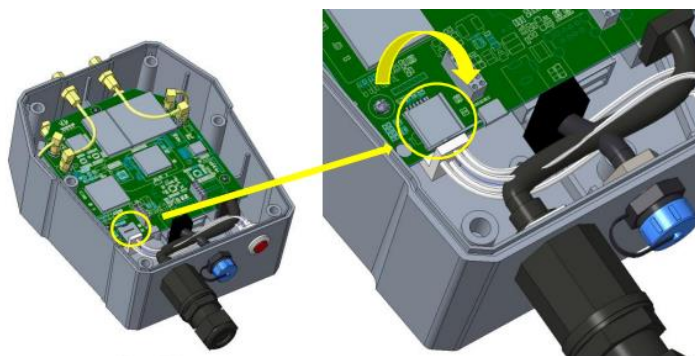


Figure 3-18: Micro-SIM Card Socket

An uninterruptible power supply (UPS) was connected to the gateway as a power backup during load shedding to ensure continuous communication between the sensor and the gateway. It switches to direct current (DC) battery power and inverts it to alternating current (AC) when power drops during a power outage to run the gateway. The extension cord and the two antennas, 4G and LoRa, were installed onto the gateway; and powered on. The red LED light went through three (3) stages after powering the gateway:

- Stage 1: Stayed on for 2-3 seconds, then went off.
- Stage 2: Stayed OFF for about 30 seconds, then started flashing as it was connecting to the internet.
- Stage 3: LED light stayed ON as soon as the gateway was connected to the internet.



Figure 3-19: Seede SenseCAP LoRaWAN Gateway

3.7.2.2 Gateway Registration on The Things Network (TTN)

The gateway service address was set up, and a user account was created on The Things Network website to access TTN console to manage the system devices. The gateway was registered on the website that stores and displays data using a LoRa application known as ThingSpeak, which allows tracking, analysing and visualising water level data in real-time on the cloud.

3.7.2.3 Sensor Node

The sensor node was assembled and comprised four (4) components: Microcontroller Unit (MCU), sensor, Printed circuit board (PCB), and battery as the power supply, all placed in an enclosed compartment for safety and waterproofing purposes shown in **Figure 3-20**. The MCU comprised the LoRa antenna and Pycom LoPy4 development board, fixed onto the Open Water Network PCB, allowing transmissions over an 868MHz frequency band.

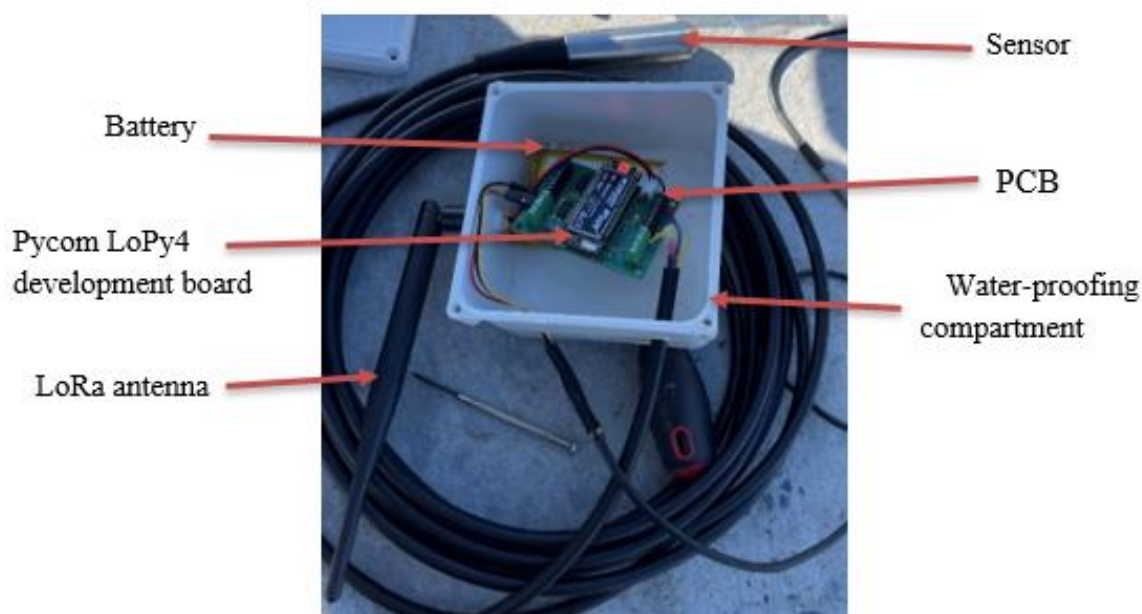


Figure 3-20: Components of the Sensor Node

3.7.2.4 Water Level Sensor

In this study, a Hefei WNK8010 submersible water level sensor, a third-party sensor, was used to send raw data to the Sseed SenseCAP LoRaWAN gateway. The sensor comprises a 6 m long cable and a corrosion-resistant stainless-steel housing material. It was connected to the node using the ADC3, GND and VCC terminal blocks on the Open Water Network PCB to create a circuit for the measurement and transfer data from the sensor to the gateway where it was stored and processed. **Table 3-14** describes the colour-coded pins of the water level sensor.

Table 3-14: Description of the Colour Coded Pins of the Sensor

Terminal Block	Water level Colour Coded Pin	Description
ADC3	Yellow	ADC line/Data
GND	Black	Ground
VCC	Red	Power

The sensor has a measurement range of 0 to 5 m and an output voltage of 0.33 – 297 VDC and converts analogue current to digital currents that the MCU can process. A code was developed and used to produce a Micro Python Script for the sensor shown below.

```
# Measurement of Water Level Sensor
# *****#
def measureWaterLevel():
    adsDataRate=6 # for ADS reading
    RANGE = 5000 # Depth measuring range 5000mm (for water)
    VOLTAGE_INIT=0.33 # Voltage @ 0mm (uint: Vdc)
    DENSITY_WATER=1 # Pure water density normalized to
    (ADCreading,voltage)=adsx15read(ads,irq_pin,adsDataRate,adsChannel=2)

    while True:
        depth = (voltage - VOLTAGE_INIT) * (RANGE/ DENSITY_WATER / 2.64)
#Calculate depth from voltage readings
        if depth is not None:
            return depth # TempCelsius exit loop and return result

WaterLevel=measureWaterLevel()

print("Water level= %6.3f" % WaterLevel)
```

Figure 3-21: Micro Python Script used for the Water Level Sensor

The sensor has an onboard voltage divider that converts electrical resistance into water level depth. It transfers the pressure of the water to the current signal with its reliable amplified circuit and precision temperature compensation using **Equation 8**.

$$P = \rho gh + P_o \quad \text{Equation 8}$$

$$h = \frac{P - P_o}{\rho g} \quad \text{Equation 9}$$

Where:

P - Pressure of the liquid

- ρ - Density of the liquid
- g - Gravity acceleration
- h - Depth (Distance from the surface of the liquid to the sensor)
- P_o - Atmospheric pressure at liquid surface

The voltage values were converted into depth values using **Equation 10**

$$h = (V - V_{h_0}) \times \left(\frac{R}{\rho(V_{h_5} - V_{h_0})} \right) \quad \text{Equation 10}$$

Where:

- h - Liquid level (m)
- V - Voltage output signal (volts)
- V_{h_0} - Voltage output corresponding to a depth of 0m
- V_{h_5} - Voltage output corresponding to a depth of 5m
- ρ - Density of the liquid (kg/m^3)
- R - Maximum range of height (m)

Figure 3-22 and **Figure 3-23** show the Hefei WNK8010 submersible water level sensor and the installed sensor in the MON71 Borehole respectively.



Figure 3-22: Hefei WNK8010 Submersible Water Level Sensor



Figure 3-23: Installed Water level Sensor in the 45 m deep Borehole

3.7.2.5 ThingSpeak Application

The water level data on TTN was analysed and visualised using MATLAB and the ThingSpeak application. A channel was created on the ThingSpeak website to generate a write API to connect the TTN and ThingSpeak and perform an in-depth analysis of the data, view/graph the necessary variables, send alerts, and export the data to Microsoft Excel.

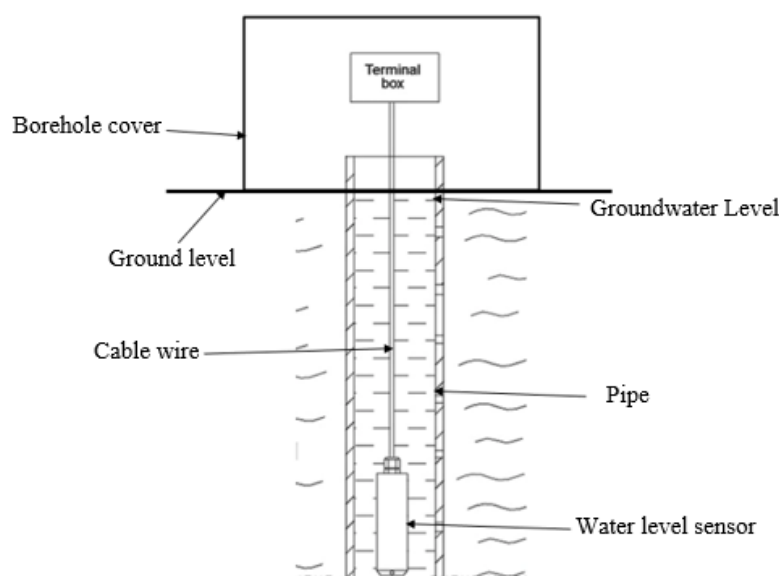
3.8 IoT-based Data Validation

Data validation is a an essential part of determining a suitable level of accuracy of the collected IoT data to ensure that it is of good quality for an application to avoid any errors in the analysis (Johansen. *et al.*, 2022). In this study, the IoT-based water level data was validated using the manually recorded water level data at the MON71 borehole, once a month as part of the New Water Programme of the CCT.

The water levels are monitored using a manual water level dip logger that records the water depth when it touches the water surface, i.e., it records the distance from the top of the pipe to the water surface. However, the Hefei8010 WNK submersible water level sensor used in this study reads the water depth above the sensor in meters. Therefore, there was a need to obtain the groundwater levels in meters above sea level (m.a.s.l). The reduced level of the top of the pipe, 28.47 m.a.s.l, and other dimensions taken from the site, as shown in **Table 3-15** were used in the to compute the meters above sea level. The manual water level data in meters above sea level was compared with the IoT water level data recorded on particular dates, and the variation between the two records was used to determine the accuracy of the IoT data.

Table 3-15: Computation of the Groundwater level

Measured distances	m
Distance from top of the cover to pipe opening	0.46
Distance from top of the cover to ground level	0.71
Distance from top of the pipe opening to water level on 21/07/2022	2.22
Elevation	m.a.s.l
Cover level	28.93
Ground level	28.22
Water level on 21/07/2022	26.25
Top of the pipe	28.47
Length	m
Length of cable wire of the water level sensor	6.00

**Figure 3-24: Schematic cross-section through the MON71 Borehole**

3.9 Groundwater Flow Modelling with MODFLOW

3.9.1 Overview

All the collected datasets, both existing and IoT-based, were used to develop and calibrate a numerical groundwater model in MODFLOW. A model was developed in MODFLOW software

to assess groundwater flow and water levels in the study area. **Figure 3-25** shows the procedure/flowchart followed in developing the model.

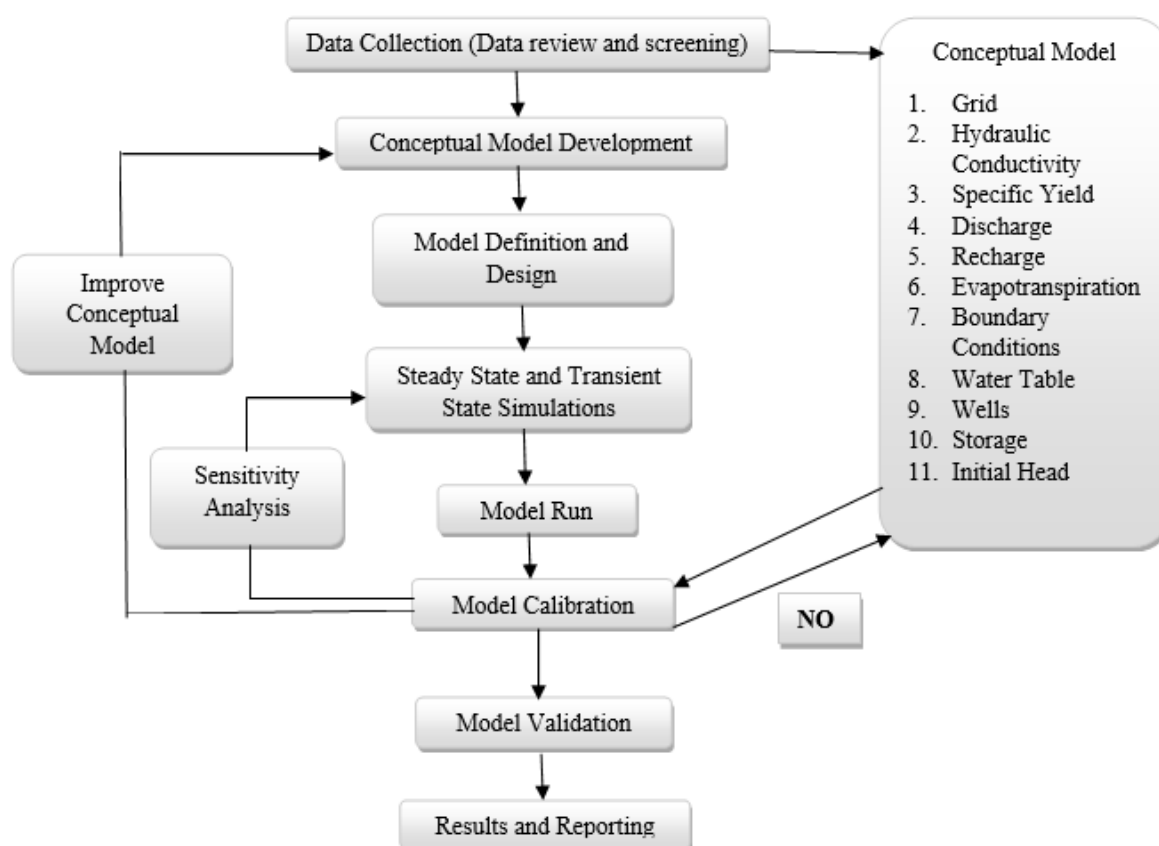


Figure 3-25: Groundwater Modelling Flowchart

3.9.1.1 Description of MODFLOW-NWT

MODFLOW-NWT is a newton formulation of MODFLOW-2005, a standalone program intended for solving problems involving drying and rewetting nonlinearities of the unconfined groundwater-flow equation and must be used with the Upstream-Weighting (UPW) Package (Niswonger *et al.*, 2011). The upstream weighting uses a hydraulic head in the upgradient cell to calculate the intercell conductance for a pair of cells. It constricts the flow leaving a cell which causes the cell to have zero flow and storage when the water level falls below the cell bottom elevation (Painter *et al.*, 2008; Hunt & Feinstein, 2012). MODFLOW-NWT is well suited for complex models as the Newton-Raphson (NWT) solver input file allows for the specification of over 20 variables (Niswonger *et al.*, 2011). In this study, the model was solved using a maximum number of 150 outer iterations.

3.9.2 Conceptual Model

A conceptual model is a backbone and the first step towards developing a numerical model. It is based on collected data, field reconnaissance and an in-depth understanding of the hydrological, meteorological, geological, and hydrogeological processes in the aquifer. The hydrogeological system of the aquifer is modelled in multiple layers with varying thicknesses (Qadir, 2011). A good conceptual model should include the following key issues; boundary conditions, recharge, model domain, aquifer parameters like hydraulic conductivity, water table data and aquifer geometry (Husam, 2008).

DWAF (2008) described the typical stratigraphy for the Cape Flats for analysis at the regional level, and it was concluded that the unconsolidated deposits of the aquifer could be classified into two layers. In this study, the conceptual model of the unconfined aquifer was divided into two layers based on the subsurface geology of the study area. The first layer comprised sand sediments, i.e., fine to medium sand and was assumed to extend 20 m below the ground surface. The second layer consisted of Malmesbury shale sediments that extended from 20 m to 45 m (25 m thick), thus a total aquifer thickness of 45 m. The regional groundwater flow is from the Northeast towards the Southwestern part of the aquifer flowing from high-elevation to low-elevation areas.

3.9.2.1 Spatial Discretization

The aquifer system was divided into a grid of blocks known as cells, organized by rows, columns, and layers. The model domain was divided into 90 rows and 60 columns with a uniform grid cell size of 10 m x 10 m. The top surface of the double-layered model, also known as the Model_Top, represented the land surface of the study area as seen in the vertical dimension in **Figure 3-27**. The elevation of the Model_Top cells ranges between 28.94 m.a.s.l – 35.12 m.a.s.l, and this was obtained by developing a DEM using the Golden Surfer Software and the Kriging method in the ArcGIS software using 1 m contours of the study area. The elevation of the bottom cells was determined using the thickness of the layers. Both layers represent an unconfined aquifer; thus, they were defined as convertible.

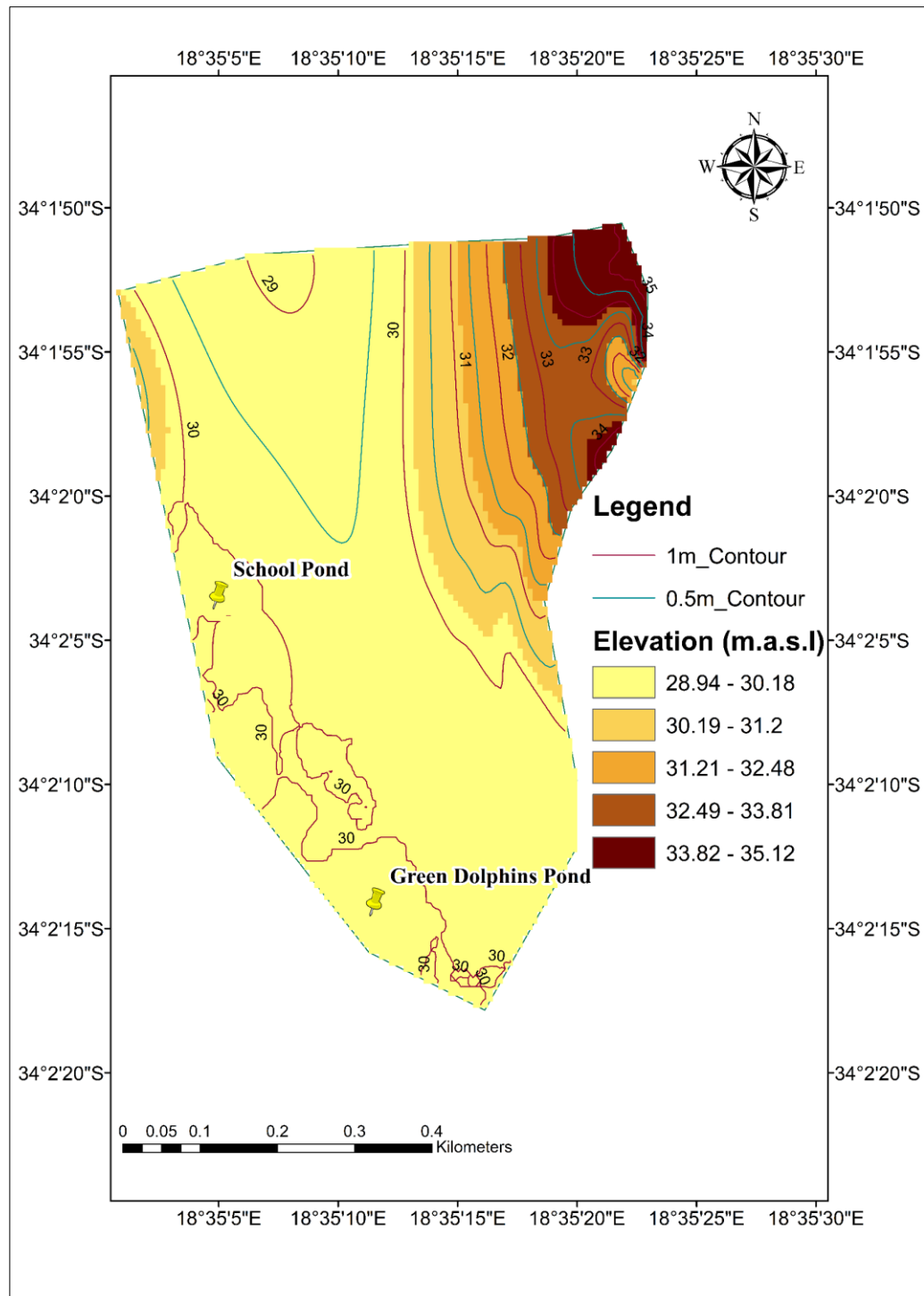


Figure 3-26: Digital Elevation Model of the Model Domain

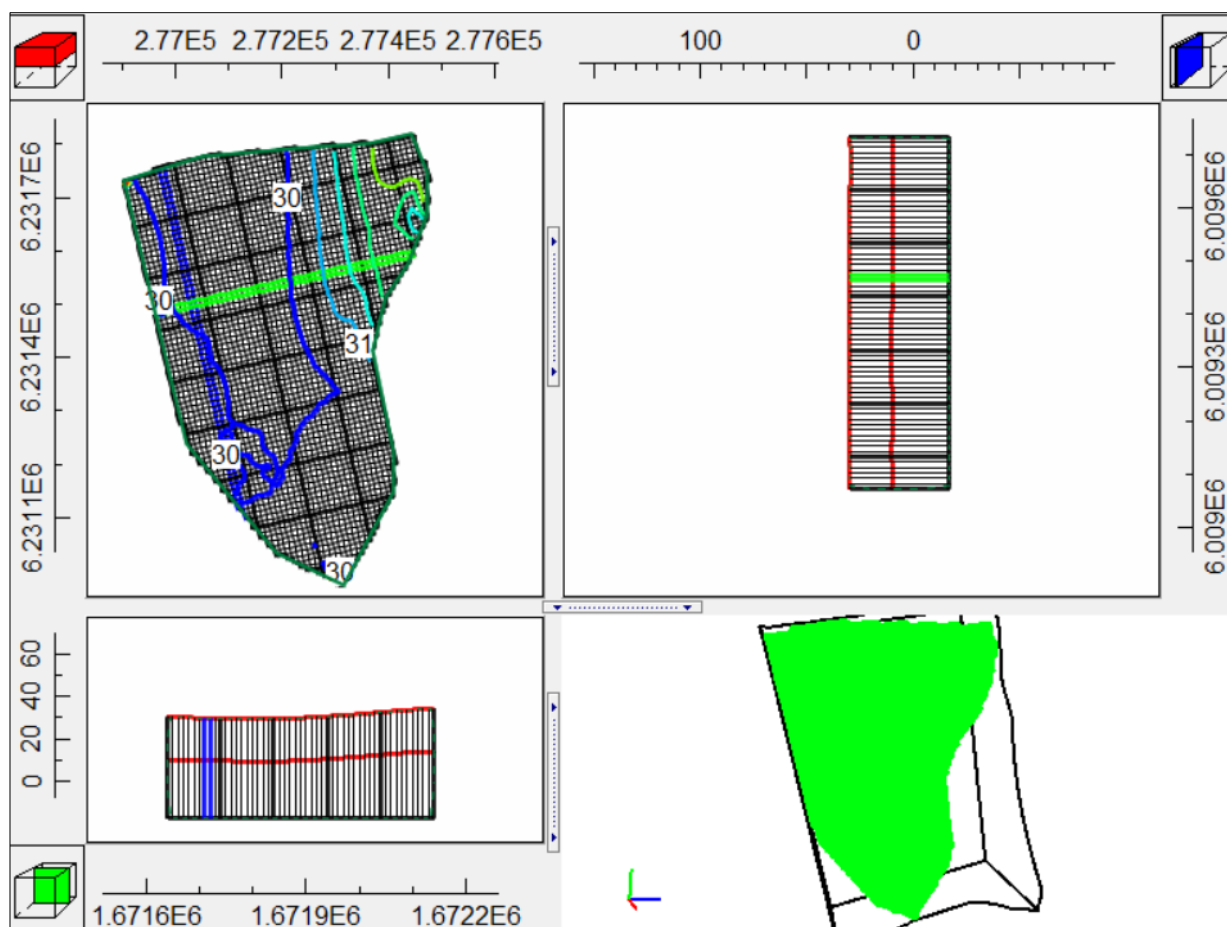


Figure 3-27: Spatial Discretization of the Study Area showing the Rows, Columns, Layers and 3D View of the Model

3.9.3 Model Input Parameters

This section presents all the parameters used in the model development. The data collected included boundary and initial conditions, water level data, hydraulic conductivity, specific yield, recharge rates, aquifer type and thickness. The model covered an area of 0.315 km², and the layers were assigned the same aquifer parameters except for the hydraulic conductivity that varied between layers. The specifications of the layers are shown in **Table 3-16**.

Table 3-16: Specifications of the Model Layers

Layer ID	Layer Geology	Aquifer type	Thickness (m)	Specific Yield (S _y)/ Storativity	Hydraulic Conductivity (K _x) (m/s)
Layer 1	Sand	Convertible	20	1.0 X 10 ⁻²	1.2 X 10 ⁻⁴
Layer 2	Malmesbury Shale	Convertible	25		6.0 X 10 ⁻⁴

3.9.3.1 Hydraulic Conductivity (K)

Hydraulic conductivity measures how easily water infiltrates a soil or rock layer. It is affected by the porosity, permeability, saturation, and hydraulic gradient of the soil. The hydraulic conductivity of the layers in the x-direction (K_x) was obtained from a groundwater model shapefile of the CFA provided by the City of Cape Town. In a study by Siarkos & Latinopoulos (2016), the conductivity in the z-direction (K_z) was assumed to be one-tenth of the x direction (K_x), and that in the y-direction (K_y) was assumed to be equal to K_x and this was adopted for this thesis. The study area was clipped from the CFA hydraulic conductivity shapefile in ArcGIS software, and it was determined that the hydraulic conductivity ranged from 10 -50 m/d, as indicated in the attribute table of the clipped shapefile. Different K_x values were assigned to the layers, given that the coarse sand in layer 2 has a higher conductivity than the fine to medium sand in layer 1. The K_x values for layers 1 and 2 were estimated as 1.2×10^{-4} m/s and 6.0×10^{-4} m/s, respectively.

3.9.3.2 Specific Yield (S_y)

Specific yield is a key parameter in estimating the groundwater table depth (Lv *et al.*, 2021). It is also referred to as storativity for unconfined aquifers and is defined as the volume of water that an aquifer releases from the storage per unit surface of the aquifer per unit decline in the water table (Freeze & Cherry, 1979). The specific yield was estimated based on the Theis solution by excel-spreadsheet and Aqua-test analysis by Gxokwe & Xu (2017) that determined the average storativity of the CFA ranges from 0.004 to 0.2 with the Phillipi borehole having storativity values of 0.1 and 0.01 in the two analytical solutions respectively. Similarly, the study area of this project is in the southern part of the aquifer as the Phillipi area; therefore, a storativity value of 0.01 was adopted for the analysis.

3.9.3.3 Initial conditions

One monitoring well was used to measure water level data from the field to dictate the initial conditions of the model.

3.9.3.3.1 Observation well

The IoT-based water level data collected from 17th July to 5th December 2022 was used during modelling to specify the initial water levels of the model. The average water level throughout the data collection period was considered in the steady state flow regime, model simulation and calibration. The results from the steady state were used as the initial conditions of the transient state simulation.

3.9.3.4 Boundary Conditions

It is very imperative to understand the boundary conditions of the study area to numerically identify the aquifer system, as an improper selection of the components may result in errors (Husam, 2008). All three classes of boundary conditions, the specified head, specified flux, and the head-dependent flux, were used in this study, as discussed below.

3.9.3.4.1 Model Boundaries

Two types of boundaries were used in the model, set to the Model_Top, i.e., the constant head boundary (CHB) specified using the CHD Package of the specified head condition and the general head boundary (GHB) of the head-dependent flux condition. The western boundary was simulated as the CHB with a boundary head (h) of 31 m, and the eastern and northern boundaries were simulated as the GBH, where h was 35 m. The model boundaries were assigned initial values according to the elevation values of the DEM, and these were eventually calibrated for the IoT-based data.

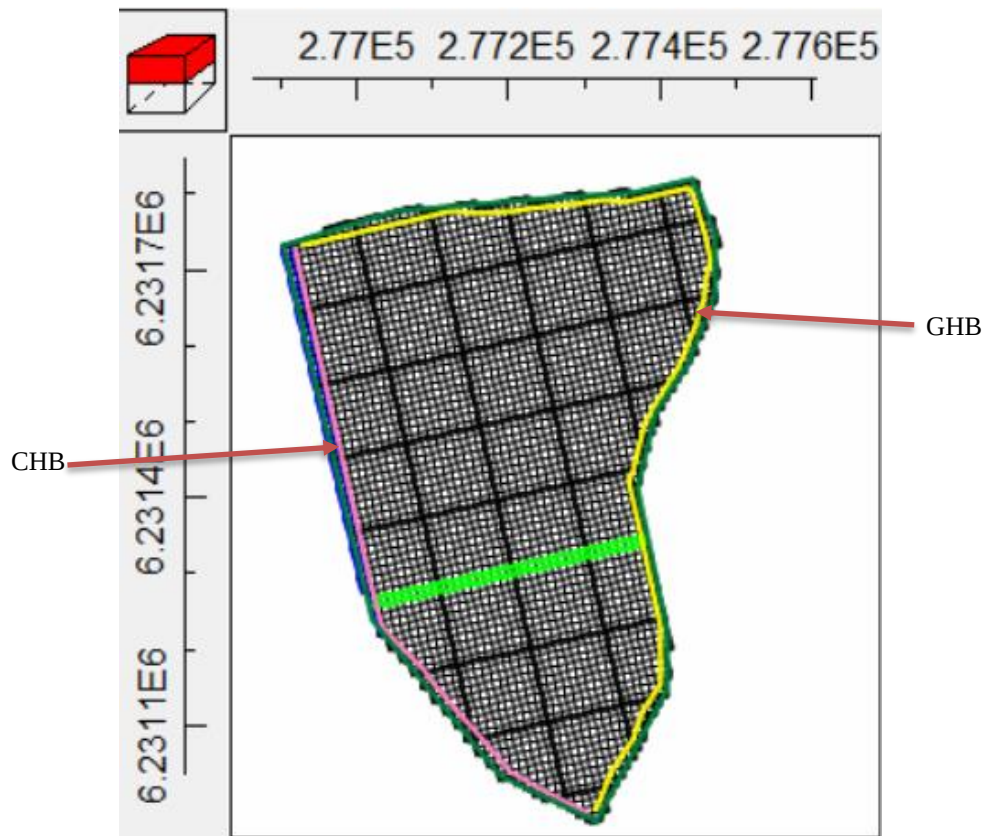


Figure 3-28: Flow Boundary Conditions

3.9.3.4.2 Recharge components

Recharge from precipitation is the primary source of recharge in the study area; thus, it was included in the model. Xu & Beekman (2019) presented the typical results of recharge studies, as shown in **Figure 3-29**. The recharge rate from precipitation of the study area was estimated as 11.3 mm/year using the average annual precipitation of 434 mm calculated in section 3.5.2.1 The estimation was based on a study by Van Wyk *et al.* (2011) funded by the South African Department of Water Affairs that provided results of recharge rates using rainfall data and the Chloride Mass Balance (CMB) method over decades. A recharge rate of 11.3 mm/year (3.6×10^{-10} m/s) was assigned to the model using the recharge package (RCH) of the specified flux.

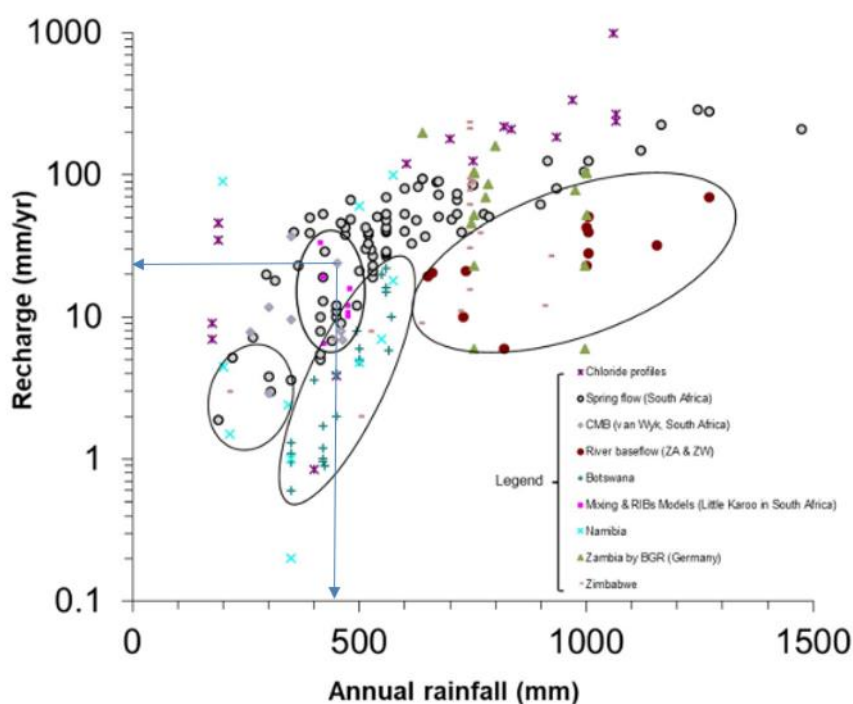


Figure 3-29: Typical Results of Recharge Rates in Southern Africa.

(Van Wyk *et al.*, 2011)

3.9.3.4.3 Evapotranspiration (ET_0)

Evapotranspiration is the outflow from the hydrologic system as a combination of evaporation from open water bodies and soil surfaces and transpiration from the soil by plants (Murray & Tredoux, 1998). Adelana (2010) calculated the daily ET_0 in Cape Town from 2000 to 2009 using the FAO Penman-Monteith equation in **Equation 11**.

The Penman-Monteith equation is as follows:

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$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad \text{Equation 11}$$

where;

- ET_o - reference evapotranspiration [mm day⁻¹],
- R_n - net radiation at the crop surface [MJ m⁻² day⁻¹],
- G - soil heat flux density [MJ m⁻² day⁻¹],
- T - mean daily air temperature at 2 m height [°C],
- u₂ - wind speed at 2 m height [m s⁻¹],
- e_s - saturation vapour pressure [kPa],
- e_a - actual vapour pressure [kPa],
- e_s - e_a - saturation vapour pressure deficit [kPa],
- Δ - slope vapour pressure curve [kPa °C⁻¹],
- Γ - psychrometric constant [kPa °C⁻¹]

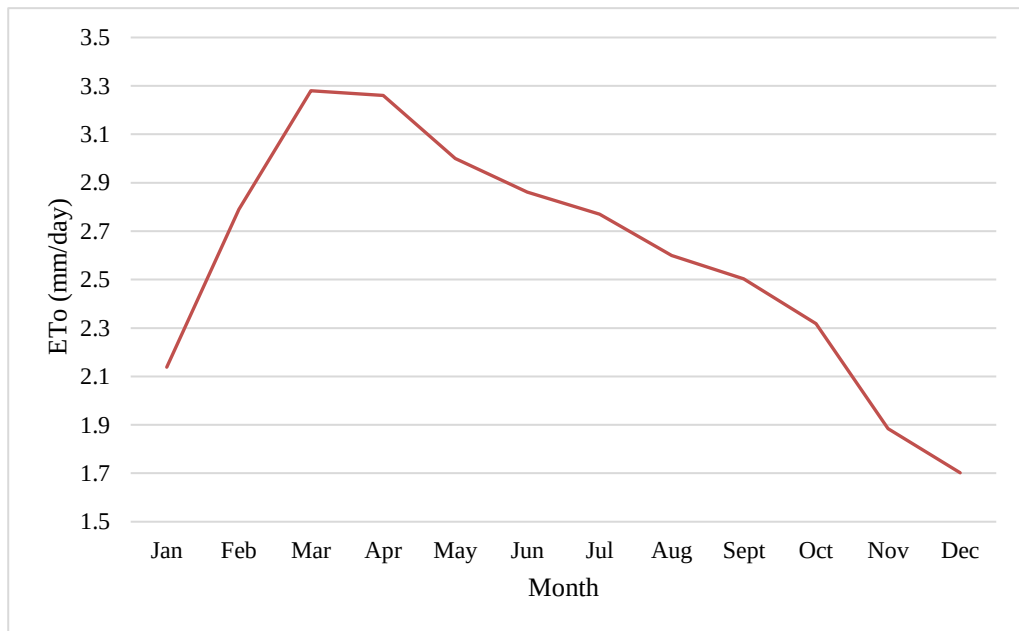


Figure 3-30: Reference Evapotranspiration for Cape Town Airport
(Adelana, 2010)

The maximum daily ET_o value was obtained as 3.28 mm/day (3.8 x 10⁻⁸m/s). This ET_o value was preferred to the pan evapotranspiration ET_o discussed in section 3.5.2.2 as available data was limited due to the vandalism of the weather station. An average ET_o value of 2.59 mm/day (3.0 x 10⁻⁸ m/s) was assigned to the modelled area using the evapotranspiration package (EVT) of the

head-dependent flux condition. The evapotranspiration surface was set to Model_Top, and an evapotranspiration depth of 0.5 m was specified.

3.9.3.4.4 Drainage Components

The drain package (DRN) of the head-dependent flux was used to simulate the amount of stormwater runoff that drains into the ponds (discharge points) to facilitate water infiltration into the subsurface layers. The drainage lines shapefile was imported into the model and assigned to the Model_Top with a conductance per unit length of 0.001.

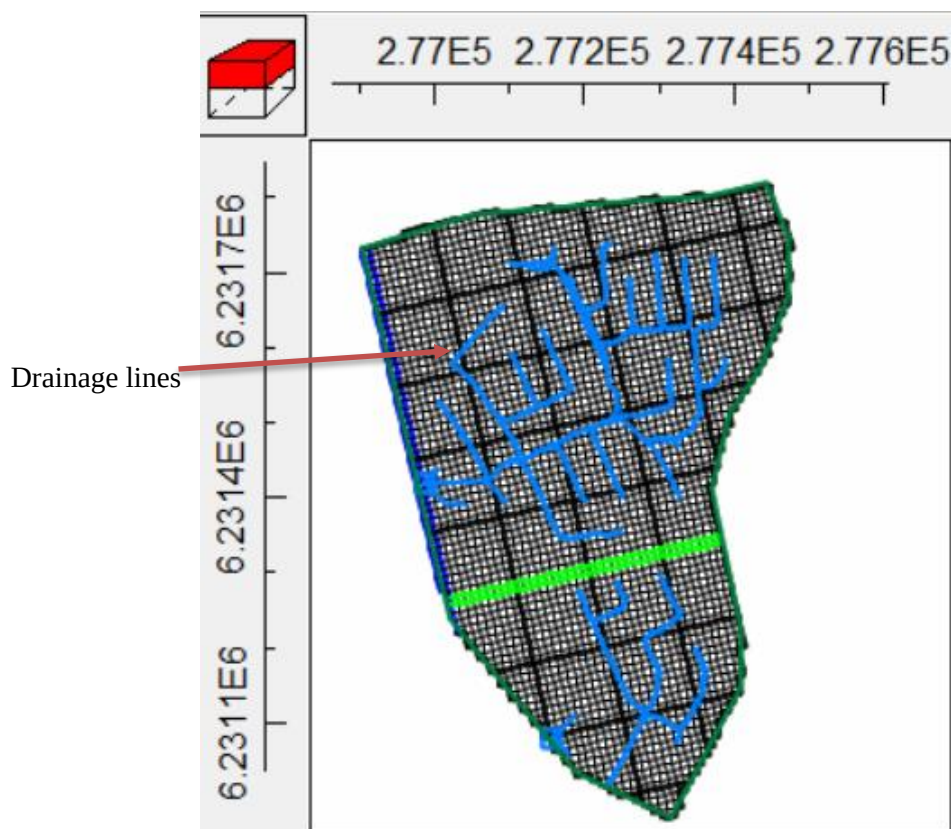


Figure 3-31: Drainage Lines in the Study Area

3.9.4 MODFLOW Stress Periods

A stress period is when all the stresses, for example, boundary conditions and recharge rates, on the system are constant. Two types of stress periods were used to run the MODFLOW model, and these included the steady state and the transient state. Steady state flow occurs when the magnitude and direction at any point in a flow field are constant with time, and transient flow occurs when the magnitude or direction of flow varies with time (Freeze & Cherry, 1979). In this study, the steady state was run with a single time step, starting time of negative one (-1) and

ending time of zero (0). The transient state was run for with a time step of 20 for 140 days, an equivalent of 12096000 seconds.

3.9.5 Model Simulation

The steady and transient state models were run, wherein meticulous attention was given to ensure that a percentage discrepancy of 0.0% was obtained in both cases, following the careful specification of all pertinent input parameters. Nevertheless, it is imperative to recognize that the attained discrepancy of 0.0% does not infer the absence of error in the model as factors like data limitations, simplifications in the model, and inherent variability in natural systems can contribute to the overall uncertainty in the results. Confidence intervals, sensitivity analyses, and other statistical measures are valuable tools used to assess and communicate the uncertainty associated with the model's predictions. Similarly, the reported 0.0% discrepancy may also be a result of rounding decimal places; therefore, should not be misconstrued as a representation of absolute perfection or lack of error in the model.

In this context, the term "discrepancy" refers to the disparity between the computed values of the hydraulic heads or other model parameters and the desired target value, all within the boundaries of the defined tolerance. In cases where the discrepancy is reported as 0.0%, it signifies that the model's solution has met the predefined convergence criteria, attaining a level of agreement with the desired values that falls within the specified tolerance.

3.9.6 Model Calibration

Model calibration is carried out using the trial-and-error method of adjusting the hydrogeological input parameters or using an automated parameter estimation code. It requires the modeller to have vast information on the field condition of the site as it entails changing the model input parameters to represent the field conditions within the acceptable criterion (Khadri & Pande, 2016). In this study, model calibration was carried out using the trial-and-error method.

The recharge rates were adjusted according to the study by Xu & Beekman (2019), which classified the recharge rates in South Africa in the range of 11-54 mm/year. The K_x values of the layers were adjusted within the allowable range of 10 -50 m/d as specified by the CFA hydraulic conductivity shapefile from which the study area was clipped. The evapotranspiration rates were obtained from the average value of the ET_o at the Cape Town Airport from 2000 to 2009. Calculated using the FAO Penman-Monteith equation by Adelana (2010). The aquifer thickness was adjusted with reference to the CFA thickness shapefile that placed the study area in two layers to a depth of 40 m.

The steady state and transient models were calibrated. The transient calibration was carried out using the steady state hydraulic heads as the initial condition to establish the parameters in the steady state model. The models were run to visualize the observed and simulated heads at MON71 Borehole. The Root Mean Square Error (RMSE) method was used to determine the

accuracy of the model calibration using **Equation 12**. An RMSE of 0 represents a perfect relationship between the observed head and simulated head values. However, there is no standard criterion for RMSE to evaluate the quality of the model as it depends on the magnitude and units of the simulated parameters and may range from 0 to infinity (Al-Taliby *et al.*, 2017). In this study, the acceptable RMSE value was considered between 0 and 1; otherwise, the input hydrogeological parameters, like the hydraulic conductivities, were changed accordingly, and the model ran until a suitable value was obtained (Pisinaras *et al.*, 2007).

$$RMSE = \sqrt{\frac{\sum (h_{obs} - h_{sim})^2}{n}} \quad \text{Equation 12}$$

where, h_{obs} is the observed water-level value, h_{sim} is the simulated water level value and n is the number of observation wells.

3.9.7 Sensitivity Analysis

A sensitivity analysis is the first step in assessing the possible range of results derived from the groundwater model by uniformly changing one parameter while keeping the other parameters to the steady state calibrated value. It is used to understand the uncertainty of the calibrated model due to limitations in the estimated aquifer parameters and stresses (Zhou & Li, 2011; Gxokwe & Xu, 2017). During model development, a sensitivity analysis was carried out to determine the effect of various parameters and stresses on the model calibration process. Different values of constant heads, aquifer thickness and hydraulic conductivity were input into the model during successive runs to test the model's sensitivity to the parameters.

Summary of Method

The secondary data collected from previous studies and water resources management agencies of South Africa was assembled to develop a hydrogeological conceptual model of the study area. The conceptual model was then used to develop a numerical groundwater flow model using MODFLOW-NWT code within the ModelMuse software package. The hydrogeological map of the area was imported into the software, and the model domain was selected. The area was divided into grid cells, boundary conditions were set, flow parameters specified, and the model was run. The numerical model was calibrated using the IoT-based groundwater level data from the CCT borehole at Green Dolphin's Pond. A sensitivity analysis was performed, and the model was validated.

4. Groundwater Potential Zone Mapping

This section describes all seven thematic layers; geology, lithology, slope, drainage density, land use/land cover, lineament density and soil in the study area. Weights and ranks were assigned to each map according to its influence on the infiltration of groundwater into the aquifer, and a final groundwater potential map was developed to delineate the best prospective locations of groundwater.

4.1 Factors Influencing Groundwater Occurrence

4.1.1 Geology

Geology plays a vital role in the occurrence and distribution of groundwater within the study area. A geological shapefile of the entire Cape Flats Aquifer was obtained from the City of Cape Town and used to extract the study area catchment. Geologically, the entire area is occupied by only the quaternary deposits, as shown in **Figure 4-1**. It consists mainly of fine to coarse-grained calcareous coastal dune sand and calcrete, which increase the infiltration rate as water moves faster through the large pores of sand.

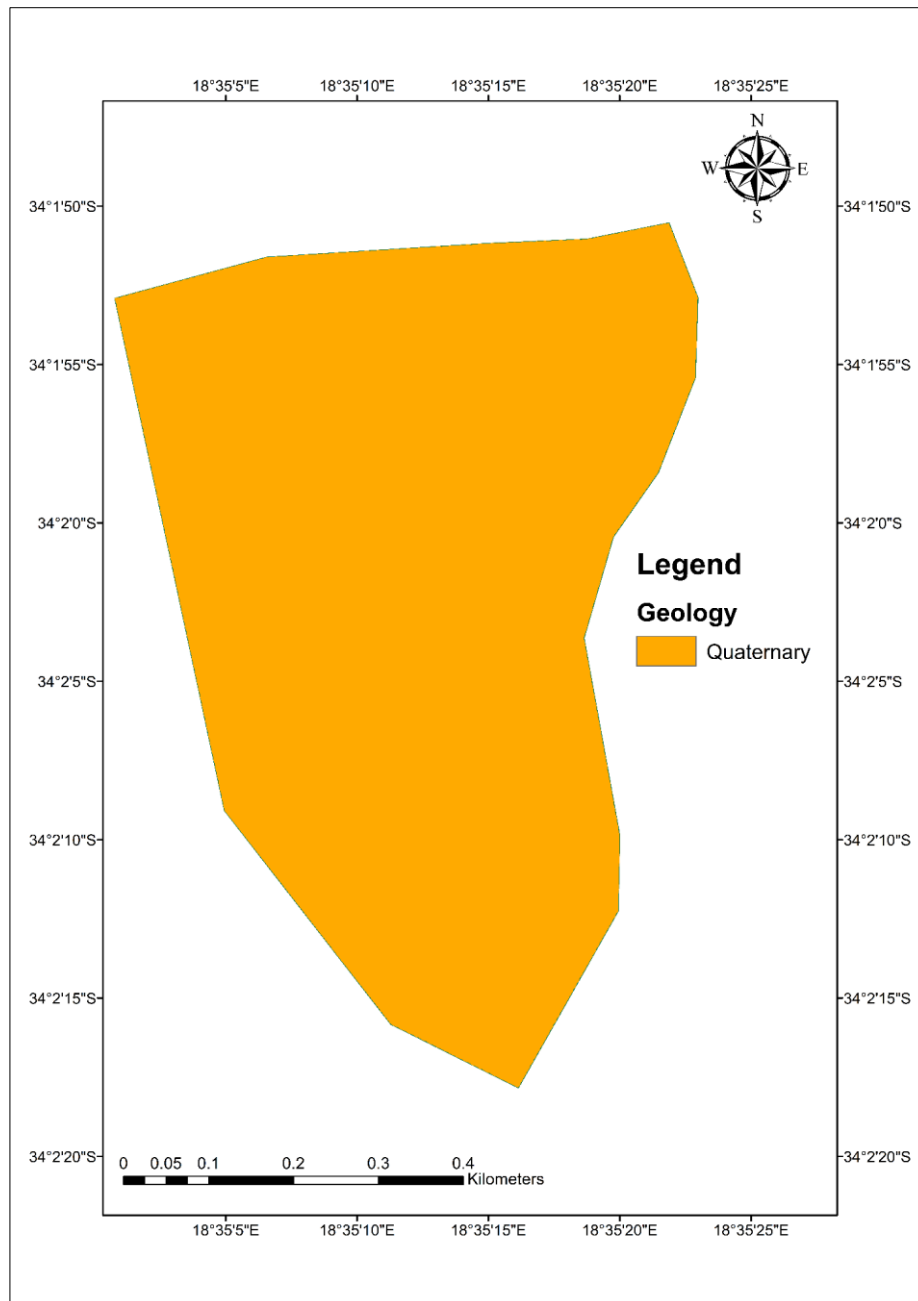


Figure 4-1: Geological Map of the Study Area

4.1.2 Lithology

The Quaternary deposits within the study area consist of two formations: Witzand and Langebaan, as shown in the figure below. The Witzand Formation occupies 0.284 km² of the study area and is easily recognized by the presence of shells shown in **Figure 3-17**, showing the lithology of the area through the CCT MON71 monitoring borehole. The Langebaan Formation occupies 0.031 km² of the entire study area and consists of calcrete and very fine to medium-

calcareous sand that increases the rate of stormwater infiltration into the aquifer. The Lithology map was extracted in ArcGIS from a lithology shapefile of the Cape Flats Aquifer obtained from the City of Cape Town.

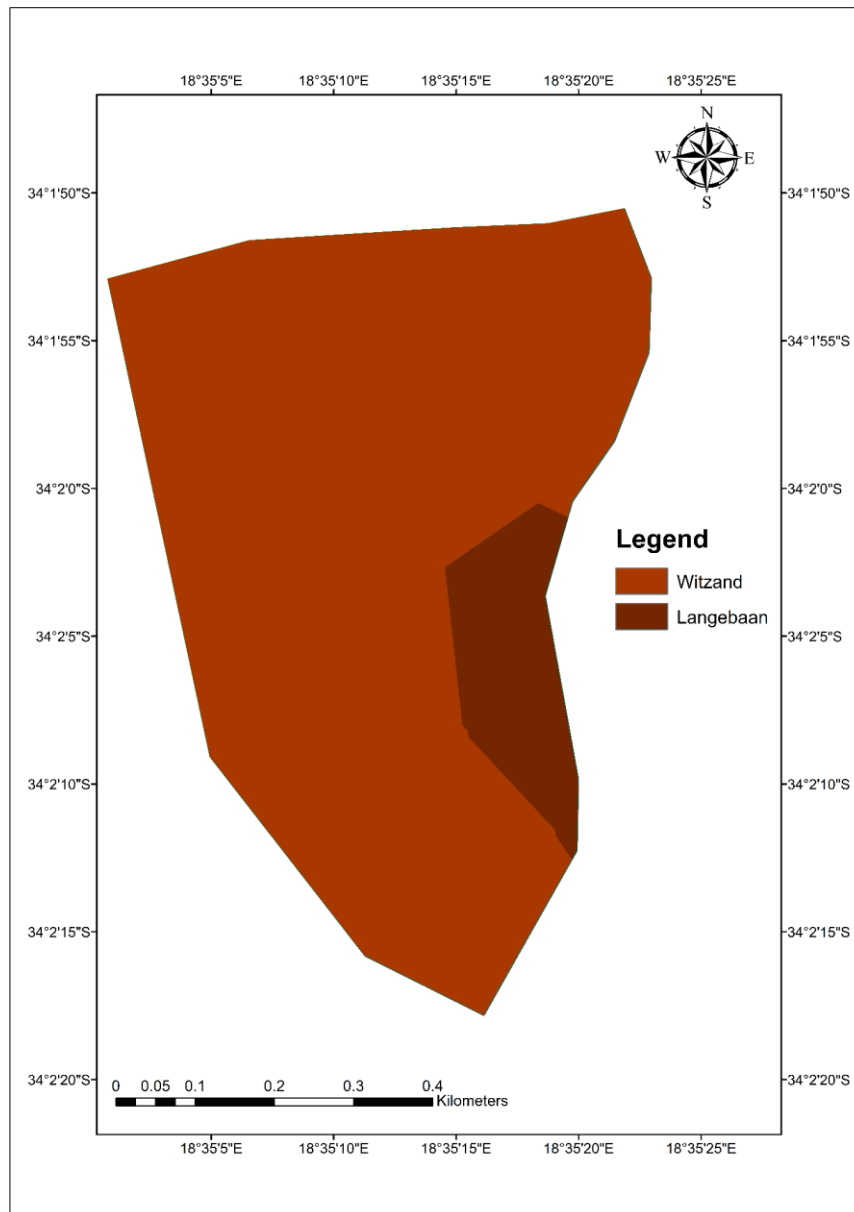


Figure 4-2: Lithology Map of the Study Area

4.1.3 Slope

The slope map in **Figure 4-3** was obtained from an SRTM DEM in ArcGIS. The slope of the area expresses the gradient of the ground, which significantly influences the rate of infiltration and surface runoff. The study area is generally flat as the slope ranged between 0 to 6.14 degrees

(0-10.7%). Flat and gently sloping areas have a high infiltration rate and therefore are capable of more groundwater potential and recharge as the stormwater slowly flows down the slope allowing for infiltration, unlike the steep slopes of greater than 20%.

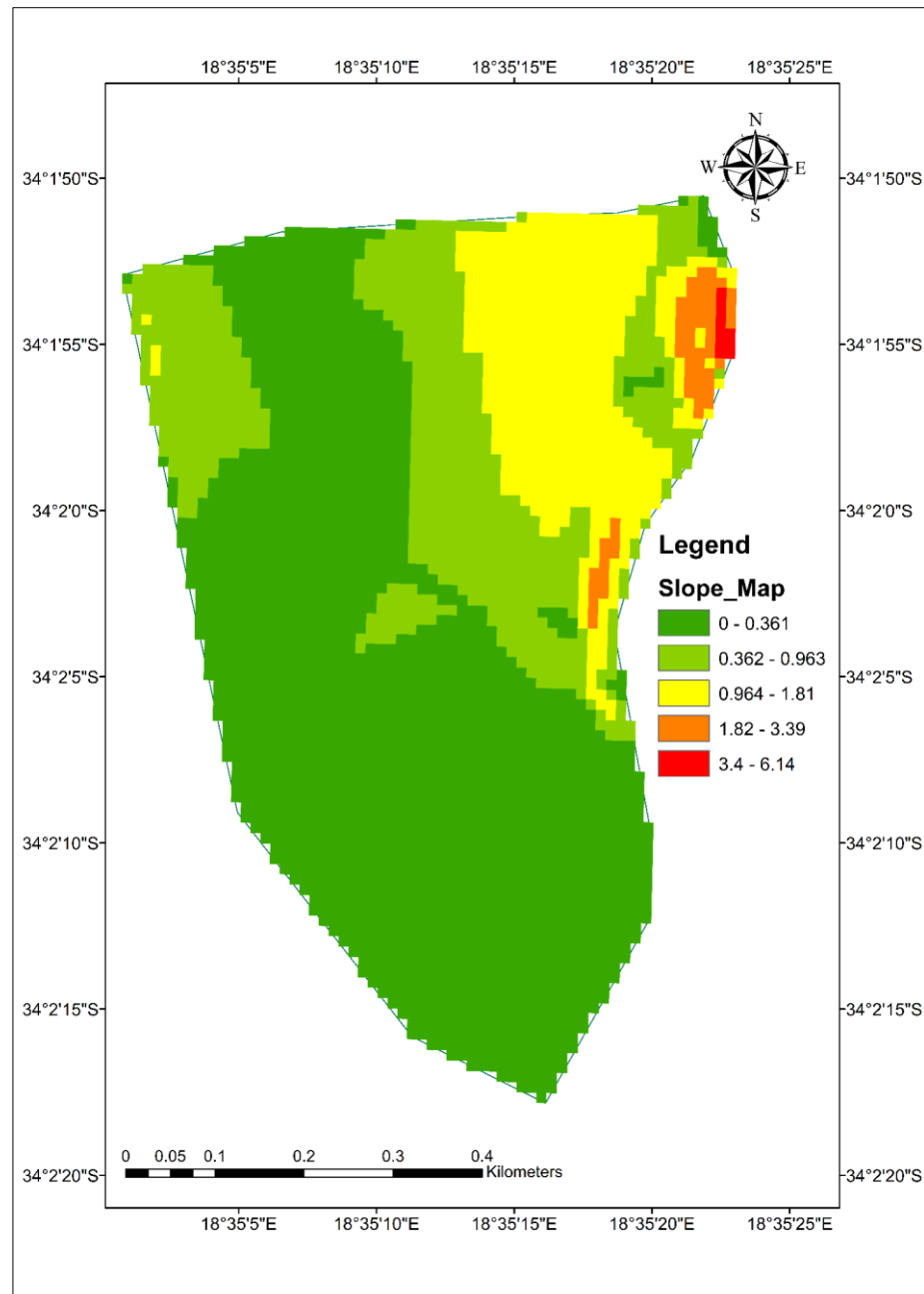


Figure 4-3: Slope Map of the Study Area

4.1.4 Drainage Density

Drainage density measures the sum of the channel lengths per unit area. It is the total length of all the streams/ drainage lines in the catchment basin divided by the total area of the basin. The

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drainage network depends on the lithology of the area and influences the infiltration rate. The lower the drainage density values, the higher the infiltration rates and lower the surface flow velocity, thus the favourable for groundwater potential. **Figure 4-4** shows the drainage density map reclassified into five categories: Very Low ($0-27.52 \text{ km/km}^2$), Low ($27.53-55.04 \text{ km/km}^2$), Moderate ($55.05-82.56 \text{ km/km}^2$), High ($82.57-110.1 \text{ km/km}^2$) and Very High ($110.2-137.6 \text{ km/km}^2$). Lower ranks were assigned to the higher drainage densities in the process of groundwater potential zoning.

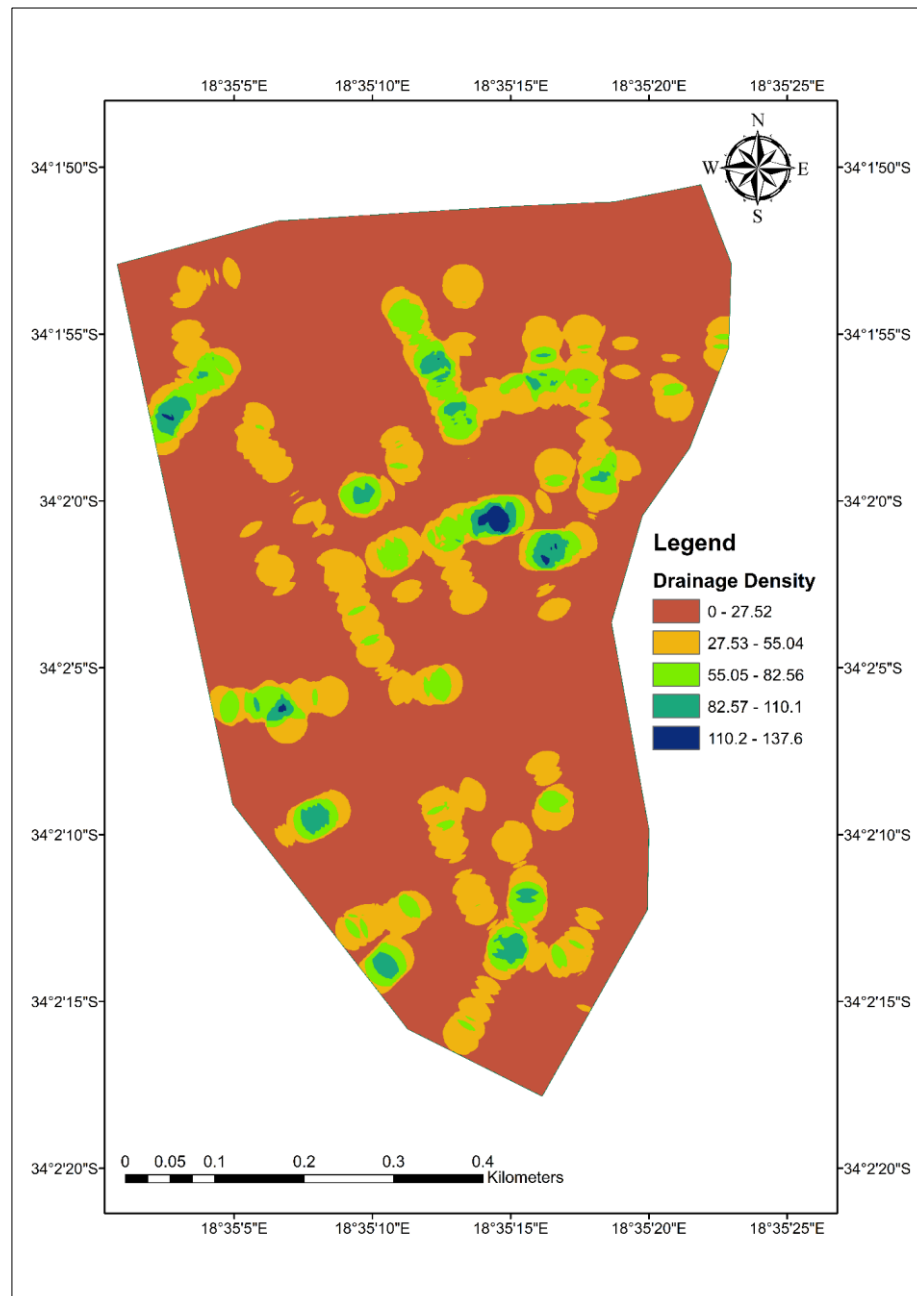


Figure 4-4: Drainage Density Map of the Study Area

4.1.5 Land Use / Land Cover (LULC)

The land use/land cover of an area provides information on the infiltration rate, soil moisture, and surface runoff of an area. **Figure 4-5** shows the LULC distribution of the study area. Using the Image Classification tool in ArcGIS, the different LULC types were delineated using a Landsat image.

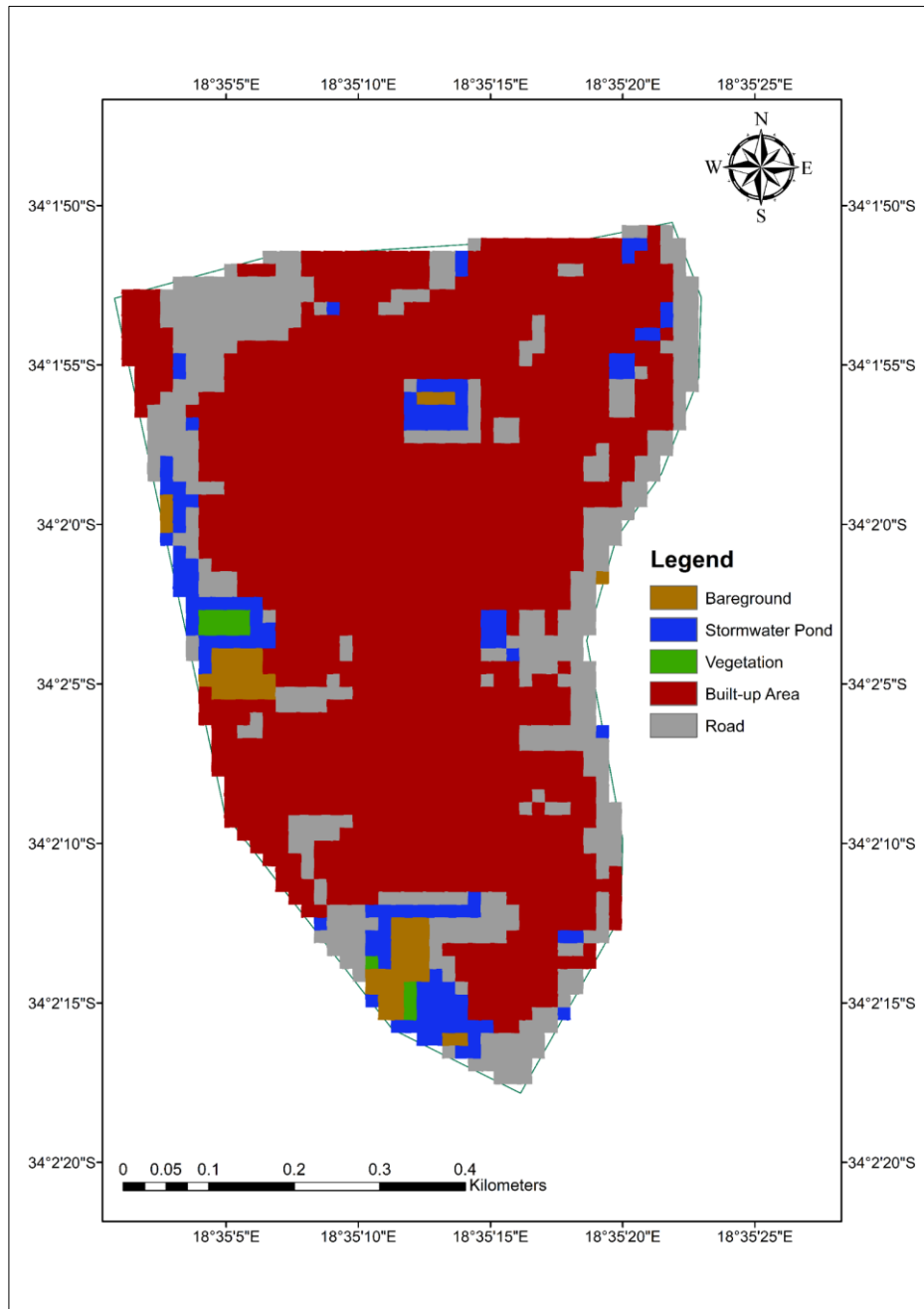


Figure 4-5: Land Use/Land Cover Map of the Study Area

The study area has five major land use types: bare ground, stormwater ponds, vegetation, built-up area, and roads. Out of which, the built-up area dominates over the other LULC types, given that the area is residential. The table below shows the area covered by the different LULC types.

Table 4-1: Area Covered by LULC Types

Land Use	Count	Area (km ²)	Percentage (%)
Bare ground	52	0.008	2.545
Stormwater Ponds	122	0.019	5.972
Vegetation	12	0.002	0.587
Built-up area	1443	0.222	70.631
Roads	414	0.064	20.264
Total	2043	0.315	100

4.1.6 Lineament Density

Lineaments are linear geological surface features that reflect a given area's tectonic history and groundwater potential. In this study, the lineaments were extracted and analysed in ArcGIS. A comparative analysis was performed on six (6) shaded relief maps extracted from various azimuth angles, altitudes, and a constant z-factor of 1. Firstly, the DEM was filled using the 'Fill' tool, and after that, the six maps were generated using the 'Hillshade' tool in ArcGIS using the different angles in **Table 4-2**.

Table 4-2: Lineament Hillshade Maps Properties

No.	Azimuth angles (°)	Altitude
1	315	45
2	270	45
3	200	50
4	90	60
5	350	45
6	250	70

All the linear geological features, like fractures in the hillshade maps, were digitalized by creating polylines in ArcGIS. The final lineament map of the study area was prepared by combining all the azimuth angle lineament outputs in one shapefile. The total number of lineaments found in the study area was 32, with a length of 1.937 km. The stormwater pond areas have high lineament densities and high groundwater potential as the fractures influence infiltration into the subsurface layers.

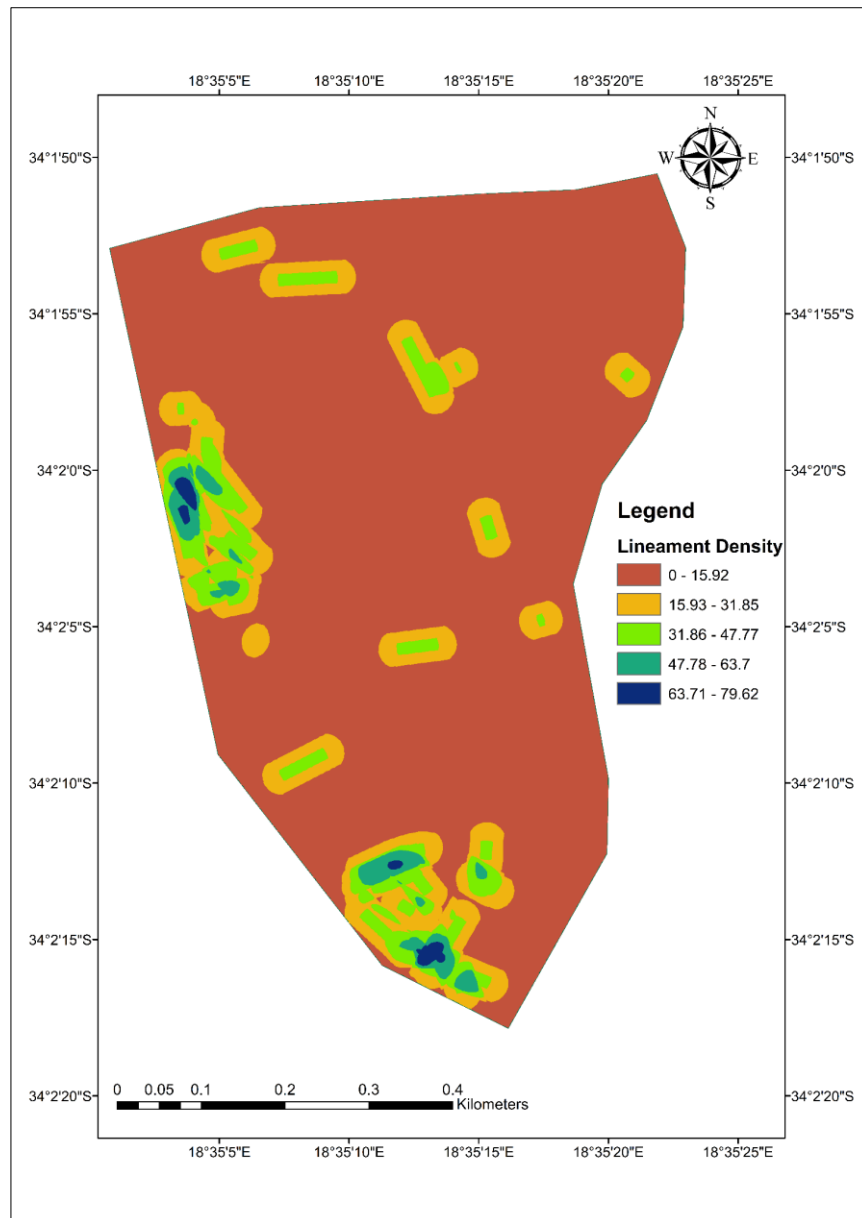


Figure 4-6: Lineament Density Map of the Study Area

4.1.7 Soil

The porosity and permeability of the soil are crucial in groundwater flow. Therefore, the soil type of an area is considered one of the prime factors that influence groundwater recharge as it determines the rate of infiltration into the subsurface layers. The soil map was extracted in ArcGIS from a soil shapefile of the Cape Flats Aquifer that was obtained from the City of Cape Town, and it was revealed that the study area is within the subdivision of the Sandveld group of soils. The area has sandy soils in the upper layers of the soil and an underlying bedrock of the

Malmesbury group shale, which are considered very good according to their influence on groundwater occurrence.

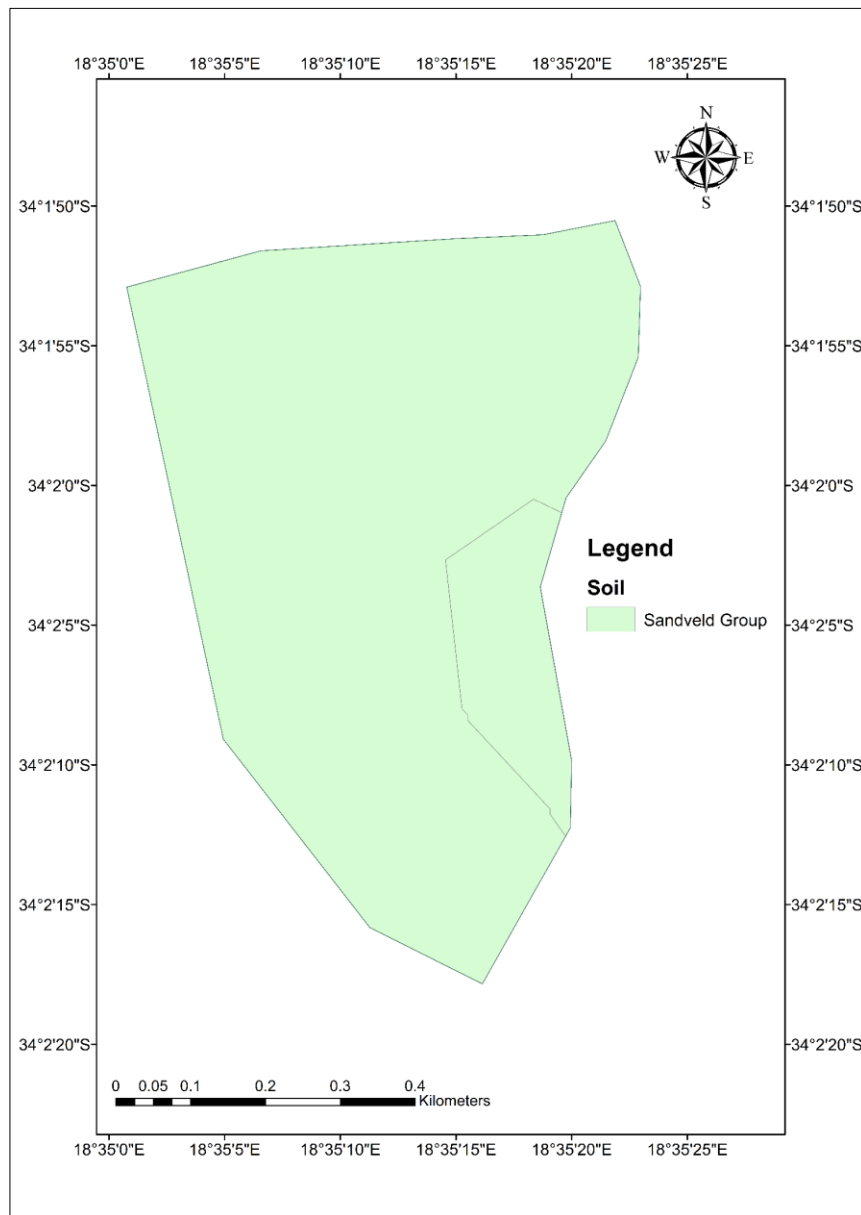


Figure 4-7: Soil Map of the Study Area

4.2 Delineation of Groundwater Potential Zones

The final groundwater potential zone map was prepared by overlaying the cumulative weights of all seven thematic layers; geology, lithology, slope, drainage density, LULC, lineament density and soil maps using the weighted overlay tool in ArcGIS. The highest weight was assigned to geology in the pairwise comparison results indicating that it has the most significant influence

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on groundwater potential in the study area compared to the other factors. A CR of 0 was obtained, indicating a perfect level of consistency in the comparison phase. The final groundwater potential map from the AHP Model was then obtained using the natural breaks classification method in ArcGIS software into two classes: Good (89%) and Excellent (10.6%). **Figure 4-8** shows the groundwater potential zones map classified into two classes.

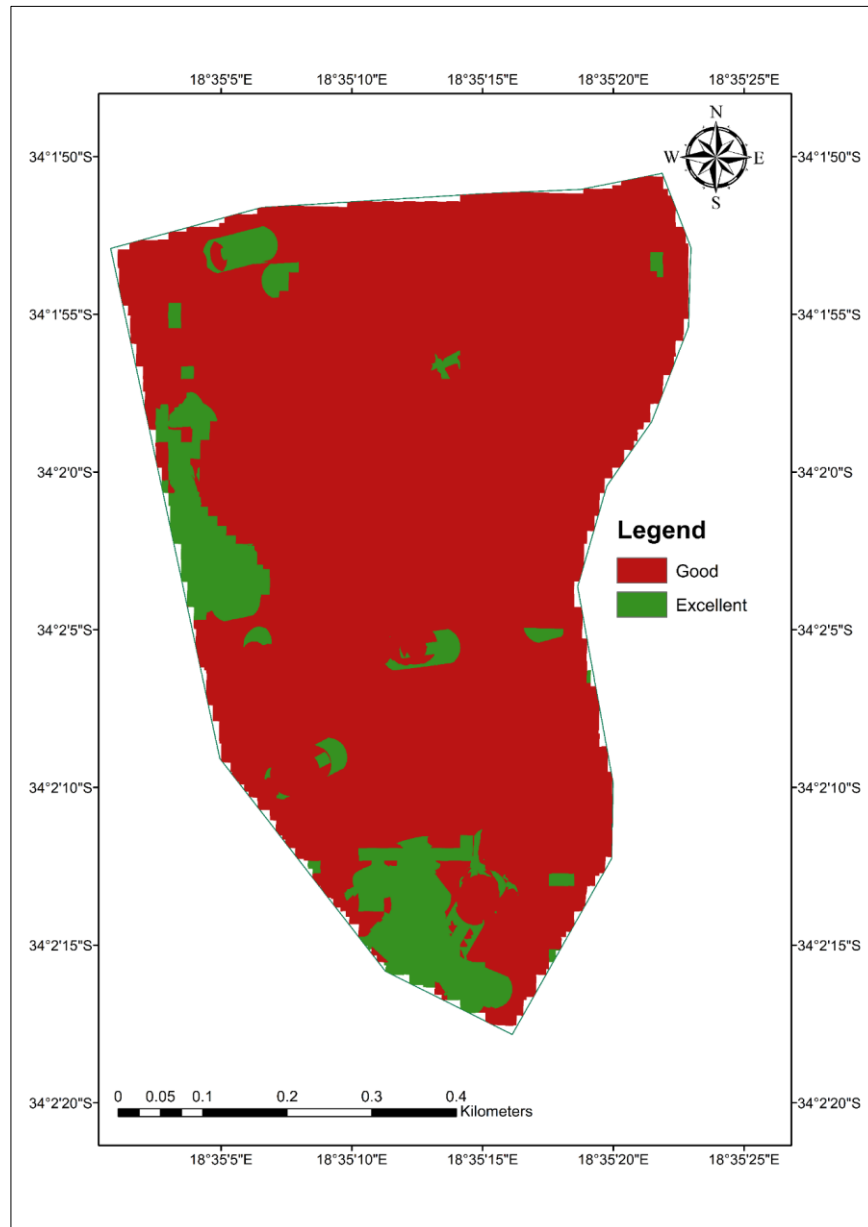


Figure 4-8: Groundwater Potential Zones Map of the Study Area

4.3 Groundwater Potential Zone Validation

It is crucial to validate the results obtained to identify their physical relevance. In this study, the groundwater potential zones map was validated using a map showing the distribution of groundwater registration and aquifers in the CCT from 2004 to 2012 obtained from Mauck (2017). **Figure 4-9** shows that the catchment of the stormwater ponds is in the high aquifer productivity area of CCT; thus, the area has a high groundwater potential, as clearly illustrated in the final groundwater potential zone map in **Figure 4-8**. Aquifer productivity is the ability of an aquifer to sustain various groundwater flows and abstraction from a borehole.

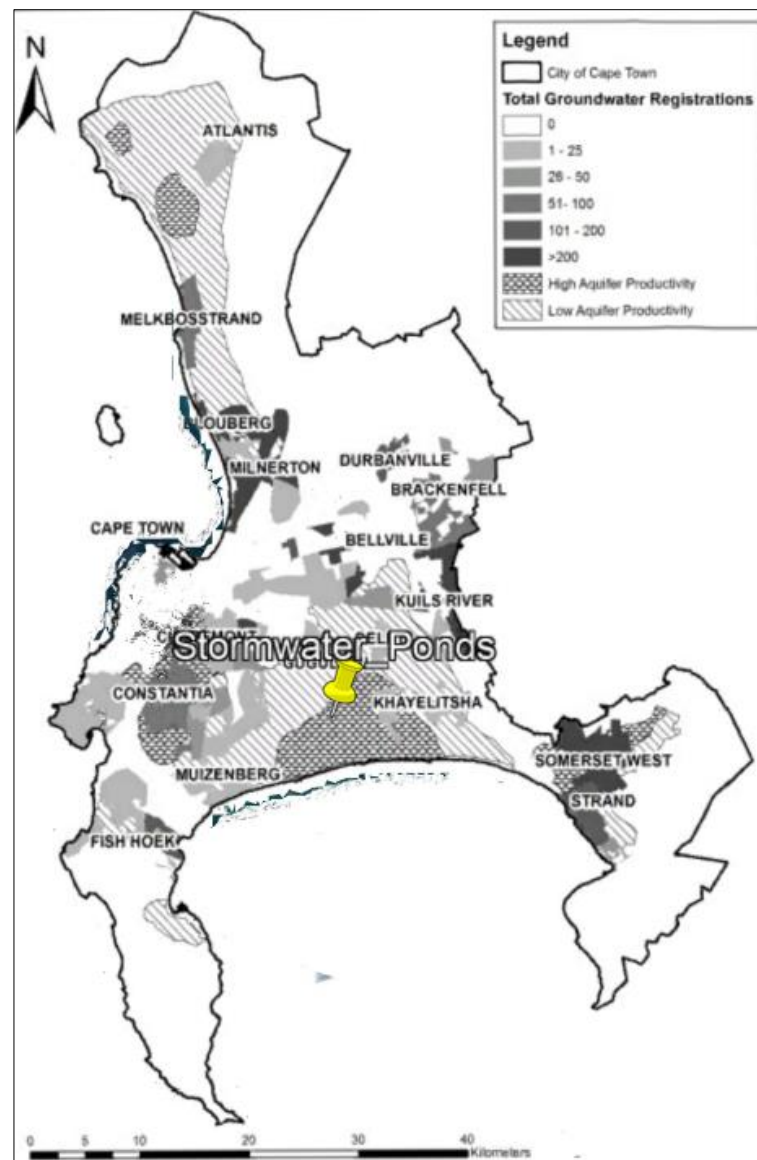


Figure 4-9: The Distribution of Groundwater Registration and Aquifers in the CCT from 2004 to 2012

(Mauck, 2017)

Table 4-3 shows the percentage of the study area that each groundwater potential zone occupies. The more significant part of the study area is in the ‘good zone’ and occupies 0.282 km², with a percentage area of 89.4% of the total area. The remaining 10.6% falls under the ‘excellent zone’ covering an area of 0.033 km² of the entire study area, of which stormwater ponds cover 0.019 km².

Table 4-3: Groundwater Potential Zones Distribution based on AHP Model

No.	Potential Zone	Count	Area (km ²)	Percentage Area (%)
4	Good	1108008	0.282	89.4
5	Excellent	131643	0.033	10.6
Total		1239651	0.315	100

Summary of Chapter

Seven factors influencing groundwater occurrence in the study area were described and selected as the thematic layers. Weights and ranks were assigned to the maps of each layer according to their influence on groundwater infiltration into the aquifer. The groundwater potential zones were delineated using the weighted overlay tool in ArcGIS to obtain a final groundwater potential map classified into two classes, which was then validated.

5. Groundwater Levels Data Outputs of the IoT System

This section represents the analysis and visualization of the groundwater level data collected for almost five months using the IoT system. The groundwater level data was initially collected at a resolution of 15 minutes for the first month. The resolution was later changed to 24 hours (daily) for the rest of the data collection period as the groundwater levels did not change much at a sub-daily time step.

5.1 Groundwater Level Data on the ThingSpeak Channel

The groundwater level data was displayed as graphs on the ThingSpeak channel in real-time and was accessible for further analysis in CSV form. **Figure 5-1** shows the time series of all the water level data collected from 21/07/2022 to 5/12/2022 as displayed on the ThingSpeak website.

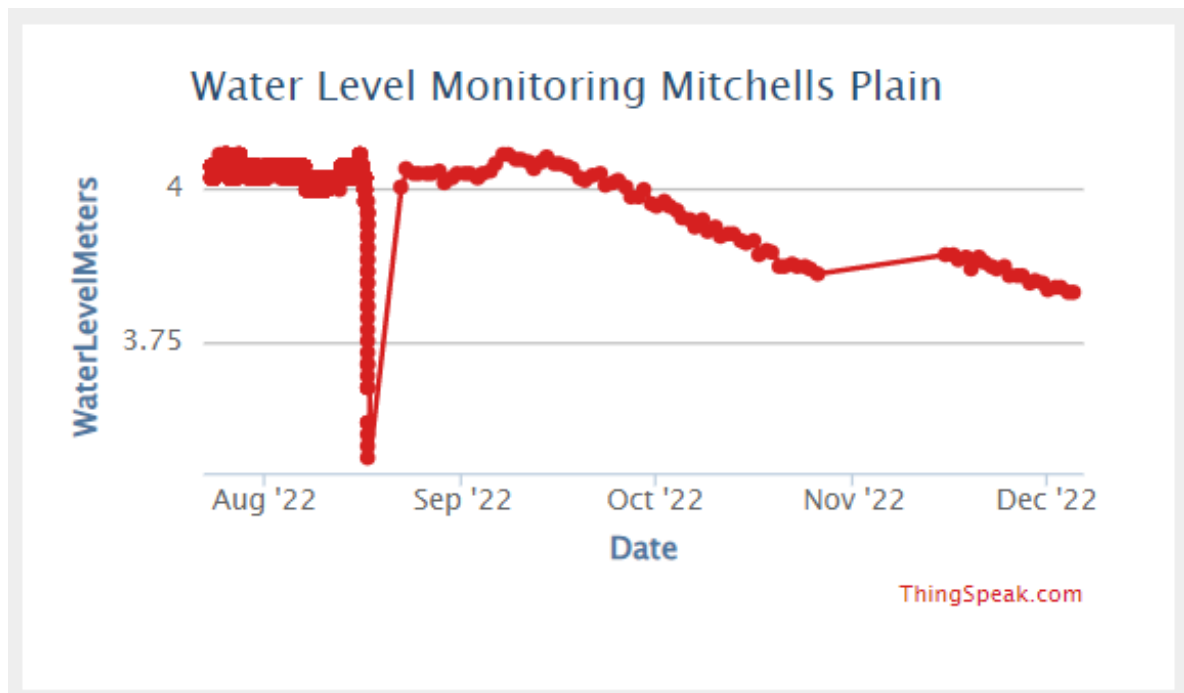


Figure 5-1: Water Levels in Meters (21/07/2022 to 5/12/2022)

A sharp decrease in the water level data was observed from 12/08/2022 to 16/08/2022, after which no data entries were recorded on the ThingSpeak channel from 17/08/2022 to 21/08/2022. The resolution of the data was changed from 15 minutes to 24 hours to receive one water level record on the cloud per day. **Figure 5-2** shows the time series of the daily groundwater levels monitored from 22/08/2022 to 5/12/2022.



Figure 5-2: Water Levels in Meters (22/08/2022 to 5/12/2022)

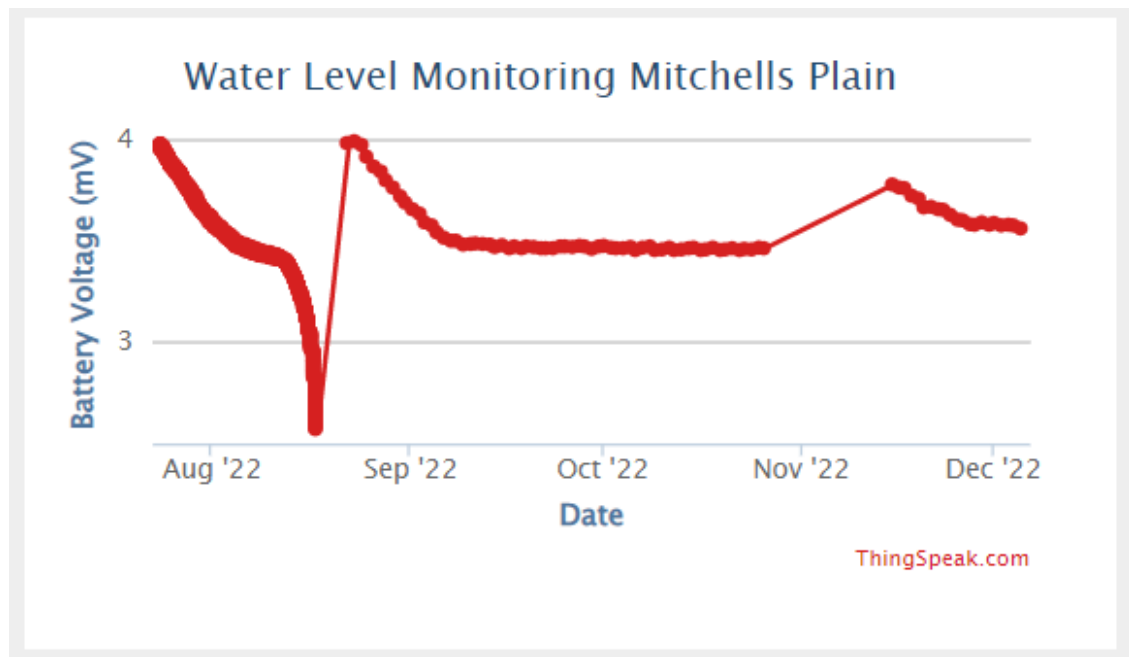
5.2 Battery Voltage of the Water Level Sensor

The battery voltage was 4.06mV on the installation day, and it drastically reduced to 2.57mV within a month because of the amount of data being recorded daily. A total of 2584 data entries were made in the first 28 days of data collection as readings were taken at intervals of 15 minutes. An average of 96 data entries were sent to the cloud, which caused the battery voltage to drop below the required 3.5 mV, and switch off, cutting off the communication between the sensor and gateway on 16/08/2022.

A new battery was installed on 22/08/2022 with an initial voltage of 3.98 mV and data was collected at a resolution of 24 hours. This explains the first sharp decrease/ jump in the groundwater level data from 12/08/2022 to 22/08/2022 as presented in **Figure 5-1**. Thirty-six (36) data entries were recorded before the battery ran flat again at a voltage of 3.46 mV on 26/10/2022. A new battery was installed on 15/11/2022 for continuous data collected, indicated by the sharp rise in battery voltage from 3.46 mV on 26/10/2022 to 3.78 mV. This is shown by the noticeable jump in the groundwater data recorded from 26/10/2022 to 15/11/2022, when the battery was replaced as illustrated in **Figure 5-1**. Therefore, the more the interval resolution of collecting data, the less the number of data entries sent to the cloud and the longer the sensor's battery life, as shown in **Table 5-1**. **Figure 5-3** shows the variation in the battery voltage over the data collection period.

Table 5-1: Effect of Data Resolution on the Battery Life of the Sensor

Start Date	End Date	Resolution (hour)	Number of Data Entries	Number of Days	Start Battery Voltage (mV)	End Battery Voltage (mV)	Variation in Battery Voltage
21/07/2022	16/08/2022	0.25	2584	28	4.06	2.57	1.49
22/08/2022	26/10/2022	24	36	36	3.98	3.46	0.52

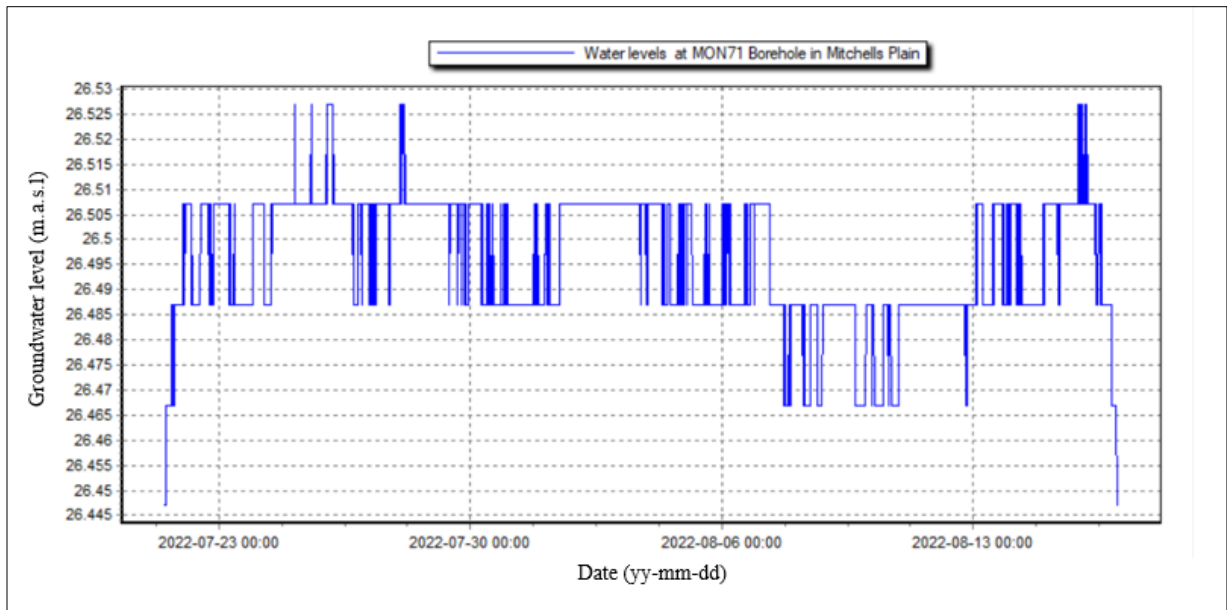
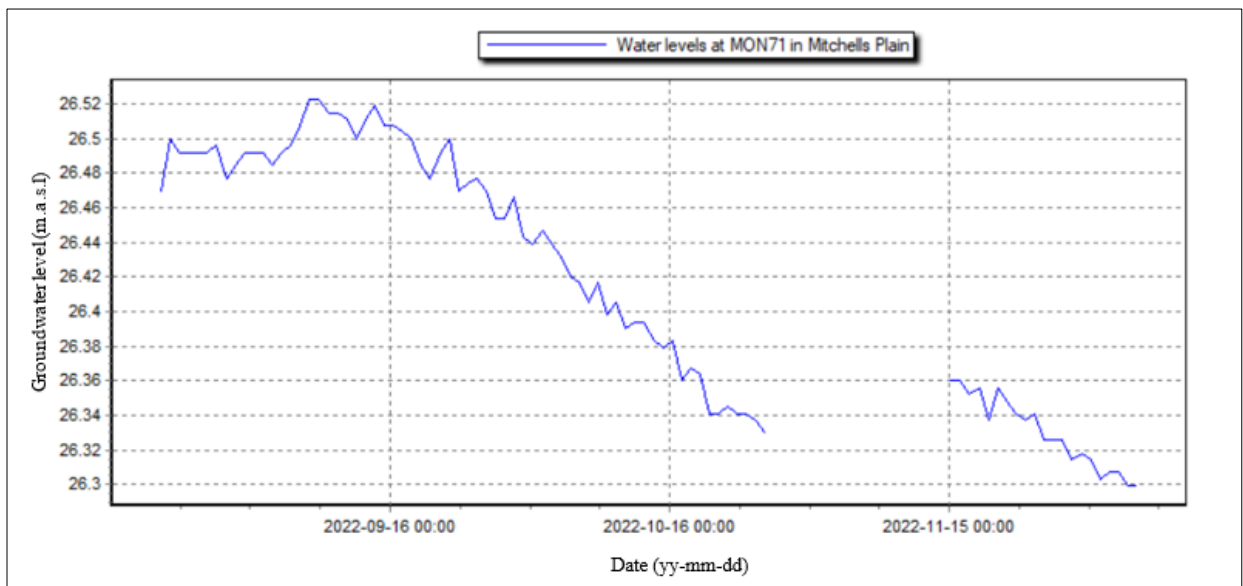
**Figure 5-3: Battery Voltage**

5.3 Collected IoT-based Groundwater Level Data

Hydrognomon software is an application used in analysing and processing hydrological data in the form of time series. The CSV file containing all the water level data collected was exported from the ThingSpeak channel into the Microsoft Excel software. All the water level depths were converted into groundwater levels in meters above sea level using the information in **Table 3-15** in section 3.8. The converted data was imported into hydrognomon software to produce time series analyses of the groundwater levels in the study area, as illustrated in **Figure 5-4** and **Figure 5-5**. The average water levels during periods 1, 2 and 3 were 26.49 m.a.s.l, 26.45 m.a.s.l and 26.32 m.a.s.l, respectively. The groundwater level observation confirmed a slight water level variation in the study area of 0.08, 0.19 and 0.06, as shown in **Table 5-2**.

Table 5-2: Summary of the IoT-based Groundwater Levels

Period	Period (Dates)	Maximum Water level (m.a.s.l)	Minimum Water level (m.a.s.l)	Variation
1	21/07/2022 to 16/08/2022.	26.53	26.45	0.08
2	22/08/2022 to 26/10/2022	26.52	26.33	0.19
3	15/11/2022 to 05/12/2022	26.36	26.30	0.06

**Figure 5-4: Groundwater Levels in m.a.s.l (21/07/2022 to 16/08/2022)****Figure 5-5: Groundwater Levels in m.a.s.l (22/08/2022 to 05/12/2022)**

5.3.1 Effect of Climate Seasonality on Groundwater Level

Groundwater levels in an aquifer are not static, as climate seasonality greatly influences groundwater. South Africa experiences four seasons: spring, summer, autumn and winter, that influence the groundwater level fluctuations due changes in rainfall **Table 3-3** in section 3.5.2.1 shows the variation of temperature and rainfall throughout the year in Cape Town obtained using data from 2002 to 2021.

High water levels were experienced during the winter months of July and August, characterised by the lowest maximum temperature and highest mean monthly rainfall throughout the year. Lower water levels were recorded during spring and summer, as indicated by the decreasing water level from September to December due to the high temperature and low mean monthly rainfall. Average water levels recorded per day were calculated from the 15-minute resolution data recorded from 21/07/2022 to 16/08/2022 to obtain a uniform 24-hour resolution dataset for the entire data collection period, and the time series was plotted using the hydrognomon software. **Figure 5-6** shows the time series of the collected IoT-based groundwater levels from July to December 2022 with missing data due to low battery indicated by no records. Detailed groundwater level data is included in **Appendix 5**.

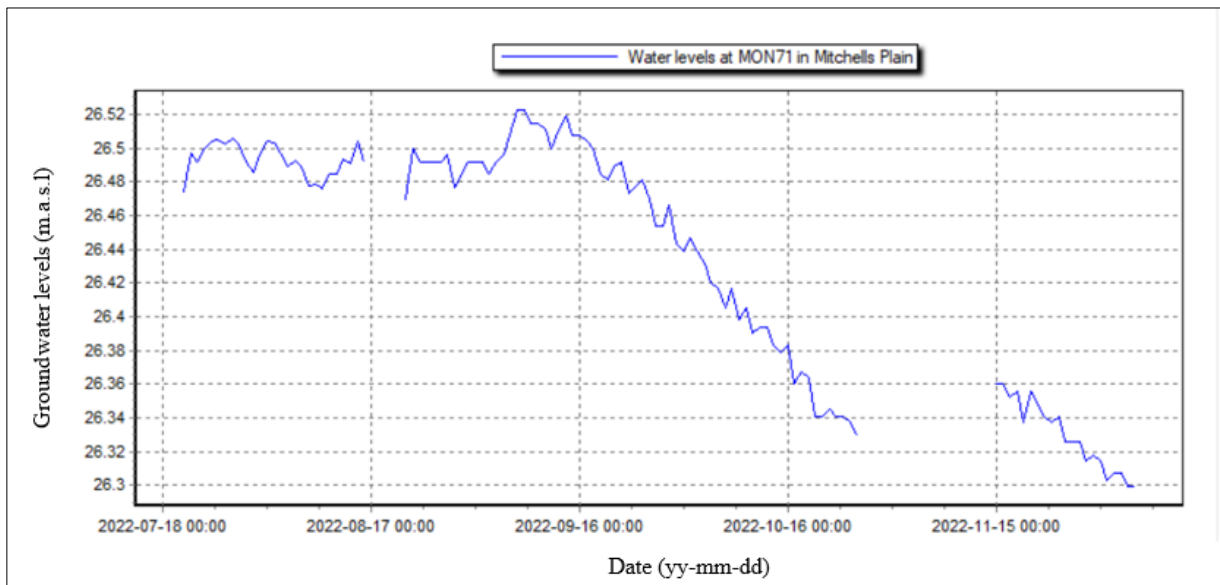


Figure 5-6: Groundwater Level Time series in the Study Area (m.a.s.l)

5.3.2 Validation of the IoT-based Groundwater Level Data

Dipped groundwater level data recorded at the MON71 borehole in August, September and October 2022 was obtained and compared with the IoT-based groundwater levels, as shown in **Figure 5-7**. There is a slight acceptable difference of less than 0.1 m for each comparison, as shown in **Table 5-3**.

Therefore, IoT technologies are feasible in collecting and analysing of large amounts of groundwater level data while maintaining the desired accuracy levels, which solves the problem of insufficient hydrogeological data in South Africa. Therefore, it is advisable to employ IoT-based systems to easily collect high temporal hydrogeological data that can be used in developing groundwater models for sustainable groundwater management.

Table 5-3: Dipped and IoT-based Groundwater Level Comparison

Date	Manual (Dipped) Groundwater level (m.a.s.l)	IoT-based Groundwater level (m.a.s.l)	Difference (m)
2/8/2022	26.55	26.51	0.04
21/9/2022	26.57	26.49	0.08
26/10/2022	26.41	26.33	0.08

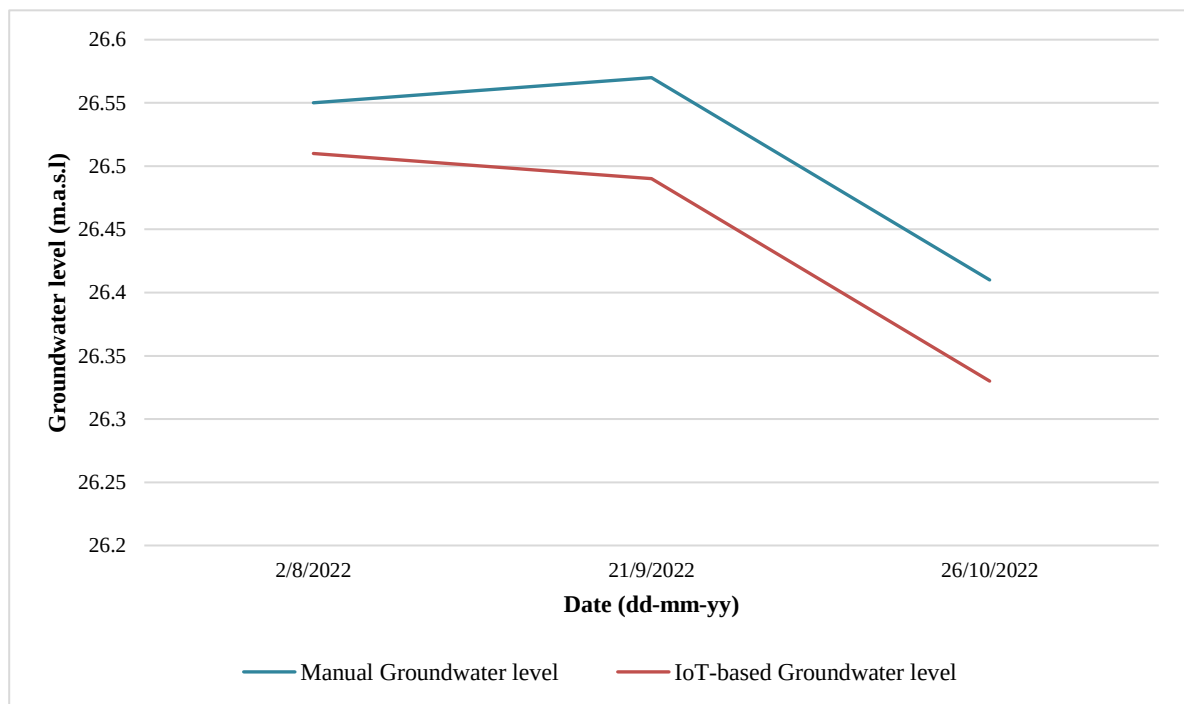


Figure 5-7: Comparison between Dipped and IoT-based Groundwater Levels

Summary of Chapter

The IoT-based data recorded on the ThingSpeak channel over the data collection period was processed and analysed. The effect of the different climatic seasons on the groundwater levels was discussed, and the IoT-based data was validated using the dipped groundwater level data recorded at the MON71 borehole.

6. Effect of MAR on Groundwater levels

6.1 Groundwater Flow Modelling using MODFLOW Software

A numerical model was developed using MODFLOW NWT with ModelMuse 4 as the graphical and visual user interface. In the calibration process, the estimated hydraulic properties of the aquifer were adjusted after each simulation in an attempt to match the observed data. The calibrated model was used to predict the changes in groundwater levels in the study area in response to stresses. The consistency of the GIS data in chapter 4 was maintained throughout the modelling process to verify the potential sites for MAR. The model was divided into two layers with varying thicknesses according to the lithology of the study area. The model was run with estimated boundary conditions and initial conditions, and groundwater level from the MON71 monitoring well was adopted to calibrate the model. This chapter includes all the results obtained from the numerical groundwater flow development, simulation, calibration and validation of both the steady state and transient state models.

6.1.1 Steady State Model

6.1.1.1 Uncalibrated Steady State Model

The steady state model was run with a single time step from a starting and ending time of -1 to 0, respectively, with an acceptable percent discrepancy of 0.0%. **Table 6-1** illustrates the water budget of the study area before calibration. The table shows that the significant inflow contributors to the water budget are the constant head, head-dependent bounds, and recharge, while the constant head, evapotranspiration and drainage in the area contribute to the outflow of the study domain.

Table 6-1: Water budget based on Uncalibrated Steady State Model

Inflow (m ³ /s)	Inflow (m ³ /s)	Outflow (m ³ /s)
Storage	0.0000	0.0000
Constant head	6.98E-02	6.31E-02
Drains	0.0000	0.4573
ET	0.0000	1.11E-02
Head Dep Bounds	0.4618	0.0000
Recharge	1.09E-04	0.0000
TOTAL	0.5317	0.5316
IN-OUT		1.27E-04
Percent Discrepancy (%)		0.0

The observed and the simulated heads at the MON71 borehole were compared and checked using the Root Mean Square Error (RMSE) method. The simulated head was higher than the observed head, giving a negative residual value. The observed head was 26.49 m, and the simulated head was obtained as 30.99 m with an error of 4.50. The error was higher than the acceptable error of less than 1; therefore, the steady state model was calibrated.

6.1.1.2 Steady State Calibration

The steady state model was calibrated to achieve a simulated head close to the field-measured head through the trial-and-error method where input hydrogeological parameters like hydraulic conductivities, recharge, aquifer thickness and boundary conditions were adjusted within the reasonable range. The steady state calibration considered the average of the IoT-based groundwater level data recorded in September as the observed head. **Table 6-2** shows the initial and adjusted values used during calibration.

Table 6-2: Model Input Parameters during Calibration

Parameters	Units	Initial Values	Calibrated Values
Recharge	mm/year	11.3	53.4
Layer 1 (K_x)	m/d	10	17.3
Layer 2 (K_x)	m/d	50	36.3
Evapotranspiration rate	mm/day	3.28	2.59
Aquifer Thickness	m	45	40

The model was run to obtain the results in **Table 6-3** with a percent discrepancy of 0.00%. The results showed a good relationship between the simulated and observed head at the MON71 borehole of 26.49 m and 27.14 m, respectively, with an RMSE value of 0.65. The simulated head was higher than the observed head, thus confirmation that the Green Dolphins Pond is highly suitable for MAR, as shown by the final map of the groundwater potential zones in section 4.2.

Table 6-3: Water-budget based on Calibrated Steady State Model

Inflow (m ³ /s)	Inflow (m ³ /s)	Outflow (m ³ /s)
Storage	0.0000	0.0000
Constant head	1.13E-01	8.58E-02
Well	0.0000	3.20E-02
Drains	0.0000	0.4980
ET	0.0000	8.95E-03
Head Dep Bounds	0.5113	0.0000
Recharge	5.1713E-04	0.0000
TOTAL	0.6247	0.6247
IN-OUT		7.53E-06
Percent Discrepancy (%)		0.0

6.1.1.3 Steady State Hydraulic Heads

The hydraulic heads were exported from MODFLOW Software as a colour grid shapefile and added into ArcGIS Software as a layer for further analysis and representation of the results. The shapefile was assigned a coordinate system in ArcGIS. The hydraulic head values from MAR for the convertible layers 1 and 2 were classified into five (5) classes. The higher hydraulic head values in Layer 1 than in Layer 2 were attributed to the lower hydraulic conductivity of the layer. **Figure 6-1** shows that the simulated heads for Layer 1 range between 29.32 m and 35 m. The higher heads were located along the northern and eastern boundaries of the study area with high elevations which the drainage lines start from and flow towards the low-elevation areas that comprise the stormwater ponds.

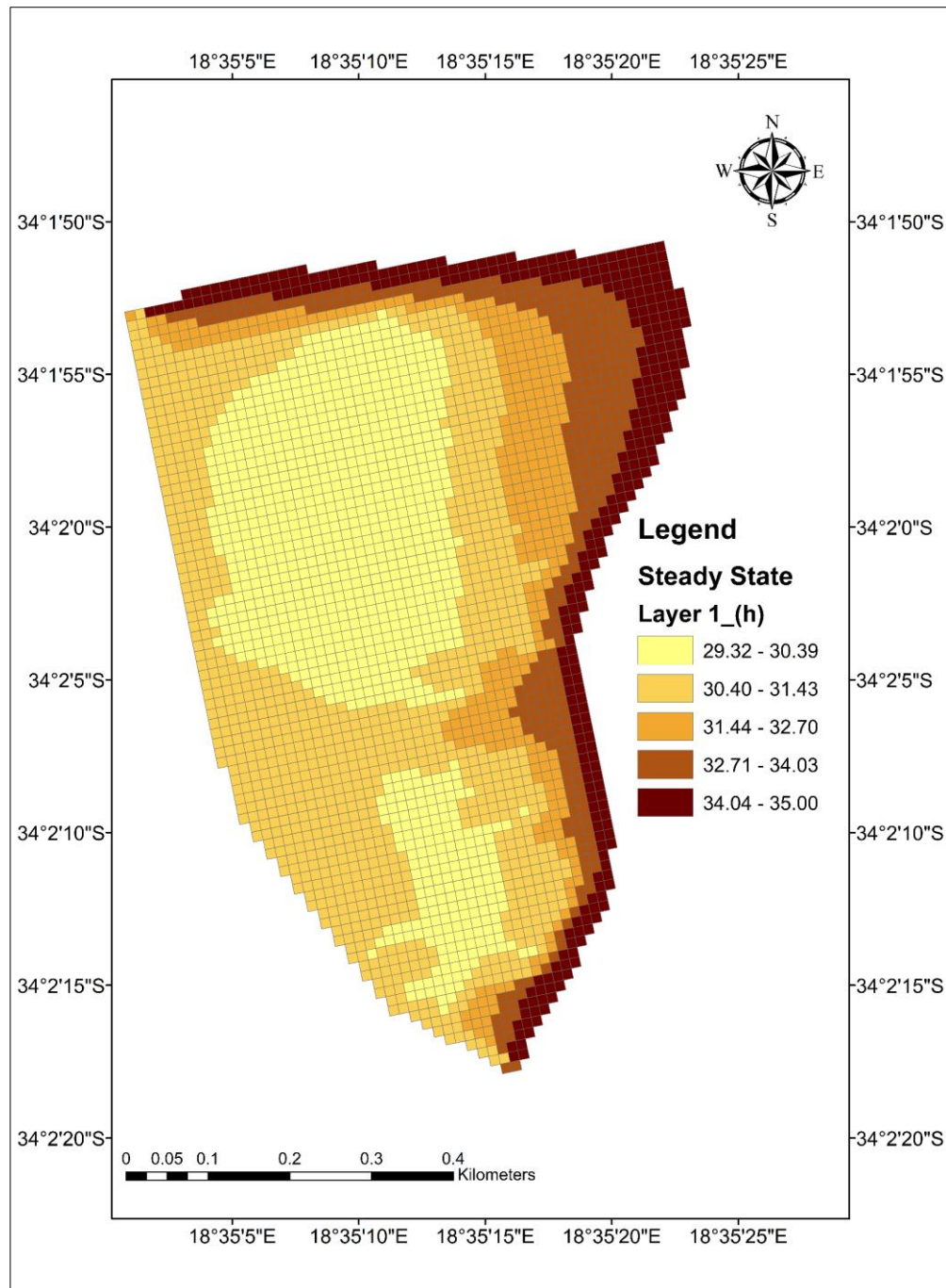


Figure 6-1: Steady State Hydraulic Head Values for Layer 1

Figure 6-2 illustrates that the hydraulic head values of Layer 2 range from 34.87 m in the high-elevation areas to 25.83 m in the low-lying areas, especially in the area of the catchment of the School Pond. The presence of coarser sands in the second layer of the aquifer contributed to the allocation of a higher hydraulic conductivity than that in the first layer, leading to a lower range of hydraulic heads in the layer.

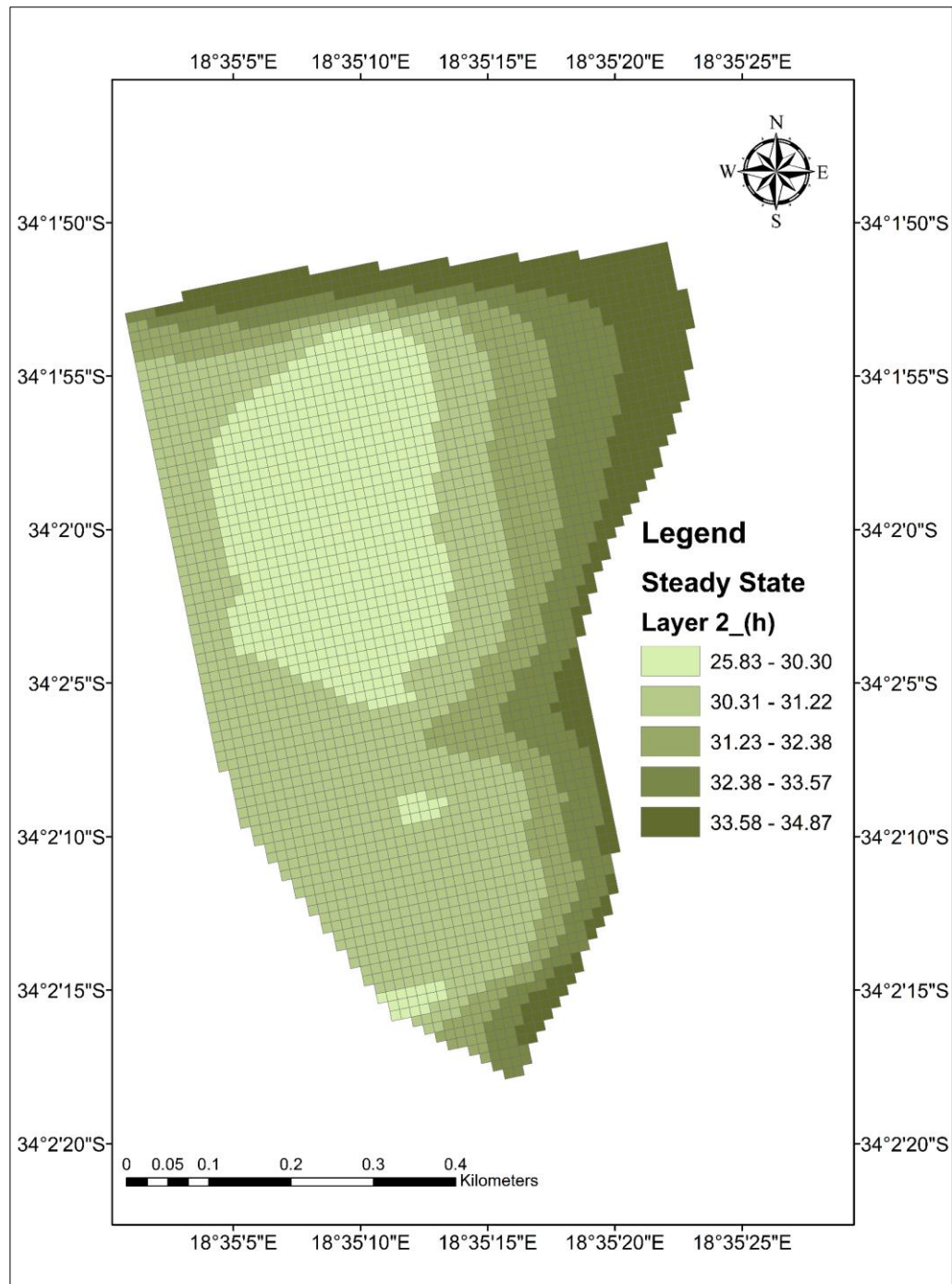


Figure 6-2: Steady State Hydraulic Head Values for Layer 2

6.1.1.4 Water Table Contours

The water table contours were exported from the MODFLOW model as a shapefile and imported to ArcGIS as a layer with a defined coordinate system. The results showed that the water table is higher in areas of high elevation and lower in areas with low elevation. The water table contours in the study area ranged between 34.80 m along the north and eastern boundaries and 29.40 m around the school pond catchment area, as it has the lowest elevation in the study area.

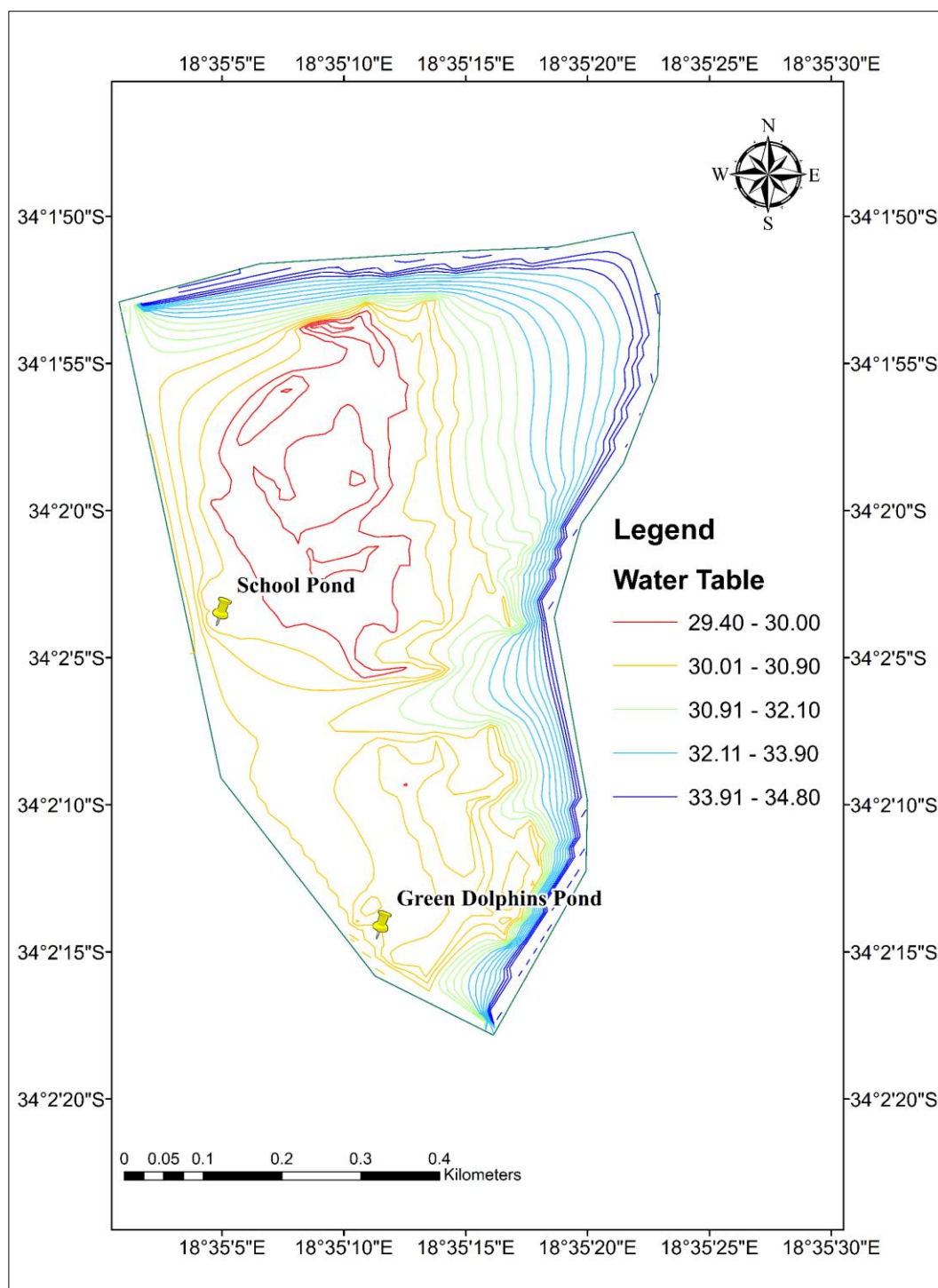


Figure 6-3: Water Table Contours around the Study Area

6.1.2 Transient State Model Calibration

6.1.2.1 Uncalibrated Transient State Model

The transient state was run using the parameters of the steady state model, with a time step of 20 for a period of 140 days, an equivalent of 12,096,000 seconds and a percent discrepancy of 0.00% was obtained. **Table 6-4** comprises the results of the 20th time step illustrating that the inflow contributors of the aquifer are constant head, head dependent bounds and recharge while the outflow is influenced by constant head, drains and evapotranspiration.

Table 6-4: Water-budget based on Uncalibrated Transient State Model

Inflow (m ³ /s)	Inflow (m ³ /s)	Outflow (m ³ /s)
Storage	7.39E-11	7.48E-11
Constant head	6.55E-02	5.88E-02
Well	0.0000	0.0000
Drains	0.0000	0.4350
ET	0.0000	1.11E-02
Head Dep Bounds	0.4394	0.0000
Recharge	1.0943E-04	0.0000
TOTAL	0.5050	0.5049
IN-OUT		8.94E-05
Percent Discrepancy (%)		0.0

The goodness of fit of the observed and simulated heads at MON71 borehole was checked using the Root Mean Square Error (RMSE) method. The observed head was 26.49 m, and this produced a simulated head of 31.00 m, giving a negative residual value. The RMSE value was 4.51 which is higher than the acceptable error of less than 1 thus the need for calibration.

6.1.2.2 Transient State Calibration

The model was calibrated using IoT-based water level measured in the MON71 borehole over the months of the wet season, July, August, and September 2022. The steady state model built in section 6.1.1.1 was used as the initial condition to determine the reliability of the parameters described in the steady state model. An abstraction rate of 32l/s, specific yield of 0.01 and recharge rate of 11.3 mm/year were applied to the 40 m thick transient model to obtain a percent discrepancy of 0.0% for the 20th time step as shown in **Table 6-5**. The difference between the inflow and outflow storage values is attributed to the managed aquifer recharge in the area.

Table 6-5: Water-budget based on Calibrated Transient State Model

Inflow (m ³ /s)	Inflow (m ³ /s)	Outflow (m ³ /s)
Storage	6.83E-11	6.56E-11
Constant head	8.96E-02	6.00E-02
Well	0.0000	3.20E-02
Drains	0.0000	0.4173
ET	0.0000	1.12E-02
Head Dep Bounds	0.4308	0.0000
Recharge	1.0943E-04	0.0000
TOTAL	0.5205	0.5205
IN-OUT		5.96E-08
Percent Discrepancy (%)		0.0

The values were checked, and the model was observed to be more stable with lower hydraulic conductivity values in Layer 1 than in Layer 2. The final calibrated model confirmed that the residual value between the observed and simulated heads were around 26.49 m and 27.35 m with an acceptable RMSE of 0.86.

6.1.2.3 Transient State Hydraulic Heads

The shapefile of the hydraulic heads was exported from MODFLOW as a colour grid shapefile and added to ArcGIS Software, where it was assigned a coordinate system in ArcGIS. The hydraulic heads for each layer were classified into five classes. **Figure 6-4** shows the simulated hydraulic heads for Layer 1 between 29.29 m and 35 m. It was observed that the hydraulic heads reduce towards the location of the stormwater ponds, i.e., from areas of high elevation to low elevation.

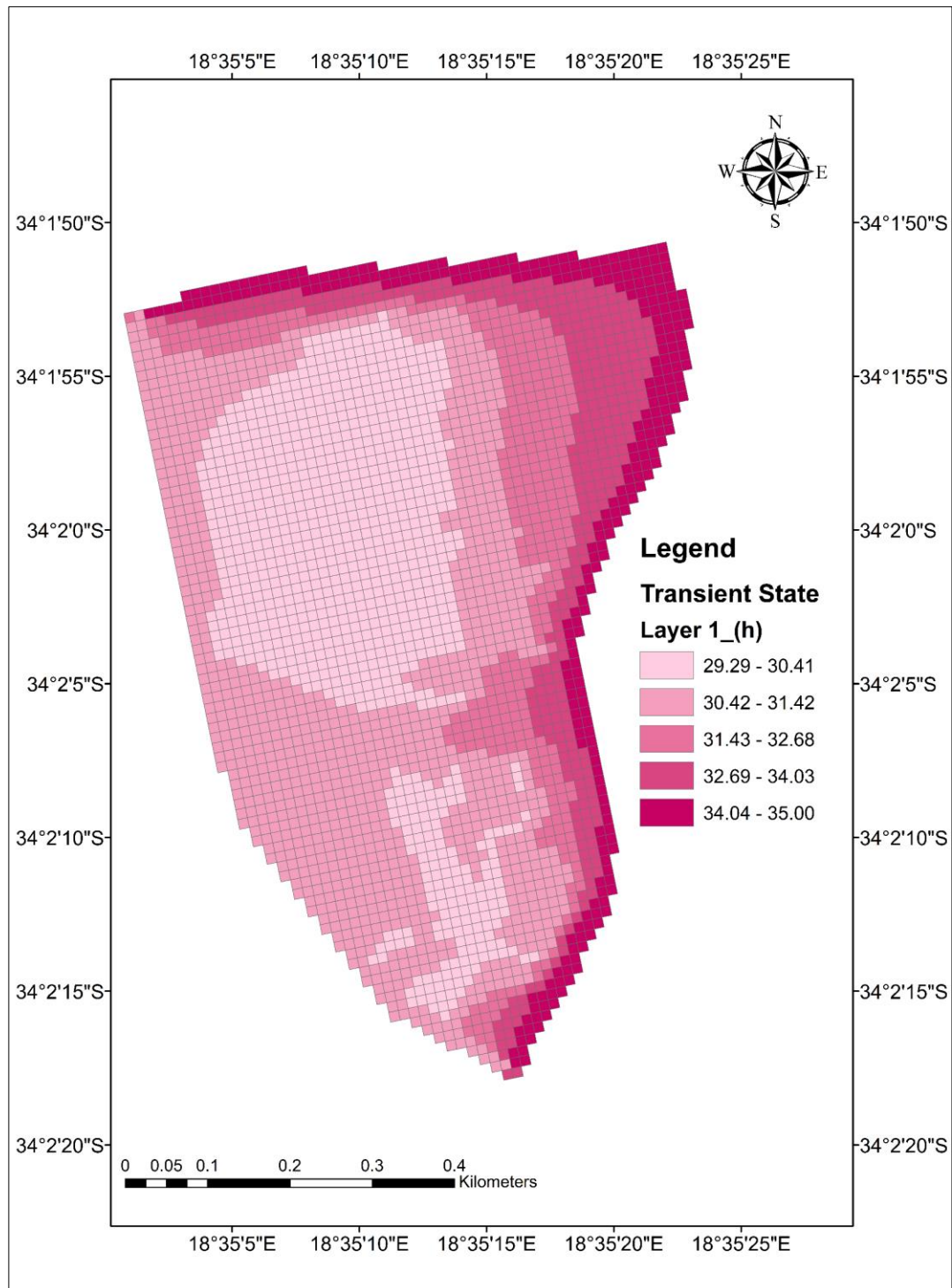


Figure 6-4: Transient State Hydraulic Head Values for Layer 1

The hydraulic head values of Layer 2 range from 34.71 m in the areas with high elevation to 26.29 m in the low-lying areas, as shown in **Figure 6-5**. The presence of coarser sands in the

second layer of the aquifer contributed to the allocation of a higher hydraulic conductivity than that in the first layer, which led to the low values of hydraulic heads.

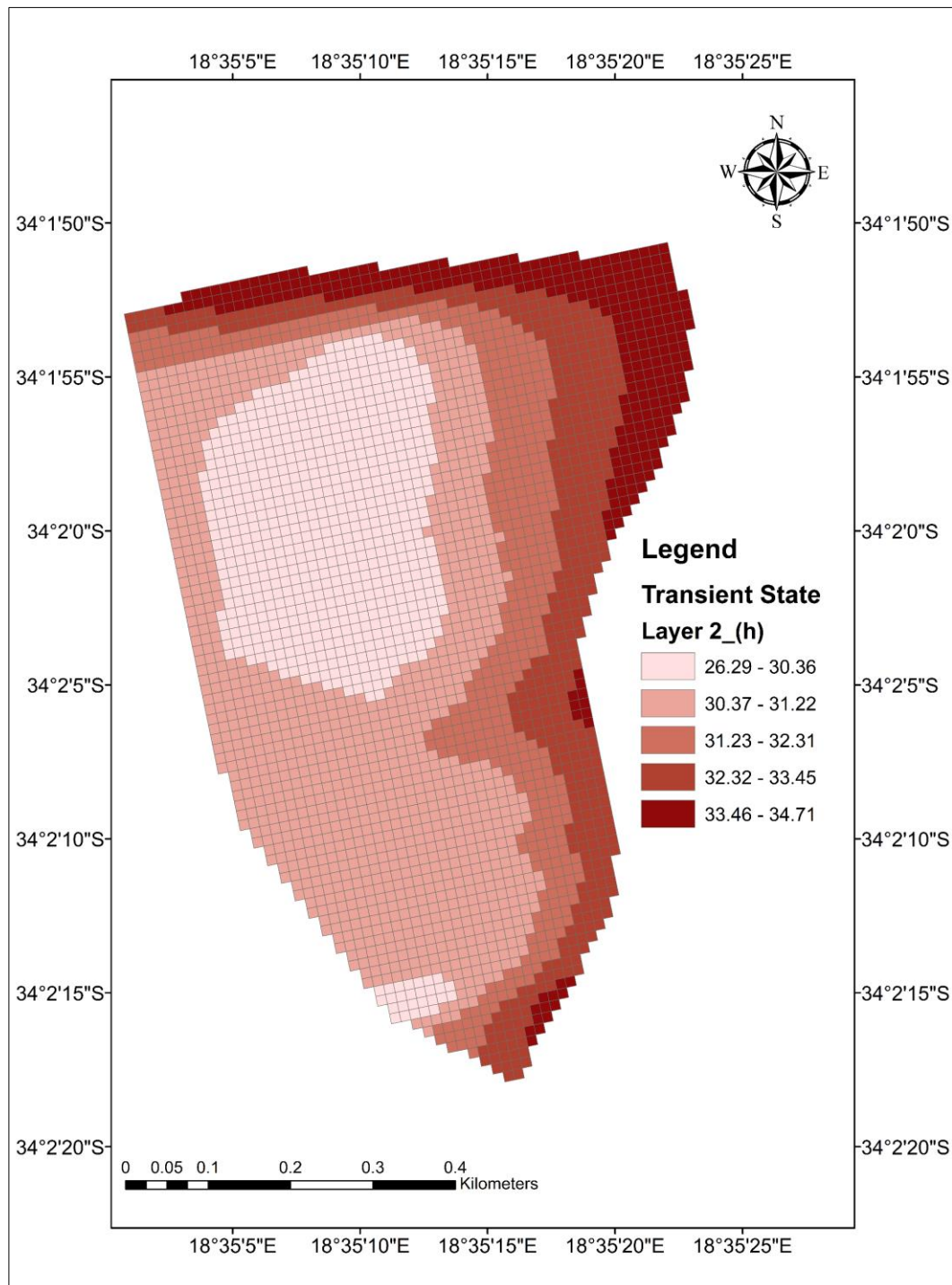


Figure 6-5: Transient State Hydraulic Head Values for Layer 2

6.1.3 Interpretation of Results

6.1.3.1 Sensitivity Analysis

A numerical MODFLOW model was developed to represent the groundwater flow process in the stormwater ponds catchment in Mitchells Plain, located in the Cape Flats Area. Aquifer parameters were varied between acceptable ranges for the study area from previous studies and water resources management agencies of South Africa to develop the model. The model showed that varying recharge rates, hydraulic conductivity, and aquifer thickness influences the fluctuations in the water table and the outflows presented in the water budget tables. An increase in the recharge rate registered an increase in the water table and outflow values; thus, groundwater levels are directly proportional to recharge. The results from the abstraction rate showed that groundwater levels are inversely proportional to the abstraction rate within the area; as an increase in the abstraction rate decreased the water table, more water was taken from the aquifer. A reduction in the hydraulic conductivity in Layer 2 caused a decrease in the water table, while an increase in the hydraulic conductivity in Layer 1 led to an increase in the water table in the area.

6.1.3.2 Calibrated Transient State Results

Figure 6-4 and **Figure 6-5** comprise the results obtained from the calibrated transient model of the study area. The model was run, and the 20th time step was analysed to determine the groundwater processes in the aquifer. There was an increase of 0.86 m between the observed head value and simulated head value at the MON71 borehole; thus, a confirmation that MAR occurred at the Green Dolphins pond for the simulated period. Therefore, artificial recharge at the stormwater pond increases the water table in the aquifer.

7. Conclusions and Recommendations

7.1 Conclusions

This study aims to introduce a novel approach by leveraging Internet of Things (IoT) technology considering the existing challenges and limitations in groundwater resource management in Cape Town. While IoT has been in existence for some time, its potential in addressing the specific water scarcity issues and groundwater management in Cape Town has not been extensively explored. This study seeks to bridge that gap by investigating how IoT can enhance the monitoring, analysis, and optimization of groundwater resources in the region. This research provides a comprehensive framework that improves the efficiency, accuracy, and accessibility of groundwater data and information by integrating IoT sensors for remote monitoring, data analytics, and predictive modelling. The novelty of the study lies in its application of IoT technology to address the unique challenges faced in Cape Town, including the need for high-quality data, spatial variability, and limited accessibility to available datasets. Therefore, the study has advanced existing knowledge by demonstrating the added value of IoT in effectively managing and conserving groundwater resources. The insights gained from this research hold significant potential for both academics and practitioners involved in groundwater resource management.

Consequently, the specific objectives of the study were all met successfully. The study effectively implemented an IoT monitoring system for groundwater level data collection, estimated stormwater storage and recharge potential, identified groundwater potential zones, and assessed groundwater recharge rates and processes as discussed below;

i. Groundwater level data collection and monitoring

IoT technologies are the solution to the lack of high-quality groundwater data to develop groundwater models for Integrated Water Resources Management (IWRM) to promote groundwater sustainability in Cape Town, South Africa. IoT technologies maintain the desired accuracy and ensure speedy and exact information analysis, which solves the problem of inadequate hydrogeological data in South Africa. This study involved groundwater level data collection at the MON71 borehole located at the Green Dolphins pond for almost five months using an IoT monitoring system. The system was easy to use and had the potential to accurately collect, analyze and process large amounts of groundwater level data. The IoT-based data was validated based on the manually collected data and thus used to calibrate the MODFLOW model. Therefore, IoT technologies need to be used in assessing hydrogeological parameters as it ensures the collection of high-quality and consistent data and can deal with immense data records. However, the key challenge faced during the data collection was that the high frequency of data collection and transmission to the cloud resulted in rapid battery drain. This was solved by

reducing the data collection interval from 15 minutes to 24 hours, which reduced the number of data entries sent to the cloud, thus prolonging the sensor's battery life.

ii. Estimation of stormwater storage and recharge potential

The objective of quantifying the volume of stormwater that can be stored within the CFA and assessing its recharge potential using a MODFLOW model was successfully achieved. The study employed a combination of GIS-based analysis, AHP techniques, and the MODFLOW software to verify the areas suitable for managed aquifer recharge (MAR). A numerical groundwater flow model was developed in MODFLOW, keeping the GIS data used to map the groundwater potential constant. The model was run for 140 days and calibrated using IoT-based groundwater levels in the transient state with known boundary and initial conditions to determine the difference between the simulated and observed head at the MON71 borehole. The simulated head value at the MON71 borehole showed an increase of 0.86 m compared to the observed head value, confirming the occurrence of MAR at the Green Dolphins pond during the simulated period. This result serves as evidence that stormwater ponds are a practical and effective means of replenishing the aquifer through infiltration.

iii. Identification of Groundwater Potential Zones

It is vital to perform a comprehensive hydrogeological assessment of an aquifer to identify suitable groundwater zones through mapping using accurate data. This study investigated the transition and suitability of IoT-based data for managing groundwater resources and MAR using the school and green dolphins stormwater pond catchment. A combination of GIS and AHP techniques was employed in this study to identify the groundwater zones in the study area. A total of 7 thematic layers were considered in the developing the MAR suitability map of the study area. The map classified the study area into two groundwater recharge zones; high (good) and very high (excellent) GWPZ, with the stormwater ponds being classified in the latter zone. The results revealed that integrating GIS techniques and the AHP method provides a suitable tool for improved groundwater level monitoring, as the MAR suitability map obtained was used groundwater flow modelling using MODFLOW Software.

iv. Assessment of groundwater recharge rates and processes

The study conducted data analysis, modelling, and field investigations to determine the recharge mechanisms, quantify recharge rates, and understand the factors influencing groundwater recharge. The study used the MODFLOW software to develop a numerical groundwater flow model, which was calibrated using IoT-based groundwater levels. The model was run, and the 20th time step was analysed to determine the groundwater processes in the aquifer. The fluctuations in the water table and the outflows presented in the water budget tables were influenced by different recharge rates, hydraulic conductivity, and aquifer thickness, as demonstrated by the model. The model indicated that a higher recharge rate leads to an increase in both the water table and outflow values. Therefore, there is a direct relationship between

groundwater levels and recharge rates. The findings regarding the abstraction rate revealed an inverse relationship between groundwater levels and the rate of abstraction in the area. Increasing the abstraction rate resulted in a decrease in the water table, indicating that more water was being extracted from the aquifer.

7.2 Recommendations

The following recommendations address specific issues and provide guidance for future studies or projects based on the findings from the study.

i. Resolution intervals for groundwater level data collection

It was observed that collecting groundwater level data at daily resolutions was sufficient, as the water table in the study area did not show significant variations at sub-daily intervals. Longer resolution intervals should be considered when using IoT monitoring systems to conserve the sensor battery life and ensure longer data collection periods. This reduces the number of data entries to the cloud, allowing for extended data collection before battery replacement.

ii. Power supply for the IoT monitoring system

The gateway of the IoT monitoring system should have a constant power supply to maintain communication with the sensor and cloud for data storage. However, since South Africa experienced an energy crisis in 2022 which led to successive rounds of load shedding/power outages due to insufficient generation capacity to meet the country's demand. In this study, a standby UPS was connected to the gateway for the entire data collection period to ensure continuous data transmission between the sensor and gateway, safeguarding the accuracy of the collected groundwater level data. Therefore, it is important to provide an alternative power source for IoT devices to prevent data loss during power interruptions.

iii. Water level sensor selection and validation

Extensive research should be conducted to identify the most efficient and accurate water level sensors suitable for the specified project requirements. Validation and verification checks should be performed on the sensors to ensure that the data collected using IoT technology falls within the manufacturer's recommended accuracy range. This validation process should compare the IoT data with data collected through manual methods of measuring hydrogeological parameters.

iv. Reliability of the Sensors

The use of reliable groundwater level sensors is crucial for accurate monitoring of the aquifer behaviour, effective resource management, early warning systems, decision support, and scientific research. Reliable sensor data enables efficient allocation and management of groundwater resources to determine the available water reserves in the aquifer and plan

abstraction rates accordingly which prevents overexploitation of groundwater. Similarly, timely detection of these changes allows for prompt response and appropriate mitigation measures to protect water resources and prevent adverse impacts on ecosystems and water supply systems. Accurate sensor data also improves the quality of groundwater models, enhances understanding of aquifer behavior, recharge mechanisms, and groundwater-surface water interactions. Therefore, it is vital to acknowledge the limitations and uncertainties associated with sensor data thus the need for utilization of reliable sensors to account for the potential of errors in the sensor values to ensure the validity and robustness of the study outcomes. This can include implementing quality control procedures, calibrating the sensors regularly, conducting validation checks with manual measurements, and applying statistical techniques to quantify and account for the margin of errors.

v. Estimation of model parameters for the groundwater MODFLOW model

The estimation of model parameters such as abstraction proved challenging due to the lack of registered boreholes for domestic use with water management agencies. The abstraction rate was estimated depending on studies carried out on other larger study areas of the CFA and assumed to be the same at the MON71 borehole. Therefore, it is recommended to have multiple registered boreholes distributed throughout the study area to improve the calibration process of the groundwater MODFLOW model. This would allow for a more accurate assignment of hydrogeological parameters, enhancing the model's representation of the actual field processes.

vi. Real-time modelling framework combined with web services

Conventional data collection methods involve manual measurements at infrequent intervals, leading to gaps in information thus the need for a real-time modelling framework combined with web services which enables continuous monitoring of groundwater levels. This approach provides a comprehensive and continuous view of groundwater dynamics, facilitating improved management of groundwater resources. Real-time modelling allows decision-makers to have access to the most up-to-date groundwater level data, enabling them to respond quickly to changing conditions. Decision-makers can monitor groundwater levels using real-time maps for visualization and comprehension of complex data, helping them make proactive and effective decisions. These maps are interactive, enabling exploration of different areas and zooming in on specific locations of interest. Such visual representations simplify the identification of trends, patterns, and potential issues related to groundwater levels.

Similarly, IoT plays a crucial role in the real-time modelling framework in that IoT devices, such as groundwater level sensors, can continuously collect and transmit data to a central server. The model can be executed on the server, which not only processes the data but also relays the results simultaneously to the web portal. This integration allows for seamless data flow, analysis, and dissemination, ensuring that decision-makers have access to the most recent and relevant information. Therefore, a real-time modelling framework combined with web services, IoT integration, and server-based model execution is important as it empowers informed decisions,

effective monitoring of groundwater resources, engagement of stakeholders, and the implementation of sustainable groundwater management practices.

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Appendices

Appendix 1: Ethics Research Clearance

Application for Approval of Ethics in Research (EIR) Projects
Faculty of Engineering and the Built Environment, University of Cape Town

ETHICS APPLICATION FORM

Please Note:

Any person planning to undertake research in the Faculty of Engineering and the Built Environment (EBE) at the University of Cape Town is required to complete this form **before** collecting or analysing data. The objective of submitting this application prior to embarking on research is to ensure that the highest ethical standards in research, conducted under the auspices of the EBE Faculty, are met. Please ensure that you have read, and understood the **EBE Ethics in Research Handbook** (available from the UCT EBE, Research Ethics website) prior to completing this application form: <http://www.ebe.uct.ac.za/ebe/research/ethics1>

APPLICANT'S DETAILS		
Name of principal researcher, student or external applicant		Miriam Arinaitwe
Department		Civil Engineering
Preferred email address of applicant:		ARNMIR003@myuct.ac.za
If Student	Your Degree: e.g., MSc, PhD, etc.	MSc (Eng) (by dissertation)
	Credit Value of Research: e.g., 60/120/180/360 etc.	180
	Name of Supervisor (if supervised):	Dr John Okedi
If this is a research contract, indicate the source of funding/sponsorship		Building Research Active Academic Staff Grant (B.R.A.A.S)
Project Title		Viability of Internet of Things Data in Assessing Managed Aquifer Recharge - Case of Cape Town, South Africa

I hereby undertake to carry out my research in such a way that:

- there is no apparent legal objection to the nature or the method of research; and
- the research will not compromise staff or students or the other responsibilities of the University;
- the stated objective will be achieved, and the findings will have a high degree of validity;
- limitations and alternative interpretations will be considered;
- the findings could be subject to peer review and publicly available; and
- I will comply with the conventions of copyright and avoid any practice that would constitute plagiarism.

APPLICATION BY	Full name	Signature	Date
Principal Researcher/ Student/External applicant	Miriam Arinaitwe		31/07/2021
SUPPORTED BY	Full name	Signature	Date
Supervisor (where applicable)	John Okedi		31/07/2021

APPROVED BY	Full name	Signature	Date
HOD (or delegated nominee) Final authority for all applicants who have answered NO to all questions in Section 1; and for all Undergraduate research (Including Honours).	Prof. Alphose Zingoni		08/09/2021
Chair: Faculty EIR Committee For applicants other than undergraduate students who have answered YES to any of the questions in Section 1.			

Miriam Arinaitwe: Transition to Novel Internet of Things Technology for Management of Groundwater Resources – Case of Cape Town, South Africa

Appendix 2: SAWS Disclosure Statement

FORM: DISCLOSURE STATEMENT



The provision of the data is subject to the User providing the South African Weather Service (SAWS) with a detailed and complete disclosure, in writing and in line with the requirements of clauses 1.1 to 2.4 (below), of the purpose for which the specified data is to be used.

- 1 Should the User intend using the specified data for commercial gain then the disclosure should include the following:
 - 1.1 the commercial nature of the project/funded research project in connection with which the User intends to use the specified data;
 - 1.2 the names and fields of expertise of any participants in the project/funded research project for which the specified data is intended; and
 - 1.3 the projected commercial gains to the User as a result of the intended use of the specified data for the project/funded research project.
- 2 Should the User intend using the specified data for the purposes of conducting research, then the disclosure should include the following:
 - 2.1 the title of the research paper or project for which the specified data is to be used;
 - 2.2 the details of the institution and supervisory body or person(s) under the auspices of which the research is to be undertaken;
 - 2.3 an undertaking to supply SAWS with a copy of the final results of the research in printed and/or electronic format; and
 - 2.4 the assurance that no commercial gain will be received from the outcome from the research.

If the specified data is used in research with disclosure being provided in accordance with paragraph 2 and the User is given the opportunity to receive financial benefit from the research following the publication of the results, then additional disclosure in terms of paragraph 1 is required.

The condition of this disclosure statement is applicable to the purpose and data requirements of the transaction recorded in Schedule 1 below.

SCHEDULE 1

Please note: The South African Weather Service will only act upon customer requirements noted on this disclosure statement and not from any other correspondence.

FULL PERSONAL DETAILS OF USER

Full Names	Miriam Arinaitwe
University/school/organisation	University of Cape Town
Student Number (if applicable)	ARNMIR003
Email address	ARNMIR003@myuct.ac.za
Cellphone	0639476758
Supervisor	Dr John Okedi
Project/Thesis Title	Viability of Internet of Things Data in Assessing Managed Aquifer Recharge. Case of Cape Town. South Africa
Current registered degree (e.g. BSc)	MSc (Eng) by dissertation



FORM: DISCLOSURE STATEMENT

Expected finalization date (MM/YYYY) 31/12/2022

The South African Weather Service reserves the right to request, at any time, from the student proof of registration for the Degree at the University.

THE PURPOSE (Please indicate a detailed description of the purpose for which the data will be used)

I intend to use the data in the development and calibration of my groundwater Modflow model. To determine how much stormwater is stored within the aquifer and how easily it can be recharged in terms of infiltration, runoff and deep percolation under known boundary conditions.

DATA REQUIRED (Indicate weather elements (e.g. rain, temp), place/s, time period and resolution (e.g. daily, hourly))

My study area is a stormwater school pond located in the Mitchells Plain West Catchment of the CFA at coordinates latitude 34° 2'3.00"S and longitude 18°35'4.70"E. Therefore, climate data from the nearest rain gauge stations will be of great help.

The following data sets are required; Resolution (Daily data)

- Evapotranspiration data 20-30years
- Rainfall data for the past 20-30 years
- Temperature data for the past 20-30years

I hereby accept that:

- SAWS will be acknowledged in the resulting thesis/project or when published, for the data it provided.
- SAWS will be provided with a copy of the final results in printed or electronic format.
- The data received shall not be provided to any third party.

Signature of the User:

Date: 01/03/2022

(Please sign the document and do not type your name in as this is a legal document and requires a signature.)

PROTECTION OF PERSONAL INFORMATION ACT (POPIA)

SAWS value its customer's privacy and strives to continuously ensure compliance with POPIA, to protect and safeguard against unauthorised use of personal information.

The Customer hereby accepts that:

Public Document

Document Reference: WCS-CLS-FRM-004.1

Page 2 of 3

**FORM: DISCLOSURE STATEMENT**

-
- He/she has read and understood the customer processing POPIA notice found on <https://www.weathersa.co.za/home/popia>

Signature of the User:

Date:01/03/2022

A handwritten signature in blue ink, appearing to be "J. H. H. H.", written over a yellow rectangular background.

(Please sign the document and do not type your name in as this is a legal document and requires a signature.)

Appendix 3: CCT Research Request Confidentiality Agreement

RESEARCH REQUEST CONFIDENTIALITY AGREEMENT			 CITY OF CAPE TOWN ISIXEKO SASAKAPA STAD KAAPSTAD
W 8/BM/Research Confidentiality Request	2021/06/01	WATER AND SANITATION DEPARTMENT	Version: 00
COMPILED BY: RESEARCH OFFICER / AO2			APPROVED BY: HEAD: BI
All CONTROLLED documents are located in the SAP DM system			Printed 2022/12/08
Printed documents are NOT CONTROLLED except if signed and dated			Page 1 of 7

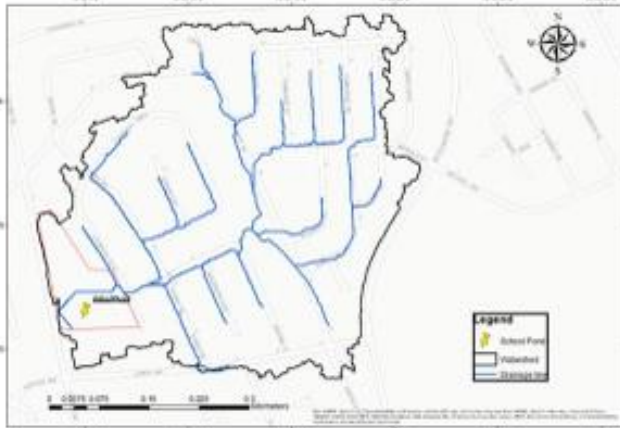
EXTERNAL RESEARCH ASSISTANCE OR INFORMATION / DATA REQUEST AND CONFIDENTIALITY AGREEMENT:

- All applicants must please answer each category in detail.
- Applications do not necessarily guarantee commitment by the Research Section to consider or provide the requested research assistance or information/data
- The research section reserves the right to decline such application based on specialised research requirements and availability of resources/data
- This document should be signed and attached to the research approval report for final approval signatures
- All research requests to be approved by the Office of the Executive Director: Utility Services
- Applicants must ensure that duplicate applications are not submitted via alternative City of Cape Town application processes including submissions to the Open Data Portal or in terms of the Promotion of Access to Information Act. Any such applications must be withdrawn before submitting a research request

Section 1: Requesting Institution/Organisation Details	
Institution/Organisation Name:	University of Cape Town
Department/Section Name:	Civil Engineering
Institution/Organisation Address:	Rondebosch, Cape Town, 7700
Section 2: Requesters Details	
Requesters Name:	Miriam Arinaitwe
Student Number or Designation:	ARNMIR003
Contact Details of Requester:	Tel: 0639476758
	Cell:
	Email: ARNMIR003@myuct.ac.za
	Fax:
Person Accepting Responsibility for Provided Information:	Miriam Arinaitwe
Section 3: Requested Research Assistance or Information	
Please provide a detailed description of the research assistance or information / data you require:	Study area – A stormwater school pond located in the Mitchells Plain West Catchment of the CFA at coordinates latitude 34° 2'3.00"S and longitude 18°35'4.70"E as shown in the figure below.

Miriam Arinaitwe: Transition to Novel Internet of Things Technology for Management of Groundwater Resources – Case of Cape Town, South Africa

RESEARCH REQUEST CONFIDENTIALITY AGREEMENT			 CITY OF CAPE TOWN ISIXEKO SASERAPA STAD KAAPSTAD
W&B/Research Confidentiality Request	2021/06/01	WATER AND SANITATION DEPARTMENT	Version: 00
COMPILED BY: RESEARCH OFFICER / AO2			APPROVED BY: HEAD: BII
All CONTROLLED documents are located in the SAP DM system			Printed 2022/12/08
Printed documents are NOT CONTROLLED except if signed and dated			Page 2 of 7

	 Listed below are the datasets required. • the residential reported boreholes in my study area watershed • Pumping rates at the various boreholes • Aquifer Elevation data • Aquifer layer thickness • Recharge rates • Aquifer storability • Evapotranspiration data • Historical changes in the water table elevations • Rainfall data (daily rainfall data) • Temperature data
What is the Purpose / Objective of the required research assistance or information / data, i.e. for completion of tertiary study, etc.	I intend to use the data in the development and calibration of my groundwater Modflow model. To determine how much stormwater is stored within the aquifer and how easily it can be recharged in terms of infiltration, runoff, and deep percolation under known boundary conditions.
Please name the Project / Initiative for which this research assistance or information/data will be needed:	Viability of Internet of Things Data in Assessing Managed Aquifer Recharge: Case of Cape Town, South Africa

RESEARCH REQUEST CONFIDENTIALITY AGREEMENT			 CITY OF CAPE TOWN ISIXEKO SASEKAPA STAD KAAPSTAD
W8/BM/Research Confidentiality Request	2021/06/01	WATER AND SANITATION DEPARTMENT	Version: 00
COMPILED BY: RESEARCH OFFICER / AO2			APPROVED BY: HEAD: BII
All CONTROLLED documents are located in the SAP DM system			Printed 2022/12/08
Printed documents are NOT CONTROLLED except if signed and dated			Page 3 of 7

Section 3: Requested Research Assistance or Information (continued)		
Category of Service (please tick applicable option/s):	Research Assistance, i.e. Analysis, etc.	Visual Data, Samples, i.e. Photographic, Sampling, Site Visits, etc.
	Research Information or Data i.e. Water Consumption Figures, etc.	Interviews with City Experts and Professionals
	Other:	
If you require research information/data, what will the information/data be used for?	It will be used in the development and calibration of my groundwater Modflow model.	
Where will this research information/data be stored?	On my hard drive	
Will this information/data be discarded after use? If no, please explain	No, the data will be used in other related projects.	
Will this information/data be shared with other institutions, organisations or individuals? If yes, please explain	No	
By when do you require this research assistance or information/data?	At most in a week's time. 18 th March 2022	
Have you submitted a duplicate or similar application via other City of Cape Town application processes such as the Open Data Portal or in terms of the Promotion of Access to Information Act?	I sent an email to water@capetown.gov.za but did not receive a response	
Please tick whether specialised software programme analysis will be required, if applicable.	SWIFT: ☐ IMQS: ☐ WADISO: ☐ SAP: ☐ Other: __MODFLOW__	
Please provide any additional preferences and specifications regarding your request:		

RESEARCH REQUEST CONFIDENTIALITY AGREEMENT			 CITY OF CAPE TOWN ISIXEKO SASEKAPA STAD KAAPSTAD
W&B/Research Confidentiality Request	2021/06/01	WATER AND SANITATION DEPARTMENT	Version: 00
COMPILED BY: RESEARCH OFFICER / AO2			APPROVED BY: HEAD: BII
All CONTROLLED documents are located in the SAP DM system			Printed 2022/12/08
Printed documents are NOT CONTROLLED except if signed and dated			Page 4 of 7

Section 4: Research Information, Data and Intellectual Property Confidentiality Agreement

3. Definitions

- (1) **Trade Marks:** Means all marks, designs, service marks, logos, brand names, slogans and designs (whether registered or not) to which the City of Cape Town has any rights at the Signature Date or at any time during the currency of this Agreement;
- (2) **Intellectual Property:** Means any patents, inventions, designs, applications for the foregoing Trade Marks, copyright, trade secrets and service marks and other intellectual property rights residing in any process belonging to the City of Cape Town and rights to claim something as its confidential information, including in other jurisdictions, that grant similar rights as the foregoing, including those subsisting in inventions, drawings, software, business names, goodwill and the style of presentation of goods or services and in applications for the protection thereof;
- (3) **Know-How:** Means all Confidential Information of whatever nature relating to the Intellectual Property and its exploitation as well as any other confidential information generally relating to the manufacture, use and sale of the Products, including technical information, manufacturing techniques, design specifications, formulae, systems, processes, information concerning materials and business information generally;
- (4) **Permitted Recipients:** Means employees, directors, officers, professional advisors, agents, financiers and consultants of Recipient;
- (5) **Confidential Information:** Means any information of whatever nature, which has been, or may be obtained directly or indirectly received by the Recipient from the City of Cape Town, whether in writing or in electronic format, or pursuant to discussions held between the Parties, or which can be obtained by examination, testing, visual inspection or analyses, including, without limitation, the City of Cape Town's Know-How and Intellectual Property and all information relating to the City of Cape Town's past, present and future research and development or its business activities, products, services, clients, or to its technical knowledge, including, without limitation, the City of Cape Town's trade secrets, as well as the terms and conditions of this Agreement, instruction books, technical pamphlets, catalogues, advertising material, specifications and other materials and documents made available to the Recipient by the City of Cape Town relating to the Products, any information identified as confidential, and any other material which contains or otherwise reflects, or is generated or derived from any such information as is specified in this definition; and
- (6) **Recipient:** Means the Institution/Organisation described in clause 1 herein.

4. Clauses

4.1 Rights in Confidential Information & Intellectual Property

- (1) The City of Cape Town's Confidential Information and Intellectual Property are assets in which it has proprietary or other rights or interests, the unauthorised disclosure or use of which may cause harm to the City of Cape Town.
- (2) The Recipient will not acquire any rights in respect of the Confidential Information or Intellectual Property save as stated in this Agreement

RESEARCH REQUEST CONFIDENTIALITY AGREEMENT			 CITY OF CAPE TOWN ISIXEKO SASAKAPA STAD KAAPSTAD
W8/BII/Research Confidentiality Request	2021/06/01	WATER AND SANITATION DEPARTMENT	Version: 00
COMPILED BY: RESEARCH OFFICER / AO2			APPROVED BY: HEAD: BII
All CONTROLLED documents are located in the SAP DM system			Printed 2022/12/08
Printed documents are NOT CONTROLLED except if signed and dated			Page 6 of 7

Section 4: Research Information, Data and Intellectual Property Confidentiality Agreement (Clause 4 Continued)

4.2 Disclosure and use of Confidential Information & Intellectual Property

- (1) The Recipient will not disclose Confidential Information to any third party or use the Confidential Information or Intellectual Property without the written consent of the City of Cape Town, save in accordance with this Agreement.
- (2) The Recipient may disclose the Confidential Information or Intellectual Property to its Permitted Recipients, provided that:
 - (a) the recipient will disclose any research papers, articles, presentations, data or output documents; that contains City information or data; to the City for its sanctioning before release within the public domain.
 - (b) the Recipient will take such steps as are necessary to ensure that its Permitted Recipients to which Confidential Information or Intellectual Property are disclosed adhere to this Agreement;
 - (c) any disclosure by a Permitted Recipient of the Confidential Information or Intellectual Property contrary to this Agreement will constitute an unauthorised disclosure by the Recipient.
- (3) The City of Cape Town may authorise the Recipient to disclose its Confidential Information or Intellectual Property to a third party other than a Permitted Recipient provided that such permission shall be valid:
 - (a) only if given in writing;
 - (b) for disclosure only to the third party identified in the written authorisation; and for that specific instance of disclosure only,
 - (c) and clause 5.2(2) shall apply as if the third party were a Permitted Recipient.
- (4) In the circumstances listed in clause 5.2(4), the Recipient shall:
 - (a) limit the disclosure only to that which is necessary to comply with the law;
 - (b) advise the City of Cape Town in writing as soon as reasonably possible of the disclosure or intended disclosure specifying:
 - (i) the Confidential Information or Intellectual Property subject to disclosure;
 - (ii) the reasons for the disclosure;
 - (iii) the law under the direction of which the disclosure is or will be made; and
 - (iv) where applicable, the identity of any third party requiring disclosure; and
 - (iv) provide the City of Cape Town with all reasonable cooperation to limit or prevent the disclosure.

4.3 Use of Confidential Information & Intellectual Property

- (1) The Parties will not use the Confidential Information or Intellectual Property for any purpose other than:
 - (a) that for which it is disclosed in connection with this transaction;
 - (b) as otherwise permitted by the City of Cape Town in writing; or
 - (c) in accordance with this Agreement.

RESEARCH REQUEST CONFIDENTIALITY AGREEMENT			 CITY OF CAPE TOWN ISIXEKO SASEKAPA STAD KAAPSTAD
W 8/BII/Research Confidentiality Request	2021/06/01	WATER AND SANITATION DEPARTMENT	Version: 00
COMPILED BY: RESEARCH OFFICER / AO2			APPROVED BY: HEAD: BII
All CONTROLLED documents are located in the SAP DM system			Printed 2022/12/08
Printed documents are NOT CONTROLLED except if signed and dated			Page 8 of 7

Section 4: Research Information, Data and Intellectual Property Confidentiality Agreement (Clause 4 Continued)

- (2) The Recipient and/or any of its directors, employees and/or representatives will not:
- (a) copy, reproduced or duplicated in whole or in part if the Confidential Information or Intellectual Property for any purpose other than a purpose envisaged in terms of this Agreement, or after having received the written consent of the City of Cape Town; and
 - (b) use the Confidential Information or Intellectual Property for its own benefit or the benefit of any other person (other than the City of Cape Town) except as provided for in this Agreement.

4.4 Standard of Care

- (1) The Recipient will receive and use the Confidential Information or Intellectual Property in such a way as to prevent any unauthorised access to it.
- (2) In the event that the Recipient becomes aware that the Confidential Information or Intellectual Property have been disclosed by it or its Permitted Recipients contrary to the terms of this Agreement, the Receiving Party will:
 - (a) inform the City of Cape Town in writing specifying what Confidential Information or Intellectual Property have been disclosed, how and to whom it has or may have been disclosed, when the unauthorised disclosure took place and what steps will be taken to retrieve the Confidential Information or Intellectual Property and prevent future unauthorised disclosures;
 - (b) take such steps as are necessary or as the City of Cape Town directs to retrieve the Confidential Information or Intellectual Property from unauthorised persons and to prevent further unauthorised disclosure of the Confidential Information or Intellectual Property; and
 - (c) co-operate with the City of Cape Town in taking any steps taken by it to retrieve the Confidential Information or Intellectual Property from unauthorised persons and to prevent further disclosure of the Confidential Information or Intellectual Property.
- (3) Clause 5.2(4) is without prejudice to any rights of the City of Cape Town arising from the unauthorised disclosure of its Confidential Information or Intellectual Property.

4.5 No Warranties regarding Confidential Information & Intellectual Property

The City of Cape Town does not warrant that the Confidential Information or Intellectual Property it discloses are accurate or complete and the City of Cape Town will not be liable for any losses, damages, costs or penalties suffered by, or claims made against, the Recipient as a result of any inaccuracies in, or incompleteness of, the Confidential Information or Intellectual Property disclosed.

4.6 Return of Confidential Information & Intellectual Property

- (1) Upon the request of the City of Cape Town, the Recipient will return, destroy or expunge from any storage device all Confidential Information other than documents prepared by the Recipient provided that if required by law or for purposes of this Agreement, the Recipient may retain one copy of the Confidential Information for the period so required.
- (2) Where the City of Cape Town has required destruction of the media containing Confidential the Recipient will, on request, confirm in writing that it has destroyed all Confidential Information and made reasonable efforts to expunge Confidential Information stored electronically from any storage device on which it was held.
- (3) All requests in terms of this clause 5.6 will be complied with within five (5) Business Days.

RESEARCH REQUEST CONFIDENTIALITY AGREEMENT			 CITY OF CAPE TOWN ISIIXEKO SASEKAPA STAD KAAPSTAD
W 8/BM/Research Confidentiality Request	2021/06/01	WATER AND SANITATION DEPARTMENT	Version: 00
COMPILED BY: RESEARCH OFFICER / A02			APPROVED BY: HEAD: BII
All CONTROLLED documents are located in the SAP DM system			Printed 2022/12/08
Printed documents are NOT CONTROLLED except if signed and dated			Page 7 of 7

Section 4: Research Information, Data and Intellectual Property Confidentiality Agreement

5. Indemnities

The Recipient hereby indemnifies the City of Cape Town and holds it harmless against all loss or damage which the City of Cape Town may sustain, and against any claim which may be made against the City of Cape Town by any other person, as a result of or arising out of:

- (1) a breach by the Recipient of any of its obligations in terms of this Agreement;
- (2) any wilful or negligent act or omission, or unauthorised or unlawful conduct by the Recipient or any of its employees, agents, directors or representatives; and
- (3) the disclosure or unauthorised use of Confidential Information or Intellectual Property, contrary to this Agreement, by the Recipient, the Permitted Recipients or third parties in respect of whom the Recipient has been authorised to make disclosure.

Signature of **Recipient**: 

Signed at 7:00pm on 12/03/2022

Signature of **authorised City Official**:

Designation of authorised City Official:

Signed at on

Appendix 4: Historical Climatic Data

Monthly Rainfall Totals

	Monthly Rainfall Totals at CT-AWS (2002-2021)											
Year	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
2002	61.0	4.4	8.6	24.8	69.2	68.8	97.6	60.0	23.0	27.0	21.2	16.4
2003	2.8	7.6	44.4	9.6	34.0	24.4	27.4	82.6	54.2	15.8	0.0	21.0
2004	6.0	0.4	12.2	64.0	8.8	85.4	65.0	156.2	20.4	96.2	3.8	8.6
2005	25.8	1.8	7.8	91.8	75.2	89.2	67.6	80.2	27.8	9.4	18.0	1.2
2006	0.0	11.2	4.2	22.2	99.6	11.2	72.0	61.8	19.4	40.2	36.0	11.6
2007	0.4	29.8	19.4	69.6	109.2	135.4	163.6	107.2	19.0	29.0	25.0	15.6
2008	2.8	11.8	4.0	11.2	34.4	58.6	148.2	87.2	139.8	14.4	51.2	6.6
2009	1.0	3.8	2.6	31.6	73.8	119.4	104.2	68.8	69.6	26.2	93.4	4.8
2010	2.6	8.8	10.4	14.0	91.4	78.0	47.6	30.8	22.2	22.4	28.4	22.2
2011	6.0	3.4	6.2	25.8	53.8	91.6	30.8	44.4	21.6	14.6	28.2	16.6
2012	1.2	5.6	22.8	54.8	48.6	82.8	91.6	104.6	64.0	31.8	10.0	1.0
2013	12.2	35.6	15.2	47.8	67.2	126.8	51.8	167.6	23.6	15.4	86.4	4.4
2014	27.8	1.8	46.0	27.6	69.2	133.4	103.0	99.4	30.0	5.0	20.8	1.8
2015	13.6	3.0	1.8	5.2	28.4	114.2	94.2	41.2	25.4	8.4	27.2	11.6
2016	9.4	2.8	37.8	49.0	16.6	64.8	93.4	52.0	36.0	11.8	2.0	20.2
2017	3.6	0.0	5.0	14.0	7.2	92.8	35.6	48.6	16.6	25.4	29.6	7.8
2018	4.0	9.2	8.4	24.0	72.2	83.4	47.4	56.2	49.0	10.2	9.6	13.6
2019	12.2	6.0	26.6	17.8	49.8	84.2	111.6	34.8	19.8	63.6	1.6	16.2
2020	9.0	6.8	1.4	31.4	62.8	95.2	87.2	115.6	64.4	7.8	29.4	7.2
2021	3.4	2.0	44.4	1.2	104.0	133.2	82.2	85.4	9.8	49.2	40.2	10.0

Mean Maximum Temperature

	Mean Maximum Temperature at CT-AWS (2002-2021)											
Year	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
2002	32.6	36.6	34.6	31.6	32.4	24.6	24.3	28.2	30.4	32.7	32.6	37.2
2003	30.0	37.5	34.4	33.6	31.9	26.2	27.8	26.8	26.3	35.3	30.9	31.4
2004	36.3	34.3	34.8	33.8	26.7	30.4	26.6	24.6	30.1	29.0	29.5	31.5
2005	33.7	35.9	34.4	32.8	27.8	24.1	26.7	19.8	26.3	33.7	32.6	32.1
2006	34.5	33.8	37.1	31.2	31.5	27.6	25.4	27.4	29.6	30.9	30.3	30.5
2007	37.3	32.0	34.5	32.1	32.2	26.1	24.0	26.4	27.0	33.0	26.5	35.4
2008	31.1	32.1	33.3	36.0	30.0	22.8	23.8	25.9	31.4	29.2	32.2	31.4
2009	30.2	35.0	37.8	35.5	29.3	26.2	27.4	25.3	24.7	30.2	32.5	30.8
2010	37.5	35.3	37.6	33.5	29.8	26.8	27.7	27.9	27.4	31.8	29.8	31.9
2011	34.5	35.5	36.1	33.5	31.2	27.5	27.1	28.1	28.2	32.4	31.6	31.6
2012	34.6	36.9	33.3	36.9	25.7	28.0	26.7	20.7	34.4	27.1	30.8	33.8
2013	34.1	33.9	37.3	34.8	29.4	27.1	25.6	28.4	19.8	29.1	30.9	32.7
2014	35.3	35.4	30.0	37.9	26.7	27.7	24.9	29.5	31.0	33.7	31.1	31.5
2015	35.4	32.7	42.4	31.2	30.1	23.5	25.5	27.3	30.4	36.1	33.2	39.6
2016	35.8	33.8	32.4	33.0	30.9	28.4	29.2	29.5	25.9	34.4	32.9	32.0
2017	31.8	34.2	38.2	36.6	31.3	25.5	30.3	26.6	33.5	33.1	29.4	33.1
2018	35.9	35.7	30.4	31.6	29.4	28.8	28.6	22.5	33.3	36.2	32.6	32.5
2019	34.1	36.8	31.5	29.2	28.1	27.7	22.4	29.9	36.7	28.5	33.5	33.6
2020	31.7	36.8	36.3	32.5	30.1	27.4	27.5	23.6	27.3	31.0	32.4	29.7
2021	33.6	33.6	33.1	36.7	33.4	28.2	26.0	27.2	28.7	32.6	30.7	32.0

Mean Minimum Temperature

	Mean Minimum Temperature at CT-AWS (2002-2021)											
Year	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
2002	10.7	11.4	5.7	5.1	4.6	1.1	0.1	-0.1	5.9	3.9	4.8	12.0
2003	11.5	12.0	9.3	7.3	4.0	2.1	0.6	-0.1	4.0	6.1	10.0	9.6
2004	14.4	12.5	9.7	6.9	3.4	1.6	2.1	4.1	3.9	5.0	10.2	13.1
2005	13.6	13.4	7.9	7.7	3.5	2.3	3.6	2.5	3.5	4.7	7.4	8.3
2006	13.7	11.6	5.8	6.1	2.9	3.7	3.1	2.2	4.8	3.7	7.7	11.9
2007	10.1	12.5	7.9	6.3	3.2	2.6	1.7	1.2	4.4	3.9	8.0	15.8
2008	12.4	15.0	11.7	8.5	9.5	5.9	3.5	3.9	3.7	6.6	9.4	9.6
2009	12.7	14.1	11.9	10.0	7.3	4.6	4.3	5.4	6.6	7.8	12.6	12.3
2010	14.0	13.6	12.8	5.1	5.7	3.3	3.3	3.4	5.9	7.7	8.4	12.9
2011	13.8	15.0	11.7	5.5	6.4	3.9	2.9	2.7	5.7	6.3	6.9	8.2
2012	12.7	14.4	10.9	7.4	4.3	3.5	2.5	2.9	3.4	6.9	8.2	14.8
2013	10.8	13.6	11.2	8.0	5.3	3.2	5.1	3.5	5.0	8.7	11.1	14.1
2014	13.2	13.6	8.2	6.2	4.8	2.6	1.1	3.8	4.0	6.3	8.1	14.4
2015	13.3	9.3	13.1	8.2	7.1	4.1	2.9	4.1	6.5	6.5	10.1	14.1
2016	15.8	13.1	10.6	8.1	6.5	2.8	1.6	2.8	4.3	7.7	10.7	9.3
2017	12.5	14.5	10.4	9.1	5.3	2.6	0.9	3.8	6.4	5.8	9.3	13.3
2018	12.8	12.7	10.5	7.3	6.8	3.6	2.5	2.8	2.7	7.4	6.6	11.4
2019	11.8	13.0	12.1	8.8	7.0	2.4	1.5	5.0	7.0	5.9	9.0	9.9
2020	14.2	12.6	9.8	5.9	5.0	4.5	2.1	2.8	4.4	4.9	8.4	12.4
2021	11.7	12.5	10.1	9.9	5.4	5.0	1.0	2.9	3.5	6.5	9.4	12.2

Appendix 5: IoT-based Groundwater Level Data

IoT-Based Groundwater Data recorded at MON71 Borehole in m.a.s.l (2022)						
	July	Aug	Sept	Oct	Nov	Dec
1	-	26.50	26.49	26.44	-	26.30
2	-	26.50	26.49	26.45	-	26.31
3	-	26.50	26.49	26.44	-	26.31
4	-	26.50	26.49	26.43	-	26.30
5	-	26.49	26.50	26.42	-	26.30
6	-	26.49	26.51	26.42	-	
7	-	26.49	26.52	26.41	-	
8	-	26.48	26.52	26.42	-	
9	-	26.48	26.52	26.40	-	
10	-	26.48	26.52	26.405	-	
11	-	26.49	26.51	26.39	-	
12	-	26.48	26.50	26.394	-	
13	-	26.49	26.51	26.394	-	
14	-	26.49	26.52	26.383	-	
15	-	26.50	26.51	26.379	26.36	
16	-	26.49	26.51	26.383	26.36	
17	-	-	26.50	26.36	26.352	
18	-	-	26.50	26.367	26.356	
19	-	-	26.49	26.364	26.337	
20	-	-	26.48	26.341	26.356	
21	26.47	-	26.49	26.341	26.348	
22	26.50	26.47	26.49	26.345	26.341	
23	26.49	26.50	26.47	26.341	26.337	
24	26.50	26.49	26.48	26.341	26.341	
25	26.50	26.49	26.48	26.337	26.326	
26	26.50	26.49	26.47	26.329	26.326	
27	26.50	26.49	26.45	-	26.326	
28	26.51	26.50	26.45	-	26.314	
29	26.50	26.48	26.47	-	26.318	
30	26.49	26.49	26.44	-	26.314	
31	26.49	26.49		-		

Appendix 6: Specifications of the SenseCAP Gateway



SENSECAP

An Industrial Wireless Sensor Network Solution

SenseCAP Gateway - LoRaWAN



Introduction

SenseCAP LoRaWAN Gateway(*) is based on LoRaWAN®(**) protocol, applicable for low-power, long-distance environmental data collection and monitoring in scenarios such as smart agriculture and smart city, etc. As the central device of the LoRa network, the gateway is used for collecting data from different Sensor Nodes and transmit the data to the SenseCAP Portal via 4G or Ethernet cable. Equipped with a high-performance processor and telecom-operator-level LoRa chip, this gateway ensures stable and high performance in a large-scale network. The gateway is designed with an IP68-protection-level enclosure, making it suitable for industrial applications in severe outdoor environments.

Specifications

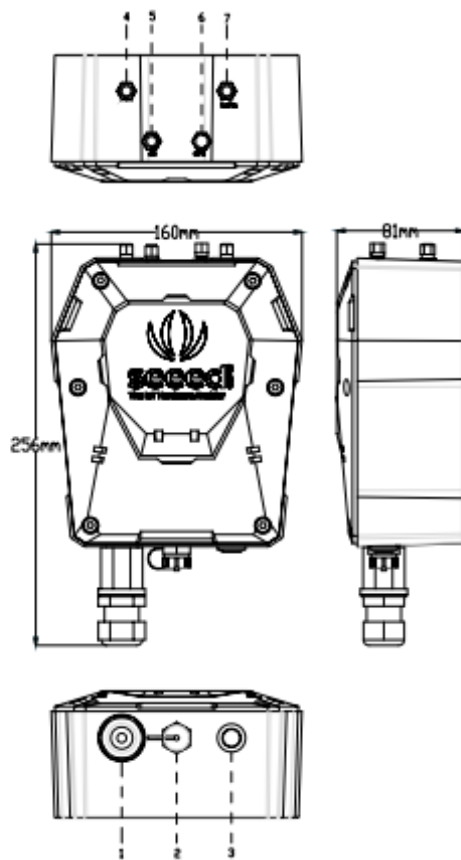
Product Model	
Model	Region
LoRa-G-470-E/4G	Asia (China)
LoRa-G-868-E/4G	European, Africa, Asia (India etc.)
LoRa-G-915-E/4G	North America, South America, Oceania, Asia (Japan, Korea, Thailand, etc.)
LoRa Parameters	
Protocol	Based on LoRaWAN v1.0.2 protocol
Channel Plan	470~510MHz 863~870MHz 902~928MHz
Power Output	24dBm 25dBm 25dBm
Sensitivity	-140dBm -139dBm -139dBm (SF12BW125) (SF12BW125) (SF12BW125)
General Parameters	
CPU	TI AM3358 Cortex-A8 1GHz
System	Linux Debian
RAM	DDR3 512MB
Memory	8GB eMMC
Ethernet	100Mbps FE (RJ-45)
4G Band	LTE-FDD: B1/B2/B3/B4/B5/B7/B8/B12/B13/B18/B19/B20/B25/B26/B28 LTE-TDD: B38/B39/B40/B41 WCDMA: B1/B2/B4/B5/B6/B8/B19 GSM: 850/900/1800/1900MHz
4G Features	Support non-CA Cat 4 FDD and TDD LTE-FDD: Max 150Mbps (DL), Max 50Mbps (UL) LTE-TDD: Max 130Mbps (DL), Max 30Mbps (UL)

General Parameters	
UMTS Features	Support 3GPP R8 DC-HSDPA, HSPA+, HSDPA, HSUPA and WCDMA DC-HSDPA: Max 42Mbps (DL) HSUPA: Max 5.76Mbps (UL) WCDMA: Max 384Kbps (DL), Max 384Kbps (UL)
LoRa Antenna	CN470: 0.5dBi gain / Vertical polarization / Omni-directional / SMA-J connector EU868: 2.5dBi gain / Vertical polarization / Omni-directional / SMA-J connector US915: 2.5dBi gain / Vertical polarization / Omni-directional / SMA-J connector
4G Antenna	0-4 dBi gain / Linear polarization / Omni-directional / SMA-J connector
LED Indicator	Indicating network condition (online/offline)
Grounding	Reserved 1 screw hole for GND
Power Consumption	3.6W
Power Supply	DC 12V/2A
IP Rating	IP68
UV Resistance	anti-aging (from rain/sun exposure): UL746C F1
Enclosure Material	PC
Operating Temperature	-40 °C to +70 °C
Operating Humidity	0 to 100 %RH (non-condensing)
Installation Method	Wall or pole mounting
Device Weight	777g

4

SenseCAP Gateway - LoRaWAN

Device Dimensions



1. Ethernet Port
2. Power Connector
3. LED
4. Reserved
5. 4G Antenna Connector
6. Reserved
7. LoRa Antenna Connector

Certification



Appendix 7: Water level Sensor Specifications

Water Level Sensor Specification	
Output	4~20mA, 0-10mA, 0-5V, 1-5V customization
Measured range	0-0.5~200mH ₂ O
Overload	150% of sensor range
Accuracy	$\leq \pm 0.2\%FS$,
Stability	$\pm 0.25\%$ FS/year
Housing material	Stainless steel
Cable material	Polyvinyl Fluoride, PTFE
Power Supply	0.33 -2.97VDC
Process temperature	-30~85°C
Compensation temperature	-20~70°C
Protection class	IP68